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SURFACE REHABILITATION OF LAND DISTURBANCES RESULTING FROM OIL SHALE DEVELOPMENT

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June 1974

ENVIRONMENTAL RESOURCES CENTER

Colorado State University
Fort Collins, Colorado

Technical Report Series No. 1

SURFACE REHABILITATION OF LAND DISTURBANCES RESULTING FROM OIL SHALE DEVELOPMENT

Final Report, Phase I

March 1, 1974

to the

COLORADO DEPARTMENT OF NATURAL RESOURCES
Thomas W. Ten Eyck, Executive Director

under terms of

Contract Encumbrance No. 2656 and Control No. 4061
dated July 1, 1972

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Price $10.00

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Chapter 1

GEOMORPHOLOGY OF PICEANCE CREEK BASIN

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INTRODUCTION

The Piceance Creek structural basin is located in northwestern Colorado (Fig. 1). It is a regional feature that is about 95 miles long and 50 miles wide. Part of this structural basin forms a distinct physiographic unit, the Roan Plateau, which is bounded on the east by the Grand Hogback, on the south by the Colorado River and the Book Cliffs, on the west by Douglas and Salt Creeks and the Cathedral Bluffs, and on the north by the White River. This is the Piceance Creek oil shale area of Colorado, and it occupies the easternmost portion of the Tavaputs Plateau, which is part of the Uinta Basin Section of the Colorado Plateau Physiographic Province (Thornbury, 1965, p. 425.)

The Piceance basin was a depositional low throughout Eocene time when the shales, marlstones, and sandstones of the Wasatch Formation and overlying Green River Formation were deposited (Donnell, 1961). These sediments are thickest at the axis of the basin and thin towards its perimeter. As a result, over almost the entire area the Evacuation Creek Member, the youngest unit of the Green River Formation, is exposed at the surface. Around the margin of the plateau and in canyons rock units are exposed in an orderly sequence from youngest to oldest. The Wasatch Formation is exposed along the base of the Grand Hogback to the east, in the valley of the White River to the north, in the Cathedral Bluffs to the west, and at the base of the Roan Cliffs and in Parachute and Roan Creek valleys to the south.

General Geomorphology

The Roan Plateau in the past has been of little interest to geomorphologists. As a result, the Uinta Basin Section has never been systematically studied. Only a very general description of the eastern part of the Tavaputs Plateau of which the Roan Plateau is a part is available, as follows: "The interstream divides are broad, consisting of a series of discontinuous cuestas upheld by local sandstones and indurated limey and siliceous zones. Both stream and dry washes are deeply incised in canyons. The topography is large scale and coarse grained, with distances of half a mile to a mile between tributary drainages. The entire topography is subsequent and in late youth. The area is completely drained, relief is at a maximum, and the largest streams are beginning to develop small flood-plain scrolls along their lower courses. Even the longest streams are mere trickles at the bottom of canyons almost 1000 feet deep; flash floods accomplish most of the erosion." This general description by Clark (1957) can be partly applied to the Piceance Creek area, but it provides neither useful information on landscape details nor on the erosional and depositional processes operating within the area.

The Piceance Creek area can be subdivided geomorphically into two parts, the boundaries of which are defined by the drainage divides between Piceance, Douglas, Roan and Parachute Creeks. The canyons and steep escarpments of the Douglas, Roan and Parachute Creeks drainage basins are in sharp contrast to the more subdued topography of the plateau surface which comprises the greatest part of the area (Fig. 2). Some observations of a reconnaissance nature provide a description of these two areas and serve to define the major geomorphic problems.

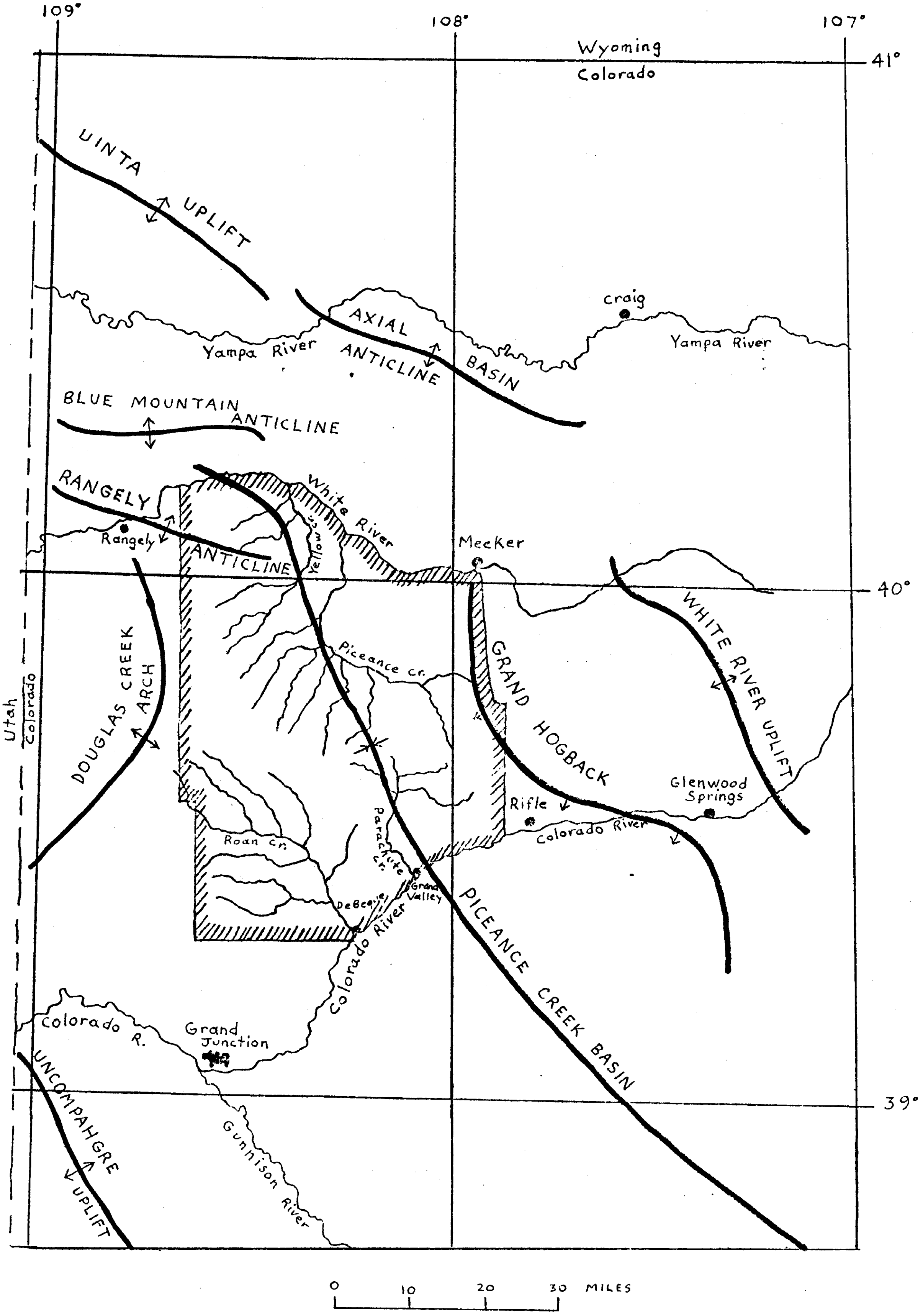

Fig. 1. Index map of northwestern Colorado showing location of study areas (Fig. 2) and major structural features of the region. (after Donnell, 1961)

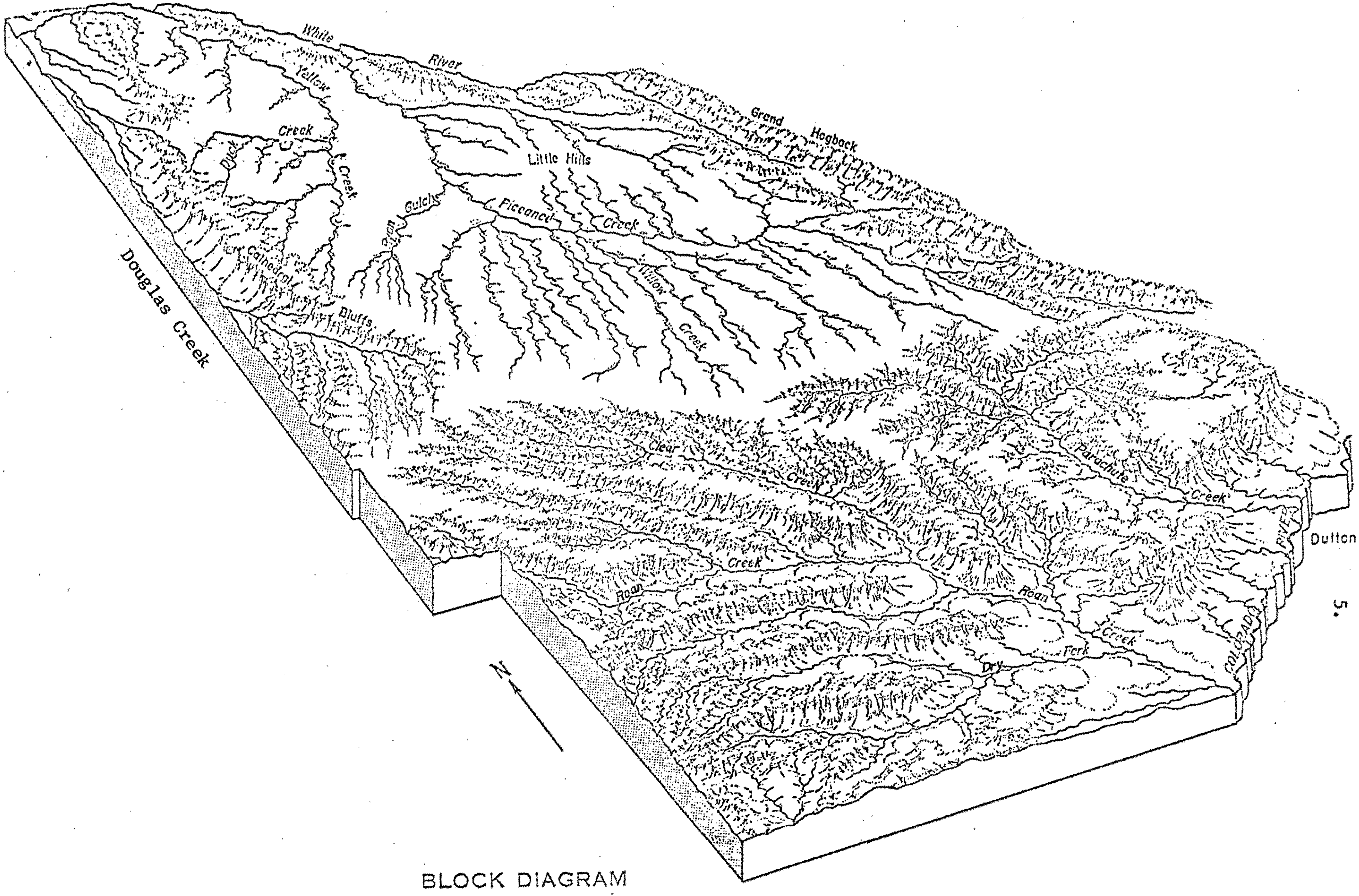

Fig. 2. Physiographic diagram of Piceance Creek area. For locations, see Fig. 1. (from Coffin et al, 1971)

Canyons and Escarpments

That portion of the area west of Cathedral Bluffs is rugged and not easy of access. Dendritic drainage patterns are incised into deep valleys, and V-shaped valleys with narrow flat alluvial floors are typical. The gradients of the tributaries to Douglas Creek are steep. For example, Philadelphia Creek rises at an altitude of 8000 feet, and it enters Douglas Creek at an altitude of 5800 feet. The 2200 feet of fall occurs over an airline distance of from 4.5 to 5.0 miles. These channels are efficient conveyors of water and sediment to Douglas Creek. This is especially true because the alluvial floor of each valley is trenched by a gully. Douglas Creek itself has incised into the alluvium of its valley.

The incision of Douglas Creek probably occurred during historic times, and it is this incision that is responsible for tributary erosion. Near the junction of East and West Douglas Creeks a small log cabin is partly buried in the alluvium of East Douglas Creek. This cabin is probably less than 80 years old and its door fronts directly on a 20-foot drop into the deep gully of East Douglas Creek. There appears to be little doubt that the incision of Douglas Creek has occurred since the construction of this cabin. The valleys of the Piceance Creek area are fragile, and where they are untrenched they are susceptible to erosion. In the Douglas Creek area erosion of the valley floors is rapid, and large quantities of sediment are delivered to Douglas Creek and thus to the White River itself.

To the south Roan and Parachute Creeks deeply dissect the Roan Plateau, forming steep-walled canyons that widened sufficiently downstream to permit agricultural activity on the valley floors. Total relief in the Roan Creek basin is about 4000 feet.

The steep cliffs and escarpments flanking the Roan Plateau should be susceptible to mass movement or landslides. Evidence for landslides along the Cathedral Bluffs is not obvious, but recent geologic mapping in the area indicates that it has occurred in the past (Roehler, 1972a, 1972b). It is clear also that landslides have occurred in the Roan Creek basin, during the recent geologic past, and the possibility of reactivating old slides or causing new ones is a concern in these valleys.

Plateau

On the plateau the topography is less rugged and the processes of slope erosion characteristic of semiarid regions become dominant (Schumm, 1964, 1967; Schumm and Chorley, 1966).

The drainage patterns are controlled at least in part by the dip of the Evacuation Creek member of the Green River Formation, and the alignment of headwater tributaries suggest a major control of their orientation and spacing by joints (Fig. 8). Further study of the effect of structure on drainage patterns and on the occurrence of mass movement would be of interest; however, the emphasis is placed on evaluating the stability of valley-floor alluvial deposits.

The streams occupy valleys that are very different from those in the Douglas Creek, Roan and Parachute Creeks drainage basins; they are less deep, and they have a flat valley floor, which may or may not be incised. Of major concern is the condition of these valley floors. Unlike Douglas Creek, the valleys do not everywhere contain a well-defined channel, but discontinuous gullies are common. The fact that the channels are not continuous means that much of the sediment conveyed through these discontinuous gullies does not reach White River or Piceance Creek, and that the sediment is retained within the basin. For example, Ryan Gulch is trenched only near the junction of several of its major tributaries, but downstream no well-defined channel occupies the valley floor.

The channels and valleys of the plateau at present do not appear to deliver appreciable quantities of sediment downstream, but the valley floors are inherently unstable and release of water into these channels could trigger a dramatic erosional response.

The development of discontinuous gullies, their coalescence to form arroyos, and the eventual healing of these channels by renewed deposition is a sequence of events that can be readily documented throughout the western United States (Schumm and Hadley, 1957). Therefore, the apparent stability of the alluvial valley-fill deposits in the area is deceptive, and the current condition of sediment storage could change quickly to major export of sediment with serious downstream consequences if and when the drainage lines become continuous.

The flat-floored valleys are separated by convex or flat-topped ridges. At present the erosion rates on these interfluve areas range from slight to critical with 3% of the areas in the Yellow Creek Unit subjected to slight erosion, 67% to moderate erosion, and 30% to critical erosion, according to an evaluation of present erosion conditions by the Bureau of Land Management (1971). The obvious effect of slope aspect is important with north-facing valley sides being better vegetated, gentler, and less susceptible to erosion. South and west facing slopes and valley-sides are steeper, less well vegetated, and obviously more vulnerable to raindrop impact and surficial runoff. The north-facing slopes will be subjected to more cycles of freeze and thaw during the year and probably soil creep occurs on these slopes. The asymmetry of some valleys (Figs. 10 and 11) apparently is the result of these very different erosion processes and rates of erosion on slopes of different aspect (Carson and Kirkby, 1972, p. 384-389).

Approach

The investigation of the geomorphology of the Piceance Creek basin was directed toward what appeared to be the two most significant geomorphic problems within the area, valley-floor stability and mass movement. These two subjects are considered in some detail in the remainder of this report. The study of valley-floor stability was completed by Mr. P. C. Patton (1973) as part of a regional investigation of gully erosion with financial support from Colorado Agricultural Experiment Station. The study of mass movement was undertaken by Mr. R. W. Olson. Both investigations were performed under the general supervision of the senior author, and this report is a summary of the results.

Another important objective of any geomorphic investigation is to determine present rates of erosion and deposition. Therefore, during July, August, and September 1972, field investigations in the Piceance Creek area were carried out in cooperation with the Water Resources Division of the U. S. Geological Survey, Denver, Colorado.

The purpose of this effort was to determine present rates of erosion and deposition in the Piceance Creek and Yellow Creek drainage basins. In order to accomplish this objective about 30 channel cross sections were located and surveyed. The cross sections will provide a basis for identifying changes in sediment yields which may accompany the development of the oil-shale resource.

In order to estimate rates of erosion on hillslopes, erosion transects were established on slopes of differing steepness, exposure, vegetation, bedrock, and elevation. Where pipelines cross the slopes, erosion transects were established, both on the revegetated pipeline path and on the adjacent natural slopes in order to compare the effects that disturbance and revegetation have had on the normal rates of erosion. The results of these erosion studies will be reported by the U. S. Geological Survey.

An approach to the quantitative description of terrain was also investigated. A computer program was developed that will produce a landform map based on slope inclination and slope aspect. These variables can be related to solar radiation, and it is possible that the generation of such maps may have application to the problems of hillslope erosion and to the variability of erosion and vegetation within the Piceance Creek area. However, the high cost of such map preparation prevented further work of this type.

VALLEY-FLOOR STABILITY, YELLOW AND PICEANCE CREEKS

A major objective of the geomorphic investigation was to develop criteria for the identification of sites where gully erosion is most likely to occur in the valleys of the Roan Plateau. Schumm and Hadley (1957) provided the basis for this part of the study by demonstrating that discontinuous gullies develop on over-steepened valley slopes, and they suggested that the slope at which gullying occurred was probably related to discharge. It is obvious that when the oil shale resource is developed, the changing character of the land, its vegetation and hydrology may render the fragile alluvial valley floors unstable. The ability to recognize incipiently unstable valleys should be of value in management and rehabilitation of the area.

The Piceance and Yellow Creek drainage basins (Figs. 1 and 2) are characterized by narrow linear alluvial valleys, steep valley-side slopes and broad interfluves. Maximum relief is about 3000 feet, ranging from an altitude of 8500 feet on Cathedral Bluffs to 5700 feet at the junction of Piceance Creek and White River. The drainage pattern is remarkably parallel and strongly suggestive of structural control (Fig. 8).

Piceance Creek, which has its headwaters east of the axis of the Piceance structural basin (Fig. 1), has a drainage area of 629 square miles. The stream flows west and north through the northern half of the basin, and the major tributaries enter from the south. Piceance Creek has perennial flow, but the majority of its tributaries have only ephemeral flow, with the exception of a few which have intermittent flow from springs. Yellow Creek (Fig. 8), which has a drainage area of 258 square miles, rises on Cathedral Bluffs, and flows northeastward to White River. It is an asymmetrical drainage basin with the largest tributaries entering from the west. Yellow Creek has intermittent discharge, but most of its tributaries flow only during and after precipitation events.

The Evacuation Creek and Parachute Creek Members of the Green River Formation form the plateau surface. The Evacuation Creek Member is a light brown and gray sandstone with interbedded siltstones and marlstones (Duncan and Denson, 1945). The underlying Parachute Creek Member is a black, brown, and gray marlstone, which is economically important as the principal oil shale member.

The climate on the plateau is semiarid (Trewartha, 1954), and precipitation increases with elevation, exceeding 24 inches per year above an elevation of 8500 feet (Marlatt, 1971). Much precipitation occurs as snow, and at Meeker 90 inches of snowfall is the yearly average. This provides about half of the average annual total.

In the alluvial valleys, sagebrush and greasewood are the predominant vegetative cover, although alfalfa is grown on the flood plain of the Piceance Creek and in a small area along Yellow Creek. Scattered pinion pine and juniper grow on the hillslopes and divides. Mountain mahogany and scrub oak grow at higher elevations.

The effect of the valley aspect on microclimate and, therefore, on vegetative cover is striking, particularly when the valleys trend east-west and have north and south facing slopes.

Gully Erosion

Gullying occurs throughout both the Yellow Creek and Piceance Creek drainage basins. Three alluvial valleys were surveyed to determine if, indeed, channel incision is caused by locally steeper reaches of the valley floor. The longitudinal profiles and channel cross sections of the valley reaches selected for detailed study are shown in Figures 3, 4, and 5.

Middle Barcus Creek joins Barcus Creek about six miles upstream from the junction of Barcus Creek and Yellow Creek (Fig. 8). The gullied part of the valley is located in section 24, T1N, R99W, about 0.75 miles upstream from the junction of Barcus Creek, and it is shown on U.S.G.S. 7 1/2 minute Barcus Creek SE topographic quadrangle. The gully is about 1300 feet long, has a five foot headwall, and reaches a maximum depth of 8 feet (Fig. 3). There is no well defined channel upstream from the vertical headwall, instead several anastamosing depressions cross the valley floor, and sediment is being deposited in this reach.

Valley slope above the vertical headwall is 0.009 ft/ft, whereas valley slope ranges from 0.023 to 0.020 ft/ft where incision has occurred. The gully has developed in a portion of the valley alluvium which is locally steeper than that upstream or downstream.

Greasewood Creek enters Yellow Creek about 2.5 miles upstream from the junction of Yellow Creek and the White River (Fig. 8). The valley longitudinal profile was taken from U.S.G.S. 7 1/2 minute Barcus Creek and Rough Gulch topographic quadrangles. The gully is about 12,000 feet long and has a vertical headcut 26 feet high (Fig. 4). The location of the headcut is about five miles upstream from the junction with Yellow Creek in section 36, T2N, R99W.

The slope of the valley above and below the gully is about 0.018 ft/ft, but the gully is entrenched in a steeper segment of the valley, where the slope is 0.027 ft/ft.

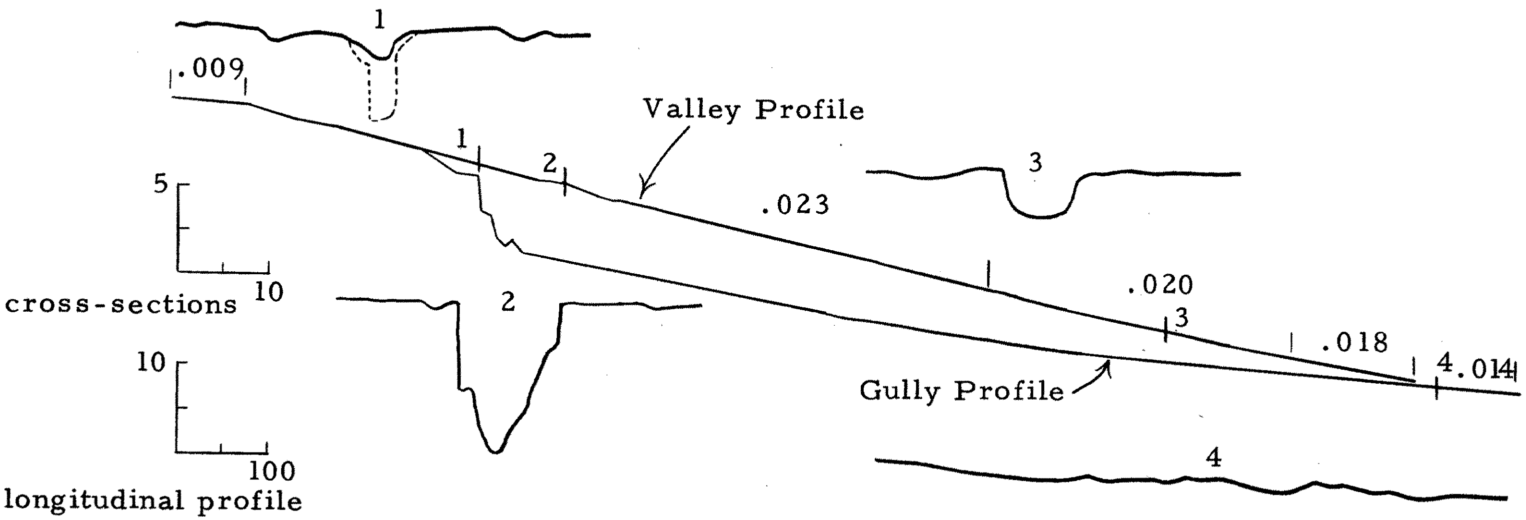

Figure 3. Longitudinal profile and cross-sections, Middle Barcus Creek.

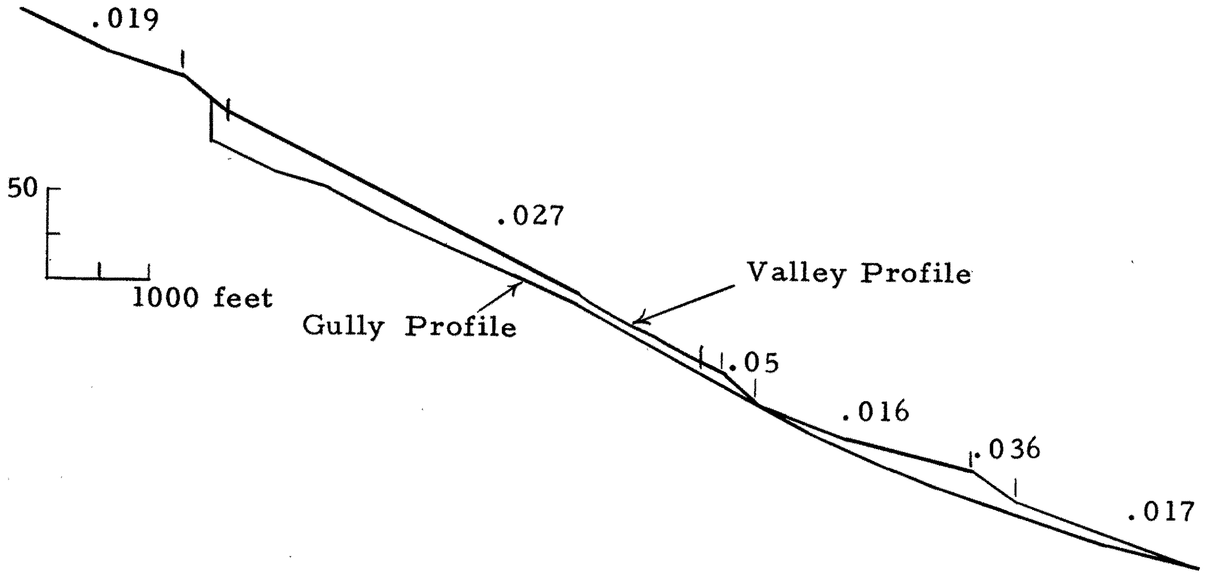

Figure 4. Longitudinal profile, Greasewood Creek.

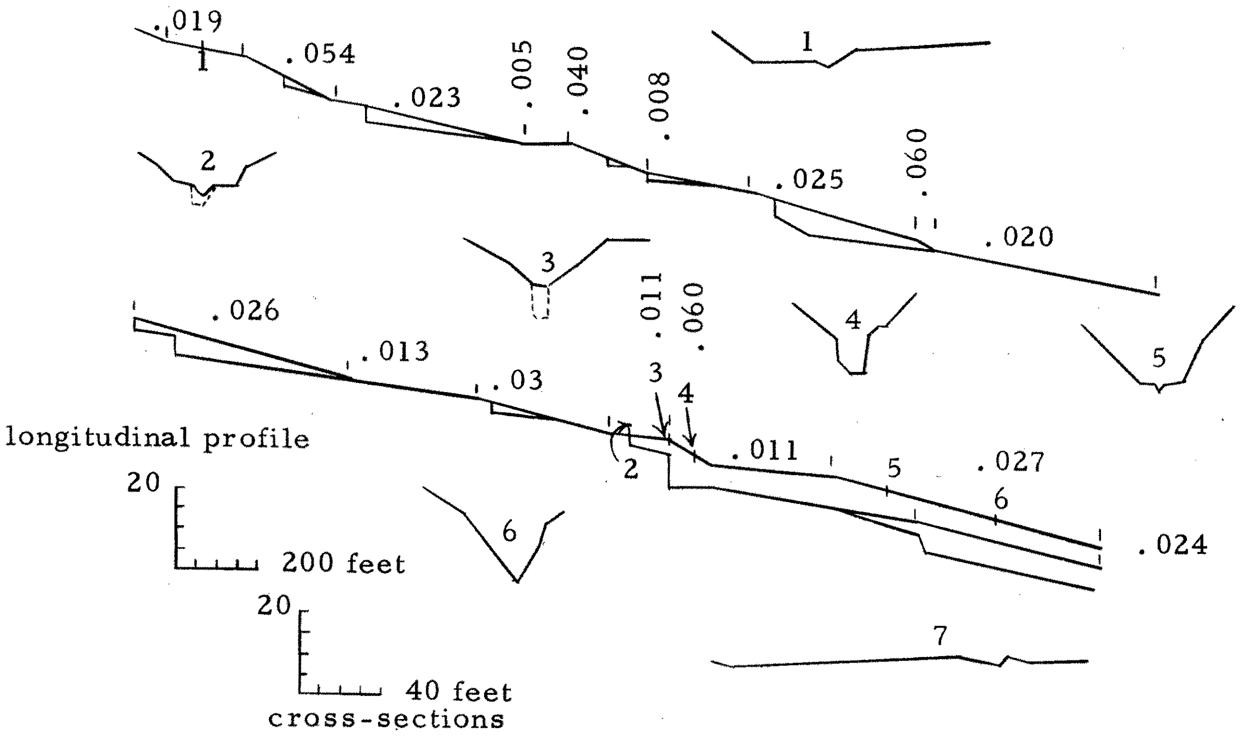

Figure 5. Longitudinal profile and cross-sections, Scandard Gulch. Cross-section 7 is located just upstream from the junction with Willow Creek.

Scandard Gulch is a tributary of Willow Creek about two miles upstream from the junction of Willow and Piceance Creeks. The gully is located in section 24, T3S, R97W, about 3.5 miles upstream from the junction with Willow Creek, on the U.S.G.S. Jessup Gulch 7 1/2 minute topographic quadrangle.

There is no channel at section 1 (Fig. 5), however the upper 3000 feet of the profile is characterized by a series of small discontinuous gullies, ranging in size from less than one foot deep to a maximum of five feet deep. Those gullies, which are actively eroding upvalley, are distinguished by a narrow raw channel. In contrast, those gullies that are inactive have a wider channel at the headwall and vegetation is stabilizing the channel downstream. Along this profile, it is evident that the gullies form where the valley alluvium is critically oversteepened, as is the case in Middle Barcus and Greasewood Creeks.

Effect of the alluvial fans: The irregular nature of valley profiles in an arid or semiarid climate is not a new observation, and Rich (1911) recognized that these irregularities are the product of tributary streams, which deposit large quantities of material and form alluvial fans on the otherwise flat alluvial valley floors.

The effect of alluvial fan deposition on the valley profiles is particularly noticeable in the narrow valleys of the Piceance and Yellow Creek basins. In several valleys the alluvial fans extend completely across the valley floor and in effect create natural dams.

The relation between discontinuous gullies and alluvial fans is best illustrated in Ryan Gulch, where gullies have developed on the steeper downvalley toes of two large alluvial fans. Another effect of the alluvial fans is to confine a channel to one part of the valley and to restrict its width.

Critical Valley-Floor Slope

Discontinuous gullies in the Piceance and Yellow Creek drainage basins develop where the valley slope is steepest, and it has been suggested that for a given discharge there should exist a critical or threshold valley slope above which trenching of the valley floor should occur (Schumm and Hadley, 1957). In order to determine whether such a relation pertains for the Piceance Creek area, valley slope was measured at 22 locations where a gully exists, and the drainage basin areas above the gully was used as a substitute for discharge. This is necessary because surface water runoff data are not available, and there is a high correlation between drainage area and discharge for areas of similar climate, geology and land use (Burkham, 1966). Valley slope and drainage area were also measured for 33 ungullied-valley locations. When these data are plotted, the expected inverse relation appears (Fig. 6), but a line can be drawn through the lower limit of scatter of the points representing gullied valleys. This line represents, for a given drainage basin area, a critical value of valley slope above which entrenchment of the alluvium will occur and below which valley floors are stable. Discriminant function analysis was used in order to determine the statistical validity of the distinction, and the results, when all the data were used, were not statistically significant. However, when the discriminant function was computed for basins with drainage areas greater than four square miles, the results were significant.

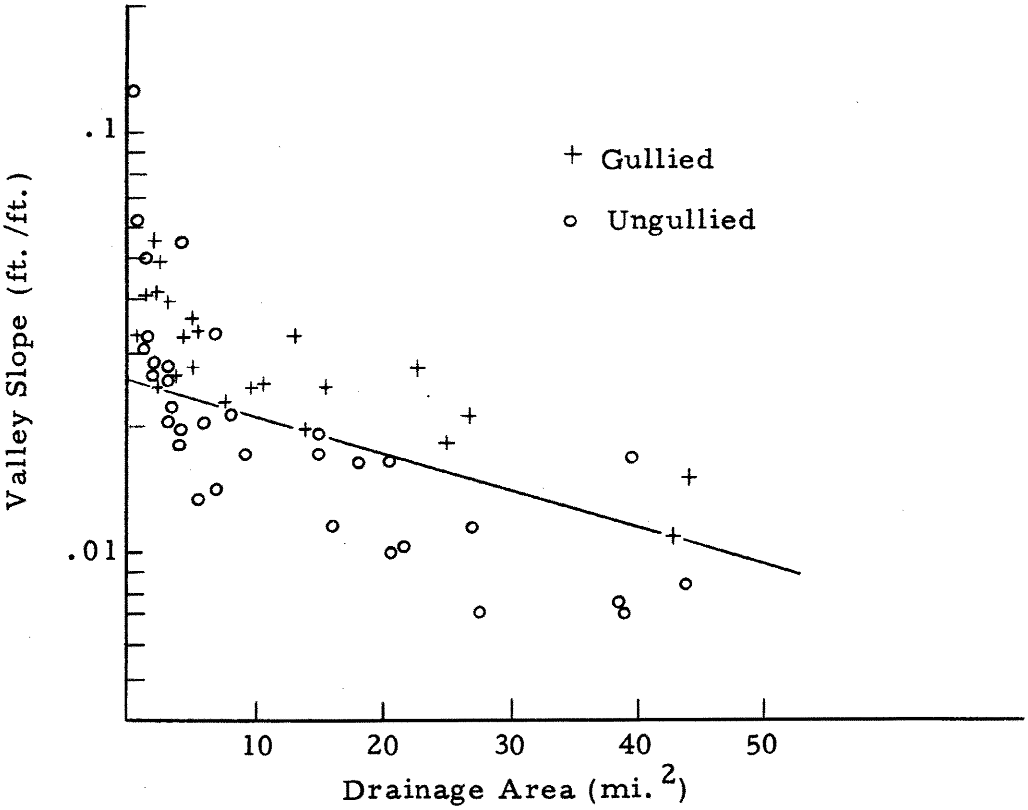

Figure 6. Slope-area relationship for gullied and ungullied valleys in the Piceance Basin.

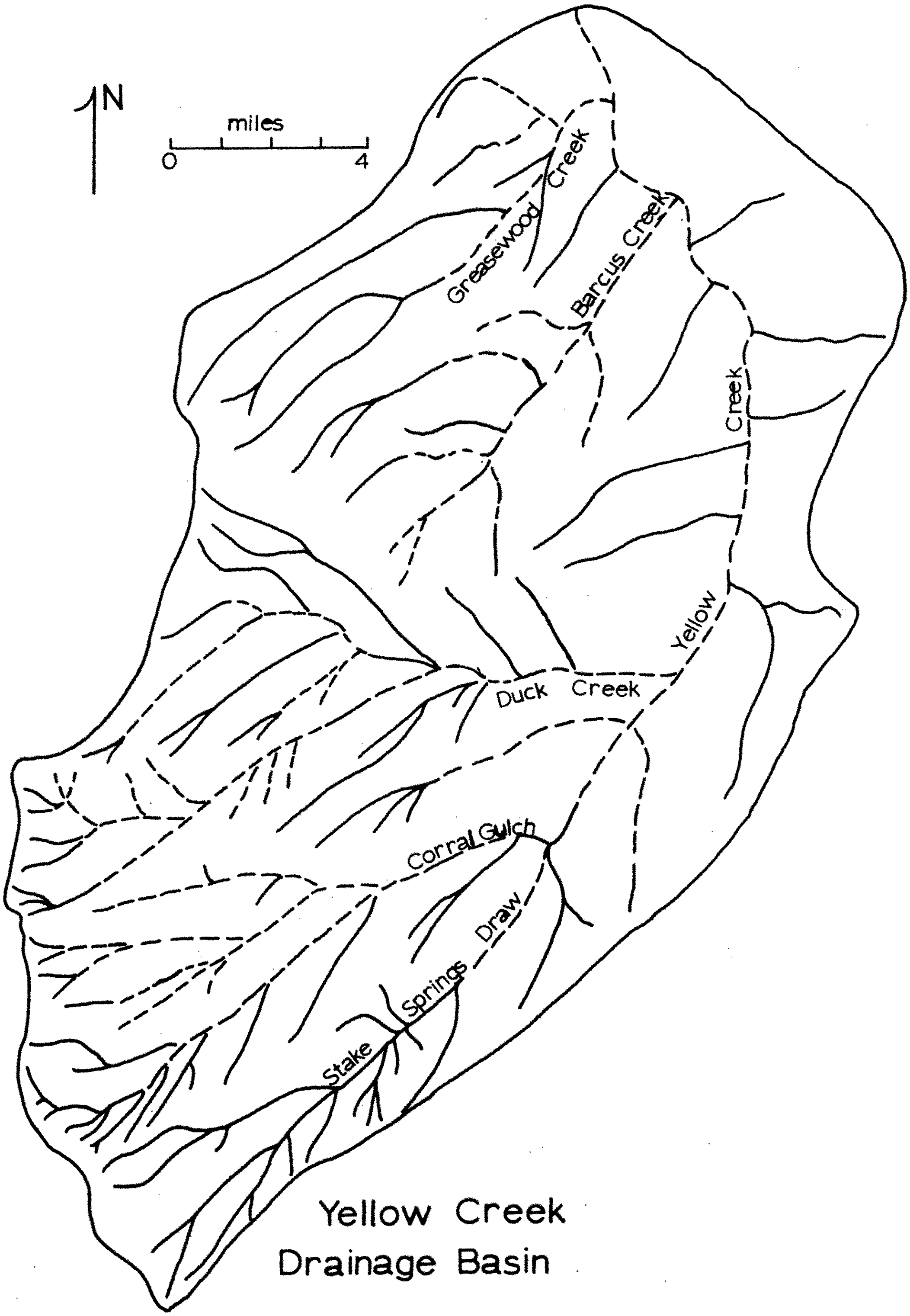

Figure 7. Map of Yellow Creek drainage basin. Dashed lines represent gullied channels.

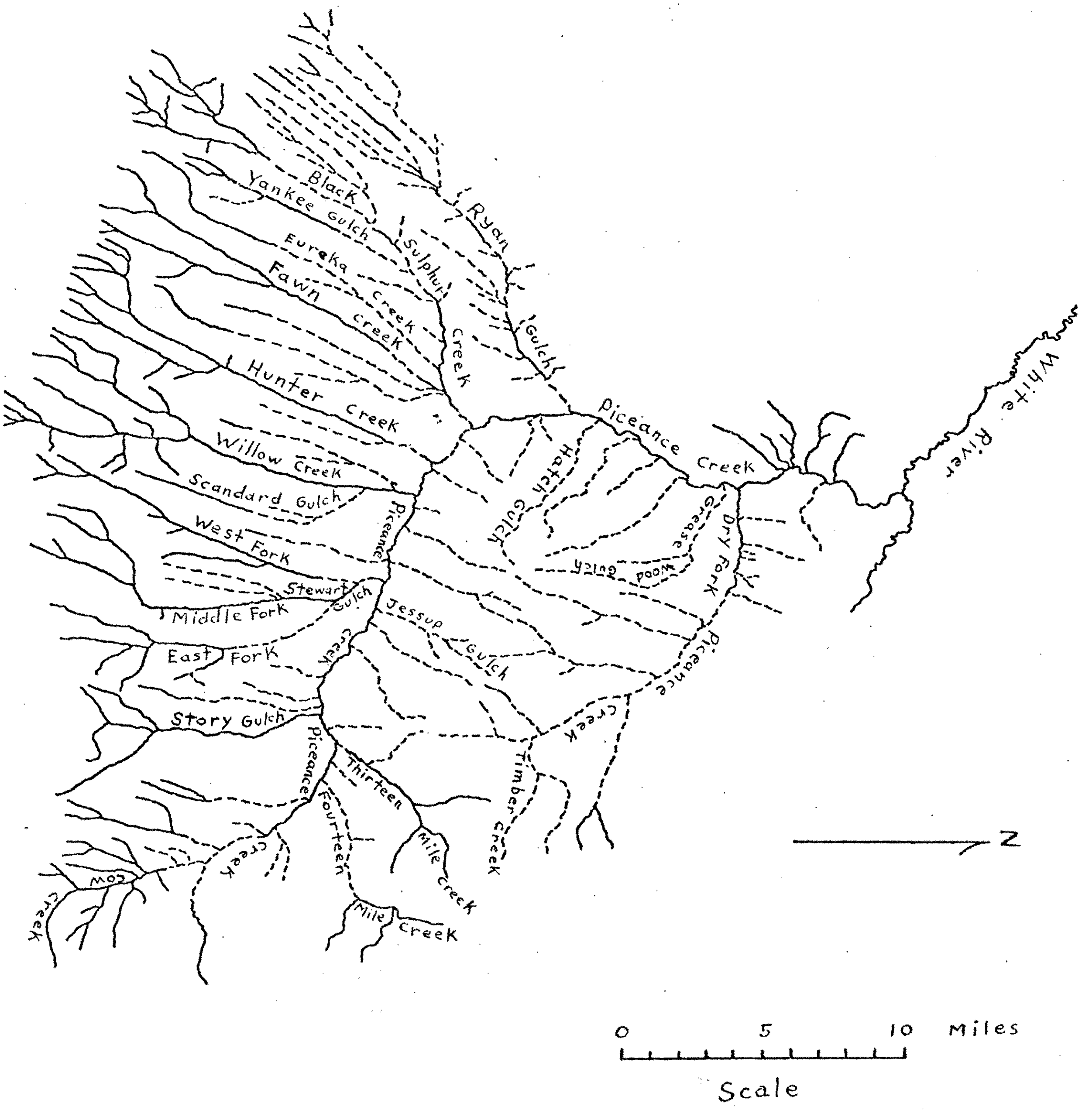

Figure 8. Map of Piceance Creek drainage basin. Dashed lines represent gullied channels. Solid lines represent stable channels or ungullied valley floors.

The lack of statistical significance, when drainage areas less than four square miles are included, is explained by the overriding influence of basin aspect. That is, in small drainage basins, which are north facing, vegetation is more dense than in south facing basins, and therefore valley slope is stable at higher slopes because of the better vegetational protection.

For drainage basins larger than four square miles, the relationship is significant, and it is suggested that ungullied valleys which plot above the critical line, represented by values at 7 and 42 square miles (Fig. 6) are highly susceptible to gullying. It must be emphasized that this relationship is only valid for this area. However, additional work elsewhere should permit development of similar relations.

Erosion potential: Discontinuous gullies are a natural occurrence in semiarid drainage basins, and they are the conduits by which sediment is moved downvalley. This process continues until the channel at the mouth of the basin becomes oversteepened from deposition, and incision occurs. When this happens, the entire basin becomes vunerable to erosion.

In the Yellow Creek basin, tributaries are being rejuvenated by the headward erosion of Yellow Creek (Fig. 7). At present there are active gullies in Greasewood, Barcus, and Duck Creeks. These gullies will eventually coalesce with upstream discontinuous gullies, thereby integrating the drainage system and permitting efficient removal of valley alluvium. In addition, the gully in the valley of Yellow Creek is only about one mile from the discontinuous channels in Stake Springs Draw and Corral Gulch valleys (Fig. 7). When these channels unite, sediment from this area will be transported into Yellow Creek. When the supply of sediment becomes too great for the channel to accommodate, deposition will begin in Yellow Creek.

In the Piceance Creek drainage basin, the situation is not as critical (Fig. 8). Although Piceance Creek is trenched near its mouth, it has eroded to bedrock and is stabilized by this natural drop structure. In many of the valleys, such as Hunter and Willow Creeks and Ryan Gulch, previously eroding gullies appear to be stabilized by vegetation, and in Willow Creek an earthfill dam, which was destroyed by gully erosion, has been rebuilt. Perhaps in the Piceance Creek drainage basin the economics are such that this maintenance is feasible, whereas in the less productive Yellow Creek drainage basin, it is not.

In summary, the development of a discontinuous gully does not in itself represent a serious problem in terms of sediment production and rangeland destruction; but it reflects valley instability and portends the possibility of the future erosional destruction of an entire drainage system.

VALLEY MORPHOLOGY AND LANDSLIDES

The high relief and rugged topography of the southern half of the Piceance Creek area presents very different geomorphic problems from those of the plateau proper. Evidence of mass movement or landsliding is obvious, especially in the 550 square mile Roan Creek drainage basin (Fig. 12), and the potential for slope failure appears significant in contrast to that in the Piceance and Yellow Creeks drainage areas.

General Geology and Geomorphology

Rock units exposed in the Roan and Parachute Creeks basins are of Eocene age and consist of the fluvial Wasatch Formation and the overlying lacustrine Green River Formation (Donnell, 1961, p. 148).

Traveling up Roan Creek from its confluence with the Colorado River at De-Beque, one can readily see the contact between the Wasatch Formation and the overlying Green River Formation. The upper Wasatch Formation is predominantly red while the lower Green River Formation is light gray or buff, and the contact is commonly marked by a change in slope. The Green River Formation forms cliffs and steep slopes of canyon walls, whereas the Wasatch Formation forms lower and flatter areas of the canyons. Badland topography is common on areas underlain by the Wasatch.

The Wasatch Formation has a maximum exposed thickness of 1100 feet in this area, and it consists of a red, gray, and maroon shale, and irregularly distributed lenticular sandstones (Waldron, F. R., J. R. Donnell, and J. C. Wright, sheets 1 and 2, 1951).

The Green River Formation is divided (in ascending order) into the Douglas Creek, Garden Gulch, Parachute Creek, and Evacuation Creek Members. The Douglas Creek Member consists of brown sandstone and gray shale, with a few beds of oolites and algae beds, and it forms slopes and low cliffs; it has an exposed thickness of about 410 feet in the vicinity of Clear Creek (Fig. 9). The Garden Gulch Member, with a thickness of 480 feet in the lower reaches of Clear Creek, consists mainly of gray marlstone and some gray and brown shale, with a few thin beds of oil shale. It weathers to smooth steep slopes. Overlying the Garden Gulch Member is the Parachute Creek Member, which varys in thickness from about 580 to over 1000 feet in the Roan Creek area and to 1200 feet in the Parachute Creek area. It weathers to light gray and light brown cliffs, and consists mainly of black, brown, and gray marlstone (the principal oil shale zones), some thin beds of altered tuff, analcite, and chert, and tongues of sandstone and siltstone at its base. Above the Parachute Creek Member is the Evacuation Creek Member,which is composed of gray and brown sandstone with interbedded gray marlstone and some beds of oil shale and siltstone towards the base. It weathers to brown and yellow rounded slopes. In the western part of the Roan Creek basin, the Garden Gulch and Douglas Creek Members grade into the Lower Shaly Member, which is composed mainly of gray marlstone (barren of oil shale) with some beds of gray and brown siltstone and limestone in the upper part, and largely of gray shale in the lower part. Exposures of the Lower Shaly Member from 1000 to 1180 feet thick appear along North Dry Fork, Kimball Creek, Carr Creek, and upper Roan Creek. It usually weathers to slopes and low cliffs. In the southern part of the Parachute Creek basin the Douglas Creek and Garden Gulch Members grade into the Anvil Points Member which consists largely of brown sandstone with some gray shale and marlstone (Waldron, Donnell, and Wright, sheets 1 and 2, 1951; Donnell, J. R., plate 48, 1961).

The Roan Creek drainage basin is located on the southwest flank of the Piceance Creek structural basin, whereas Parachute Creek is situated near the axis of this basin (Fig. 1). Beds of the Green River Formation generally dip to the northeast about 40 feet per mile in the Roan Creek area, but this orientation is complicated by two northwest-trending structural features (Fig. 9, the Clear

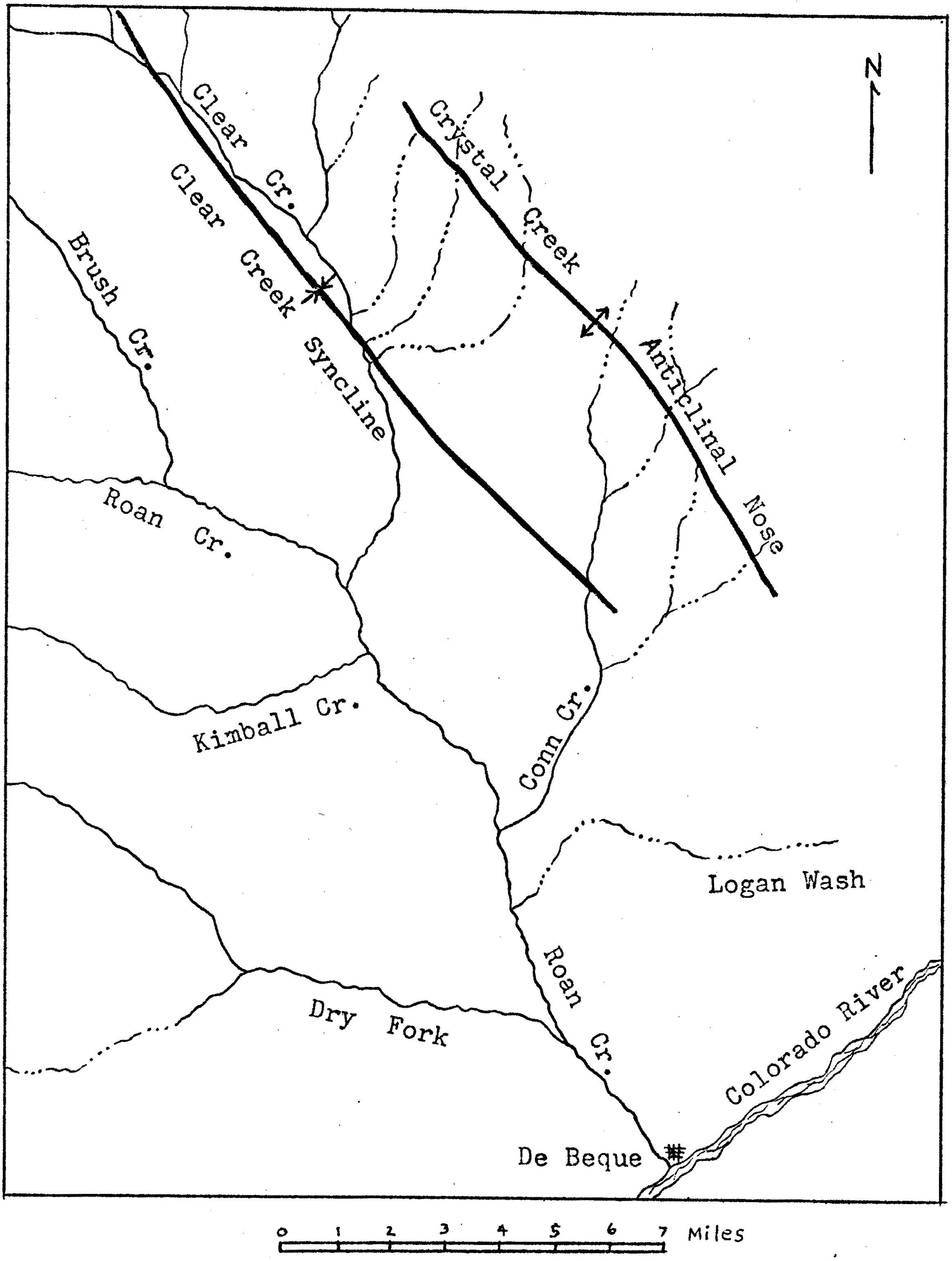

Figure 9. Structural features in the Roan Creek area. (from Donnell, Plate 48, 1961)

Creek syncline (elongate in the northwest-southeast direction), and the Crystal Creek anticlinal nose (Waldron, Donnell, and Wright, sheet 2, 1951). Beds on the northeast flank of the anticlinal nose dip about 100 feet per mile, whereas the dip is 200 feet per mile on the steepest part of the southwest flank. The average dip on the southwest flank of the Clear Creek basin is about 50 feet per mile.

Landslides

Small landslides and their scars are common in Roan Creek. These landslides are a combination of a rockslide-slump type of movement. Their recent age is demonstrated by the fresh appearance of the scars and slip faces on the slopes and by disruption of vegetation. Recent slides are found on outcrop areas of all of the formations except the Evacuation Creek Member. A total of 55 such slides were identified. Frequency of occurrence with regard to slope aspect (the compass direction toward which the landslide is facing) is as follows: north, 9; south, 2; east, 10; west, 6; northwest, 6; northeast, 10; southwest, 8; and southeast, 4. Slopes facing to the north, northeast, and east seem to be favored slightly over other directions for recent landslide development. This is expectable because these slopes receive less solar radiation and are generally wetter (Shroder, 1971).

For example, one of the most striking features in both the Roan and Parachute Creeks areas is the control that slope aspect has on vegetation. South, southwest, and west facing slopes usually have a sparse vegetative cover consisting of juniper, pinon pine, and other bushes, while north, northeast, and east facing slopes have a denser vegetative cover, consisting of Douglas fir, pinon and juniper, mountain mahogany, and grasses.

In contrast to the Roan Creek situation, there are only two rock slides in the Parachute Creek basin. They are small and involve rocks of the Wasatch Formation and the Douglas Creek Member of the Green River Formation.

In addition to the small slides, there are numerous large landslides in the Roan Creek basin. These are not recent slides, and it is assumed that the greater part of this mass movement activity occurred during the Pleistocene epoch, when the climate was cooler and wetter. During that time, glaciers were present on the Grand and Battlement Mesas to the south (Yeend, 1969), and average temperatures could have been from 10^{o} to 15^{o} lower and annual precipitation could have been 10 inches greater than at present (Schumm, 1965, p. 786). These past climatic conditions were favorable for landslide occurrence. Nevertheless, during development of the oil shale resource, and during rehabilitation, if the slopes become wetter landsliding may again become important. For this reason the major landslides were located and an explanation of ther distribution was attempted (Olson, 1974).

A notable feature of the valleys of Roan Creek and its tributaries are benches that appear one-third to about mid-way up on the valley walls (Fig. 10 and 11). Elongate in nature, these benches are found along Dry Fork, Kimball Creek, Roan Creek, Carr Creek, and to a lesser extent along Brush and Clear Creeks. Superimposed on top of some of the wider benches are rounded hills or knobs, good examples of which can be seen on the flanks of Kimball Mountain.

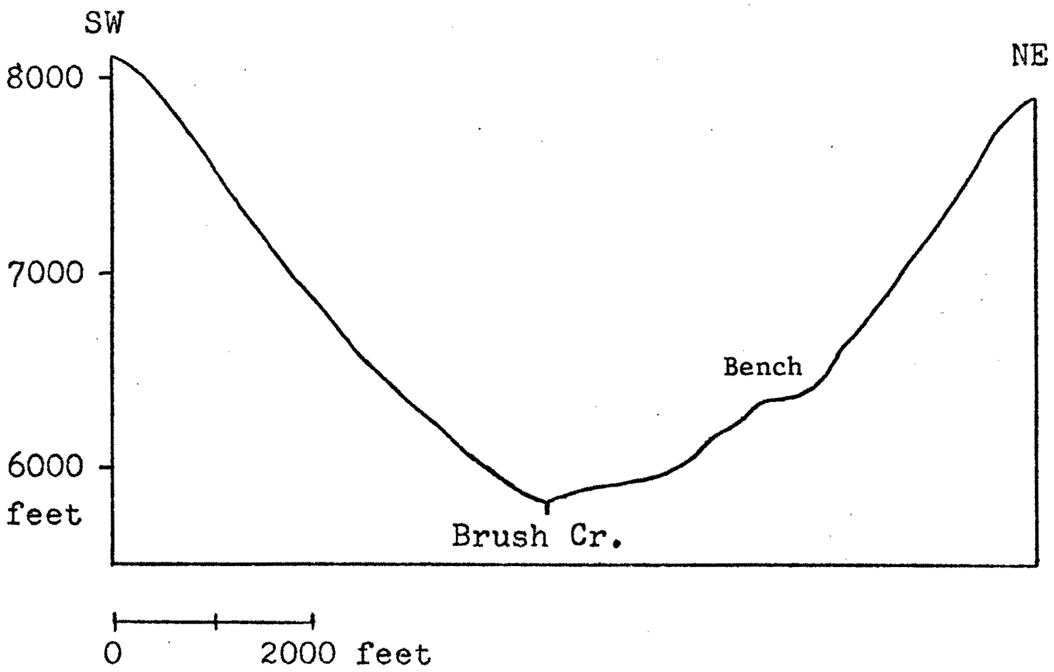

Figure 10. Cross valley profile of lower Brush Creek.

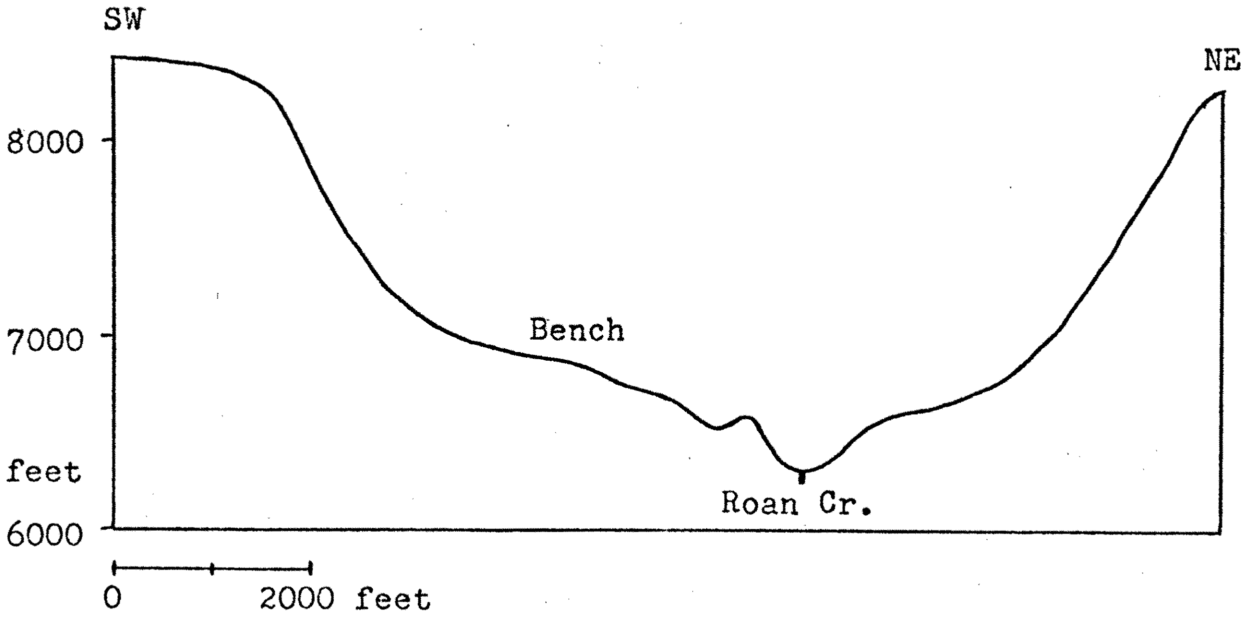

Figure 11. Cross valley profile of upper Roan Creek.

It is not uncommon to find benches in series so that the valley wall has a stair-step appearance.

Initially it was assumed that all of the benches were due to landsliding from the canyon walls, but not all benches are of landslide origin. Some are due to structural controls and others are relicts of an older valley surface. An old valley surface is suggested in some cases because the benches form a semi-continuous surface that slopes in the same direction as the present valley floor. Such surfaces can be seen in the valleys of Roan, Carr, and Kimball Creeks. In the vicinity of the confluence of Left Fork Carr Creek and Carr Creek, landslides have come to rest on this old valley surface, which is represented by a wide bench. Also, material from the lower flanks of this bench has slid off into the valley, thereby affecting the stream course. Due to the complexity of the field situation, it was necessary in many cases to utilize several types of evidence to identify an old landslide.

Identification of Major Landslides

The following criteria were used to identify landslides or those portions of benches that were influenced by mass movement processes: strike and dip of exposed formations, morphology of the benches, presence of a cliff face, and presence of hummocky topography.

The Green River and Wasatch Formations normally have very gentle dips, therefore any outcrops which contained beds dipping steeper than 8-10° were classified as landslides. All ranges of dip were encountered, the most common being 20-40°, although in some landslides vertical beds were exposed. Commonly a wide variation in bed attitude existed even within a single slide. The strike of the beds were usually parallel or sub-parallel to the valley walls. Many of the rounded hills and knobs in the Roan Creek area were found to be composed of steeply dipping beds, which suggested a landslide origin for this topography.

Bench morphology also provided a basis for landslide identification. In most cases where dipping beds were encountered, the bench surface sloped back toward the cliff. These backslopes ranged from a few degrees to as much as 30 degrees. Because dipping beds and the backslope usually occurred together, the existence of a noticeable backslope on the bench was suggestive of a landslide origin. Landslide benches and ridges usually have their long axes parallel to the valley walls so the backslope area appears as a small valley perched on the flanks of the larger valley. In many cases there are two or three benches at successively lower elevations and parallel to one another where multiple landslides have occurred.

The occurrence of fresh or recent appearing shear cliff faces also was accepted as evidence of mass movement. Although the Parachute Creek Member forms cliffs, the cliffs behind landslides have fewer ledges, and are fresher appearing than the cliffs formed by weathering.

In the canyons of upper Carr Creek, upper Roan Creek, and Kimball Creek, there are extensive areas of hummocky terrain in association with landslide benches and knobs; therefore it was assumed the hummocky terrain is also a result of landslide activity.

All of the afore mentioned criteria were used to delineate features of landslide origin, and no decision was made on one factor alone.

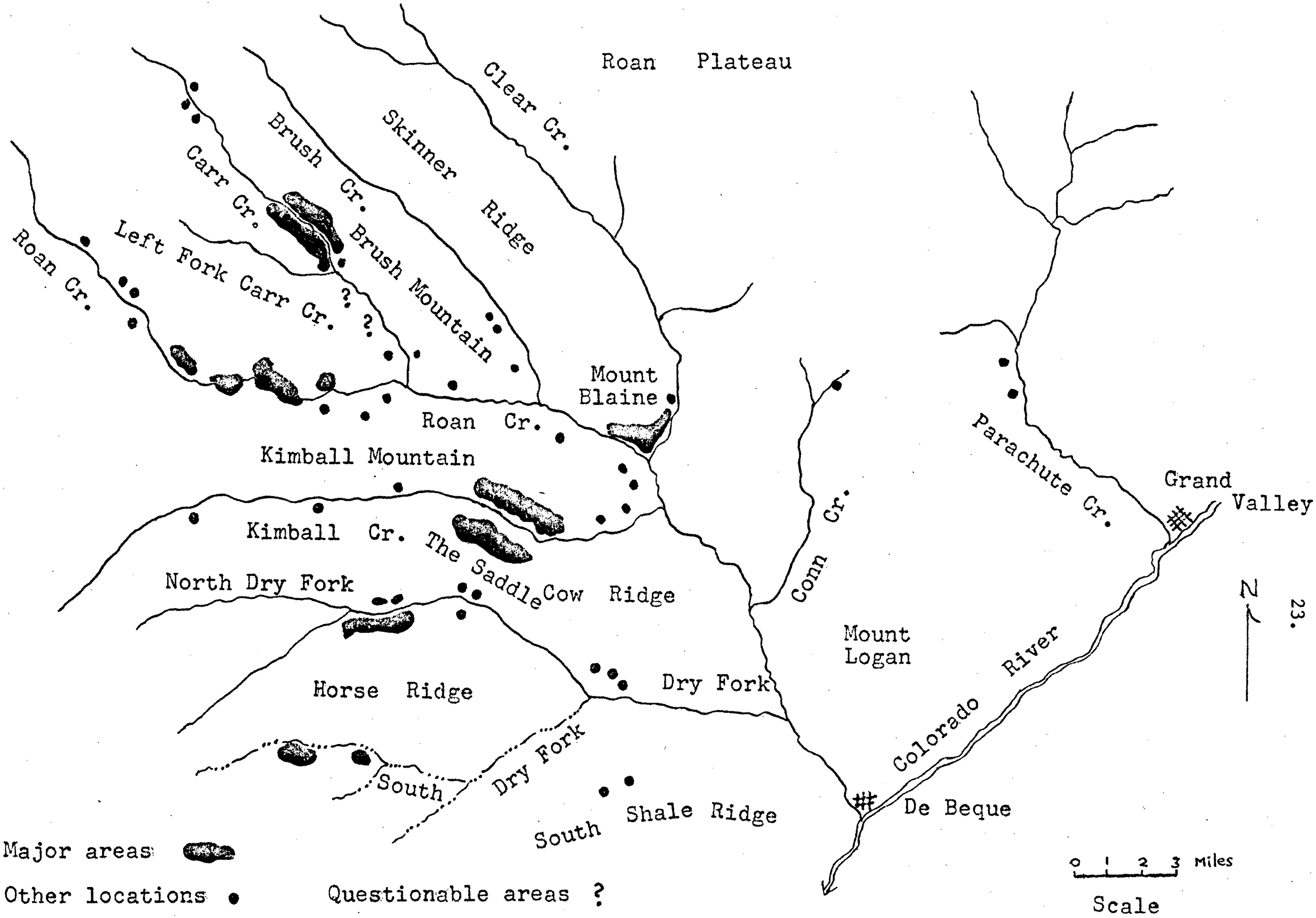

Fig. 12. Generalized map of large landslide deposits

Landslide Morphology and Distribution

Benches and ridges of landslide origin are the result of slumping. A slump is a special type of landslide (Eckel, 1958) that is due to movement on a circular shear plane. A slump block moves downslope with a backward rotation on this curved slip plane, which parallels the parent scarp or cliff face. Large landslides of this type are called Toreva-blocks by Reiche (1937), who identified them along the steep escarpments of the Colorado Plateau. The major landslide blocks in the Roan Creek basin may be up to 2000 feet along with widths exceeding 1000 feet. Smaller blocks are of course common.

Hummocky topography is commonly found on the lower flanks of the blocks, but there are hummocky areas not associated with the Toreva-blocks which are due to rock and debris slides (Sharpe, 1960, p. 74, 76) of dimensions generally smaller than the large Toreva-blocks. In the Mount Blaine area (Fig. 12) Toreva-blocks and rock slides have produced a complex landscape consisting of benches, ridges, and hummocky topography.

On Figure 12, the distribution of mapped landslides is shown. Major areas consist of landslide complexes of all dimensions, whereas isolated large landslides are designated as "other locations". It is striking that the landslides are confined to the Roan Creek drainage basin. Although Parachute Creek is only ten miles away and its morphology and geology is similar, the landslides are concentrated in the Roan Creek area. In order to explain the distribution of landslides, the following factors were considered:

1. elevation and relief
2. slope aspect and climate
3. structural and subsurface hydrologic conditions
4. lithologic controls

Elevation and relief: All of the major landslide deposits are found in an elevation range of 5600 to 7600 feet above sea level, and landslides are limited to areas of high relief, 2000 feet or more. Both Parachute and Roan Creek valleys have similar elevation and relief characteristics, therefore these factors cannot explain landslide distribution.

Slope aspect and climate: Concerning slope aspect, the following distribution has been observed:

Slope Aspect	No.of slide deposits	Slope Aspect	No.of slide deposits
N	18	NE	14
S	24	NW	3
E	3	SE	4
W	1	SW	10

Slides with a south-facing aspect outnumber those with a north-facing aspect; this seems contrary to logical expectations because slopes with a north aspect are generally wetter and are more prone to landslide activity, as evidenced by the distribution of the most recent landslides. Figure 12 shows that landslide distribution is not critically determined by slope aspect.

Parachute Creek and Roan Creek have similar precipitation characteristics. Annual precipitation is about 16½ inches for Parachute Creek (Dames and Moore, 1972), and precipitation records of the Roan Creek area (recorded by Orville C. Alterbern for the U. S. Dept. of Commerce, 1972) indicate an annual average of about 15 inches near the confluence of Brush and Carr Creeks, and about 17 3/4 inches in Upper Carr Creek canyon.

One must conclude that neither slope aspect nor present climatic differences can explain landslide distribution.

Groundwater and structure: During a study of the Piceance Creek area, Coffin and others (1971) mapped groundwater migration patterns in the Roan and Parachute Creek basins, and in all cases they show movement of water into the canyons. Also, ground water is commonly confined in certain zones in the Green River Formation because of its general impervious nature, but this can migrate vertically through the formation by way of numerous joints and fractures. Both of these situations should be conducive to landslide development, but they cannot explain the distribution of landslides shown on figure 12.

There are well-defined joint systems in the Piceance Creek basin that trend northeast and northwest, and these may influence landslides. Mr. Thomas Beard of Shell Oil Company, Denver, states that there is another major joint system that trends east-west. These three joint systems exert a strong control on the drainage patterns of the main streams and tributaries. However, the relationship of joint patterns to landslide occurrences is not clearly understood at the present time, but there are some cases where jointing may be important. For example, in the Castle Rock area of Kimball Creek Canyon, at least one tributary is strongly affected by regional jointing, and this area is the site of extensive landslide deposits.

Many of the largest landslide areas (not numbers of individual slides) have north to northeast exposures. A possible reason for this is that beds of the Green River Formation have a gentle regional dip to the northeast (Donnell, 1961, plate 48) in the Roan Creek vicinity. Water migrating downdip toward the cliff face may have had a critical effect on slope stability. Regional dips of Green River strata are due north in the Parachute Creek basin; thus, they have little effect on the stability for the predominantly east-west facing slopes of that basin (Landon, R. E., consulting geologist, personal communication, 1974).

Lithologic controls: The most convincing explanation of landslide distribution is based on the close association of landslides with outcrop areas of certain rock units, an example of which is the Lower Shaly Member of the Green River Formation. Of the 77 major landslides mapped, only 13 occur on slopes where the Lower Shaly Member is not present. Of these 13, the only major slides are located at the base of Mount Blaine and on the flanks of the eastern end of Kimball Mountain, and the remainder are small slides in the Clear and Brush Creek Basins. The Lower Shaly Member does not occur in Parachute Creek.

The Wasatch Formation is a less resistant rock unit than the Green River Formation, and there is a good possibility the Wasatch is also responsible for the occurrence of slides in lower Brush and Clear Creeks, and also at the eastern end of Kimball Mountain. It is certain the Wasatch played an important role in the formation of slides at the base of Mount Blaine, where the slopes face south. However, the Wasatch Formation is not a controlling factor in all cases because 35 major slides are not associated with this formation.

An explanation of landslide distribution cannot be based on the fact that a certain number of slides occur in association with the Lower Shaly Member or the Wasatch Formation, rather the lithology and mineralogy of all rock units in the Roan Creek area are conducive to land slide activity. There is a lower organic content and a higher content of fluvial derived material (clastics) in the rocks of the Roan Creek area than in the rocks of the interior of Piceance Creek structural basin. Rocks with a high organic content form steep cliffs and slopes and have a high tensile strength. There is also a lateral change in clay mineralogy: the percentage of montmorillonite increases in the direction of Roan Creek, and the percentage of illite increases in the direction of the interior of the Piceance Creek structural basin. Illite is a more stable mineral when wet than montmorillonite. Because the rocks of the Roan Creek area have a lower organic content, higher content of clastics, and a greater percentage of unstable clay minerals, they are inherently weaker than rocks of the basin interior; hence slope failure is more apt to occur in the Roan Creek area. This conclusion is based on reaserch by the U. S. Bureau of Mines (Smith, J. Ward, Laramie, Wyoming, personal communication, February 4, 1974).

Parachute Creek, though not the site of the richest oil shale deposits, is located nearer the axis of the basin (Fig. 1), therefore rock materials could be expected to be stronger and less susceptible to failure than those of the Roan Creek area.

In summary, the evidence indicates that landsliding is more prevalent in the Roan Creek basin because the rocks are farthest from the axis of the structural basin and, therefore, they are most susceptible to failure. This would also partly explain the occurrence of landslide deposits along the Cathedral Bluffs, as mapped by Roehler (1972a, 1972b) and Cashion (1969).

CONCLUSIONS

The geomorphology of the Piceance Creek area is not unusual. The canyons and plateau topography is similar to that over large areas of southwestern United States. However, two aspects of the geomorphology of the Roan Plateau could be significant, during development of the oil shale resource and during rehabilitation of the area. These are valley floor stability on the plateau proper and mass movement or landslides in the canyons and along the cliffs.

Channels are not continuous in the drainage systems of Yellow and Piceance Creeks. In some areas the valley floors have no channel, whereas in others a rapidly eroding gully has trenched the alluvium of the valleys. Because the gullies are discontinuous much of the eroded sediment is not transported into the main channels. However, during development of the oil shale or during rehabilitation it is possible that increased runoff, due perhaps to introduction of waste water or ground water into the valleys, will precipitate a period of accelerated erosion. Studies in these valleys show that gullying begins on the steepest parts of the valley floor. This seems to be characteristic throughout semi-arid and arid regions. In addition, it was possible to define a critical valley slope for a given drainage area above which the valley alluvium is unstable (Fig. 6). This relation is valid only for drainage areas larger than about 4 or 5 square miles, but it is possible that this relationship will be useful in locating those areas of potential instability, where future gullies will develop. That is, the line separating gullied from ungullied valleys (Fig. 6) represents a slope threshold above which the valley floor is unstable. Locations that plot near the line or above it and that as yet are not gullied, must be considered incipiently unstable and liable to failure during a major storm.

Identification of these valley reaches will permit the land manager to utilize conventional methods of erosion control to prevent failure of the valley floor. Hence, although hydrologic data are not available and drainage area is used as a surrogate for runoff, identification of valleys that will be most affected by man's influence in the Piceance Creek area is possible. If through vegetational destruction or the need to dispose of groundwater, water is introduced into the ephemeral-stream channels, then the presently stable valleys, which plot below the threshold line will, in effect, be shifted to the right on that illustration. That is, increase in runoff will be similar to an increase of drainage area. If the valley plots well below the threshold line, and if care is taken that the water is not concentrated, then only slight enlargement of downstream channels will result. However, if a point on Fig. 6 is shifted so far to the right that it crosses the threshold line, then the valley floor may fail, and a through channel will develop, which will convey the increased discharge and large quantities of sediment downstream. This type of erosional modification of the valleys must be avoided because the downstream consequences of high sediment export will be serious.

Field observation in the canyons of Roan Creek supports the theory that mass movement processes, particularly landslides, have played a major role in the development of the rugged topography of that area. Small rock falls and minor debris and rock slides have contributed material to the extensive talus slopes of the Parachute Creek basin, and talus is accumulating now in both Parachute and Roan Creek drainage basins. Large slumps and rock and debris slides, coupled with normal fluvial erosion and deposition have occurred in the past to form a complex landscape of shear cliffs, benches, and hummocky terrain in the deep canyons cut into the Roan Plateau by Roan Creek. Since water significantly aids in the genesis of landslide development, most activity probably occurred during times of more favorable moisture conditions, as large scale activity is not occurring at present. Because relief characteristics, hydrologic conditions, and lithologic, mineralogic, and structural features of rocks in the Roan Creek area are conducive to slope failure, landslide activity is more prevalent there than in the Parachute Creek basin and on the Roan Plateau.

Although many large landslides are associated with the outcrop areas of the Wasatch Formation and the Lower Shaly Member of the Green River Formation, it is the overall less stable character of all of the rocks deposited on the margin of the Piceance Creek basin that is of most significance. For example, the rocks of the Roan Creek area have a lower organic content, a high content of coarser sediment (clastics), and a large content of unstable clay minerals. Thus those formations that were deposited near the edge of the Green River Formation lake are inherently weaker than those exposed nearer the axis of the Piceance Creek Basin (Fig. 1). Therefore, areas of landslide susceptibility and past major slides are located around the flanks of the basin in Roan Creek and along Cathedral Bluffs. These slides are the result of past climatic conditions, and the cliffs are relatively stable at present. However, if during extraction of oil shale or during rehabilitation of the area water is introduced into these relatively unstable areas, the possibility of creating new slides or reactivating old slides is substantial.

In summary, future landslide activity should be minor unless man's activities in the area increase slope instability either by increasing slope moisture content or by removing support from the base of slopes that show evidence of past episodes of instability.

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Chapter 2

THE NATURAL VEGETATION IN THE LANDSCAPE OF THE COLORADO OIL SHALE REGION

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INTRODUCTION

Revegetation and rehabilitation of mined oil shale landscapes is promised. To carry this out with sufficient control, manageability, and predictability requires ecological knowledge beyond floristic and agronomic insights. For, after all, it is an ecological system that is being disturbed and an ecological system that is desired in reclamation. This report concerns understanding landscape relationships toward the end of providing such ecological knowledge. Presented first is a literature review assimilating information gathered from both published and unpublished sources concerning the vegetation of the oil shale region. Second, and more important, is the section providing the results and conclusions of our study of the vegetation of the oil shale region. The latter section may be read as a unit separate from the literature review.

LITERATURE REVIEW

Vegetation Information Available from the BLM and SCS

Field offices of the Bureau of Land Management (BLM) and the Soil Conservation Service (SCS) were visited during the period of July 26-July 31, 1972. Information was made available by Stan Colby, BLM Meeker; James Preston, SCS Glenwood; Jesse Hale, SCS Meeker; and Ron Perrin, SCS Meeker. The following is a summary of the vegetational and related information these agencies have available.

The BLM has two kinds of vegetational information. The first is part of their Unit Resource Analysis (URA). Included are vegetation maps of the Piceance oil shale region. The maps are very general, distinguishing only three vegetation types: pinyon-juniper, sagebrush, and mountain shrub. A written summary of the mapped units is given, but this includes only a list of dominant species, acreage, and average productivity given in animal unit months (AUM). The URA is probably too general for our use.

The BLM also has range survey data sheets for hundreds of sites. The data consist primarily of estimates of the abundances of plant species present and of grazing conditions, potentials, and recommendations. The sites sampled are never less than forty acres and are typically larger. Moreover, no data more recent than 1941 were found. Since these data are old and based on estimates made by different observers under different conditions, and taken from large heterogeneous areas, it is unsuitable for our use except for general patterns.

The SCS has accumulated and organized an appreciable amount of information related to vegetation. However, considerations of basic processes and structure of the plant communities are emphasized only insofar as they relate to management and manipulation.

The basis of the SCS ecological information is a set of range site descriptions. Range sites are generally the same as habitat types, biocommunity types, or potential plant communities, and are considered as management units. About 35 different range sites are expected to occur in the oil shale region, but 15 will probably account for most of the land area. Range site descriptions include geographic, topographic, and elevational occurrence as well as soil type, climate, potential vegetation, and a list of plant species classed as increasers, decreasers, or invaders.

The SCS has produced climatic zone maps for Garfield and Rio Blanco counties (generally the Piceance oil shale region). The eight climatic zones are defined by average annual precipitation and temperature, and follow elevation rather closely:

Zone I	Droughty, ppt. less than 12", warm, elev. approx. 5400'
Zone II	Semi-droughty, ppt. 12-15", mod. warm, elev. approx. 5400-6400'
Zone III	Mod. moist, ppt. 15-20", mod. cold, elev. approx. 6400-8000'
Zone IV	Moist, ppt. greater than 20", cold, elev. approx. greater than 8000'
Zone V	Droughty, ppt. less than 12", mod. warm, elev. approx. 5400-6400'
Zone VI	Does not occur in this region
Zone VII	Semi-droughty, ppt. 12-15", mod. cold, elev. approx. 6400-8000'
Zone VIII	Mod. moist, ppt. 15-20", cold, elev. approx. greater than 8000'

For each climatic zone the range sites which occur are listed according to acreage of non-federal land occupied, as well as percentage of range in "excellent", "good", "fair", and "poor" condition. Listed according to size, the predominant climatic zones present in the oil shale region of Rio Blanco and Garfield counties are zones III, II, IV, and VII. The range sites most common in the climatic zones listed for the two counties, also listed by size, are brushy loam, pinyon-juniper, rolling loam, deep loam, loamy slopes, mountain loam, aspen, deep clay loam, mountain shale, stony loam, salt flat, subalpine loam, and loamy breaks.

The SCS also has range survey data available which is often quantitative. However, only ten quadrats are sampled per survey and often the abundances are only visual estimates. Much of the data have been processed by the Range Data System (RDS) in Lincoln, Nebraska, and are available to universities and other agencies.

Since the range site descriptions are for potential and not contemporary plant communities, and since they are directed toward management use, they are of only limited use to us. However, the quantitative data, if available specifically for the Piceance area, may be suitable for indirect gradient analysis.

Vegetation Studies of the Oil Shale Region

The poverty of published literature on the vegetation of the Piceance Basin forces reliance on the general treatments given by regional vegetation maps, unpublished data available through various government agencies, and whatever can be gleaned from published studies of peripheral areas. What follows is a compilation of such information.

Vegetation maps only indicate in a general way the nature of the vegetation of this region. Küchler (1964) gives three types for the area: pinyon-juniper, sagebrush, and oakbrush. A recently revised map of Colorado vegetation (Morris and Dix 1971) is also limited in portraying the vegetation, listing essentially the same three types.

As indicated earlier in this report, the records of the Bureau of Land Management are of limited value for various reasons. The Soil Conservation Service, however, has attempted to structure management information and practices in such a way that some picture of vegetation can be derived despite the manipulative bias. The range site is the basic management conceptual tool of the SCS and it may be considered a habitat type, a plant community, a biotic community, or a potential plant community as well as a management unit.

Quantitative data are available for some range sites in some areas, but it is not now known if the areas pertinent to this report are represented. Such information, if present in the Range Data System of the SCS, may provide a first approximation to a quantitative understanding of the range vegetation of the area. It must be noted that range survey data are an indication of the species composition at the time the survey was made, while the vegetation descriptions accompanying the range site characterization are of the potential plant community.

Published literature of vegetation or vegetation related studies of the Piceance Basin proper are, as indicated above, scarce. Brown (1958) studied the oakbrush of western Colorado near the Piceance Basin. Graham (1937) published a study of the vegetation of the Uinta Basin, which also includes at least Piceance creek, but his study areas were miles away to the west. These studies are reviewed below and are mentioned here only to draw attention to: 1) their special relevance due to their stated inclusion of our area; and 2) the general lack of scientific botanical studies conducted within this important area.

Literature on Vegetation of Similar Areas

Vegetation similar to that of the oil shale region occurs in adjacent parts of Colorado and Utah, the northern parts of Arizona and New Mexico, and other parts of the Great Basin or Intermountain West. The assessment of vegetation similarity is made primarily on the basis of the co-occurrence of dominants and sometimes subdominant species. That is, it is assumed that the big Sagebrush communities of the Great Basin, or the pinyon-juniper communities of Arizona, are at least generally similar to communities dominated by the same species in the area of our concern. For this reason a brief survey of these "analogous communities" is given. Complete description is not required since the different communities are known to vary greatly in their detail.

Authors writing of intermountain vegetation almost without exception record that the vegetation shows a strong relation to altitudinal-latitudinal zones. And there is general agreement on identification, though not on nomenclature, of the zones. Graham (1937), in his study of the Uinta Basin, uses the zone approach, and since the Uinta Basin includes a portion of the oil shale region, a discussion of his zones follows.

Vegetation zonation: The mixed desert shrub zone is the lower elevation zone (4500' - 5500') and includes three plant associations that occur in the Piceance region. The zone generally includes saline flood plains and the low basin center. Woody perennials dominate the plant communities found here (Graham 1937). This zone corresponds closely with the salt and northern desert shrub types of Shantz (1925) and Cottam (1929 and 1933).

The juniper-pinyon zone occurs between 5500 to 7000 feet in the Uinta Basin (Graham 1937), and this is generally true for the Piceance Basin. This is the pinyon-juniper zone of Shantz (1925) and Sampson (1925), the pinyon zone of Tidestrom (1925) and Dixon (1935), and the pigmy forest of Cottam (1929 and 1933) and Woodbury (1947). The zone is composed of only one community type or association, the *Juniperus-Pinus* or pinyon-juniper of most authors. The forest, or more properly woodland, is classed as xerophytic evergreen. The community may at times be found below the indicated elevation in the case of zone inversion in canyons (Graham 1937 and Daubenmire 1943).

Above the pigmy conifer zone is the sub-montane shrub zone. It occurs from 7000 to 8000 feet. Big sagebrush dominates the plant association found here. Other low, deciduous shrubs of big sagebrush, serviceberry, mountain mahogany, snowberry, and bitterbrush, however, are common and give the vegetation the deciduous shrub physiognomy. This is the transition zone of Merriam (1898) and the chaparral of Clements (1920). The latter term is generally considered incorrect, "chaparral" being reserved for evergreen xerophytic, sclerophilous shrub communities of mediterranean climate (Vestal 1944).

Vegetation associations: The greasewood association is characteristic of heavy soils and of soils in which alkali content exceeds 0.5 per cent (Shantz 1938).

Greasewood tolerates variable conditions of salt content, but at concentrations greater than 1.0 per cent, it becomes dwarfed and dies (Fautin 1946). Sometimes greasewood forms pure stands in arid drainages, with grasses uncommon and weeds often virtually absent (Costello 1944). Greasewood is often associated with shad-scale, rabbitbrush, and big sagebrush but more commonly it is found in more moist locations (Fautin 1946). The same author reports the community to have a very low diversity.

Big sagebrush is the dominant plant of the association, with perhaps the greatest geographic extent of any in the Intermountain West. Floristic composition varies greatly with geographic position and is therefore not typified (Graham 1937). Other shrubs and perennial grasses are subdominant species. A rather comprehensive species list is given for the Gunnison, Colorado area by Flowers (1962).

Big sagebrush occurs mostly on deep, permeable, salt-free soil of alluvial and colluvial depositions. It obtains its greatest growth in areas of low salt content and where soil moisture is available at depths of three to six feet (Fautin 1966). However, big sagebrush not only uses surface water which it obtains by shallow, lateral roots, but, in deep, loose soil, it develops a taproot which is often fifteen feet long (Flowers 1962). This plasticity of life form probably accounts for part of the wide ecological amplitude of this species. Where soil salt content exceeds 0.5 per cent or where there is a hardpan, big sagebrush fails to thrive (Kearney, et al. 1914).

That the big sagebrush association is a grazing-fire disclimax has been argued by Pickford (1932), Stoddart (1941), Craddock and Forsling (1938), and Humphrey (1945) among others. Both grazing and fire control favor the shrub and disfavor the perennial grasses. They also argue from evidence of protected relict areas. Other workers claim that the big sagebrush community is a climatic climax (Billings 1945, Fautin 1946, Stewart, Cottam, and Hutchins 1940, and Shelford 1963). It is not apparent that the controversy is settled.

Billings (1949) divides the big sagebrush association of Clements into two parts, the big sagebrush association proper and the shad-scale or Atriplex association. In our area shad-scale is the dominant species. Each of these associations is climatically determined (Billings 1949 and Shelford 1963). Shad-scale is generally found in drier and lower elevations than the big sagebrush association and is found on gray desert soils rather than on the darker and often brownish soils of the big sagebrush association. Billings (1949) claims that the shad-scale communities are not invaded by the weedy brome grasses as easily as are the big sagebrush communities.

Juniper and pine are associated over a wide geographic range, including the Piceance Basin, and give the communities associated with them a xerophytic coniferous woodland character. Compositional variation from place to place of the associated understory species is high, and the community can only be typified for local areas. Graham (1937) gives a brief description of such vegetation as found in the Uinta Basin. However, Woodbury (1947) gives a more rigorous treatment of the type as found in Utah and Arizona, and is followed here. According to this author, the association is generally confined to the 5000 to 7000 foot zone where the average annual precipitation is 10 to 15 inches and the frost free period is 120 days. Some of the trees of this association may exceed 30 feet in height, but this is rare, 20 feet being more common. Canopy cover averages 40 per cent, while root cover is often 100 per cent. The soil of this type is coarse, rocky, and shallow compared to that of the surrounding areas which are most commonly occupied by sagebrush (Phillips 1909 and Woodbury 1947).

In plant succession juniper precedes pine in invading new sites. In Tooele and Utah counties, Utah, in 1859 the pygmy conifer association was confined to hill tops and ridges; in 1947 the association had "moved" down the hillsides. During the same period the original big sagebrush-greasewood-rabbitbrush valley bottoms and grass valley edges and hillsides were taken over by big sagebrush dominated vegetation. Woodbury (1947) does not think that juniper-pinyon can invade the deeper soils occupied presently by big sagebrush. However, the conifers may extend upward by invading the serviceberry community which occurs at higher elevations.

Gambel's oak, among other shrubs, dominates plant communities generally classified as oakbrush or browse-shrub. In western Colorado the oak is a co-dominant with snowberry, serviceberry, and big sagebrush. Brown (1958) studied oak shrub in Colorado although he attended to it primarily as it occurs south of the Piceance Basin. He found 7000 to 9000 feet to be the elevational limits of the type. In general the steeper the slope the more the oak tends to form thickets rather than clumps. In any mature stand about one half of the oak stems are less than 10 years old; the other half are in the 10 to 80 year range. A stem older than 80 years is exceptional. Younger stands are denser and are believed to be self thinning. No stands were found that were expanding.

It is interesting that net above ground productivity of the oak understory is nearly the same as that of the grass-herb layer in the open away from the oak. About 346 pounds of herbage per acre are produced in both situations, although by different species. However, total herbage yield, that is counting the overstory production, is two times greater in oak stands than in the open areas. This is true in both grazed and ungrazed cases (Moinat 1956). Medin (1960) found greater soil depth and factors which allow for greater soil moisture holding ability to correspond with greater production in other shrub communities of northwestern Colorado. It is presumed that the same factors are important in the Piceance shrub communities. Soil factors thus seem to limit production of oak stands, but soil does not limit the distribution of oak (Brown 1958).

ECOLOGICAL PROPERTIES OF THE VEGETATION OF THE OIL SHALE REGION

Introduction

The purpose of the natural vegetation section of the oil shale development rehabilitation study is to characterize the ecological properties of the extant natural, not to say pristine, vegetation. An important part of this task is to develop criteria for reestablishing adequate primary producing communities and in fact to decide in part what 'adequate' means in this context. Restored vegetation must to some degree have the same characteristics as the vegetation it replaces. The following is a discussion of some of these ecologically important properties as they are relevant to natural vegetation, and presumably as properties to be complied with by reestablished vegetation. The technology of compliance, however, is not the proper subject of this report. The discussion then is as follows: first, a description of the different kinds of plant communities identified and studied in the two previous seasons is presented; and secondly, patterns of ecological relationships within these communites are discussed. This section includes such synecological properties of vegetation as diversity, yield, and horizontal and vertical distribution of plant biomass, as well as the more common topics of composition, structure, and succession. Geographic patterns of vegetation are next discussed, relying primarily on the differences in vegetation between the northern and southern parts of the oil shale region. Within the geographic context local (primarily topographic) patterns of variation in vegetation are then discussed. The last section presents some criteria to be met by rehabilitation.

Major Plant Communities

A syllabus of 18 types of plant communities found in the Piceance oil shale region is given in Table I. The categories and divisions presented do not treat vegetational phenomena in the ways of vegetation science, but rather in ways conducive to the purposes of this applied study. The following criteria are therefore used for selecting types: 1) types are chosen to be easily identified either by their dominant plant species or topographic position; 2) communities of limited geographic extent are usually ignored, while communities occupying large portions of the landscape are included; 3) some communities, although having a small geographic representation, are included due to their aesthetic importance (aspen) or their occupancy of critical areas (riparian woodland); and 4) only self-sustaining communities are included (cultivated or recently cultivated areas are ignored).

The sequence of presentation of the community descriptions progresses roughly from low to high elevation types. The bottomland and upland categories designate relative topographic position. The bottomlands include the valley floors, are areas of erosional accumulation, and are areas which recieve water both from precipitation and run-on. Uplands include the hillsides and ridges. These are areas of erosional depletion, and precipitation is the source of water; run-off exceeds run-on.

Some of the communities described occur throughout the region while others are more restricted. And it is not to be implied that the types given represent comparable differences in variations of composition or diversity. Some types vary widely from place to place while others are nearly the same everywhere found. The descriptions provided in Table I form a necessary part of the ecological knowledge needed to sustain a revegetation program. However this information alone, and even more complete information of this sort, is not sufficient for the desired ecological end. The later sections of this report will outline some of the additional ecological relationships at work within the landscape, and it is these which are deemed most important for revegetation. It is hoped that a study of the photographs of the vegetational types presented in Figures 1 to 2 will give sufficient feel for the vegetation to benefit the reader on points articulated in the following sections.

Patterns of Ecological Relations

Natural revegetation, or rehabilitation of a landscape to a near natural state, involves much more than knowledge of native species and how to grow them. The following discussion articulates and gives examples of some important properties of the plantscape that must be duplicated or accounted for in order to truly achieve or approximately achieve the goal of rehabilitation.

Composition and structure: For revegetation, it is important to know the species composition of a site but application of this knowledge is not straightforward for two reasons. First, structure, or the proportionate amounts of each species present, must be considered. Second, the species composition itself varies even within the same recognizable vegetation type. For example, low elevation communities dominated by juniper and pinyon pine on clayey soil not only have a different species composition from high elevation, sandy soil, juniper-pinyon groves, but the species common to the two areas also occur in different amounts. This is most striking in the proportionate amounts of the dominants themselves, juniper being by far the most prevalent species in low elevation, more xeric groves while pine becomes more common in the high elevation areas. Systematic

Table I. A CLASSIFICATION OF THE NATURAL VEGETATION OF THE PICEANCE BASIN. The names in parentheses identify the mapping units of Terwillinger and Cook in this publication. Vegetational types are arranged from low to high elevations.

I. BOTTOMLANDS. (*Bottomlands*; includes A, B and C)

These are areas of erosional deposition.

A. Riparian Woodland.

This type occurs along the stream sides of Roan and Parachute Creeks and their tributaries. It is dominated by cottonwood, boxelder, and chokecherry. These sites are usually heavily grazed and the weedy understory consists of bluegrass, cheat grass, mullein, flixweed, mustards, and a variety of other weeds. (Fig. 1a)

B. Big Sagebrush Shrubland.

Well drained, broad flat valley bottoms and alluvial fans with little or no salinity are usually dominated by big sagebrush which, on these sites, reaches heights of up to two meters and a canopy cover of 75% or more. Rabbitbrush, shad-scale, and fringe sage are common shrub components. Indian rice grass and several species of wheat grasses often occur in the understory. Greasewood will be a component if some salinity is present in the subsoil; as the salinity of the surface soil increases, this type will merge with Greasewood Shrubland. Large acreages of this type have now been converted to irrigated pastures and haylands. (Fig. 1b)

C. Greasewood Shrubland.

Broad, flat valley bottoms with moderate to high salinity and alkalinity in the surface of soils are dominated by greasewood. On these sites, the water table is at or near the soil surface at some time during the year although it may maintain this position for only a few weeks. When salinities and alkalinities are relatively low in the surface soils, rabbitbrush and big sagebrush may be important components, but they tend to disappear with increased salinity and alkalinity in the surface soils. The shrubs of this community are usually 1.5-2.0 meters tall, but rarely less than 0.5 meters tall. Very often there is no understory, and nowhere is there a well developed one. Understory species include mustards, cheatgrass, and fringe sage. (Fig. 1c)

II. UPLANDS

These are areas of erosional depletion.

D. Shad-scale Shrubland. (*Desert Shrub*)

Steep and dry hillsides, particularly those with southern exposure and shale outcroppings, support an open, low (0.25-0.75 meters) shrubland dominated by shad-scale. Indian ricegrass is usually an important component of this type and is sometimes a co-dominant. This type is of particular importance on the steep canyon wall along the southern edge of the Basin. In the upper positions of the slopes, the shad-scale shrublands usually give way, because of more favorable conditions with increased elevation, to Mixed Mountain Shrubland. Among the first species to show up along this transition are mountain mahogany and wax currant. (Fig. 1d)

E. Hillside Fringed Sage and Grassland. (*Not Mapped*)

Very steep hillsides with sandy and unstable soils usually support a low shrubland dominated by fringed sage and Indian ricegrass. Big sagebrush and rabbitbrush are usually important components of this type while shad-scale, prickly pear cactus, and greasewood are often minor components. Beardless wheatgrass and cheatgrass, along with Indian ricegrass, sometimes gives this community a grassland appearance. The plant cover is usually less than 20% and the shrubs are usually less than 0.5 meters tall. (Fig. 1e and 1f)

F. Big Sagebrush Shrubland. (*Upland Big Sagebrush*)

The unifying characteristic of this type is a clear dominance of big sagebrush, although it shows considerable visual variation within the unit. The unit occupies more acreage in the Basin than any other. It extends over an elevational range from ca 1,800-2,500 meters (6,000-8,000 feet) and much of this variation seems correlated with elevational differences. In general, Big Sagebrush Shrublands are found on soils deeper than those which support Pinyon-Juniper Woodland and Mixed Mountain Shrubland.

F_1. Low Elevation Big Sagebrush Shrubland. Below 2,000 meters (6,500 feet), big sagebrush on uplands rarely achieves heights above 0.5 meters (20 inches). Here the soils are derived from interbedded layers of shales and sandstones. They are dry, because of the relative ineffectiveness of the available moisture at these low elevations, and they are typically aridisols. Soils are sometimes slightly saline but rarely alkaline. They are the shallowest soils of the Big Sagebrush series. Big sagebrush is always the clear dominant on these sites but shad-scale and spiny horsebrush are always important; winter fat is usually important if shales are present in the parent material and greasewood may be important if the soils are at all saline. The understory of this community type is usually sparse, as is the shrub canopy. The principal understory species are western wheatgrass, Hood's phlox, squirrel tail, native bluegrasses, and some junegrass and needle-and-thread.

F_2. Mid Elevation Big Sagebrush Shrubland. On rolling uplands at elevations between 2,000-2,300 meters (6,500-7,500 feet) big sagebrush attains heights of 0.50-0.70 meters. Because of increased elevations, more water is usually available for plant growth here than at lower elevations. The soils are moderately deep and have many characteristics of mollisols. Big sagebrush continues as the dominant and other shrubs are usually less conspicuous than in either F_1 or F_3. The dominant grasses of the understory are junegrass, beardless wheat grass, needle-and-thread, Indian ricegrass, and western wheatgrass. Important forbes are Hood's phlox, beardtongue, and Nuttall's golden weed.

F_3. High Elevation Big Sagebrush Shrubland. These shrublands occur above 2,285 meters (7,500 feet) and are the most mesic of the big sagebrush types. Big sagebrush attains heights of 0.70-1.00 meters and is usually accompanied by the shrubs bitterbrush, service berry, mountain mahogany, and snowberry. Important grasses are Kentucky bluegrass, several species of needle grass, several species of brome grass, and Idaho fescue. The common forbes are lupine, Indian paintbrush, sulfur flower, dandelions and yarrow. The soils are usually deeper than 0.5 meters and are mollisols.

F_4. Big Sagebrush Shrublands of Cliffs and Rocky Breaks. This type usually occurs at intermediate elevations and develops in pockets of deep soil. Because of the soil moisture available in the deep pockets, these sites support a species composition similar to High Elevation Big Sagebrush Shrubland.

G. Mixed Mountain Shrubland. *(Mixed Mountain Shrub)*

This unit is dominated by a variety of tall shrubs, especially Gambel's oak and serviceberry, and occurs at elevations of 2,100-2,400 meters (7,000-8,000 feet) on deep mollisols. These tall shrublands often achieve heights of 3 meters or more and are usually restricted to protected topographic positions such as gullies and northerly exposures. Oak appears to require a site with more moisture than those dominated by serviceberry, but the two species may occur together on intermediate sites. Chokecherry, snowberry, big sagebrush, and especially mountain mahogany may become local dominants, or may share dominance, along this moisture gradient. (Fig. 2a)

G_1. Oakbush Shrubland. Gambel's oak and associated species are not widespread in the Piceance Basin but restricted to gullies, depressions, and lower slope positions of the upper Piceance Creek and to the edges of valley bottoms and gullies along Roan and Parachute Creeks. Gambel's oak dominates the overstory of these communities and often forms a canopy cover of 80% or more. Mature oak commonly reaches 3 meters in height and 10 cms. in diameter. Important associated shrubs are mountain mahogany, chokecherry, snowberry, rose, and big sagebrush. Important herbaceous plants are several wheat grasses, Indian ricegrass, fringe sage, lupine, and needle-and-thread.

G_2. Serviceberry Shrubland. This type is characterized by a variety of tall shrubs, but serviceberry is usually present in substantial amounts and is often the dominant. The type is widespread throughout the Piceance country and occupies substantial acreages at mid and upper slope positions on northerly facing hillsides. The shrub canopy is often 80% or more and reaches a height of more than 3 meters. The principal shrubs are serviceberry, mountain mahogany, chokecherry, snowberry, juniper, big sagebrush, and rabbitbrush. Understory species are wheat grasses, bluegrasses, needle-and-thread, balsamorrhiza, Indian ricegrass, lupine, and fringed sage.

H. Pinyon-Juniper Woodland (*Pinyon-Juniper Woodland*)

Pinyon pine and Utah juniper dominated vegetation occupies large acreages in the northern and central parts of the Basin within the elevational range of 1,850-2,300 meters (6,000-7,500 feet), approximately the same range as Upland Big Sagebrush Shrubland (F). These two types account for approximately 70% of the vegetational cover in the Basin. They are separated primarily by differing requirements for soil depth: Pinyon-Juniper Woodland is found on soils shallower than those which support Big Sagebrush Shrubland and the types integrate when the soils are intermediate in depth. Pinyon-Juniper Woodland consist of evergreen trees about 3-5 meters in height and sufficiently far apart to permit easy walking. There is considerable variation in the species composition of the type, which is related primarily to elevation and soil parent material. With the decrease in wild fires during the 20th Century, many open Pinyon-Juniper Woodland sites have tended to thicken up and to accumulate leaf litter. This litter has tended to repress the development and productivity of the shrub and herbaceous understories. This is particularly true in the High Elevation Pinyon-Juniper Woodland (H_2). (Fig. 2b)

H_1. Low Elevation Pinyon-Juniper Woodland. Below 2,100 meters (7,000 feet) the type is dominated by Utah juniper and on many sites this is the only tree species present. The soils are dry and are largely poorly developed aridisols. This unit may be divided further on the basis of parent materials.

On shales, Utah juniper is usually the only tree present. Little or no big sagebrush is present and the understory consist of scattered and stunted individuals of junegrass, beardless wheatgrass, needle-and-thread, squirreltail, and Indian ricegrass. Stunted plants of bitterbrush and mountain mahogany may also be present. As soils deepen, this unit integrates to Low Elevation Big Sagebrush Shrubland (F_1).

On sandstone, Utah juniper, while still dominant, may be joined by pinyon pine. Big sagebrush is usually present in the understory and many of the shrub and herbaceous species characteristic of Mid Elevation Big Sagebrush Shrubland (F_2) are prominent. This includes junegrass, western wheatgrass, beardless wheatgrass, needle-and-thread, and Indian ricegrass. Plant productivity is much higher and soil profiles much better developed here than on shale sites. As these soils deepen, the plant composition grades toward Mid Elevation Big Sagebrush Shrublands (F_2).

H_2. High Elevation Pinyon-Juniper Woodland. Above 2,100 meters (7,000 feet) pinyon pine becomes the dominant tree, although Utah juniper is usually present and is sometimes abundant. Differences in species composition and productivity with differences in parent materials, so important in Low Elevation Pinyon-Juniper Woodland, tend to be minimized at these elevations. The soils are usually well developed mollisols. The shrub layer is dominated by big sagebrush, rabbitbrush, and bitterbrush while some mountain mahogany, chokecherry, and serviceberry may be present or even common. The principal grasses are junegrass, beardless wheatgrass, needle-and-thread, Indian ricegrass, and western wheatgrass. Important forbes are beardtongue, Hood's phlox, and Nuttall's golden weed. As soils deepen, this type tends to grade into High Elevation Big Sagebrush Shrubland (F_3). With a decrease in wild fires, tree densities and leaf litter tend to increase, causing a subsequent decrease in the productivity of the shrub and grass layers.

H_3. Pinyon-Juniper Woodland on Cliffs and Rocky Breaks. On these sites, the woodlands described above (H_1 and H_2) tend to become depauperate. If the parent material is shale, Utah juniper will form very open woodlands while, if the parent material is sandstone, pinyon pine will do the same. These open woodlands may form at all elevations within the general range of Pinyon-Juniper Woodland. Usually the shrub and herbaceous layers are poorly developed on these sites, although they will usually be similar in species composition, but not productivity, to Pinyon-Juniper Woodlands at similar elevational positions. When pockets of deep soil accumulate within these landscape features, an appropriate elevational type of Big Sagebrush Shrubland (F) will dominate.

I. High Elevation Grasslands. (*High Elevation Grasslands*)

Shallow and rocky to gravely soils at elevations of 2,330-2,750 meters (8,000-9,000 feet) on the wind swept ridges of Cathedral Bluffs along the western edge of the Piceance Basin are dominated by high altitude grasslands. The principal species are several native bluegrasses, junegrass, and Idaho fescue. Rabbitbrush and burrow weed are common shrubs but here they reach heights of 15 cms. or less. This type, which has a distinctly stunted appearance, seems restricted to these wind swept ridges.

J. Douglas Fir Forests. (*Forests*)

This type is restricted to gullies and north facing slopes at elevations of 2,400-2,500 meters (7,500-8,000 feet) and occupies a very small proportion of the total landscape. Douglas fir is the clear dominant; it usually forms a closed canopy and the trees often attain diameters of 30 cms. Ponderosa pine sometimes occurs with Douglas fir. The shrub layer of this type is usually well developed and is dominated by serviceberry, chokecherry, snowberry, mountain mahogany, and rose. The herbaceous layer is poorly developed but several species of wheatgrass, brome, and fescue are present. A few forbes are also scattered throughout the herbaceous layer. (Fig. 2c)

K. Aspen Forests. (*Forests*)

At elevations of 2,400-2,500 meters (7,500-8,000 feet) the steep coves with northerly facing slopes may be dominated by Aspen Forests. In general, these aspen forests are better protected from solar radiation and wind than Douglas fir forests, although both forest types occur at the same general exposure and at the same elevations. The Aspen Forests usually have a closed canopy and the aspen trees often attain diameters of 20 cms. There is some aspen reproduction in these stands. These forests have a lush forb, grass, and shrub understory fairly typical of that of aspen stands throughout the western slope. The principal shrubs are oak, big sagebrush, serviceberry, snowberry, and common juniper. The shrub layer is lush and has a general cover of about 60%. The principal herbaceous species are sedge, bluegrasses, a native timothy, fescue, Indian paintbrush, and bluebell. Aspen Forests are widespread throughout the Piceance Basin but each site is usually restricted to a few acres.

Figure 1.

1a. Riparian woodland (A) on the flat valley bottom of Parachute Creek.

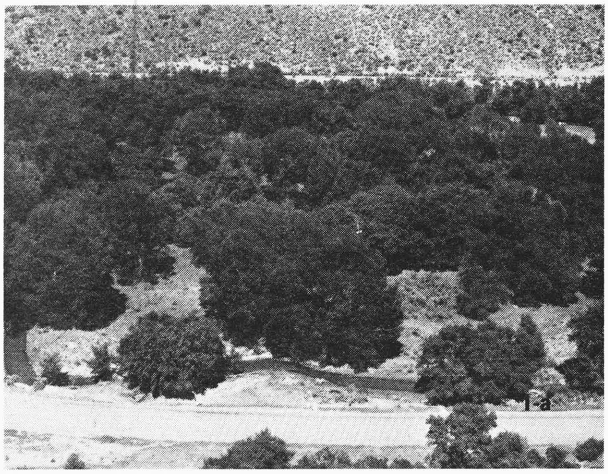
1b. Foreground Big sagebrush (B) and greasewood shrubland (C), center of valley is cultivated hay meadow, mid-ground greasewood (C), Big sagebrush (B) on alluvial fan, Pinyon-Juniper (H) on uplands.

1c. Big sagebrush (B) on alluvium in foreground, Pinyon-Juniper (H) on upland.

1d. Shad-scale vegetation (D) on hillsides.

1e. Big sagebrush (B), on alluvial fan in foreground, Hillside fringed sage (E) in background.

1f. Hillside fringed sage grassland (E) showing area of Indian ricegrass dominance.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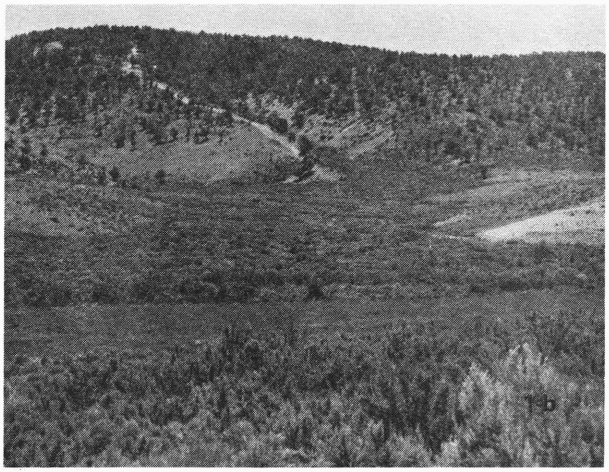
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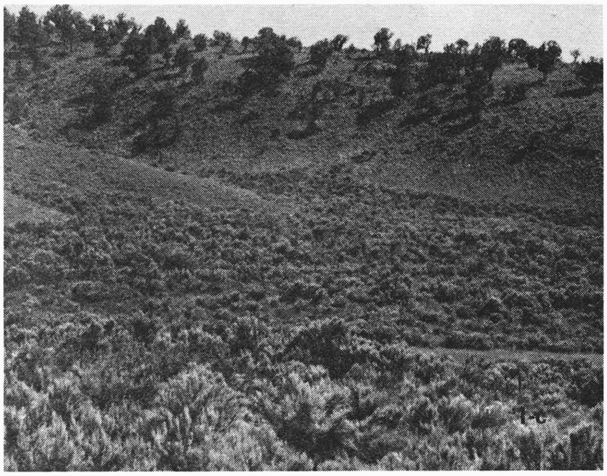
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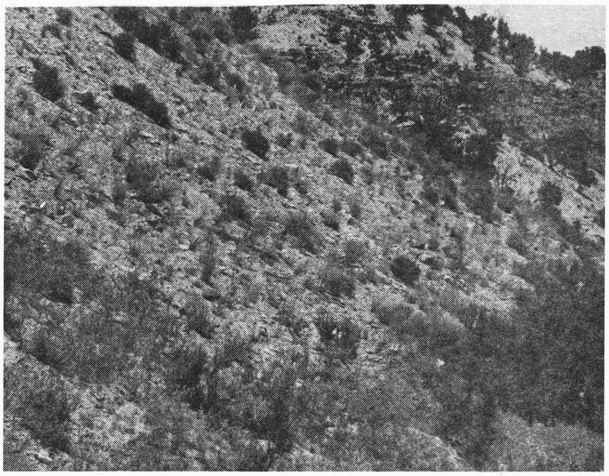

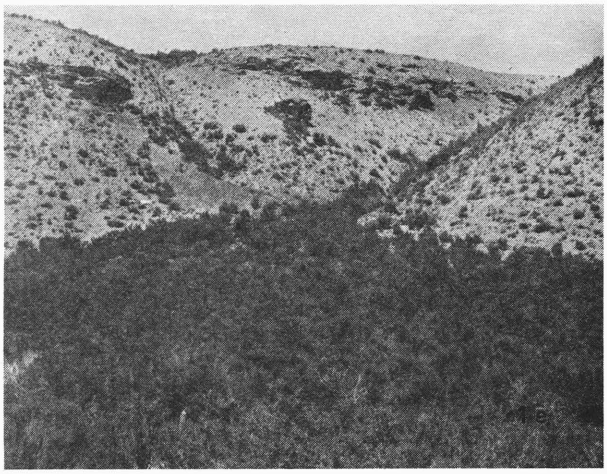
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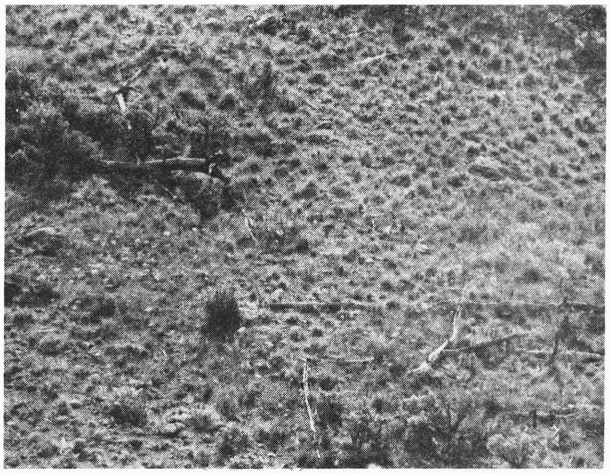


Figure 2.

2a. Mixed Mountain Shrubland (G_2) in upland area.

2b. Mid- and background Pinyon-Juniper (H_1).

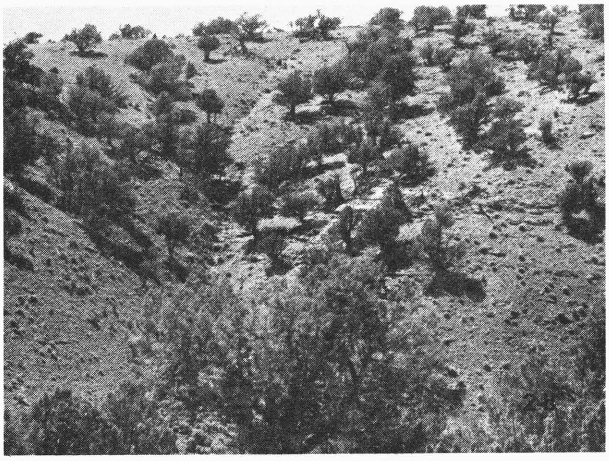
2c. Foreground Mixed Mountain Shrubland (G_1), mid-ground Douglas Fir Forest (J).

2e. Example of differences in grain throughout the vegetation mosaic. Uplands have broad blankets of vegetation (e.g. Pinyon-Juniper H on upper slope) while the Big sagebrush (B) in the fore and mid-ground occurs as ribbon-like shapes. The lower hillsides with Fringed sage (E) vegetation occurs in bands along the border of the Upland Pinyon-Juniper (H).

2f. General character of topographic features of the northern part of the oil shale region. Low rolling hills and alluvium filled valleys are the rule.

2d. General character of topographic features of the southern part of the oil shale region. High plateaus and steep hillsides are the rule.

2-a



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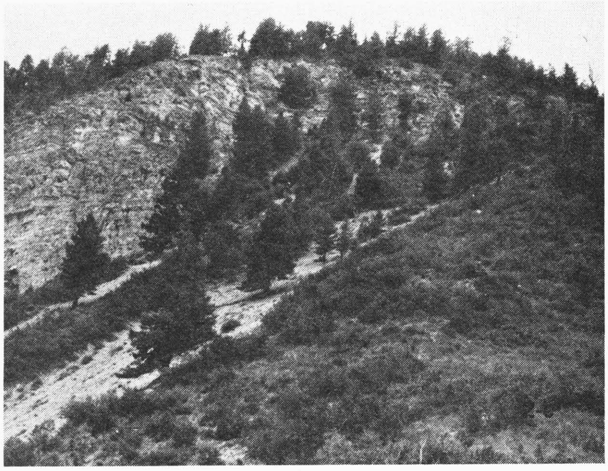

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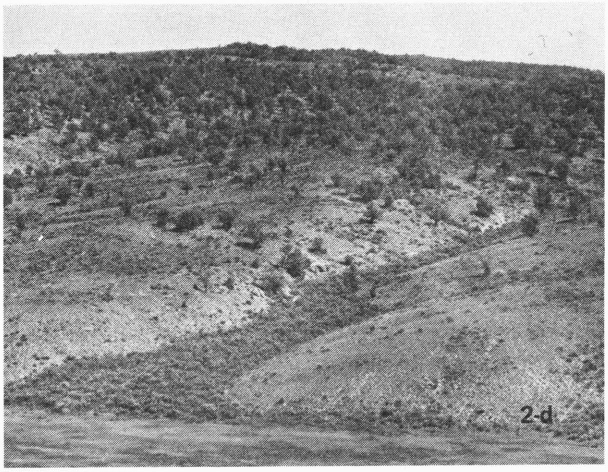

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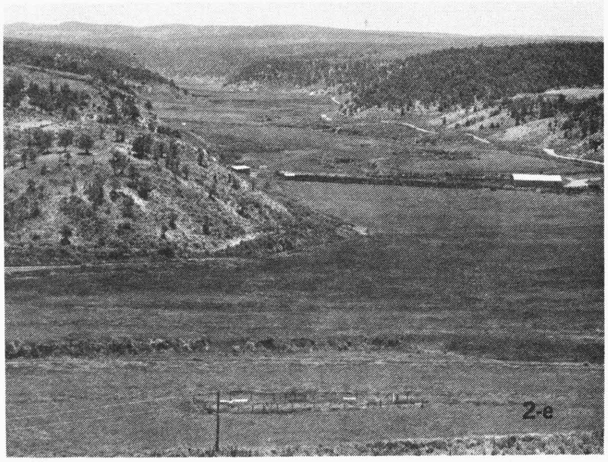

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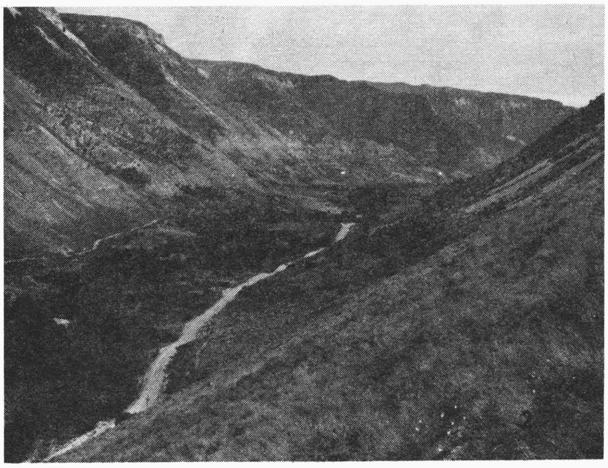

2-f

sampling would show this phenomenon repeated for all other communities and species. The meaning of this point is that if a piece of ground is to be revegetated to juniper-pinyon rather than greasewood, for example, then not only will a different spectra of species be called for but different amounts of each species will be desired depending on the kind of juniper-pinyon vegetation suited to the local area in question.

Diversity: Several aspects of diversity may be separated for discussion. Overstory versus understory diversity is one important division, and another is alpha versus beta diversity. The community types designated above are distinguished by differences in dominant, overstory plants, and there are differences in the diversity of this stratum among the communities listed. Mixed shrub communities dominated by five, six, or more species are obviously more diverse than some sagebrush communities dominated only by big sagebrush. Differences in understory diversity are striking throughout the Piceance Basin. Examples are common in communities dominated by a single set of species containing quite different understory assemblages in different places. Differences between alpha and beta diversities are differences in diversity of one site (alpha) opposed to differences in diversity from site to site (beta). Variations in both kinds of diversity are found in the vegetation of this region, and Table II gives an indication of these diversity patterns for the vegetation types discussed.

Yield and cover: The productivity of plant biomass is important for three reasons relevant to rehabilitation: 1) addition of organic matter to the reclaimed system; 2) primary production available for herbivores; and 3) soil protection. No data on productivity could be gathered, but this feature, being important, was considered insofar as production is related to standing crop which can be qualitatievely assessed. Communities which produce the most and which maintain a large standing crop would be the most favorable to achieve in rehabilitation. Table III classified the communities of the Piceance according to productivity as estimated in the field and described in the literature and Soil Conservation Service information. Several studies (Medin 1960, McColley et al 1970, and others) show that plant productivity is in a significant way related to soil depth. This is true of a wide range of vegetation, desert to shrubland, and for a variety of soil types, clay to sand. A prerequisite for high productivity is development of soil depth. However, the situation is complicated in the following way. Branson (1971) shows for several areas not unlike the oil shale region that in areas with precipitation above 300 mm per year (11.8 in) sediment yield is inversely proportional to vegetation cover, which is directly proportional to precipitation. This means that without vegetation cover sediment yield will increase, which acts counter to soil buildup and maintenance.

Horizontal and vertical patterns: Besides the kinds and amounts of plants present in a community, the geometric distribution of plant biomass is that which lends form and a recognizable aspect to vegetation. The topic can be divided into four main parts: 1) life forms of the constituent species; 2) horizontal distribution of each species; 3) association between species in their horizontal distribution; and 4) development of synusia in a community (i.e., stratification).

1. Life form. Six categories of life form are included in Table IV along with a species list for each class. The predominant life form for the oil shale region is the tall shrub. The influence and success of this adaptive mode on the aspect of the Piceance Basin shrublands is obvious. Establishment of vegetation dominated by large native shrubs is mandatory for reclamation to be judged adequate.

The small or sub-shrub life form category includes both plants dominant in some communities and plants which are components of other kinds of vegetation.

Members of the evergreen and deciduous tree life forms represented in the vegetation under discussion occupy diverse habitats. Cottonwood and box elder grow on stream sides in the southern drainages; Douglas fir and aspen grow on mesic, protected slopes, pockets, and coves; and juniper and pine grow in shallow soils in xeric situations. The part of the landscape occupied by trees is often not extensive but is very visible due to the size of the dominants.

Perennial herbs, including the grasses, form a major part of the vegetation on most of the landscape. The annuals include many weeds or invaders of disturbed and harsh sites and are primarily adapted to pioneer establishment of vegetation on these sites.

2. Horizontal distribution of individual species. The arrangements of individuals of a species on the ground range from random assortment to regular, almost row-like, patterns, to definite aggregation. A single species, Indian ricegrass, shows all three kinds of distribution and is therefore a good example. This grass grows in clumps showing aggregation. On gentle south and east-facing slopes, where it usually grows, a nearly random distribution of the clumps can be seen. And on steep slopes the clumps align in vertical rows up and down the slope.

Individual plants of big sagebrush and greasewood, which grow commonly in or near valley bottoms, often show a nearly regular pattern of dispersion. Clumped or aggregated dispersion can be seen in many species in the field, including the wheat grasses, needle grasses, bluegrasses, penstemon, fringe sage, rabbitbrush, cactus, sedge, and others.

Pattern is difficult to detect, except for the more obvious cases cited, unless much sampling is done. However, the main point is that patterning does occur, and in natural communities an array of organisms is distributed in a complicated way across the landscape.

3. Association of distributions. This phenomenon is observed for both positive and negative relationships between different species. In many big sagebrush and greasewood communities understory plants grow immediately adjacent to the dominant shrubs in the deeper soil accumulated at their base. Negative association in horizontal patterning is found, among other places, under the juniper-pinyon canopy. Here most of the understory plants do not grow directly under the canopy but rather in the open spaces between adjacent trees. A similar situation is found in oak, serviceberry, and mixed shrub communities. Some plants do well in, or in fact need, the close proximity of other species. Contrarily, other species can only grow beyond the immediate influence of other species.

4. Stratification. The majority of the communities discussed have stratified into at least two layers. The forest or tree dominated communities often have three strata. When shrubs dominate there is the shrub layer with the herbaceous layer underneath the shrubs. When trees are dominant a third layer is present. Closed canopies either in the tree or shrub strata are not typical. Only the thickest sage, oak, or other shrub stands have 100 percent crown cover. It is an open question for rehabilitation which strata need be established first in order for the others to develop, or if they can be established at the same time.

Scale: The scale of the vegetational mosaic is smaller than but follows the topography. Vegetation occupying the extensive uplands forms large blankets, while the communities occupying the valley bottoms are long and very thin. Some communities, such as oak brush or Douglas fir, are usually only represented in small patches scattered over the terrain while others, such as the serviceberry or pinyon-juniper communities, cover many contiguous acres. The size, shape, and extent of these communities are important in determining the amount of edge present in the landscape and the graininess of the vegetational habitats. (Fig. 2d.)

Tolerance spectra: Species differ in their ecological amplitudes. Broadly adapted species occur in more kinds of environments, than do specialized species. However, direct inference of a species' amplitude cannot be drawn from its pattern of distribution on the land, for it is possible that a species of narrow environmental requirements may be very common since its required environment may be especially common. Table V is a list of important plants of the Piceance arranged according to their ecological amplitude over the kinds of environments present in the region. Big sagebrush is listed as having the widest amplitude, however this is probably due to division of this group into several subspecies. Presumably the wider ranging species are more easily used in rehabilitation since their environmental restrictions are not likely to be as severe as those of the environmentally specialized. At any rate, a variety of environments, as well as a variety of ranges of environmental variation, must be provided for reestablishment of vegetation comparable to the natural scene.

Succession: Succession as such is reported on by Terwilliger and Cook in this document, however some considerations are made here based mostly on an article by Young and others (1971). These authors state that no important native annuals that can occupy low seral situations evolved in the Great Basin region of North America. However species, notably cheatgrass, occupying this position are now present, probably having come from Asia. These organisms, being annual, are proficient in invading disturbed areas. And native perennials depending on periodically favorable years for gaining establishment in new areas are preempted by the annuals which are capable of establishment almost any and every year. Non-native annuals are successful invaders of disturbed areas and by preemption can 'stop' succession. In fact it is found that they can successfully invade climax vegetation.

Geographic and Topographic Patterns in the Landscape

Geographic Patterns: The oil shale region of Colorado is large enough to include differences in the plantscape on a geographic scale. The area is divided into two parts. In the northern part are the watersheds which drain northward into the White River. This includes Piceance, Yellow, and Douglas Creeks. The southern part includes all the watersheds which flow to the Colorado River, primarily Parachute and Roan Creeks.

Table II. Community membership in alpha and beta diversity classes. The symbol in parenthesis refers to the classification in Table I.

Alpha Diversity	Beta Diversity
Low	Low
Riparian Woodland (A)	Riparian Woodland (A)
Greasewood (C)	Greasewood (C)
Big Sagebrush (B)	Big Sagebrush (B)
	Shadscale Shrublands (D)
	Hillside Fringe Sage (E)
Medium	Medium
Big Sagebrush (F)	Big Sagebrush (F)
Pinyon-Juniper (H)	Pinyon-Juniper (H)
Hillside Fringed Sage (E)	Douglas Fir (J)
Shadscale Shrubland (D)	Aspen (K)
High	High
Mixed Mountain Shrubland (G)	Mixed Mountain Shrubland (G)
Aspen (K)	
Douglas Fir (J)	

Table III. Community membership in productivity-standing crop categories. The symbol in parenthesis refers to the classification in Table I.

Low

- Shadscale Shrublands (D)
- Hillside Fringed Sage (E)
- Pinyon-Juniper (H)

Medium

- Big Sagebrush (B and F)
- Greasewood (C)
- Riparian Woodland (A)

High

- Mixed Mountain Shrub (G)
- Douglas Fir (J)
- Aspen (K)

Table IV. Life form categories and representative members.

Evergreen Tree

- Pinyon Pine
- Juniper
- Douglas Fir

Deciduous Tree

- Aspen
- Cottonwood

Tall Shrub >1m

- Serviceberry
- Oak
- Big Sagebrush
- Tall Rabbitbrush

Small Shrub <1m

- Fringed Sage
- Short Rabbitbrush
- Horsebrush
- Mormon Tea

Perennials-Herbs

- *Agropyron*
- *Stipa*
- *Festuca*
- *Oryzopsis*
- *Penstemon*
- *Malva*
- *Opuntia*

Annuals-Herbs

- *Bromus*
- *Lepidium*
- *Cirsium*

Table V. Ecological amplitude of some major plant species

Wide

- Big Sagebrush
- Indian Ricegrass
- Fringed Sage

Medium

- Serviceberry
- Bitterbrush
- Greasewood
- Pinyon Pine

Narrow

- Oak
- Rabbitbrush
- Chokecherry
- Shadscale
- Snowberry
- Maple
- Cottonwood
- Aspen

The northern and southern areas differ in two important respects. First, the southern region has more land area within the drier climatic zones. Second, the southern area has greater relief and therefore a 'longer' topographic gradient (Figs. 2e and 2f). These differences are reflected in part by the fact that different plant communities occur in each region.

Although the vegetation patterns most obvious throughout the oil shale region are those related to topography, the northern and southern parts are sufficiently different in the detail of topographic variation to warrant separate treatment. This is the subject of the following section.

Topographic patterns: Local patterns in vegetation correspond to patterns in topography. Break points in the topographic profile visually correspond to community borders. For example, on Piceance Creek the break in slope between upland and hillside, the brow, corresponds to a vegetation border between pinyon-juniper (H) and hillside fringe sage grassland (E). And corresponding to the slope break at the foot of the hill there is another vegetation change from the fringe sage (E) to the bottomland big sagebrush type (B). Corresponding changes in topography and vegetation also occur in the Parachute Creek Valley. However the particular community type associated with each topographic category may be different. Also important is that when the topographic diversity is increased the number of different kinds of plant communities found is greater. Therefore on Parachute and Roan Creeks, where relief is greater and more topographic categories are found, the gamma diversity of the primary producing communities is also greater. Correspondingly, when topographic differences are small there are fewer vegetation types present. This can be seen in the upper ends of the tributaries to Piceance Creek. Here there is essentially no hillside and therefore no hillside fringe sage (E) between the upland pinyon-juniper (H) and bottomland big sagebrush (B).

An idealized depiction of the vegetational features on the landscape is presented in Figures 3 and 4. No particular valley in the region appears as in the figures, but rather the vegetational patterns from many areas are abstracted and placed within the diagrams. The foregrounds of the figures represent the lower elevational areas of the northern and southern geographic regions. The backgrounds of the figures correspondingly represent the higher elevations nearer the drainage divides. The vegetational categories are named to correspond to Table I, and they are generally expressed in the landscape associated with the particular topographic categories indicated in the figures.

Interpretation: Interpretation of these vegetational patterns in terms of environmental factors affecting the organisms is not straight-forward. There are differences in soil properties which correlate with differences in vegetation. However, soil and vegetation develop with mutual interaction and both develop under the influence of climate, relief, and parent material. Therefore explanation of vegetation patterns cannot stop with soil differences. This feature has implications for reclamation and will be returned to later. As shown above, differences in relief, exposure, and elevation account for the large part of vegetational variation and the suggestion is that moisture and substrate stability are the underlying principal gradients to which vegetation responds.

Figure 3. Idealized diagram of the broad vegetation features of the northern part of the oil shale region. Community names and letter designation correspond to Table I.

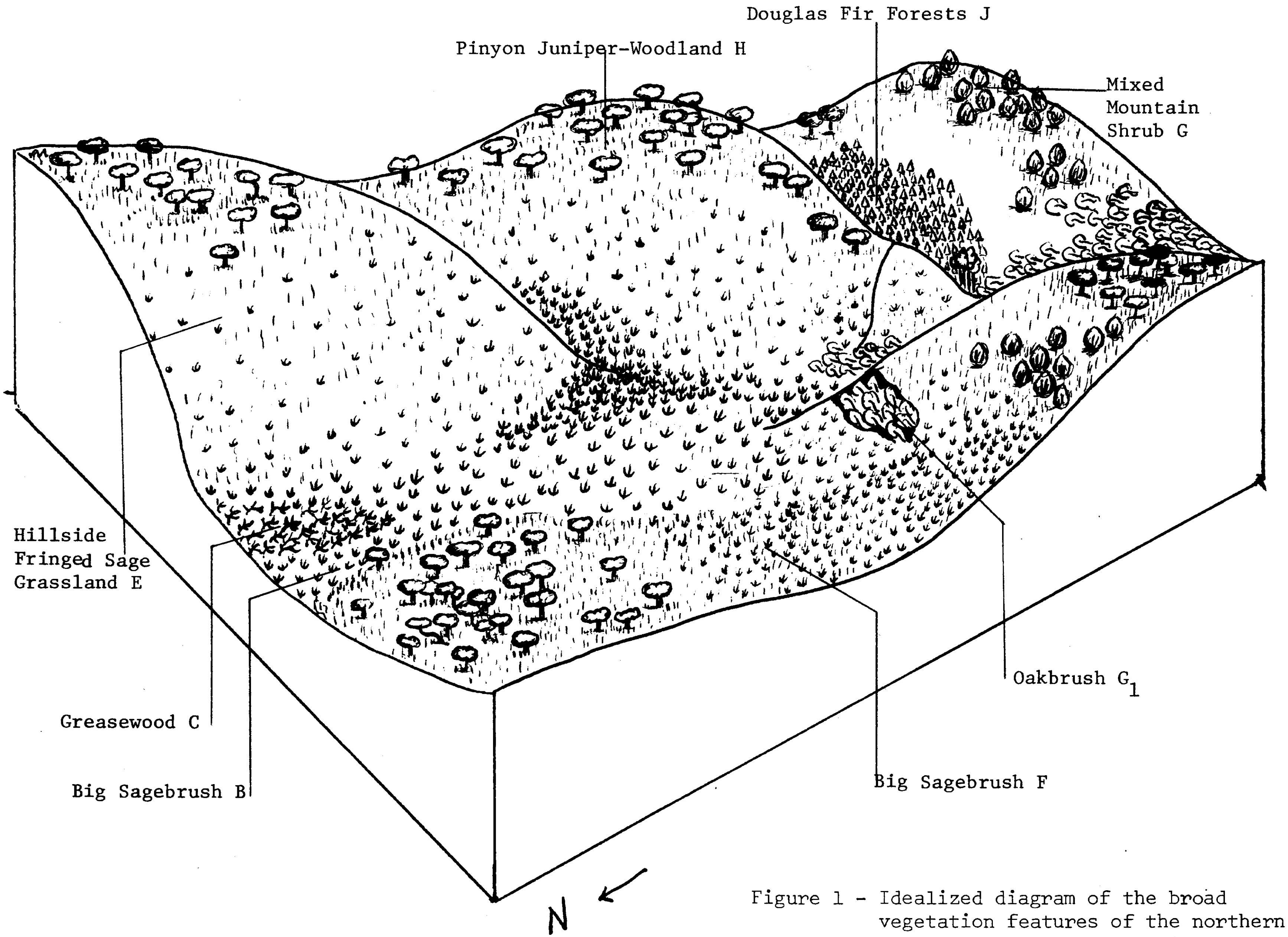

Figure 1 - Idealized diagram of the broad vegetation features of the northern part of the oil shale region. Community names and letter designation correspond to Table I.

Figure 4. Idealized diagram of the broad vegetation features of the southern part of the oil shale region. Community names and letter designations correspond to Table I.

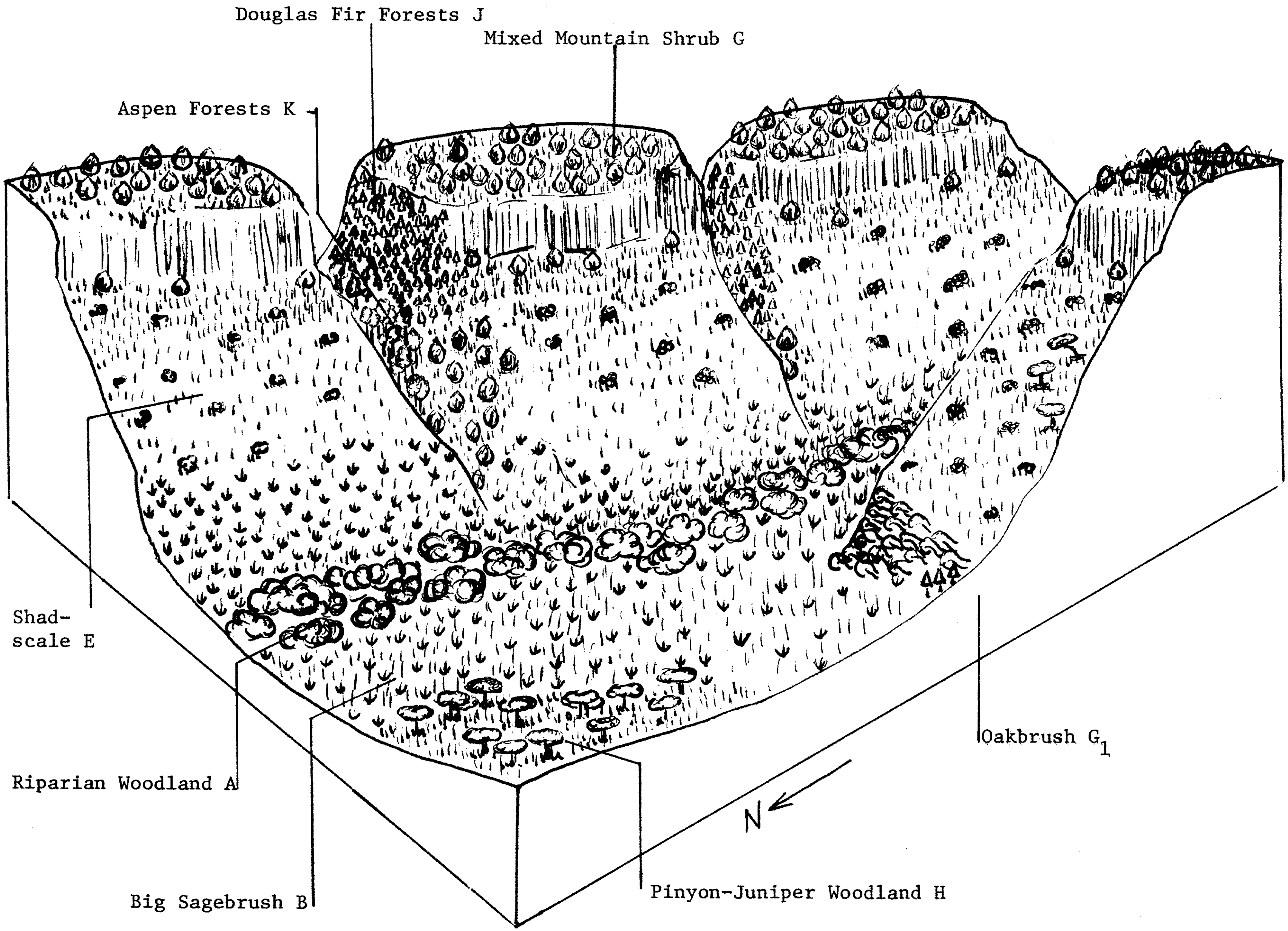

Figure 2 - Idealized diagram of the broad vegetation features of the southern part of the oil shale region. Community names and letter designations correspond to Table I.

In general, lower elevations, hillsides, and uplands are drier than higher elevations, valley bottoms, coves, gullies, and concave slopes. Hillsides are more unstable than level uplands or valley bottoms. Hillsides therefore tend to be drier and more unstable than other parts of the landscape. High elevation areas have moist uplands because of the elevation and moist valley bottoms because of topographic position. Quantification and detailed examination of the environmental factors affecting the vegetation is the next step to be taken in understanding ecological properties pertinent to revegetation.

Conclusion

Restored vegetation must have the same essential characteristics as the vegetation it replaces, and be compatible with the vegetation it will co-occur with. Not only must composition and structural characteristics of native plant communities be copied in the correct proportions, but ecologically relevant properties of diversity, graininess, horizontal and vertical distribution of biomass, species-species associations, and succession must be taken into account.

RECOMMENDATIONS AND SUGGESTIONS FOR ADDITIONAL RESEARCH

The several recommendations for the rehabilitation of vegetation scattered through this report can be characterized simply as the near duplication in restored plant communities of all the ecologically relevant attributes of naturally occurring communities. These include composition, structure, diversity, pattern, specific associations, graininess, tolerance spectra, and others.

Although simple to state, the recommendations are not simply accomplished; it is to the accomplishment of reclamation that future research should be directed. There are two areas of concern. First, the evaluation and quantification of the vegetation to be replaced, in terms of the ecological properties listed above and presented in detail elsewhere in the report, must be made. Second, the technology of compliance to these aspects of vegetation needs working out. For example, to meet structural and compositional requirements the technology of selecting, growing, and maintaining native species on reclaimed substrates is in progress. But study is needed on the specification and accomplishment of appropriate stratification, productivity, surface plant cover, graininess, diversity, and patterning in the entire vegetation mosaic.

SUMMARY

Published and unpublished sources were examined for information on the vegetation of the Colorado oil shale region. Federal agencies (BLM and SCS) have accumulated many records over the years, which, although useful to their particular planning programs, are of limited value to a baseline understanding of the vegetation of the region. Basic studies of the vegetation are lacking, therefore inferences from studies in related areas must be drawn. While these provide a pattern of probability for the delineation of ecological relationships of the plant communities in the Piceance Basin, the necessary understanding can be achieved only through direct study.

This report considers the appropriate characterization of the ecological properties of the existing natural vegetation and, based upon many days of field observations, presents a preliminary syllabus of 18 self-sustaining plant communities deemed critical to reclamation in the Piceance Basin (see below). The communities range from riparian woodlands of bottomlands, through pinyon-juniper and various shrublands of the upland slopes, to isolated groves of Douglas fir or aspen in rather steep-sided coves. These are discussed in relation to topographic patterns within the geographical context of the Piceance Basin.

Restored vegetation must have the same essential characteristics as the vegetation it replaces, and be compatible with the vegetation it will co-occur with. Characteristics of the vegetation which need to be understood in detail and accounted for by reclamation include: floristic composition and proportionate and vertical patterns, including life form and stratification; patterns of texture in the vegetational mosaic; and the ecological amplitudes of species.

Acceptable revegetation and rehabilitation of mined oil shale land must yield an evident harmony with natural vegetation in the present landscape.

SUMMARY CLASSIFICATION OF THE NATURAL VEGETATION OF THE PICEANCE BASIN.

The names in parentheses identify the mapping unit of Terwilliger and Cook in the parent publication. Descriptions of the types are provided in the parent publication.

I. Bottomlands. (*Bottomlands;* includes A, B, and C)
These are areas of erosional deposition.
  A. Riparian Woodland
  B. Big Sagebrush Shrubland
  C. Greasewood Shrubland

II. UPLANDS
These are areas of erosional depletion.
  D. Shad-scale Shrubland (*Desert Shrub*)
  E. Hillside Fringed Sage and Grassland (*Not Mapped*)
  F. Big Sagebrush Shrubland (*Upland Big Sagebrush*)
    F_1. Low Elevation Big Sagebrush Shrubland
    F_2. Mid Elevation Big Sagebrush Shrubland
    F_3. High Elevation Big Sagebrush Shrubland
    F_4. Big Sagebrush Shrublands of Cliffs and Rocky Breaks

G. Mixed Mountain Shrubland (*Mixed Mountain Shrub*)
    - G_1. Oakbush Shrubland
    - G_2. Serviceberry Shrubland

H. Pinyon-Juniper Woodland (*Pinyon-Juniper Woodland*)
    - H_1. Low Elevation Pinyon-Juniper Woodland
    - H_2. High Elevation Pinyon-Juniper Woodland
    - H_3. Pinyon-Juniper Woodland on Cliffs and Rocky Breaks

I. High Elevation Grasslands (*High Elevation Grasslands*)

J. Douglas Fir Forests (*Forests*)

K. Aspen Forests (*Forests*)

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PLANT NAMES

Common and Latin plant names

TREES

Aspen	*Populus tremuloides*
Boxelder	*Acer negundo*
Cottonwood	*Populus acuminata*
Douglas fir	*Pseudotsuga menziesii*
Juniper	*Juniperus utahensis*
Pinyon pine	*Pinus edulis*
Ponderosa pine	*Pinus ponderosa*

SHRUBS

Big sagebrush	*Artemisia tridentata*
Bitterbrush	*Persia tridentata*
Burroweed	*Gutierrezia sarothrae*
Chokecherry	*Prunus virginiana*
Fringed Sage	*Artemisia frigida*
Gambel oak	*Quercus gambelii*
Greasewood	*Sarcobatus vermiculatus*
Mountain mahogany	*Cercocarpus montanus*
Prickly pear cactus	*Opuntia polycantha*
Rabbitbrush	*Chrysothamnus nauseosus*
Rose	*Rosa* spp.
Serviceberry	*Amelanchier* spp.
Shad-scale	*Atriplex confertifolia*
Snowberry	*Symphoricarpos albus*
Spiny horsebrush	*Tetradymia spinosa*
Wax currant	*Ribes cereum*
Winter fat	*Eurotia lanata*

GRASSES AND SEDGES

Beardless wheatgrass	*Agropyron inerme*
Bluegrasses	*Poa* spp.
Cheatgrass	*Bromus tectorum*
Idaho fescue	*Festuca idahoensis*
Indian ricegrass	*Oryzopsis hymenoides*
Junegrass	*Koeleria cristata*
Kentucky bluegrass	*Poa pratensis*
Needlegrass	*Stipa* spp.
Needle-and-thread	*Stipa comata*
Sedge	*Carex* spp.
Squirrel tail	*Sitanion histrix*
Timothy	*Phleum* spp.
Western wheatgrass	*Agropyron smithii*

FORBS

Balsamorhiza	Balsamorhiza sagittata
Beardtongue	Penstemon spp.
Bluebell	Mertensia spp.
Dandelion	Taraxacum spp.
Flixweed	Descurainia spp.
Hood's phlox	Phlox hoodii
Nuttall's goldenweed	Haplopappus nuttallii
Indian paintbrush	Castilleja spp.
Lupine	Lupinus spp.
Mullein	Verbascum thapsus
Sulfurflower	Eriogonum umbellatum
Yarrow	Achillea lanulosa

Chapter 3

ECOSYSTEMS AND THEIR NATURAL AND ARTIFICIAL REHABILITATION

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TABLE OF CONTENTS

INTRODUCTION

The chapter, natural and artificial rehabilitation of disturbed areas, is divided into two sections. The first section discusses natural rehabilitation (succession) while the second section covers artificial rehabilitation (reseeding) of disturbed areas.

A description of the ecosystems (identified by vegetation and land form) encountered in the oil shale study area is presented in detail. The broad ecosystems are delineated on a fold-over map included at the back of this report. The vegetation association used as mapping units were described and referred to by Ward, Slawson and Dix, Chapter 2. The plant communities are described in their present condition. It is not implied that this vegetation is climax, also no attempt is made to describe the vegetation that would exist under different management.

It is a pleasure to acknowledge organizations and inviduals who have contributed to the progress of this project. Substantial cooperation was contributed by the Bureau of Land Management, Soil Conservation Service and the Colorado Division of Wildlife. These organizations were very helpful in the preparation of the vegetation map. Special acknowledgement is due the Colorado Division of Wildlife for the use of Little Hills Experiment Station as a base of operations during the summer, 1972.

Individuals who gave freely of their time and knowledge were Jesse Hale and Ron Perrin, SCS Meeker; Stan Colby, BLM Meeker and Philip Threlkeld, who worked in the field on the vegetation map and the succession study.

NATURAL REHABILITATION

Introduction

The use of oil shale requires the disturbance of the ecosystems overlying these reserves. In many cases this disturbance will take the form of complete destruction of the existing vegetation and a mixing of top soil with subsoil material. It is likely that this mixture will then be used as a covering of the disturbed area. The replacement of the vegetation community will take place in this soil material. It will develop through artificial rehabilitation or through various stages of succession until a stable community occupies the disturbed area. A knowledge of the successional pattern and the length of time required is needed in order to effectively plan for rehabilitation and the impact that resource development may exert on the ecosystems.

Reseeding has been used as a tool in rehabilitation, thus knowledge of the effects of this practice on secondary succession is also needed. This is true since the simple act of reseeding should not be considered as having rehabilitated a disturbed area. Complete rehabilitation of an area requires the development of a stable plant community. Man's effort to rehabilitate an area should be such that they assist the natural processes. Therefore, knowledge of the effect of various reseeding practices on the process of secondary succession is needed to plan a proper reseeding program.

The ecosystems of the Piceance Basin have been subjected to various types of disturbances since man has used its resources. Those disturbances which occurred within the last 18 years and for which records are available served as research material for this study. It would be desirable to have a longer period following disturbance but identification of such areas could not be made and records of the disturbance were not available. This report can only discuss the successional trends taking place during relatively early stages of succession. However, this is probably the most critical period and the period during which reseeding will have its greatest impact.

The objectives of this study were to:

1. Identify the ecosystems which exist within the Piceance-Yellow Creek Basins.
2. Document the successional trends following various types of disturbances.
3. Determine the influence of artificial rehabilitation on complete restoration or developmental successional trends.

Review of Literature

Ecosystems and Ecosystem Potential

The literature does not report any studies concerning the identification of ecosystems in the oil shale area of western Colorado. Most of the information that is available is found in the records of the Bureau of Land Management, the Colorado Division of Wildlife and the Soil Conservation Service in the form of vegetation inventories. These are reviewed by Ward, et al., Chapter 2 of this report.

Literature concerning local studies of the potential of the ecosystems for the production of vegetation includes one study on the oil shale area (Medin 1960). Using correlation-regression techniques Medin found that soil depth, clay content and surface stoniness were the significant factors in predicting production on landscapes developed on shale. The sandstone landscapes were significantly higher in production than the shale landscapes. Soil nutrients did not appear to cause differences in mountain mahogany production. Additional studies by Smith (1966), Robertson et al. (1966), and Cunningham (1971) evaluated landscape-vegetation relationships in sagebrush ecosystems in North Park, Colorado and at Maybell, Colorado.

Successional Trends in Existing Vegetation

Unpublished inventory data available from records of the Bureau of Land Management, Colorado Division of Wildlife and the Soil Conservation Service indicate that pinyon-juniper, sagebrush and mixed mountain shrub communities occupy about 56 percent, 21 percent and 15 percent respectively, of the area in the oil shale study area.

The pinyon-juniper community usually grows on ridges and on the more shallow soils. Woodbury (1947) indicated that he did not think that pinyon-juniper could invade the deeper soils occupied by sagebrush (<u>Artemisia</u> spp.)

However, Blackburn (1967) and Reveal (1944) reported that since about 1900 it has invaded these deeper soils. According to these authors juniper (Juniperus spp.) invades the sagebrush community first and is then followed by pinyon (Pinus edulis). The resulting sagebrush community with scattered pinyon and juniper, in time, gives away to a closed pinyon-juniper stand with little understory.

Many ecologists have reported that sagebrush-grass vegetation is a disclimax resulting from excessive grazing by livestock (Stoddart, 1941; Hull and Hull, 1974; Humphrey, 1945; Stewart, 1941). In apparent support of these ecologists, studies have indicated that desirable grasses and forbs decrease under heavy use by livestock while sagebrush and rabbitbrush (Chrysothamnus spp.) increase (Robertson and Kennedy, 1954; Blackburn, 1967; Tucker, 1962; Daubenmire, 1950; Ellison, 1960; Hanson and Stoddart, 1940; Robertson, 1947).

On the other hand, many workers claim that the sagebrush community is a climax with a normal understory of grasses (Fautin, 1946; Shelford, 1963; Tisdale, et al., 1969; Hugie, et al., 1964; Passey and Hugie, 1962; Passey and Hugie, 1963). The latter researchers found sagebrush as a major component of vegetation in relict areas which had never been grazed. From all indications the sagebrush-grass community is a climax type at least in many areas but succession due to grazing especially with cattle will reduce the grass understory and increase the density of sagebrush. A technique to distinguish a grassland site as compared to a sagebrush-grass site is needed to manage these communities realistically. Sagebrush density can be controlled by using a grazing system of spring deferment followed by heavy late-fall grazing with sheep (Laycock, 1967).

Another successional trend noted in the sagebrush community is the apparent replacement of sagebrush with greasewood (Sarcobatus vermiculatus) on bottomland sagebrush sites. Observations in the oil shale area and elsewhere in northwestern Colorado indicate that in many cases sagebrush is found on the youngest terraces along the drainages while a greasewood or sagebrush-greasewood community is found on the older terraces. This can be accounted for by the salinization of soils as they become older due to the cycling of salts by greasewood. These plants absorb salts and deposit them on the soil surface when leaves fall. This results in a gradual increase of salt in the surface soil. Such soil changes favor a successional trend favoring greasewood over sagebrush (Roberts, 1950; Sharma and Tongway, 1973).

Primary Succession

Chadwick (1960) reported the only study of primary succession in an ecosystem resembling those found in the Piceance Basin. His study was conducted in an area supporting a mixed shrub community with pinyon-juniper on the surrounding hills having sandy soils.

The stages of primary succession and years since initiation of succession are shown in Table 1.

The final bitterbrush-chokecherry community had an understory composed of needle-and-thread (Stipa comata), thickspike wheatgrass (Agropyron dasystachyum), sandberg's bluegrass (Poa secunda), sand dropseed (Sporobolus cryptandrus), indian ricegrass (Oryzopsis hymenoides), and arrowleaf balsamroot

(Balsamorhiza sagittata). Cheatgrass (Bromus tectorum) was present as a minor component of the final community.

Table 1. Stages of primary succession and length of time since initiation of succession on sandy soils in southeastern Idaho (Chadwick, 1960).

Stage	Plant Community	Years of Succession
1	Ryegrass-psoralea	-
2	Rabbitbrush-ryegrass-psoralea	20
3	Bitterbrush-rabbitbrush	50
4	Bitterbrush-big sagebrush-chokecherry	100
5	Bitterbrush-chokecherry	700

Secondary Succession

The initial stages of secondary succession following complete disturbance are usually composed of either native annual forbs such as buckwheat (Eriogonum sp.), waterleaf (Nama sp.) and Phlox (Navarretia sp.) or alien annual forbs such as tumbling mustard (Sisymbrium altissimum), Russian thistle (Salsola kali), and tansy mustard (Descurainia pinnata) (Young and Evans, 1973). The alien forbs are more aggressive and develop if a seed source is available. If cheatgrass seed is available and if the seedbed is characterized by plant litter and a rough micro-topography, then cheatgrass would be the initial dominant (Young, et al., 1969; Young and Evans, 1973).

Intermediate stages of succession are not documented in this case. However, abandoned fields on sagebrush-bitterbrush sites in Idaho supported a grassland vegetation after 30 years. The vegetation was dominated by needle-and-thread with lesser amounts of Sandberg's bluegrass and cheatgrass (Chadwick, 1960).

Succession following fire: Succession following fire in the sagebrush-grass community results in a rapid increase in the amount of rabbitbrush and horsebrush (Tetradymia canescens) as well as thickspike wheatgrass and bluebunch wheatgrass (Agropyron spicatum). After 12 years these species tend to decrease and they returned to their original composition after about 30 years. Bluegrass (Poa sp.) and Idaho fescue (Festuca idahoensis) which were originally reduced by fire increased gradually during the following 30 year period (Harniss and Murray, 1973). This pattern was also found to hold true by Pechanec, et al., 1954; Chadwick, 1960; Blaisdell and Mueggler, 1956. However, the end stage of succession was determined by the specific habitat-type. Bitterbrush may reinvade burns rather rapidly since it may sprout following fire (Blaisdell and Mueggler, 1956).

Methods and Materials

Study Area

General description: The study area is located in northwestern Colorado and lies between the White River on the north and the Roan Cliffs on the south. It is bounded on the east by the Grand Hogback and on the west by the Cathedral Bluffs and Roan Creek. This area is about 42 miles wide and 54 miles long with a surface area of 2268 sq. miles. Elevations range from about 54oo feet at the northwest corner of the area to about 8600 feet on the divide between the White River and the Colorado River.

Drainage is toward the north in the northern two-thirds of the area. Piceance Creek and Yellow Creek are principal drainages in the northern part while in Parachute Creek and Roan Creek, in the southern one-third of the area, drainage is southward into the Colorado River.

Three major land forms are found within the area. The dominant form is a rolling upland with residual soils. This landform comprises about 92 percent of the total area. Another 4 percent is alluvial bottomland along all major drainages. The remaining 4 percent is composed of cliffs and rock lands and is situated in a topographic position between the bottomland and rolling upland. Management and rehabilitation characteristics of the cliffs and rock land depend more on its topographic form than on other characteristics of the ecosystem.

Climate in the Yellow Creek - Piceance Basin is typified by hot-dry summers and dry to moist cold winters. Precipitation varies with elevation averaging about 11 inches in the northwest corner where elevation is about 5400 feet. This increases to about 18 inches at 7500 feet. The major portion of the basin receives 14 to 15 inches of moisture with about an equal monthly distribution. In the upper portion of the basin, above 7500 feet, and on the Roan plateau the summer temperatures are cooler and precipitation increases to a maximum of about 25 inches. The major portion of the plateau receives about 20-23 inches with about equal monthly distribution.

Ecosystems of the study area: The ecosystems of the Yellow Creek - Piceance Basin are represented in part by the six major vegetation associations listed below:

1. Desert shrub
2. Sagebrush uplands
3. Sagebrush bottomlands
4. Pinyon-juniper
5. Mixed mountain shrub
6. Forest

The upland sagebrush, pinyon-juniper and forest associations are very diverse and are subdivided into the ecosystems indicated below:

Upland sagebrush
  a. Low elevation sagebrush
  b. Intermediate elevation sagebrush
  c. High elevation sagebrush
  d. Sagebrush on cliffs and rocklands
Pinyon-juniper
  a. Low elevation pinyon-juniper
  b. High elevation pinyon-juniper
  c. Pinyon-juniper on cliffs and rocklands
Forest
  a. Douglas fir forest
  b. Aspen forest

Each of these ecosystems will tend to react to management and to disturbance in an individual way and the potential for rehabilitation is different.

Desert Shrub -- The desert shrub covers only one tenth of one percent of the area of the basin and is located mainly at the mouth of Piceance and Yellow Creeks on sites underlain by the Green River geological formation. Vegetation is dominated by shadscale (Atriplex confertifolia) and winter fat (Eurotia lanata) with sagebrush and douglas rabbitbrush (Chrysothamnus nauseosus) being represented in the overstory along with horsebrush and greasewood. Grasses include western wheatgrass, bottlebrush squirreltail (Sitanion hystrix) and saltgrass (Distichlis stricta).

Sagebrush Bottomlands -- Sagebrush bottomland covers about four percent of the basin. This ecosystem is typified by very tall sagebrush sometimes growing to a height of five feet or more. In certain areas, especially on the older terrain and in areas with high alkalinity, the sagebrush is replaced by greasewood. This has occurred in much of the bottomlands near the mouth of Piceance Creek and Yellow Creek. In other cases greasewood and sagebrush are mixed in various proportions.

The understory associated which greasewood is usually saltgrass, bottlebrush squirreltail, numerous mustards (Lepidium spp.) and kochia (Kochia sp.). In the sagebrush stands western wheatgrass, bottlebrush squirreltail and cheatgrass are the most common understory plants. In local areas remnants of the once plentiful basin wildrye (Elymus cinerous) can be found.

Upland Sagebrush -- The upland sagebrush association covers about 32 percent of the area in the basin. It is represented by three relatively distinct ecosystems, identified as the low, middle and high elevation sagebrush communities.

The low elevation sagebrush ecosystem is typified by a low growing big sagebrush and rabbitbrush overstory with a grass and forb understory. This system has a sparse understory with western wheatgrass and needle-and-thread grass as dominants. Blue grama (Bouteloua gracilis) and sandberg's bluegrass are also represented. A part of the overstory is commonly made up of shadscale and winterfat especially in the Yellow Creek drainage.

The middle elevation system produces taller sagebrush plants with a better developed understory in which beardless wheatgrass (Agropyron inerme), June grass (Koeleria cristata) and bluegrass produce a much greater ground cover. Arrowleaf balsamroot is generally a prominent forb.

A high elevation sagebrush ecosystem occurs from about 7000 feet to the top of the basin. This community is dominated by big sagebrush with snowberry (Symphoricarpos tetonensis) and antelope bitterbrush as dominants. The grass and forb understory is very rich with columbia needlegrass (Stipa columbiana), (stipa lettermani), letterman's neddlegrass (Stipa lettermani) and nodding brome (Bromus anomalus) being the most prominent grasses. Lupine (Lupinus spp.), penstemon (Penstemon spp.), indian paintbrush (Aquilegia spp.), western yarrow (Achillea lenulosa), and sulfur flower (Eriogonum umbellatum) add additional variety to this highly diverse ecosystem.

Pinyon-juniper -- The pinyon-juniper association covers about 35 percent of the basin. It is commonly found on sites with shallow soils. The overstory is composed of approximately equal portions of Utah juniper (Juniperus osteosperma) and pinyon pine.

The lower elevation system occurs especially on shale outcrops. Its understory is extremely sparse made up mainly of scattered plants of bitterbrush and mountain mahogany (Cercocarpus montanus). Bottlebrush squirreltail, indian ricegrass and beardless wheatgrass are common grasses.

At higher elevations and on sandstone parent material the understory is better developed and is composed of such shrubs as sagebrush, bitterbrush, Oregon grape (Berberis repens), and buckwheat. The grass cover is composed of the same species as in the lower elevation type but ground cover is much greater. Golden weed (Haplopappus nuttallii), Phlox (Phlox spp.) and arrowleaf balsamroot are also present. This ecosystem is referred to as the high elevation pinyon-juniper.

Mixed Mountain Shrub -- The mixed mountain shrub covers 20 percent of the basin. This association is usually found at elevations above about 7000 feet and is composed of a mixture of serviceberry (Amelanchier alnifolia), bitterbrush, chokecherry (Prunus virginiana), mountain mahogany and oak brush (Quercus gambellii) growing in association with sagebrush. On certain sites oak brush or serviceberry may dominate. The grass and forb understory is usually very rich with such grasses as columbia needlegrass, letterman's needlegrass and nodding brome lending dominance. The major forbs include lupine, balsamroot, larkspur (Delphinium spp.), indian paintbrush, western yarrow, and penstemon.

Forest Associations -- The forest association covers about 5% of the area and is composed of both aspen (Populus tremuloides) forest and douglas fir (Pseudotsuga menziesii) forest.

The aspen forest is typified by a dense understory composed of snowberry and rose (Rosa spp.), with columbia needlegrass, letterman's needlegrass, brome grass and Kentucky bluegrass (Poa pratensis) dominating the grass layer. Columbine, penstemon, paintbrush, lupine, bracken fern (Pteridium aquilinum), and larkspur represent the highly diverse forb component. The community is most common on the deep, moist, rich soils.

The douglas fir community occurs on the more shallow soils and does not develop a very rich understory due to dominance of the tree cover and litter. Arnica (Arnica spp.), lousewart (Pedicularis spp.), and calamograstis (Calamagrostis spp.) are most common.

The vegetation of the Roan Plateau is composed of only the high elevation communities, mixed mountain shrub, high elevation sagebrush and the forest types. In general sagebrush is located on the ridge tops and in the valleys while mixed mountain shrub occurs on south facing slopes and the forest communities on the cooler and more moist north facing slopes.

Study Site Selection

Sampling strata: Areas were selected to sample successional trends across the major drier low elevation landscapes as one strata and across the moist higher elevation landscape as a second strata. This approach seemed to offer a chance to obtain a reasonable amount of information in the time available.

Low Elevation Strata -- Since low elevation pinyon-juniper and low and intermediate elevation sagebrush covered about 89 percent of the low elevation strata, attention was directed toward these major ecosystems. The understory vegetation within each of these areas was quite similar as to the species represented. Thus it was believed that early successional patterns would be similar even though succession would end in sagebrush in one case and in a pinyon-juniper community in the other.

High Elevation Strata -- In the case of the high elevation strata, high elevation sagebrush, high elevation pinyon-juniper and mixed mountain shrub communities cover a relatively large portion of the area and were most important for this reason. Again the grass and forb components of the three ecosystems were very similar and the soil was relatively uniform. Observations indicate that early successional patterns would be similar in these three ecosystems.

Essential criteria for selecting study sites: The following criteria were followed in selecting study sites:

1. Date of disturbance must be available.
2. A series of disturbance over time must be available for each ecosystem.
3. Disturbed areas must not have been redisturbed at some later date.
4. Boundary of disturbed area must be identifiable.
5. Replication must be available for each successional period following disturbance in each ecosystem.
6. Disturbed areas must be accessible.

Availability of disturbed areas within strata: Two possibilities for studying secondary succession following disturbance were available in the basin. Some sites have had all the vegetation removed and in addition, they have had soil disturbance which resulted in mixing of the top soil with subsurface material. This mixing of soil material has reduced the supply of residual seed which had accumulated in the topsoil from plants which had previous growth on the area. The soil available for plant growth was not as desirable as the original soil and it thus would have some effect on rate of succession and on the plant communities which develop during succession. Included in the above disturbances were pipelines, drill sites, and road barrow pits.

Since drill sites and road barrow pits were continuously redisturbed they did not meet the criteria for study areas. Pipelines were selected for the study of completely disturbed areas except in the case of new drill sites which were useful for studying the pioneer species invading such areas. The above types of areas are referred to in the text as area with completely disturbed vegetation or as completely disturbed areas. Thirty-six such areas were studied to evaluate secondary succession.

The second type of study areas were those which were only partially disturbed. In most cases the original soil was mainly in place. Only the very surface soil had been disturbed. While some of the original vegetation was still established certain components, usually the dominance overstory, had been removed. Such areas included burns of various ages and chaining to remove pinyon and juniper. In the former case sagebrush, pinyon, juniper and some forbs and grasses were killed. In the latter case little damage was done to the understory and some young pinyon and juniper still remained. These areas were used to study succession on partially disturbed areas.

Burns which occurred in 1962 and 1963 were located in the high elevation strata. Three areas disturbed by fire in 1960, 1964 and 1971 were located in the low elevation strata.

Extensive areas in the lower strata were chained in 1967 and 1969. Fourteen such sites were selected for sampling. Chaining in the high elevation strata occurred between 1958 and 1963. Four sites were selected on areas chained in 1958 and two each in areas chained in 1960, 1962 and 1963.

Measurement and Analysis Technique

On each study site, three 9.6 square foot plots were established. The total number of grams of green weight and the percent composition was estimated for each species on each plot.

The data for each study area were summarized by listing all species which occurred and then recording the average percentage composition for each species. These summaries were combined for each type of disturbance and for different lengths of time following disturbance. Information showing relationships between species composition and time after disturbance were assembled and analyzed. The nature of secondary succession results in extreme variability in species encountered and in their percentage composition. Sufficient replication and control of the design to overcome these problems were not possible in this type of a survey. Therefore, plant association data could only be assumed to indicate successional trends.

Results and Discussion

Results will be presented and discussed individually for each type of disturbance and for each ecosystem in which the type of disturbance was found.

Secondary Succession Following Complete Disturbance

Low elevation ecosystems: All study sites except a few of the newly disturbed ones had been seeded to crested wheatgrass (*Agropyron cristatum*). The first year following disturbance on the sites which had been seeded, Russian thistle accounted for 51 percent of the composition while crested wheatgrass and indian ricegrass accounted for 23 and 11 percent respectively. Eight years after disturbance crested wheatgrass increased to 48 percent and Russian thistle was reduced to 17 percent. Shrubby plants, douglas rabbitbrush and snakeweed (*Gutierrezia sarothrae*), had invaded the area accounting for 18 percent of the composition.

After fifteen years, crested wheatgrass remained only as an occasional plant while Indian ricegrass and rabbitbrush remained as prominent components of the vegetation. Cheatgrass which had not been prominent in earlier stages of succession now accounted for about 18 percent of the vegetation. In addition, beardless wheatgrass and eriogonum were present in conspicuous amounts.

It is interesting to note that the average after 17 years showed that cheatgrass, rabbitbrush and goldenweed made up 37 percent of the composition. Perennial grasses were represented by bottlebrush squirreltail which made up only 4 percent of the composition. Very possibly grazing by livestock had reduced the amount of perennial grass present. In these disturbed and reseeded areas the use by livestock is probably excessive since the animals are attracted to these relatively small areas by the presence of the palatable grasses which had been seeded. Heavy utilization of these seeded introduced grasses and the accompanying native grasses favors the growth of rabbitbrush, cheatgrass and unpalatable forbs. Sagebrush was not present in these disturbed areas even after 17 years.

One newly disturbed well site which had not been reseeded showed Russian thistle, lambsquarters (Chenopodium album) and miner's candle (Cryptantha servicea) to be the pioneer species revegetating the area. They occupied 41 percent of the composition. Native perennial grasses, Indian ricegrass and beardless wheatgrass, made up 8 and 34 percent of the composition respectively. The spring and early summer of 1973 was very favorable in terms of moisture. This early spring moisture may have contributed to the presence of so many beardless wheatgrass plants.

High elevation ecosystems: All disturbed areas at the higher elevations had been reseeded following disturbance. However, those disturbed in 1969 did not have reseeded species growing on the areas at the time of this study. Russian thistle accounted for 50 percent of the composition while Indian ricegrass and beardless wheatgrass accounted for 22 percent and 12 percent respectively. A variety of native forbs and shrubs were also present in small amounts. Apparently 1969 was not a favorable year for the establishment of crested wheatgrass. In effect, secondary succession on this area occurred without the influence of crested wheatgrass.

On areas disturbed eight years prior to this study, big sagebrush accounted for 40 percent of the composition while crested wheatgrass made up 15 percent of the composition and beardless wheatgrass accounted for 9 percent. In addition, forbs such as knotweed (Polygonum aviculare), stickseed (Lappula redowski), and dandelion (Taraxacum officinale) accounted for another 17 percent. Numerous other forbs were present in small amounts. The diversity of forb understory was the greatest at this time following eight years of secondary succession. Big sagebrush increased to about 60 percent of the composition after about 15 years and then remained about the same.

Reseeding these sites with crested wheatgrass did not appear to suppress the invasion of big sagebrush as it may have done in the low elevation ecosystems. Snowberry, serviceberry, along with rabbitbrush and gambel oak became prominent by the 17th year following disturbance. All shrubs accounted for 82 percent of the composition. Crested wheatgrass was reduced to 8 percent and only small amounts of forbs were present in the understory. This lack of understory may again be due to livestock concentrations on disturbed areas which had been reseeded.

Bottomland sagebrush ecosystems: All completely disturbed areas in the bottomland-sagebrush ecosystems were reseeded except for one which was disturbed in 1971. On the recently disturbed areas Russian thistle accounted for 99 percent of the vegetation while lambsquarter accounted for the other one percent.

One area disturbed in 1972 and seeded to ryegrass (*Lolium* sp.) was dominated by this species while Russian thistle made up only 2 percent of the vegetation.

All other completely disturbed areas were reseeded with crested wheatgrass. This species accounted for 99 percent of the vegetation after 2 years of secondary succession. By the eighth year following disturbance crested wheatgrass accounted for only 24 percent of the vegetation while cheatgrass had invaded and accounted for 10 percent of the composition. In addition to crested wheatgrass and cheatgrass, the understory had a prominent forb component composed of pepperweed (*Ledpdium* spp.), lambsquarter and stickseed. Two native shrubs, rubber rabbitbrush and greasewood had invaded and accounted for 43 percent of the composition.

Areas disturbed in 1961 contained no crested wheatgrass at the time of this study but big sagebrush accounted for 82 percent of the composition. The understory was mainly cheatgrass with small amounts of Indian ricegrass and the forb, scarlet globemallow (*Sphaeralcea coccinea*).

After 18 years crested wheatgrass averaged only 2 percent while cheatgrass averaged 18 percent. At this time the successional stage was dominated by greasewood and big sagebrush with some forbs such as pepperweed, Russian thistle, stickseed, golden corydalis and tumbling mustard making up the forb component.

Ecosystems Disturbed by Fire

Low elevation ecosystems: Considering sites which had been disturbed by fire two, nine, and thirteen years prior to this study, only the ones disturbed thirteen years before had been reseeded to crested wheatgrass. The others experienced natural succession without the influence of competition from seeded species.

The areas disturbed as recent as 1971 were dominated by western wheatgrass and scarlet globemallow. These species were about equally abundant and together accounted for 88 percent of the composition. A number of other native forbs were also present but only Russian thistle and knotweed accounted for as much as one percent of the composition.

Nine years after burning, big sagebrush had invaded the area and comprised 80 percent of the composition with indian ricegrass as the main understory species. Needle-and-thread grass, aster (*Aster* spp.) and snakeweed were also present.

Thirteen years following fire and reseeding to crested wheatgrass, this species still made up 24 percent of the composition. Big sagebrush contributed 48 percent to the total vegetation while indian ricegrass, needle-and-thread grass and snakeweed were also present in about the same amount as on the unseeded areas. In addition, forbs such as Osterhout's penstemon (Penstemon osterhoutii) and daisyleaf aster (Aster leucanthemifolius) had started to invade along with bitterbrush.

On the low elevation ecosystems reseeding to crested wheatgrass apparently reduced the invasion of big sagebrush to a limited extent.

High elevation ecosystems: In the high elevation pinyon-juniper ecosystems only two areas disturbed by fire 10 years prior to this study were available. One of these had been reseeded while the other had undergone succession without the influence of reseeding. Since these sites were similar they could be used to reflect the effect of reseeding on successional trends.

The burned area which had not been reseeded was dominated at the time of this study by tumbling mustard which accounted for 32 percent of the vegetation. Indian ricegrass, cheatgrass and western wheatgrass accounted for 25, 11 and 7 percent of the vegetation respectively while mountain mahogany accounted for 16 percent.

On the reseeded area, crested wheatgrass accounted for 39 percent of the total vegetation while tumbling mustard accounted for 4 percent and indian ricegrass 9 percent. Cheatgrass was somewhat higher on the reseeded area.

Reseeding with crested wheatgrass increased the amount of perennial grass in the vegetation and decreased the amount of annual forbs. Evidently reseeding speeds up the process of secondary succession by replacing the early annual forb stage with the perennial grass stage. In this and other areas cheatgrass appears to be associated with the perennial grass stage of succession rather than the early annual weed stage. Shrubs had only started to invade this area, thus the influence of reseeding on shrub invasion could not be determined.

Ecosystems Disturbed by Chaining

Chaining of ecosystems kills the overstory trees but it may leave some young trees which are limber and able to bend without breaking or being uprooted. This type of disturbance makes available to the existing understory vegetation the water and nutrients which had been utilized by the trees.

The area immediately under the uprooted trees may be completely disturbed thus exposing such areas to the same secondary successional processes as occur on completely disturbed areas.

Low elevation ecosystems: These areas which had been chained in 1967 and 1969 had not been disturbed sufficiently long to express different stages of succession. Therefore, the data for both areas were averaged for final evaluation.

Indian ricegrass made up a small percent of the original vegetation but it responded rapidly by an increase in size of existing plants and by the establishment of new plants. It made up 7 percent of the composition 4 years after chaining and 25 percent after 6 years.

Other native grasses also increase in amounts. These included western wheatgrass, beardless wheatgrass, bottlebrush squirreltail and blue grama. Cheatgrass which made up 18 percent of the composition after 4 years contributed only about 1 percent after six years.

Shrubs such as big sagebrush, bitterbrush and mountain mahogany plants also increased following chaining. Big sagebrush and bitterbrush both averaged about 9 percent of the floristic composition while mountain mahogany averaged 5 percent.

Russian thistle was the dominant species on the completely disturbed spots. It averaged 26 percent after four years but was less important after six years. At the end of six years of sucession the general aspect of the areas was grassland with a few young juniper trees visible.

High elevation ecosystems: High elevation ecosystems which had been chained from 10 and 15 years prior to the study displayed an aspect of sagebrush or mixed mountain shrub with a few scattered plants of young pinyon and juniper.

Snowberry and big sagebrush both made up somewhat over 20 percent of the composition after 10 years of secondary succession. Mountain mahogany represented 12 percent of the composition after 10 years. It was present in moderate amounts after 11 years but was not a significant component on the areas disturbed 13 and 15 years previously.

Serviceberry increased from 2 percent after 10 years, to 19 percent of the vegetation cover after 15 years of secondary succession. Grasses as a group made up nearly 50 percent of the vegetation after 10 years of succession but made up only about 20 percent after 15 years of secondary succession. Indian ricegrass and Junegrass decreased from 24 percent and 14 percent respectively to zero on areas 15 years old. Beardless wheatgrass increased during this same period. Forbs such as Osterhout's penstemon, hood's phlox (Phlox hoodii), loco (Astragalus spp.), eriogonum and oregon grape were also represented on the older chaining but not on the younger ones.

ARTIFICIAL REHABILITATION

Revegetation of Strip Mined Oil Shale Lands

The most important limiting factor in successful rehabilitation of disturbed land surfaces is precipitation and soil moisture. Much of the area in Colorado underlain by surface minable oil shale receives less than 15 inches of precipitation annually. Therefore, it is obviously essential that all moisture conserving practices should be considered and utilized in all rehabilitation projects. Other problems confronting satisfactory rehabilitation practices of surface mine spoils are salinity, alkalinity, toxicity, high clay content, and deficient plant nutrients including nitrogen and phosphorus.

Most of the oil shale area in Colorado receives most of its subsoil moisture from snow. This is supplemented by intermittent spring and summer rainfall. The amount and distribution of precipitation during the growing season are important factors in establishing vegetation.

Reclamation is frequently difficult because precipitation is not only low but it is also eratic and unpredictable. The success of reclamation or revegetation of desert lands and semiarid areas will be dependent on supplying the key requirements necessary. The essential ingredients of water, plant nutrients, and tolerant species of vegetation must be supplied or influenced artificially, otherwise the essential combination of factors may not be present during the year of seeding. This critical time varies with geographic location and with elevation. The lack of any one crucial factor or the timing of its availability will detrimentally influence results.

Rehabilitation of spoil banks resulting from surface mining for oil shale presents site conditions that do not normally occur under most surface soil disturbances. Spoil banks have characteristic steep figuration, exposed subsoils, and frequently no native seed source is available.

Factors Affecting Revegetation

Typically, mine spoil banks vary chemically, physically and texturally from location to location and from spot to spot within a particular location. Therefore, the seeding problems are extremely variable. It is basic then that the seeded mixture contain a varied group of species. The best time to plant is just before the period of normal precipitation so that the planted seed will have assured moisture for germination and survival. Any seedbed treatment that preserves soil moisture increases the chances of seedling establishment (Cook et al, 1970). Precipitation can be conserved in several ways that greatly enhance the possibility of establishing desirable vegetation. This can be accomplished by incorporating proper spoils drainage design and by reducing gradients of mine spoils terrain, by mulching with organic mulches to reduce evaporation and erosion and increase infiltration (National Academy of Sciences, 1973).

Topographic features of gradient and exposure are important factors influencing seedling establishment and rehabilitation. Steep slopes may be successfully revegetated, but ordinarily mine spoils are typically unstable when left with steep slopes, and it is folly to attempt revegetation until physical slope stability is achieved. This is accomplished by reducing gradients usually to 3:1 ratio or less. The steepness of slope affects the amount of precipitation that actually infiltrates the soil and becomes available for plant growth (Hodder et al, 1972)

South and west facing slopes are considerably drier than the east and north facing slopes. Solar interception and direction of prevailing winds create a different microclimate on each aspect of a given topographic configuration. Over time such varied topographic features have led to wide differences in character of both soil development and vegetative cover.

Effective design of the spoil bank material is to a large degree dependent on the subsequent use to be made of the area. Effective design should incorporate practical, useful, attainable and permanent principles. Alignment and topographic profile of the overburden should blend into the surrounding terrain and reflect the normal landscape as nearly as possible (National Academy of Science, 1973). Vegetational life forms as well should be in harmony with the surroundings. A reforestation approach in the desert areas, for instance, should not be condoned.

Methods of Seeding Spoil Banks

Topsoiling: It is generally recommended that 4 to 6 inches of top soil be stockpiled to be redistributed over the spoil bank following leveling. It must be remembered, however, that 4 to 6 inches of top soil spread over rock fragments will not support a satisfactory vegetation cover. The soil and subsoil should be at least 18 to 24 inches in depth to store surplus moisture for plant growth during more arid periods during growth.

Top soil should be identified with respect to texture, minimum organic matter, salt content and pH. It is suggested that top soil dressing should contain at least 10% clay but not more than 35 percent. Likewise quality top soil should not contain more than 20% gravel, 65% sand or 80% silt. In addition, organic matter should be in the range of 3 to 20 percent (Cook et al, 1970).

Planting methods: In most cases seed is planted by drilling or by broadcasting. Generally drilling gives better results and is recommended if the terrain allows operation of wheeled machinery. Drilling has consistently produced more favorable responses because the seed is distributed and covered more uniformly (Vallentine et al, 1963).

Any method that scatters the seed directly on the soil surface without soil coverage is termed broadcasting. Two types of equipment are commonly used: (1) hydroseeders which apply the seed mixed in water and (2) implements known as fan or air blast seeders. The seed, however spread, should be covered with soil in some way if it is to germinate and become established. This is especially true in arid areas or on unfavorable sites such as south and west facing slopes. In all cases, broadcast seed covered with soil is much superior to no coverage of seed by soil, even on favorable sites (Cook et al, 1970). Most seed should be covered rather shallow for best results.

If mulches are used in conjunction with broadcast seeding, best results can be obtained by broadcasting the seed, covering with soil and then applying the mulch.

Rate of seeding: Intensity of seeding involves quantity of viable seed per acre. Wide drill-row spacings are undesirable since they allow competition from weeds between the rows and prolong stand establishment.

For planting, the quantity of viable seed is generally expressed in pounds per acre because the actual number of seed per unit area of soil surface must be considered. Thus, when planting a small-seeded species less pounds per acre are generally required because of the greater number of seeds per pound.

It is generally acknowledged that broadcasting requires at least twice as much seed as drilling. In addition, poor sites require more seed than favorable sites. For example, if crested wheatgrass or a species with similar sized seed were drilled, about 15 pounds of viable seed per acre would be needed on south and west exposures but only about 7 to 10 pounds would be needed on east and north exposures. When broadcasting, about 30 pounds of viable seed per acre should be seeded on south and west slopes, but only about 15 pounds would be needed on east and north exposures.

Adapted Species: Selection of the proper species to plant is extremely important in revegetation of spoil bank material in oil shale strip mining areas of Colorado.

In arid sandy soils, the native species such as sand dropseed (Sporobolus cryptandrus) and indian ricegrass (Oryzopsis hymenoides) are desirable. When seeded as single species, about 2 to 4 pounds of sand dropseed or 5 to 10 pounds of indian ricegrass per acre should be drilled and twice this quantity if broadcast.

In arid areas when annual precipitation is perhaps no more than 8 to 9 inches it is often better to use an assortment of native species that are found in the area. Many native shrubby species such as sagebrush, rabbitbrush, and 4-wing saltbush have been used rather successively (Merkel et al, 1973). Also most of the native grass species are suitable and in many cases the seed is available on the commercial market (Cook et al, 1970).

Fertilizers: Some soil nutrients will undoubtedly be low in exposed subsoils. Nitrogen is generally the element most likely to be limiting for plant growth. Seeds generally germinate and emerge even though soil nutrients are lacking because of the stored food reserve in the seed. Likewise the young seedling has a limited area of soil feeding zone because of a small and underdeveloped root system. The developing seedling however requires moisture and nutrients to extend its root system in the soil and produce photosynthetic tissue for food manufacture.

There is a close relationship between the benefits of nitrogen fertilizer and soil moisture. Nitrogen applications may be detrimental under arid or drought conditions but extremely beneficial when soil moisture is available (Welch et al, 1962).

Fertilizers, consisting of nitrogen or phosphorus or the two in combination, when applied at the time of planting, have not always shown beneficial effects to seedling establishment. Adding rather high quantities of nitrogen does produce some added benefits but these may not be of sufficient magnitude to justify the cost. Phosphorus alone or with nitrogen even at 80 pounds of each per acre has not consistently influenced seedling establishment. Work in North Dakota indicated that surface-mining spoil banks were extremely low in phosphorus (Bond et al, 1971). Applying nitrogen at the time of planting may increase weed growth and subsequent competition for moisture and nutrients.

Mulches: Because of the extreme difficulty experienced in revegetation of disturbed arid ecosystem in the West the use of mulches has received considerable attention during the past few years.

There are many mulching materials including straw, hay, sawdust, woodchips, wood fiber, bark manure, boughs, jute or burlap, gravel, peat, paper, leaves, and plastic films. The need for a mulch depends upon physical properties of the soil, land form, slope, aspect, aridity of the site and annual precipitation.

Seeding harsh sites are always benefited by the use of mulches to conserve soil moisture. However, such an expenditure is costly and must be evaluated on the basis of the essentiality of obtaining a plant cover rapidly and with assuredness. Mulches break the impact of the raindrop sealing and thus increase infiltration. Mulches also reduce runoff and erosion and increase soil moisture by reducing evaporation (Barnett et al, 1967, Jacoby 1969, Klomp 1962, Mannering et al, 1963, Richardson et al, 1961, Cook et al, 1970).

Trials show that arid desert areas where precipitation is from 5 to 8 inches annually are almost impossible to seed artificially and therefore natural seeding will be the only means of stabilizing cuts and fills. In arid areas of the West where annual precipitation is less than 8 inches, native vegetation will reinvade disturbed areas if the north and east facing slopes are at least a three to one and preferably a four to one, and south and west facing slopes are at least a four to one and preferably five to one (Cook et al, 1970). In addition, the surface should be rough as a result of scarification treatments or pitted to retain natural runoff (Hodder et al, 1972).

All conventional mulches provide protection to the soils surface against evaporation and erosion. Mulches conserve substantial soil moisture to a depth of 12 inches or more. Studies show that mulches produce a greater number of established seedlings and a more dense herbage cover than areas seeded without mulches (Cook et al, 1970). In addition erosion is substantially reduced during seedling establishment. In most cases mulches shorten the period required to establish a plant cover. The commonly used mulches include:

(1) Wood fiber applied 1,000 to 2,000 pounds per acre gives consistently favorable results under all conditions except in areas where frost heaving or excessive surface water flow exists.

(2) Other wood residues are sawdust, woodchips, bark and shavings. These are rather abundant in the West. They are easy to apply and are long lasting. However, on steep slopes they slide down the hill. In addition they compete with plants for nitrogen. Excelsior mats have been effective as mulches but they are expensive, decompose rather rapidly and attract mice.

(3) Hay or straw applied at 2,000 to 6,000 pounds per acre, bound with asphalt at 300 gallons per acre, gives beneficial results but this mulch is susceptible to being carried away by wind and water. Straw is often contaminated with grain and weed seed that produces fatal competition with newly planted grass seedlings. Native bailed hay is preferred over straw since it has fewer weed seed. Either straw or hay can be distributed uniformly over the soil surface after broadcast seeding and held in place by punching it into the surface soil with either a mulch tiller, a modified sheepsfoot roller, or a weighted agricultural type disk. The foregoing mulch anchoring methods adequately cover the seed; therefore, it is not necessary to cover it with soil prior to adding mulch.

(4) Macerated paper mulch is produced by passing newspaper through a hammer mill operating at a moderate speed with a 10-mm screen opening. When applied as a slurry at 1,500 to 2,500 pounds per acre, it gives satisfactory results but is not as long lasting as wood fiber, straw-asphalt mulches or native hay punched into the soil.

(5) Some areas are subject to severe wind or water erosion and must be securely protected during the period of plant establishment. Such protection can best be brought about by the use of mats or mesh covers.

Jute mesh or burlap is effective in stabilizing steep slopes and in establishing seedlings but it is expensive and laborious to apply. If not properly applied, water will run beneath the mesh and create gullies. Jute mesh is, however, long lasting and may be justified on unstable sloping sandy soils or on critical drainage areas. In Wyoming (Jacoby, 1969) it was found that a combination of straw and jute netting was exceedingly effective as a mulch. Excelsior mats are effective for temperature modification, moisture conservation and seedling establishment. However, the mulch is expensive, laborious to apply.

(6) Plastic materials are best applied by diluting them with water and then spraying them on the soil surface. They produce a rubbery film that is resistent to erosion (Chepil et al, 1963). The film limits infiltration of precipitation but does increase the germination of seed since it reduces evaporation from the soil surface by acting as a vapor barrier.

(7) Gravel, stones and crushed rock are effective mulches and withstand both wind and water erosion. The most effective size for a surface application is from 1/2 to 3 inches in diameter. This size range remains in place well and allows adequate interspaces for seedling emergence. Work in Utah (Cook, et al, 1970) found that a gravel mulch with aggregates ranging from 0.75 inch to 2.0 inches at a depth of about 2 inches modified the soil surface temperature extremes, increased infiltration of precipitation, conserved moisture through reduced evaporation, restricted surface erosion and promoted better stands of grass when compared to other mulches and bare ground. One disadvantage of gravel mulches for seeding soil bank material is that they gravitate down a slope, thus accumulating at the base and finally being too deep at the bottom and leaving the soil surface almost bare at the top.

(8) Frequently a cereal sorghum crop is first grown and the perennial revegetation species are seeded into the stubble or aftermath after the annual planted crop is harvested or has matured. This aftermath material serves as a mulch and this practice has been a widespread practice throughout the northern Great Plains region.

Weed control: Annual weeds rapidly invade disturbed areas. This is a blessing in some respects since it aids in the control of water and wind erosion but in other respects annual weeds delay the establishment of more permanent vegetation. Therefore it is frequently desirable to control these weeds by some mechanical or chemical means prior to seeding.

Prior to seeding it is common practice to control weeds during the growing season prior to seeding in order to conserve soil moisture. This method of soil preparation conserves soil moisture that otherwise would be used by the weeds. Preventing weeds from going to seed reduces the likelihood that thick stands of weeds will compete with the newly emerged planted grass seedlings. Summerfallowing can be done effectively by tillage or by chemicals. Tillage is costly on steep or rocky slopes since general farm implements do not work effectively. Under such conditions selective herbicides are generally used since neither burning nor mowing roadsides is an effective means of summer-fallowing.

In the arid West, annual weeds present harmful competition to seeded perennial species during the first two to three seasons after planting. Control of this annual weed competition during the early period of seedling establishment has been the difference between success and failure (Cook, 1965). The most common means of control to date has been through the use of selective herbicides.

In arid areas it is often necessary to control annual weeds and grasses during at least the first year of perennial grass seedling development. In semi-desert areas, seeding success may depend upon control of weedy competition during both the first and second growing seasons of the newly planted grass seedlings.

The post-emergence herbicide 2,4-D may be applied at a rate of 1.5 pounds per acre to weeds in perennial wheatgrass-seeded areas without significantly damaging the seeded grass plants. Post-emergent herbicides applied in the late spring during either the first or the second growing season or during both the first and second growing seasons, produce significantly more established grass plants. These plants have higher vigor and cover the ground surface more rapidly than those in seeded plots where herbicide is not applied to control annual broadleafed weed growth.

Grazing Management Following Planting

The final step in obtaining a satisfactory cover of vegetation following seeding is the grazing management during seedling establishment. It is common practice to protect a new seeding from grazing for at least the first two growing seasons and frequently as long as three or even four growing seasons. Young seedlings should not be grazed until they are firmly rooted. Plants are not established if they can be pulled from the ground by a tug by the hand.

Fencing will usually be required to prevent grazing at least during the establishment period. Otherwise it may be necessary to remove livestock from adjacent areas.

Ecological Types and Rehabilitation Potential

As stated previously climate, espeically rainfall, is to a large degree the determining factor in rehabilitation of disturbed land surfaces. It is responsible for what was present before land disturbance and will be responsible for what can be maintained there naturally after disturbance.

Ecosystems of the study area with a high potential for rehabilitation include the forests, grasslands and the mixed mountain shrub types which grow in altidudinal zones where precipitation is favorable for plant growth and where rather deep fertile soils have developed. Therefore unless substrata of undesirable character are left exposed the probability of satisfactory revegetation is high. This of course presumes that the best methods for rehabilitation will be followed. In these zones complete satisfactory rehabilitation could reasonably be expected within three to five years.

Ecosystems with moderate potential for rehabilitation include the entire foothill zone of the Piceance-Yellow Creek Basin. This broad type is highly variable. It consists of valley basins, and alluvial plains with intricate dissected drainage systems. The substrata is likewise highly variable. This possesses a highly delicate reconstruction process for a favorable rehabilitation site with respect to handling substrata and topsoil. The receipt of precipitation is erratic and varies widely by seasons and among years. However, past history of rangeland seeding has shown that satisfactory results can be accomplished if the best known methodology is practiced. In some cases parts of the seeding process may have to be redone when unfavorable climatic conditions occur during the rehabilitation period. Most of this zone can be identified by the presence of big sagebrush or mixed pinyon-juniper stands. Steep slopes, south and west slopes and unsuitable substrata underlying the replaced topsoil can present difficult problems.

Difficult areas, where immediate reclamation is doubtful with present technology, include the desert areas which appear in the lower portion of the valley basins or in small local areas lying among low elevated relief of hills, ridges or mesas. These areas receive low annual precipitation, may be alkaline, and may possess no A horizon or suitable topsoil for a plant growth medium for imposed cultural seeding procedures. In these desert areas natural regeneration of the dominant plant species occurs only every five to seven years. This perhaps takes place only when two better than average years occur in succession.

In any event the reestablished cover should not be expected to be greater than the original and this can occur only through an implemented process of natural ecological succession. Experience shows that such a process requires from perhaps twenty to fifty years even when a parent seed source is close by and the disturbed areas are not extensive.

It is evident that complete rehabilitation of difficult areas such as deserts will not be brought about by conventional means. It would appear that induced natural succession would substantially hasten the rehabilitation period. Natural succession can be complemented by the following factors: 1) the use of native seed from native plants, 2) additions of irrigation water initially, 3) replacement of topsoil or a soil suitable for plant growth, 4) construction of small basins or terraces for retention of natural runoff, and the application of mulches to reduce evaporation and protect seedlings.

SUMMARY AND CONCLUSIONS

Natural rehabilitation of completely disturbed areas progresses through annual forb, grass-forb, and shrub-grass stages of succession. The shrub-grass stage developed in about 17 years in low elevation ecosystems but it developed in about 8 years in high elevation ecosystems.

The time required for natural succession from apparent bare soil to a closed plant community will of course depend primarily upon the general climate of the area, the soil material available as a plant growth medium and the topographic features with respect to degree and aspect of slope. Natural secondary succession could conceivably require from 20 to 50 years or even a hundred years in some areas of the oil shale study area.

Rainfall between 20 and 25 inches annually is perhaps optimum and soils consisting of a sandy loam texture with rather high organic matter where the topography is considerably less than the natural incline of normal repose would complete the natural succession processes in a comparatively short period of time if parent seed sources were readily available. However, desert areas receiving only 5 to 6 inches of precipitation annually where rather heavy sterile soils are left exposed to erode to a natural incline of repose by natural sloughing away of the slope would conceivably require fifty to a hundred years or more. The natural processes of ecological succession might be further hampered by the absences of parent seed sources and the presence of salts in the oil that are toxic to plant growth.

Seeding to perennial grasses such as crested wheatgrass speeds up succession in that a perennial grass-weed stage is established in a relatively short period of time. This stabilizes the area rapidly and favors the invasion of desirable perennial native forbs. Reseeding also reduces the rate of shrub re-invasion and reduces the density of shrubs during the period of succession under study.

Seeding an area following disturbance will not, in itself, result in rehabilitation but seeding followed by management to favor natural succession will accomplish rehabilitation.

Cheatgrass was not important in early stages of succession in this study area. However, the literature indicates that under certain conditions cheatgrass may be a pioneer species if a seed source is available. If it is established as a dominant in the pioneer community the area may be held in this annual grass stage for an extended period (Young and Evans, 1973).

As with natural succession rehabilitation by artificial means is dependent upon climatic and edaphic and topographic conditions. Most areas receiving 10 inches or more annual precipitation with moderate slope and a satisfactory plant growth medium can be successfully rehabilitated by presently known techniques.

All of the best known methods of revegetating disturbed areas should be used for obtaining highest probabilities of success on all ecosystems. These include saving the top soil to be redistributed over the replaced overburden to depths of at least 4 to 6 inches. The combination of top soil and subsoils should be at least 18 to 24 inches in depth to store moisture for plant growth.

In most cases drilling the seed is preferred to broadcasting. In all cases the seed should be covered to a shallow depth with soil. If mulches are used in conjunction with seeding on the more harsh sites the seed should be planted and covered with soil before the mulch is added. Intensity of seeding is important in any revegetation practice. Poorer sites generally require twice as much seed as favorable sites and broadcasting requires twice as much seed as drilling.

Selecting adapted species for the various sites to be seeded may be the difference between success or failure of the seeding venture. In the oil shale area of Colorado there is a choice of at least 10 to 15 native species for each local area and perhaps 3 to 4 introduced species that would adapt to the various sites.

In many cases fertilizers such as nitrogen and phosphorus may aid in the rate of plant establishment on disturbed areas. Where possible supplemental water should be added to initiate plant establishment.

It may be necessary to control annual weed growth before planting or following seeding to enhance seedling establishment. This may best be accomplished by the use of appropriate pre- and post- emergence herbicides.

The final step in obtaining a satisfactory cover of vegetation following seeding is the grazing management while the seedlings are becoming established. Young seedlings should not be grazed until they are firmly rooted. Fencing may be required to control grazing for at least three to six years following planting.

Vegetation types with moderate potential for rehabilitation include the entire foothill zone of the Piceance-Yellow Creek Basin. Past history of seeding shows that satisfactory results can be accomplished if the best known methodology is used.

Vegetation types that will be difficult to rehabilitate include the desert areas which appear in the lower portion of the valley basins. These areas receive low annual precipitation, may be alkaline, and the soil may be poorly developed. Revegetation will not be accomplished by conventional artificial means. Therefore natural succession can be implemented by adding water initially and planting native seed sources in terraces or basins.

Ecosystems with a high potential for rehabilitation include forests, grasslands and mixed mountain brush types which grow at higher altidudinal zones where precipitation is favorable for plant growth.

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APPENDIX TABLE 1

List of species found in plots in the Yellow Creek - Piceance Basin. Listed in alphabetical order by common name.

Common Name	Scientific Name
arnica	arnica spp.
arrowleaf balsamroot	Balsamorhiza saggittata
aspen	Populus tremuloides
aster	Aster spp.
basin wildrye	Elymus cinevens

beardless wheatgrass	*Agropyron inerme*
big sagebrush	*Artemisia tridentata*
bitterbrush	*Purshia tridentata*
bluebunch wheatgrass	*Agropyron spicatum*
blue grama	*Bouteloua gracilis*
bracken fern	*Pteridium aquilinum*
buckwheat	*Eriogonum* spp.
cheatgrass	*Bromus tectorum*
chokecherry	*Prunus virginiana*
columbine	*Aquilegia* spp.
columbia needlegrass	*Stipa columbiana*
crested wheatgrass	*Agropyron cristatum*
daisyleaf aster	*Aster leucanthemifolius*
dandelion	*Taraxacum officinale*
Douglas fir	*Pseudotsuga menziesii*
four-wing saltbush	*Atriplex canescens*
Gambel oak	*Quercus gambellii*
gilia	*Navarretia* spp.
golden corydalis	*Corydalis aurea*
goldenweed	*Haplopappus nuttallii*
greasewood	*Sarcobatus vermiculatus*
hood's phlox	*Phlox hoodii*
horsebrush	*Tetradymia canescens*
Idaho fescue	*Festuca idahoensis*
indian paintbrush	*Castilleja* spp.
indian ricegrass	*Oryzopsis hymenoides*
junegrass	*Koeleria cristata*
juniper	*Juniperus* spp.
Kentucky bluegrass	*Poa pratensis*
knotweed	*Polygonum aviculare*
kochia	*Kochia* spp.
lambsquarters	*Chenopodium* album
larkspur	*Delphinium* spp.
Letterman's needlegrass	*Stipa lettermani*
loco	*Astragalus* spp.
lousewort	*Pedicularis* spp.
lupine	*Lupinus* spp.
miners candle	*Cryptantha sericea*
mountain mahogany	*Cercocarpus montanus*
needle and threadgrass	*Stipa comata*
nodding brome	*Bromus anomalus*
Oregon grape	*Berberis repens*
Osterhout's penstemon	*Penstemon osterhoutii*
penstemon	*Penstemon* spp.
pepperweed	*Lopidium* spp.
phlox	*Phlox* spp.
pinyon	*Pinus edulis*
rabbitbrush	*Chrysothamnus* spp.
reedgrass	*Calamagrastis* spp.
rose	*Rosa* spp.
rubber rabbitbrush	*Chrysothamnus nauseosus*
Russian thistle	*Salsola kali*

ryegrass	Lolium spp.
saltgrass	Distichlis stricta
sandberg's bluegrass	Poa secunda
sand dropseed	Sporobolus cryptandrus
scarlet globemallow	Sphaeralcea coccinea
serviceberry	Amelanchier alnifolia
shadscale	Atriplex confertifolia
snakeweed	Gutierrezia sarothrae
snowberry	Symphoricarpos tetonensis
squirrel tail	Sitanion hystrix
stickseed	Lappula redowski
sulfur flower	Eriogonum umbellatum
tansy mustard	Descurainia pinnata
thickspike wheatgrass	Agropyron dasystachyum
tumbling mustard	Sisymbrium altissimum
Utah juniper	Juniperus osteosperma
waterleaf	Nama spp.
western wheatgrass	Agropyron smithii
western yarrow	Achillea lanulosa
winterfat	Eurotia lanata

APPENDIX TABLE 2

List of species found in plots in the Yellow Creek - Piceance Basin. Listed in alphbetical order by scientific name.

Scientific Name	Common Name
Achillea lanulosa	western yarrow
Agropyron cristatum	crested wheatgrass
Agropyron dasytachyum	thickspike wheatgrass
Agropyron inerme	beardless wheatgrass
Agropyron smithii	western wheatgrass
Agropyron spicatum	bluebunch wheatgrass
melanchier alnifolia	serviceberry
Aquilegia spp.	columbine
Arnica spp.	arnica
Artemisia tridentata	big sagebrush
Aster spp.	aster
Aster leucanthemifolius	daisyleaf aster
Astragalus spp.	loco
Atriplex canescens	four-wing saltbush
Atriplex confertifolia	shadscale
Balsamorhiza saggittata	arrowleaf balsamroot
Berberis repens	Oregon grape
Bouteloua gracilis	blue grama
Bromus anomalus	nodding brome
Bromus tectorum	cheatgrass
Calamagrastis spp.	reedgrass
Castilleja spp.	indian paintbrush
Cercocarpus montanus	mountain mahogany
Chenopodium album	lambsquarters

Chrysothamnus spp.	rabbitbrush
Chrysothamnus nauseosus	rubber rabbitbrush
Corydalis aurea	golden corydalis
Cryptantha sericea	miners candle
Delphinium spp.	larkspur
Descurainia pinnata	tansy mustard
Distichlis stricta	saltgrass
Elymus cinereus	basin wildrye
Eriogonum spp.	buckwheat
Eriogonum umbellatum	sulfur flower
Eurotia lanata	winterfat
Festuca idahoensis	idaho fescue
Gutierrezia sarothrae	snakeweed
Haplopappus nuttallii	goldenweed
Juniperus spp.	juniper
Juniperus osteosperma	Utah juniper
Kochia spp.	kochia
Koleria cristata	Junegrass
Lappula redowski	stickseed
Lepidium spp.	pepperweed
Lolium spp.	ryegrass
Lupinus spp.	lupine
Nama spp.	waterleaf
Navarretia spp.	gilia
Oryzopsis hymenoides	indian ricegrass
Pedicularis spp.	lousewort
Penstemon spp.	penstemon
Penstemon osterhoutii	Osterhout's penstemon
Phlox spp.	phlox
Phlox hoodii	Hood's phlox
Pinus edulis	pinyon
Poa pratensis	Kentucky bluegrass
Poa secunda	Sandberg's bluegrass
Polygonum aviculare	knotweed
Populus tremuloides	aspen
Prunus virginiana	chokecherry
Pseudotsuga menziesii	douglas fir
Pteridium aquilinum	bracken fern
Purshia tridentata	bitterbrush
Quercus gambellii	gambel oak
Rosa spp.	rose
Salsola kali	Russian thistle
Sarcobatus vermiculatus	greasewood
Sisymbrium altissimum	tumbling mustard
Sitanion hystrix	squirrel tail
Sphaeralcea coccinea	scarlet globemallow
Sporobolus cryptandrus	sanddropseed
Stipa columbiana	columbia needlegrass
Stipa comata	needle-and-threadgrass
Stipa lettermani	Letterman's needlegrass
Symphoricarpos tetonensis	snowberry
Taraxacum officinale	dandelion
Tetradymia canescens	horsebrush

Chapter 4

EVALUATION OF MINING TECHNIQUES

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EXPLORATION CORE-DRILLING

The first step in the development of an oil shale mining operation is exploration. Probably the most effective and efficient technique utilized in exploring for oil shale is diamond drilling. The amount of land disturbed by exploratory diamond drilling is dependent upon (1) company preference as to the number of drill holes per unit area necessary for efficient mine planning, and (2) the size of the drilling equipment used. Due to the rather regular and predictable occurrence of the oil shale strata in the Piceance Creek Basin, exploratory drilling is expected to be minimal as compared to most hard-rock exploration drilling programs.

Following are the equipment capabilities, personnel requirements, and the amount of surface areas necessary for typical core-drilling operations (Dept. of Interior, Vol. 1, III9, 1972).

	Large Rig	Small Rig
Equipment Capabilities (feet)	to 8,000	to 4,000
Required Personnel (number)	10-15	4-6
Amount of Surface Area Disturbed (acres)	10-15	3-5

The diameter of the core ranges from 1-7/8 inch for the small rigs to 4-7 1/2 inches for the large rigs. Air is usually preferred as the coring fluid, but water and/or drilling mud is also used.

Most environmental impacts of core drilling are of a temporary nature. Following completion of the drilling operation, the land surface is restored according to the stipulations set forth in the special land use permit issued by the Bureau of Land Management for operations on public lands. This special permit stipulates, among other things, that the drill site area must be seeded (the establishment of vegetative cover) after the core drilling operations are completed. Nonetheless, some impacts on the area cannot be erased very quickly. For instance, scraping of access roads to the location and leveling of the drill site involve removal of surface vegetation such as sagebrush and small trees which require many years to replace; the use of heavy equipment may produce differential soil compaction; surface grades may be changed which can have an effect on drainage patterns; and new patterns of erosion may be established by the local alteration of the land surface. These potential hazards are greatly reduced as the result of stipulations pertaining to environmental protection and control which have been incorporated into all coring permits. These stipulations concern (1) field operations, (2) restoration of land, (3) protection of current surface uses, and (4) the protection of fresh water aquifers that might be affected by drilling. The drilling operator must submit a plan specifying location, drilling method, size of casing, safety precautions, abandonment procedures, and a scheduled work performance.

Access roads to potential mining sites, drilling sites and spent shale disposal areas will disturb amounts of land dependent upon their size. For example, a sixty foot right-of-way requires eight acres per mile of road while a twenty foot right-of-way requires only 2.4 acres per mile of roadway. Power, gas, oil, and water lines will also require land acreages. These requirements are entirely dependent upon the distance the facilities traverse.

In general, the land disturbed by pre-mining development of oil shale in the Piceance Creek Basin is a function of the final selection of mining sites and on the extent of exploratory core drilling. It is believed that four exploration holes per section (1 square mile) may be sufficient under normal circumstances. However, if the operation is dependent upon the secondary minerals in order to be economically viable, then additional amounts of drilling will be necessary because of the mode of occurrence and the lack of continuity often associated with these materials.

UNDERGROUND MINING

Room and Pillar

When contemplating the mining of oil shale by an underground method, it appears that the most viable approach would be the room and pillar technique or some modification thereof. This technique would yield an estimated sixty percent extraction of the Mahogany Zone by mining rooms on the order of 50-60 feet high and 60 feet wide and leaving pillars with dimensions approximating 60 feet by 60 feet.

Rooms would probably be advanced by utilizing a benching operation. The upper heading would be driven 15 feet high thus providing adequate height for using down-hole drills for drilling the remaining 30-35 foot bench. This height would also be convenient for rock bolting the roof strata. It is recommended that bolts of various lengths be utilized in the normal bolting patterns for increased operating safety. The extraction of the remaining bench would be completed in a manner consistent with the development and production sequence within a given mining area.

The amount of oil shale which can be extracted without appreciable surface subsidence depends upon the size and spacing of the rooms and pillars, the physical properties of the oil shale formation as well as the overlying formations, and the depth of overburden. Assuming a mining thickness of 50 feet, an extraction rate of 60 percent, a Modulus of Elasticity of 2.1, Poisson's Ratio of 0.286, an overburden depth of 1000 feet, and that the resulting pillars do not crush out, then the maximum anticipated surface subsidence would be something less than an inch (approximately 0.6 inches). This amount of subsidence would probably never appear on surface, however, due to bed separation, volume increase, degree of consolidation, etc.

The percentage of extraction usually decreases as the mining depth increases. However, if fill (spent shale) were used a higher extraction rate could probably be achieved with little additional adverse subsidence effects. This is not to say that subsidence would be reduced or even remain constant. On the contrary, subsidence could possibly be much higher, depending upon the physical properties of the spent shale and the size and positioning of the final pillars, if any.

If spent shale is to be introduced underground as fill material, the room and pillar technique will probably be modified to a panel and pillar method in order that mined-out panels may be completely filled thus utilizing this material more efficiently and effectively. With various modifications such as these, an effective extraction ratio of about 80 percent could probably be achieved without serious surface consequences because the fill would reduce large displacements or deterioration within the mined-out sections or panels.

Estimated land requirements for underground, surface, and in situ mining operations are presented in Table 1.

Table 1. Land requirements for oil shale processing, Department of the Interior, Volume 1, III-11, 1972.

Function Mining and Waste Disposal	Land Required, Acres
Surface Mine 1/ 2/ (100,000 bbl/day)	
Mine Development	30 to 85 per year
Permanent Disposal, overburden	1,000 (total)
Temporary Storage; low grade shale	100 to 200 (total)
Permanent Disposal; processed shale	140 to 150 per year
Surface Facilities 3/	200 (total)
Off-site Requirements 4/	180 to 600 (total)
Underground Mine 2/ (50,000 bbl/day)	
Mine Development (surface facilities)	10 (total)
Permanent Disposal	
All processed shale on surface	70 to 75 per year
60 pct. return of processed shale underground	28 to 30 per year
Surface Facilities 3/	140 (total)
Off-site requirements	180 to 225 (total)
In situ Processing (50,000 bbl/day)	
Surface Facilities 3/	50 (total)
Active well area and restoration area	110 to 900
Off-site requirements	180 to 600 (total)

1/ Area required is dependent upon the thicknesses of the overburden and oil shale at the site. Acres shown are for a Piceance Creek Basin site, with 550 ft. of overburden and 450 ft. of 30 gallon/ton shale (approx. 900,000 bbl/acre).

2/ Assumes 30 gallons per ton oil shale and a disposal height of 250 feet.

3/ Facilities include shale crushing, storage and retorting (excluded for in-situ processing), oil upgrading and storage, and related parking, office and shop facilities.

4/ Includes access roads, power and transmission facilities, water lines, natural gas and oil pipelines; actual requirements depend on site location. A 60-foot right-of-way for roads requires a surface area of about 8 acres per mile. Utility and pipeline corridors 20 ft. in width require 2.4 acres per mile.

Block caving

Block caving is a mining method whereby large blocks of ore are developed and then allowed to cave due to the weight of the ore material. This broken material is drawn from the bottom of the block thus allowing additional caving upward.

Not all types of deposits are amenable to block caving. The success of this method depends largely on whether the ore caves readily into small fragments. This, in turn, depends upon the extent of "inherent fractures" within the cavity unit. So called "weak ore", defined as easily fragmented ore, is generally considered ideal for block caving operations. In the case of oil shale, additional fracturing for efficient block caving may be required. This could be accomplished by controlled blasting in the block area. Other deposit requirements for efficient block caving operations are as follows:

1) clean ore - minimum of clays, etc., which may cause arching above draw points.
2) weak capping - overburden must be fairly weak and cave readily. Capping must not "hang-up" over stopes and possibly collapse at a future date.
3) massive ore body - required large ore body to be economical due to (a) large development requirements and (b) dilution from thin ore bodies.
4) uniform ore body - this is a non-selective method which does not allow sorting of waste material.

Block caving operations are typically characterized by high-volume, high productivity (tons/man-shift), and low unit costs. For instance, Magma Copper Company's San Manual Mine at San Manual, Arizona, is a block caving operation and currently the largest underground mine in the world. This mine produces, on average, 60,000 tons per day with production coming from blocks averaging 140 ft. by 180 ft. by 300-600 ft. high.

Because of the low mining cost associated with block caving it is an attractive extraction method providing the deposit fits the method requirements. In general, it is safe to assume that some variation of block caving could be applied to mining oil shale. However, the following disadvantages of block caving operations should also be considered:

1) non selectivity
2) rather inflexible method
3) must be able to tolerate surface subsidence
4) spent shale must be disposed on the surface.

Occidental processing method: The Occidental Processing Method is essentially a process wherein underground mining techniques are utilized to prepare the shale for retorting.

With this approach, the thickness of the oil shale should be at least 60 feet but more preferably, 200 feet or more. Shale assaying below 15 gallons per ton may be included in the zone. The basic Occidental system consists of mining out rooms above, below, and/or at intermediate levels within the zone to be retorted. Vertical 4" longholes are drilled through the remaining oil shale and loaded with ANFO. After detonation, the fragmented oil shale fills both its initial volume and that of the mined out rooms, giving the appearance of a tall vertical chimney of broken rock. Air flow is established from top to bottom and underground combustion is initiated with the aid of an outside fuel source for a few hours only. The fuel supply is discontinued and the fire becomes self-sustaining. Oil produced by the resultant thermal decomposition is collected in sumps at the bottom. The gas from the process is split into two streams. One is scrubbed for sulfur removal and then burned for power generation. The second stream is recycled to the retort to control the oxygen concentration and reaction conditions.

One of the primary advantages of this technique is that the extraction process is conducted underground. The only facility on surface would be the power plant. The oil shale conventionally mined as a result of initially developing the rooms could be sold to another company having a surface retorting facility. When processing oil shale near the exposed flanks of the basin, very low grade rock (less than 10 to 15 gallons per ton), can be mined and disposed of without processing.

Shafts and adits: Access to sub-surface orebodies is usually attained through shafts or adits and should a mining property lend itself to either approach the adit is generally the choice. Exploitation by way of adits offers lower cost of driving the opening, safety, ease of materials handling, better mine drainage, less surface plant needs, and numerous other advantages. In view of the low value of oil shale the lowest possible exploitation cost is a most important consideration and horizontal openings offer this advantage. Whether entry is by shaft or adit has little effect upon the mining method used in extracting the ore and when feasible, mining through adits should be selected rather than using shafts.

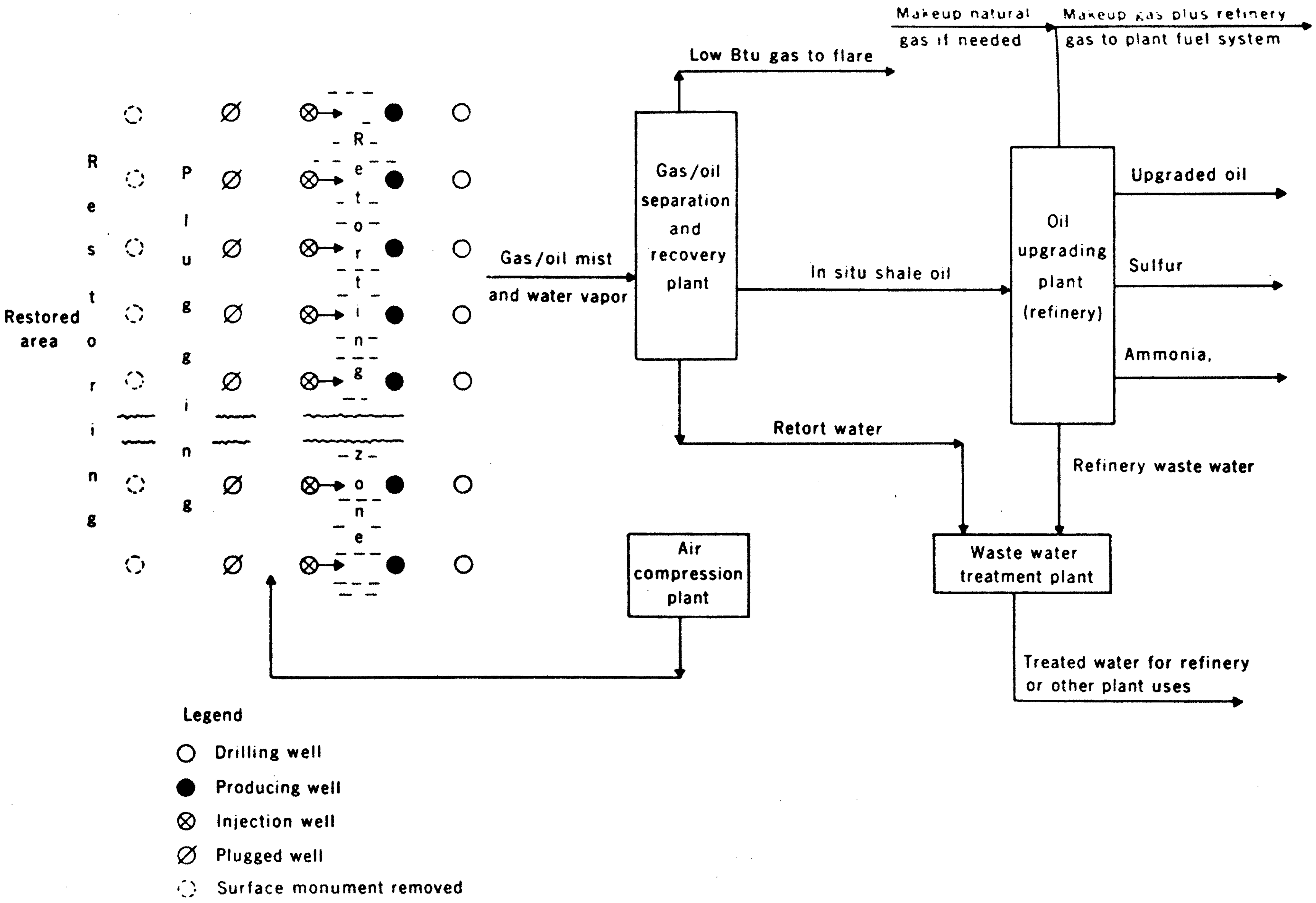
SURFACE MINING

The U.S. Department of Interior study determined that the area most amenable to open pit mining of oil shale was a tract designated as Colorado C-a owned by the United States. This 5,130 acre tract of oil shale is located in T.1S., R.99W, in sections 32, 33, and 34, and in T.2S., R.99W., in sections 3, 4, 5, 8, 9, 10. The lands described are all within Rio Blanco County, Colorado.

The Mahogany zone in this tract is 50 feet thick, averaging 30 gallons of oil per ton with 450 feet of 30 gallons per ton oil shale directly beneath the Mahogany zone. Overburden in the tract varies from 100 feet to 850 feet in thickness with an average of about 450 feet.

It would not be economically feasible to mine only the Mahogany zone, therefore, open pit mining must also include the lower 450 foot thick oil shale zone. In mining the two zones, amounting to 500 feet in thickness, plus the average overburden of 450 feet the ore to waste ratio would be slightly less than 1:1 in favor of the ore.

Assuming a daily production of 100,000 barrels of oil per day, a production of almost 147,000 tons of 30 gallons per ton ore at 100% oil extraction would be required. In addition, the removal of overburden would amount to some 145,000 tons of waste rock for a total daily mining rate of just under 300,000 tons. Mining at this capacity would require the application of 200 ton trucks and auxiliary equipment to accommodate this high production rate. On such a large scale of production the mining cost should be in the range of 40-50 cents per ton of ore going to process. Typical open pit mining does not lend itself to accepting waste fill until the mining has been completed, however, it is believed that an open pit mining plan can be developed to dispose of the overburden waste in the open pit while advancing on the production of oil shale. By doing so, would reduce the cost of disposing waste overburden into box canyons and disturb less of the existing environment. Much of the overburden in the early years of mining would have been used to fill box canyons and thus would leave much space in the open pit for disposal of spent shale. Proper scheduling of filling the open pit would be necessary in order to have a layer of spent shale above the overburden waste which in turn would be covered by the original top soil for revegetation.



(Dept. of Interior, Vol. 1, I-67, 1972)

Figure 1 - Flow Diagram of 50,000 Barrel per Calendar Day In-Situ Recovery System

It is expected that through the knowledge and efforts of the agricultural and forest engineers the revegetation of the mined out area would be acceptable to even the more critical ecologists and environmentalists.

IN SITU PROCESSING

Perhaps the most alluring method, at least in theory, for producing shale oil is by in situ retorting. This process contemplates the extraction of oil from the shale in place, by heating the shale while it is underground. This approach would eliminate the mining of oil shale, the problem of disposal of spent shale, and the possible contamination of surface or subsurface waters as a result of surface disposal of these materials. In addition, air pollution would be reduced or minimized when compared with that expected from surface retorting. It is envisioned that in situ processing would be most applicable to the thick, deep layers of oil shale occurring near the center of the Piceance Creek Basin.

Various techniques for supplying or creating heat have been tried or proposed including superheated steam, underground combustion, heated natural gas or carbon dioxide gas, hot solvents, and combinations of the above. The principal technical problem is that most oil shale beds have practially no permeability and are rather poor conductors of heat. Two prerequisites for in situ retorting are (1) the creation of sufficient surface area and fluid permeability with the rock mass to sustain combustion, and (2) to provide flow paths for oil, gas, and combustion products. There are two primary approaches currently under investigation. One approach proposes limited fracturing by rather "conventional" techniques utilizing (1) hydraulic pressure, (2) high voltage electricity, (3) superheated steam, and (4) chemical explosives. The other approach proposes massive fracturing by a nuclear explosion. This possibility has been under consideration since 1958. This technique would probably fracture several million tons of shale at one time. Because of their very nature, nuclear explosions would be amenable primarily to relatively thick deposits under substantial overburden. Such deposits occur over a large area of the Piceance Creek Basin in lands that are Federally owned. At present, there are many factors associated with nuclear explosions which need special attention and study. These factors are: (1) ground motion, (2) containment of radioactivity released from the explosion, (3) size and shape of the chimneys, (4) size distribution of the broken rock, (5) the type and amount of radionuclides, (6) the air pressure required to retort the shale, (7) the efficiency with which the shale could be retorted from the chimney, and (8) the impact on ground water quality. The lack of firm data precludes further analysis of this technique at this time.

Based on current petroleum technology conventional in situ retorting would include the following four basic steps: (1) well drilling, (2) fracturing to permit heat transfer and movement of liquids and gases, (3) application or creation of heat, and (4) recovery of products. To date a commercial in situ processing system has not been demonstrated, but a number of field-scale experiments involving wellbores from the surface have been conducted by government and industry during the past 20 years. The major problems encountered from these experiments were (1) the inability to concurrently recover associated minerals unless some type of in situ leaching technology is developed, (2) insufficient naturally occurring permeability, or failure to artifically induce permeability so as to allow passage of gases and liquids, and (3) the inability to remotely control the process with sufficient accuracy through well bores from the surface. Besides surface well bores, other methods proposed for introducing heat underground include mine shafts, tunnels, and fractures created by a variety of other techniques discussed above.

If it can be developed, in situ processing is envisioned as being a dynamic technique which continues to move across the surface of the area being developed. Figure 1 illustrates this procedure. Five rows of wells would comprise various operational modes; the first row of wells would be in drilling and preparation stage and the second row would be producing liquid and gaseous products driven by the injection of air or some other oxygen containing gases into the third row. Behind this area, plugging and restoration would be taking place. In this concept up to 100 wells may need to be drilled each month while the same number would need to be plugged as the combustion zone advanced through the producing zone. The active area encompassed by the five well patterns would total about 115 acres if 100 foot spacings were used between wells. Obviously fewer wells would be required if greater spacing between wells can be utilized to effectively retort the area. If such an operation, as described here, is conveivable, then careful preplanning would be required to reduce the environmental impact caused by a number of truck-mounted drilling rigs and other heavy equipment. Since about four wells would be required for each acre, a large portion of the area would be contacted by this equipment.

Another non-nuclear alternative to in situ processing is to use a combination of underground mining and in situ retorting. This concept visualizes development of a strata of oil shale having a suitable thickness and sufficient overburden. Approximately 30 percent of the in-place shale would be mined by an appropriate underground method and transported to the surface for conventional retorting. The remainder would be fragmented, probably by large, well placed conventional explosives to fill the mined-out voids and thus prepare a strata amenable to subsequent in situ retorting by the usual fire-flooding techniques. This technique has not been tested and should be considered only conceptual in nature.

A commercial in situ processing system has not yet been demonstrated. Therefore, it is impossible to adequately predict the amount of surface subsidence which might result as a consequence of in situ retorting. It is the general concensus that in situ retorting will produce a minimal amount of surface subsidence under normal conditions and probably indistinguishable amounts if retorting is carried out in the deeper portions of the Piceance Creek Basin. Additional field-scale operations are needed, however, before quantitative predictions can be made with any associated degree of accuracy.

Because of the more experimental current status of in situ oil shale technology, it is expected that a longer period of development time will be required before commercial level production might be feasible and subsequently attained. Considerable further improvements in technology are still required before industrial-scale in situ recovery of shale oil can become a reality.

DISPOSAL OF SPENT SHALE

Spent shale refers to the solids residue left behind after retorting of oil shale. It is a complex waste product whose physical and chemical properties will vary widely. Primary controlling factors are: (1) composition of the oil shale before retorting, (2) preparation of the shale for retorting, (3) type of retorting process used, and (4) the conditions encountered after retorting. Depending on the grade of shale being processed, the weight of spent shale is about 80-85 percent of that of the originally mined oil shale. The volume of the spent shale, even after compacting, is at least 12 percent greater than its in-place volume. This is due to void spaces in the mass of crushed and retorted material which are not present in the shale prior to mining. Table 2 shows the relationship of mined oil shales, shale-oil produced, and spent shale volumes for various rates of shale oil production.

Because of the volume increase, spent shale generated from a 50,000 to 100,000 bbls per day operation would be considerable and disposing of this material constitutes one of the greatest environmental issues associated with the development of an oil shale industry. Depending on the retorting process, the spent shale may vary in size from a fine powder to about 10 inches in diameter and would be discharged from the retort as a dry material. Transport to the disposal area may be accomplished by a hooded belt conveyor, trucks, or by a water slurry system - excess water being recovered and recycled.

There are three alternatives available for the disposal of spent shale: (1) find practical uses for it, (2) put it back in the mine, and (3) store it on the surface. Disposal methods for this spent material will vary and depend on the type of mining system used.

In the case of underground mining operations the replacement of spent shale in previously mined rooms or voids would be desirable from an environmental standpoint and possibly from an economic viewpoint also. The introduction of spent shale into underground openings could produce the following desirable results: (1) provide some underground support, thus possibly reducing surface subsidence, and (2) provide temporary pillars for support, enabling the removal of additional in-place shale pillars. This could significantly increase oil shale extraction via underground mining.

If spent shale is to be introduced underground, compaction will be necessary to insure maximum volume replacement, to prevent mineral leaching by water percolating through the material, and to help control possible surface subsidence. Unfortunately, current technology for underground compaction of spent shale is not adequately advanced to accomplish all of these objectives. Even if this technology were available, and the spent shale could be adequately and effectively drained of its water (from the slurry), it is expected that only 50 to 70 percent of the spent shale could be returned to the mine. This is because of its increased volume over the original in situ volume. Therefore, it would seem necessary to permanently store at least a portion (about 40 percent), if not all, of the spent shale on surface.

In open pit operations it is hoped that eventually much of the spent shale can be put back into the pits and revegetated. Replacement of spent shale can proceed when (1) sufficient space becomes available in one portion of the pit which has reached final pit limits, or (2) when a later pit operation is ready to fill the void created by an earlier pitting operation in a multiple pit arrangement. However, as with underground mines, considerable volume removal has to precede any replacement, so that the spent shale disposal operations do not interfere with mining.

It is commonly assumed that the surface disposal of most spent shale will, initially at least, be in box canyons within the Piceance Creek Basin. The engineering design of spent shale disposal must consider the physical properties

Table 2

Quantities of In-Place and Spent Shales
(Dept. of Interior, Vol. I, I-24, 1972)

Upgraded Shale Oil, barrels per day	Shale Mined, million tons per year	Shale Volumes, billion cu. ft. per year		
		In-Place	Spent (loose)	Spent (compacted)
50,000	26.9 - 29.9	0.40 - 0.45	0.60 0.70	0.45 - 0.52
100,000	53.8 - 59.8	0.80 - 0.90	1.20 - 1.40	0.90 - 1.04
250,000	134.5 - 149.5	2.00 - 2.25	3.00 - 3.50	2.25 - 2.60
1,000,000	538.0 - 598.0	8.0 - 9.00	12.00 - 14.00	9.00 - 10.40

Basis: Oil shale assaying 30 gallons per ton; upgraded oil yield of 86 - 95 vol. pct., based on in-place crude shale-oil potential; loosely dumped spent-shale bulk density of 71 - 75 lbs. per cu. ft.; compacted spent-shale density of 90 - 100 lbs. per cu. ft.

of the foundation material upon which this shale will rest in these canyons as well as those of the spent shale (i.e. the angle of repose which will assure stability). The height of the spent shale piles will depend on the slope which is attempted. The determination of the slope to be used would require many tests to determine the characteristics of the surface and subsurface foundation material as well as those of the spent shale.

Hutchins, et. al. (1971), envisions placing processed shale in a series of horizontal layers some one to two feet thick such that the upper surface would always be a temporary surface until the last layer is placed. However, each layer would be started a little further back into the canyon (providing a terrace effect), giving the front surface of the pile, or permanent surface, a 1:3 slope. This slope is well below the angle of repose and insures frictional stability. Overall stability of the embankment is also assured by compaction, vegetation, and placement of broken rock on the permanent face. Proper contouring will help the spent shale piles to blend in nicely with the natural topography.

Compaction will be used to control not only the movement of temporary surface material by wind or water, but to eliminate the possibility of liquefaction. Moistening and compacting spent shale as a part of the disposal procedure can materially expedite the natural surface-cementation reactions, resulting in a nearly impervious condition which will retard leaching of the soluble components in spent shale. Proper compaction can be accomplished by mechanical devices as well as the weight from additional layers of spent shale.

Compaction will probably be an effective combatant to spent shale erosion during normal runoff; however, additional measures will have to be implemented to cope with the summer flash floods common to this area. These steps are:

(1) Construction of a control reservoir upstream from the disposal pile
(2) Installation of a conduit or other facility to transport water from the reservoir to a location downstream from the pile
(3) Construction of a retaining dam and pond downstream from the pile to collect surface runoff from the pile and allow any sediments to settle out, and,
(4) Installation of pumping facilities to remove the collected water from the settling pond and deliver it to the process area for use in moistening the spent shale.

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Chapter 5

PHYSICAL AND CHEMICAL CHARACTERISTICS OF OVERBURDEN, SPOILS, AND SOILS

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INTRODUCTION

Building sites, drill sites, roads, mine shafts, in addition to very large open pit mines, will all in some manner disturb the soil and rock layers overlying commercial oil shale. A number of environmental impact studies have been conducted on various phases of oil shale production, however all of them have neglected the chemical and physical properties and the effects of mining on the overburden as it relates to rehabilitation.

Planning for rehabilitation before surface disturbance requires a knowledge of the soils and rock characteristics that make up the overburden, and in particular, those physical and chemical properties known to be critical for plant growth. Among the physical characteristics of interest are particle size distribution after ripping and/or blasting and regrading operations, and then the rate of breakdown of coarse fragments into soil-sized particles. If the disturbed overburden (spoil) is to support a plant cover under the climatic conditions found in the area, it must contain sufficient soil-size materials to hold water. And, on the other hand, it should not be so fine textured or dispersed that runoff will be excessive. Chemically, the items of most interest in the soils and various strata of the Green River overburden are soluble salts, pH, amount of plant available nitrogen and phosphorus, and possibly toxic elements.

If these physical and chemical characteristics of the existing soils and soil-like materials, as well as the rock spoils, are known, then it may be possible to plan the mining and spoil disposal operations so that materials (soil, spoils) best suited for plant growth are left exposed after regrading. And conversely, those spoils unsuitable for plant growth or detrimental to runoff water quality can be buried under spoils more suitable for plant growth or covered with existing soil materials.

The objective of the studies discussed in this chapter was to review available information and to contribute new information relating to the properties of the soils and geologic materials that make up the overburden, particularly those properties known to be important for plant growth.

This chapter is divided into three main sections. The first section deals with the geology of the overburden. The second section deals with disturbed overburden as a medium for plant growth. The third section is concerned with an evaluation of the adequacy of existing soils information as it relates to soil related problems associated with rehabilitation.

The information presented in this report was compiled from data made available from the Soil Conservation Service, USDA; Bureau of Land Management, USDI; from limited field, laboratory, and greenhouse investigation by the authors and other investigators and from a review of the literature.

GEOLOGY OF OVERBURDEN

Setting

The Piceance Creek Basin (Fig. 1a) is unique in that it is a topographic basin, a structural basin, and a depositional basin. It is a topographic basin with the lowest elevations, 5700', along Piceance Creek in the center of the area, and high ridges, up to 9000', around the edges of the basin. It is a structural basin with all of the strata tilted toward the center of the area, thus the greatest depths to any given strata, such as that which has oil in it, is in the center of the basin (Fig. 1a). It was a depositional basin slowly sinking in its center as sediment filled it, thus the thickest strata, including those richest in oil shale, are in its center.

Stratigraphy

All of the oil shale and overburden in the Piceance Basin is in the Green River Formation. This formation was divided into members by Bradley (1931, p. 9) as shown in Figure 1b. Of interest in this study is the oil rich Parachute Creek Member and the overlying Evacuation Creek Member which comprises most of the overburden. The richest oil shale is found below the Mahogany Marker (Fig. 1b) in the Parachute Creek Member.

Definition

Overburden is defined as being any rock lying above the upper limit of commercial oil shale. The definition of commercial oil shale depends upon the mining method, the retorting method, and the market price of oil. As these variables are different for different geographic locations in the basin, different petroleum companies, and varying world economic situations, it is not possible to be specific in defining what is commercial oil shale. Generally about 30 gal. per ton is considered to be the limit for commercial oil shale today. Thus the overburden includes the upper part of the Parachute Creek Member in some parts of the basin, and all of the Evacuation Creek Member.

Thickness

The overburden covers most of the surface of the Piceance Basin except in the valley bottoms on the basin's southern perimeter. Rehabilitation of disturbed overburden will be necessary in all parts of the basin except in these valley bottoms. Overburden thickness, thus the amount that will be disturbed, varies considerably because the thickness not only depends on the amount of Evacuation Creek Member remaining after erosion, but also on how much of the material between the base of the Evacuation Creek Member and the Mahogany Marker is commercial oil shale.

The overburden thins toward the basin's perimeters, with the thinnest areas along the west-central border. In this border area, which includes Federal lease site Ca, the overburden thickness varies from zero to about 400 feet. The overburden is thickest in the east-central part of the area where the Evacuation Creek Member is 1250 feet thick in the General Petroleum Corporation well No. 45x-29-G, sec. 29, T2S, R95W (Donnell, 1961, p. 857), and the subeconomic upper Parachute Creek Member is about 500 feet thick. In the vicinity of Federal

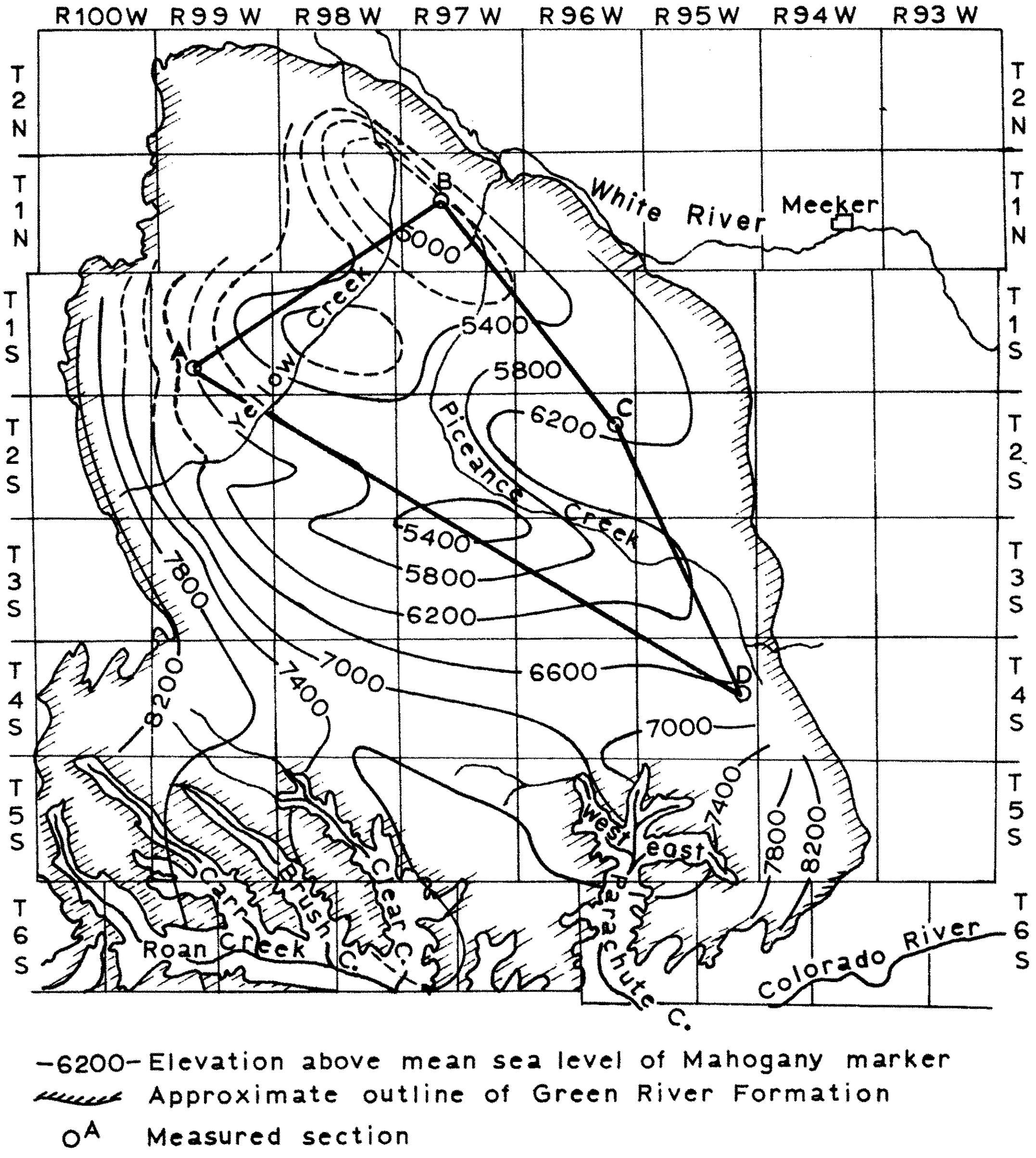

Figure 1a. Index Map showing location of measured sections and cross section.

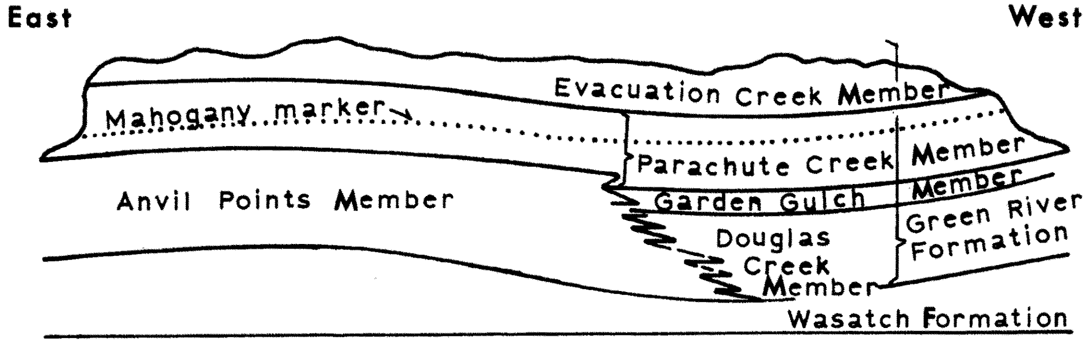

Figure 1b. Members of the Green River Formation.

lease site Cb, in the Stewart Gulch area, the overburden is about 1000 feet thick. A reasonable estimation of the thickness of the overburden for other areas may be obtained from Austin's (1971) overburden map.

Composition

Knowledge of the composition, rock type and mineralogy of overburden rocks aids in establishing suitability of these materials for plant growth. The rocks of the overburden are primarily sandstone, siltstone, mudstone, limestone, and shale, most of which are calcareous. Previous workers in the basin have called many of the rocks marlstone. Pettijohn (1957, p. 410) defines a marlstone as a rock with 35% to 65% carbonate mineral, calcite or dolomite, with a complimentary percentage of clay minerals. Picard (1953, p. 1075) has criticized use of this term as being non-descriptive and confusing. To avoid this ambiguity these rocks were classified as calcareous or dolomitic siltstone, mudstone, shales, or limestones.

The amounts of the various rock types in the overburden across the basin is highly variable. A great deal of lateral variation in the Evacuation Creek Member is common (Donnell, 1961, p. 858). To obtain an estimate of the amounts at various rock types (Table 1), three surface sections were measured and described (Figures 2 & 3, Appendix I). A survey of the literature and the Bureau of Mines files revealed no completely logged well sections of the overburden, thus surface section measuring was necessary. One well is included for comparison in Table 1 and Figure 4, however only the lower 800 feet out of 1250 feet was logged. Both Table 1 and Figure 4 should be considered to be very tentative. Though preliminary in nature, Table 1 suggests that the east central to west central portion of the basin is higher in calcareous mudstone and limestone than either the north or south edges. Both north and south edges seem to be higher in sand content. A great deal more stratigraphic work, including at least ten more measured sections, should be done to obtain more accurate estimates of amounts of various rock types and the correlations, and trends across the basin.

Mineralogy

Information on the mineralogy of the overburden rocks is very limited. An x-ray analysis of a drill core from the Bureau of Mines, Atomic Energy Commission Barcus Creek hole No. 1 (Dana, 1969) showed quartz, dolomite, calcite, sodium and potassium feldspar, and analcime with scattered illite and pyrite. No soluble minerals appeared in the x-ray analysis, but solution cavities in many sections of the Evacuation Creek Member indicate that at one time there were probably soluble salts present. Bradley (1931, p. 32) suggested that these salts are probably glauberite and anhydrite.

Compositional analysis of oil rich shale and "marlstone" from the Parachute Creek Member have been presented by several workers. As some of this type of rock is present in the overburden, its composition is shown in Table 2. Bradley (1931, p. 32) presented an analysis of a slightly richer oil shale which included the minerals beidellite clay, siderite, collophanite, apophyllite, and octahedrite as minor constituents. Stanfield, *et al*, (1951, p. 11-13) considered the clay minerals to be illite rather than beidellite.

Table 1.

% by Volume of Lithologies in the Evacuation Creek Member

	Sandstone	Siltstone	Conglomerate	Colo. mudstone and limestone	Shale	Marl	Silty marl
Measured surface* Section A, Corral Creek, sec.29,31,32, T1S, R99W	36.3	10.0	-	35.5	18.2	-	-
Measured surface* Section B, Lower Piceance Creek, Sec. 15, 16, 22, T1N, R97W	61.2	7.0	-	5.0	26.8	-	-
Well Section C, Gen. Petrol Well No. 24-12-6, sec. 12, T2S,R96W	36.4	13.2	-	-	-	27.8	22.5
Measured surface* Section D. Cow Creek, sec. 13, 24, T4S, R95W	66.8	22.4	1.8	6.70	2.38	-	-

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* Surface sections measured by L. D. Milliken for this project.

Table 2.

Typical Composition of Oil Shale Sections Averaging 25 gal. of Oil per ton in the Mahogany Zone of Colorado and Utah. (After Stanfield & others, 1951, p. 11-13. Table taken from Dept. of Interior, 1972, Vol. I, p. 1-11)

Mineral Matter:	
Content of Raw Shale	86.2
Approximate Mineral Constituents:	
Carbonates; principally dolomite	48
Feldspars	21
Quartz	13
Clays; principally illite	13
Analcite	4
Pyrite	1
Total	100

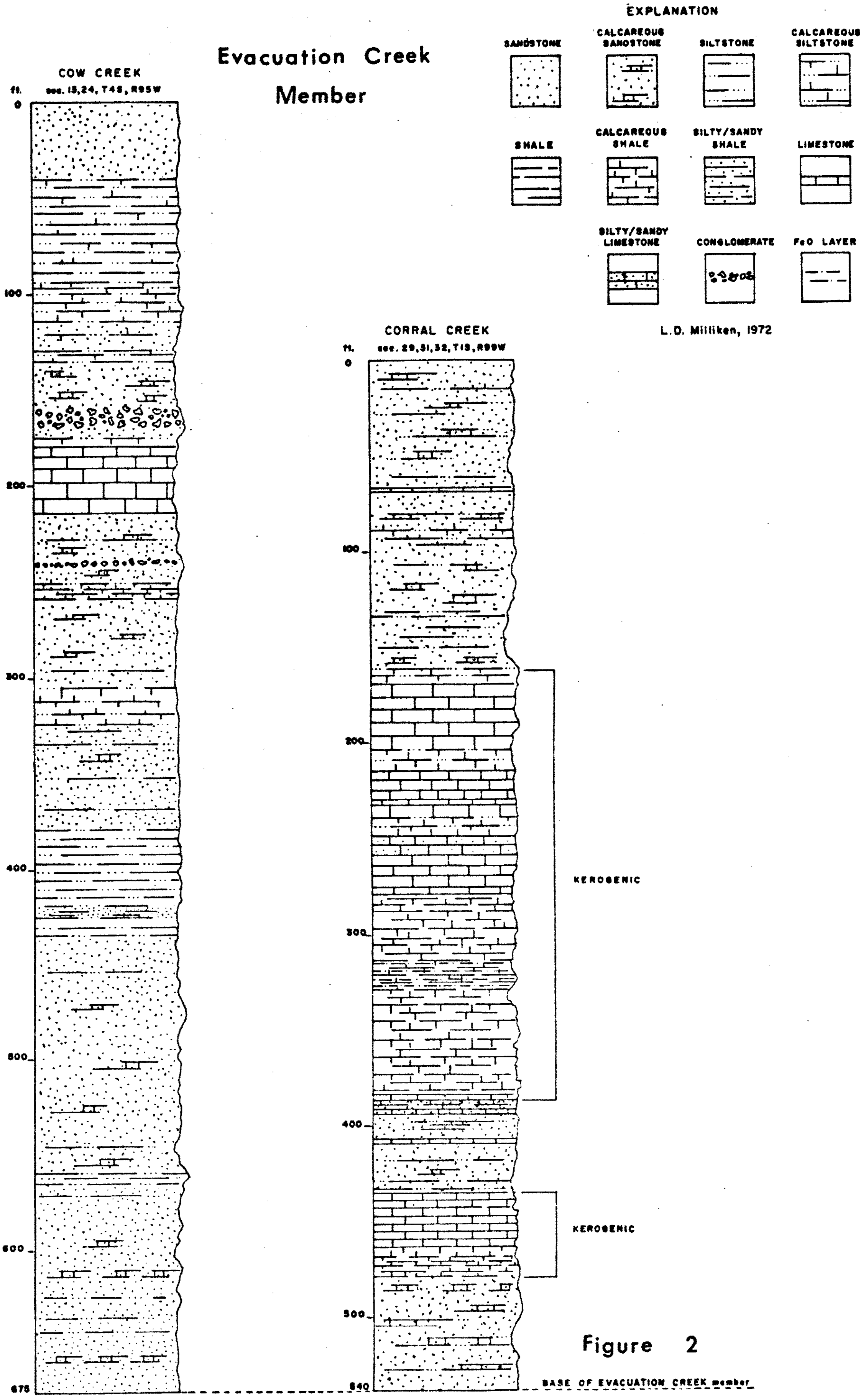
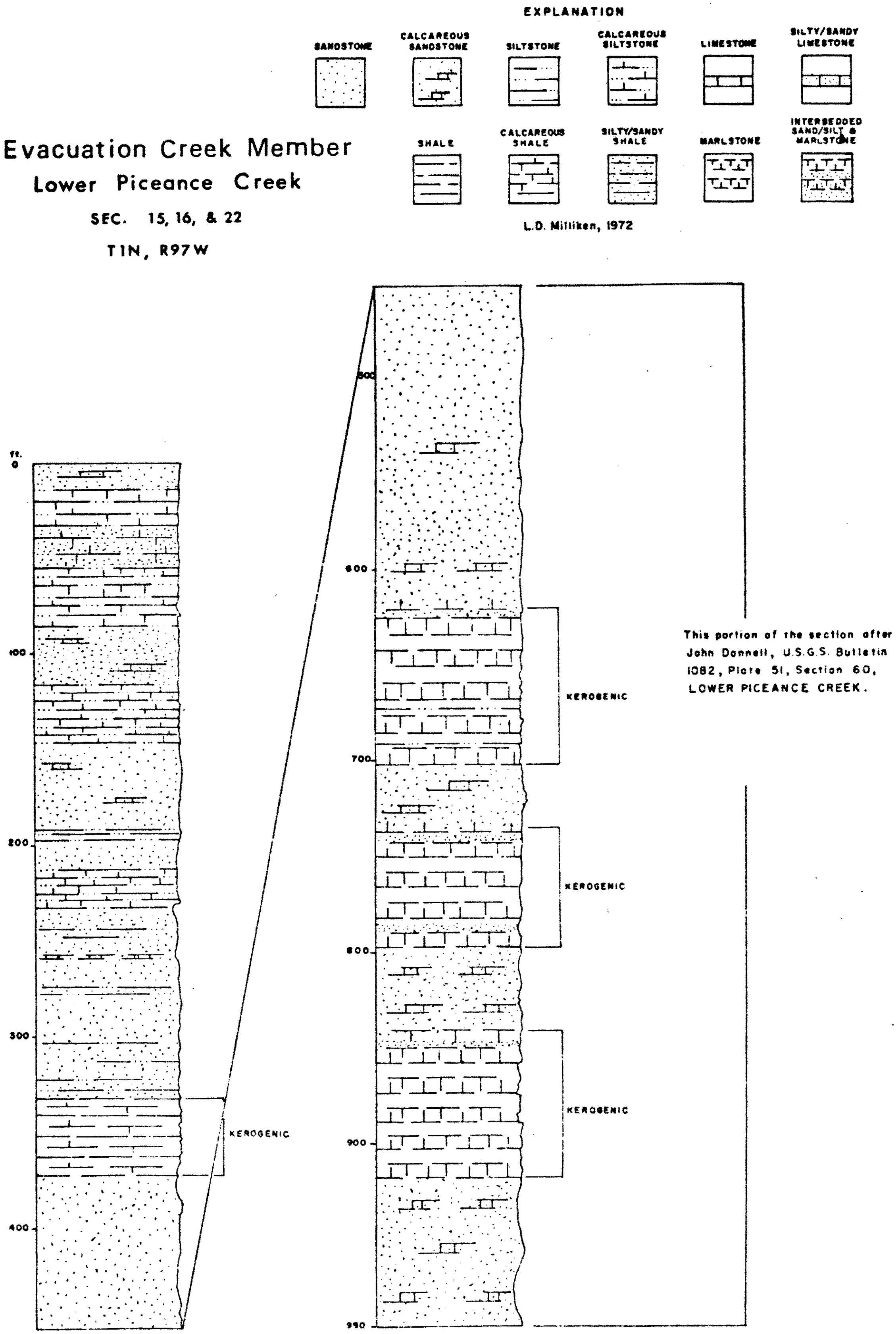

Evacuation Creek Member
COW CREEK
ft.
sec. 13,24, T4S, R95W
0
100
200
300
400
500
600
675
CORRAL CREEK
ft.
sec. 29,31,32, T1S, R99W
0
100
200
300
400
500
540
KEROGENIC
KEROGENIC
BASE OF EVACUATION CREEK member
EXPLANATION
SANDSTONE
CALCAREOUS SANDSTONE
SILTSTONE
CALCAREOUS SILTSTONE
SHALE
CALCAREOUS SHALE
SILTY/SANDY SHALE
LIMESTONE
SILTY/SANDY LIMESTONE
CONGLOMERATE
FeO LAYER
L.D. Milliken, 1972

Figure 2



This portion of the section after John Donnell, U.S.G.S. Bulletin 1082, Plate 51, Section 60, LOWER PICEANCE CREEK.

Figure 3

Because of a lack of compositional data on Evacuation Creek Member rocks, a representative group of lithologies were analyzed with the petrographic microscope. Such an analysis will give good textural and mineralogical data as well as an idea of elemental composition. Chemical and x-ray analysis, in addition to the petrographic analysis, of a great many more samples would be necessary to obtain a clear picture of compositional variation across the basin.

The stratigraphic information indicates that there are three major rock types, with gradations between each, in the Evacuation Creek Member. Three samples of each lithology were selected and thin sections prepared. A brief description of each follows, with a detailed analysis of each shown in Appendex I.

Sandstones-Siltstones

These rocks are generally moderately well to well sorted with the finer the grain size the poorer the sorting. The grain size in the three samples varies from less than 0.063 mm to 2.5 mm with median varying from 0.15 to 0.35 mm.

The major mineral component of these sandstones are quartz, feldspar (predominantly microcline) and rock fragments. The rock fragments include in order of abundance, basalt, limestone, sandstone and quartzite. Of particular interest to this project is the high percent of basalt rock fragments.

The minor components include mica, both muscovite and biotite, hornblende, plagioclase feldspar, zircon and shale rock fragments. The cementing agent is calcite. Finer grained rocks contain clay and iron oxide matrix with the carbonate cement.

Limestones-Dolomites

The limestones and dolomites are typically very fine crystalline, often finely laminated and frequently chalky. The samples analyzed contain 4 to 9% by volume of detrital minerals. These detrital minerals include quartz, microcline and a small amount of mica. The size of these grains is small with median sizes ranging from 0.012 to 0.044 mm, in the silt size range. The crystal size of the carbonate minerals is too fine for microscope identification. Where recrystallization has resulted in larger crystals the mineral is most often dolomite. The white chalky powder common in the basin may be due to weathering of the very fine carbonate, leaving somewhat coarser dolomitic carbonate powder. Shale parting is common in these rocks, causing misidentification as shale. Internal structures of two of the three samples analyzed suggest an algal controlled origin.

Shale-Siltstone

These rocks are composed of from 52% to 66% by volume of clay sized, clay minerals. Identification of these minerals which is best done by x-ray analysis was not attempted in this study. With the clay minerals, are from 9% to 46% by volume of fine crystalline carbonate minerals. These carbonate minerals are from 50% to 100% dolomite with the remainder being calcite.

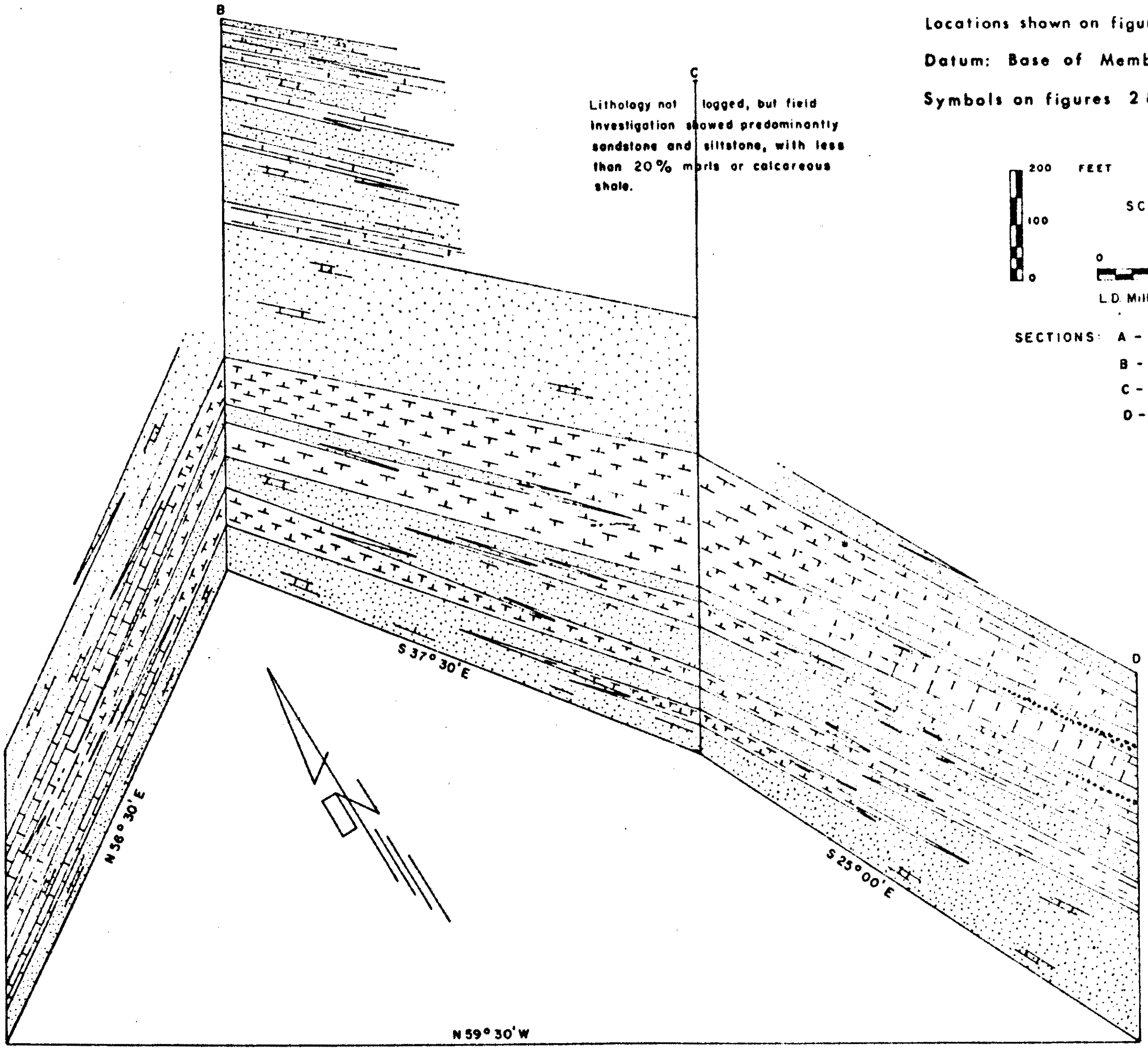
In addition to these minerals coarser grains of quartz, feldspar largely microcline, and muscovite and biotite mica are present. These grains make up from 1.5% to 30% by volume of the samples studied. These grains range in size from less than 0.0078 mm to 0.25 mm, with median sizes ranging from 0.013 to 0.033 mm. Shale parting and dark organic laminations are common in these rocks.

Fence Diagram, Evacuation Creek Member

Locations shown on figure 1a

Datum: Base of Member

Symbols on figures 2 & 3



Lithology not logged, but field investigation showed predominantly sandstone and siltstone, with less than 20% marls or calcareous shale.

SCALE:

200 FEET
100
0

0 2 4 MILES

L.D. Milliken, 1972

SECTIONS: A – Corral Creek
B – Lower Piceance Creek
C – General Petroleum Corp. well no. 24-12-G
D – Cow Creek

Figure 4

Summary of Microscope Analysis

Microscope analysis of texture and composition of Evacuation Creek Member rocks indicates that they are best divided into three simple groups. Of the various minerals that are common to these groups, the carbonate is of interest as it indicates a high calcium and magnesium content. In addition, the high basalt rock fragment content in the sandstones indicates a high calcium, magnesium, sodium as well as iron content. Chemical analysis should help to support these results.

Physical Properties

Of interest for the rehabilitation of disturbed overburden is the development of fine particles by ripping, blasting and regrading processes associated with mining, construction, road building and drilling. Too many fine particles produces a highly erodable material, and not enough fines produces a material that will not hold water for plant growth.

To obtain an estimate of particle size distribution of overburden materials, samples of the common rock types, sandstones, siltstones, shales, and limestones were analyzed. Three analyses were made on each rock type, including fresh, weathered, and crushed material. The results of these analysis are shown in Appendix I. The fresh sample is material removed from the outcrops without breaking, letting the natural fractures control the size of material. The weathered sample was collected at the base of the outcrop in talus that had not been altered by slope wash. The crushed sample was produced by crushing fresh sample in a jaw crusher which had a 2 mm minimum jaw closure. The crushed sample gives an estimate of the breaking or crushing properties of the rock. A summary of these physical properties for various rock types follows.

Mudstone-Siltstone (clay shales)

The fresh samples of these rocks tend to have 80% fragments in the 256 mm to 4 mm size range with very little, 4-5%, material less than 1 mm. The effects of crushing are difficult to judge. The process of crushing produces an artificial size distribution, thus the question becomes how much is due to the process and how much is a property of the material. To obtain an estimate of how much is a property of the rock, the samples were compared to two standards (L, and M, Appendix I) which are dense, compact, very well indurated samples. The mudstone-siltstones of the overburden produce 15 to 20% more fines than the standards, thus these rocks are considered to be moderately friable.

Sandstone

The fresh samples of sandstones tend to have about 95% of fragments in the 256 mm to 4 mm size range, with some fragments in the talus that are 90 cm x 60 cm x 30 cm. Only about 3 to 4% of the fresh sample is less than 1 mm in size. Weathering reduces the size range with about 20% less than 1 mm. Crushing the sandstone samples produced 25 to 30% more fines than the standards, thus the sandstones are generally highly friable. Notably 8% to 10% of the crushed samples are in the .063 to .031 mm size range, thus dust and silt may be a problem with this material.

Limestone (marl)

The fresh samples of limestones have about 90% of the sample between 256 mm to 4 mm. Some blocks in the talus range up to 180 cm x 60 cm x 15 cm. About 3%

to 4% of the fresh samples are less than 1 mm in size. Weathering reduces the size range such that 12% to 20% is less than 1 mm in size. The crushed samples have 16% to 21% more fines than the standards, thus are moderately friable much like the mudstone-siltstones. About 9% of the crushed samples are in the .063 mm to .031 mm size range, thus dust and silt may be a problem with disturbed overburden of this material.

Limestone (shaly)

Fresh samples of this type of limestone which is much harder and more brittle than the "marl" limestones have about 90% to 94% between 256 mm to 4 mm. Maximum size blocks in the talus range up to 90 cm x 30 cm x 2 cm. These limestones have from less than 1% to about 3% less than 1 mm in size. Weathered samples have 5% to 18% material less than 1 mm in size. The crushed samples have from 4% to 10% more fines than the standards, thus these samples are not very friable.

Summary of Physical Properties

The fresh overburden materials tend to be fairly coarse grained, with 1% to 20% of the material less than 4 mm. Both weathering and crushing (ripping, blasting and grading) tend to increase the fine-grained fragments significantly. Disturbance of the overburden by various oil shale operations should produce enough fines that the material should support plant growth. Weathering of the freshly disturbed overburden may produce too many fines, rendering the surface materials highly erodable in some materials. The rates and amounts of weathering on the fresh overburden is unknown and is currently being researched.

DISTURBED OVERBURDEN AS A MEDIUM FOR PLANT GROWTH

Sampling

A very preliminary attempt to evaluate disturbed geological materials in the lower Evacuation Creek member as plant growth media was made by sampling geological materials that had been exposed and graded in drill site preparation and then regraded in the site rehabilitation work. The samples were taken in September 1972 on sites that had been disturbed and regraded a few days or weeks before sampling. Four different sites were sampled, three (samples 1-3, Table 1) were on the oil shale lease site C-a (USDI, 1973, Vol. III) and one (two different geological materials, samples 4 and 5, Table 1) was from near the mouth of Piceance Creek.

The results of this sampling must be viewed with caution for several reasons:

1. The geological materials could have been contaminated during the drilling operation.

2. Soil and partially weathered geological materials were probably mixed with the geological materials.

3. The cuts into the geological materials were shallow (a few feet) and material exposed might have been somewhat weathered and thus produce more fine material than would the same strata further from the outcrop.

4. The samples, either 60 or 120 pounds, were taken from the surface to a depth of about 6 inches. When sampling, it was obvious that selection of the sample location would have a great influence on the amount of fine material in the sample. The samples were taken from what was judged to be typical material for the site.

Particle Size Considerations

Sample 2 (Table 1) from an alluvial fan was the only sample containing a high percentage of soil-size material. Samples from the geological materials contained moderate to rather small amounts of soil-size material. Because of the limitations of the sampling mentioned above, especially limitations 2, 3, and 4, no specific interpretations on the particle size will be made. The limitations suggest that the amount of soil-size material in the samples would be an overestimation of the soil-size material in spoils from these strata.

These spoils before grading should have a very high infiltration rate (Coleman, 1951). Compaction resulting from grading on some spoil types has been shown to reduce infiltration rates drastically and thus increase erosion and reduce rate of plant growth (Merz and Finn, 1951; Chapman, 1967; Geyer and Rogers, 1972). If compaction is a problem on spoils, then scarification of the graded surface may be necessary. However, compaction would not appear to be a problem on spoils from the strata sampled because of the relatively small amount of soil-size material.

Table 1. Some particle size and chemical characteristics of disturbed geological materials from the lower portion of the Evacuation Creek member of the Green River Formation.

Sample No.	1	2	3	4	5
Material	silty calcareous shale	alluvial fan	calcareous mudstone	sandstone	limestone
Particle Size					
>3" diameter (%)	4	0	3	7	14
1/2 - 3" (%)	34	4	32	49	54
2 mm - 1/2" (%)	33	28	36	23	19
<2 mm (%)	29	68	29	21	13
The following analyses are on the soil-size (<2mm) material:					
Particle size (hydrometer)					
Sand .05 - 2 mm (%)	47	24	12	24	32
Silt .002 - .05 mm(%)	19	33	33	36	32
Clay <.002 mm (%)	34	43	55	40	36
Texture	sandy clay loam	clay	clay	clay loam	sandy clay loam
pH[1]	8.4	7.9	8.0	8.8	8.5
Conductivity mmhos/cm[2]	4.2	9.0	4.0	2.2	1.0
$CaCO_3$ equivalent (%)	40	18	37	21	46
P ppm[3]	12	3.5	1.3	.5	2.0
K ppm[4]	82	110	68	68	55

[1] Determined on 2-1 distilled water - spoil ratio. [2] Saturation extract. [3] By sodium bicarbonate extraction. [4] Soluble plus exchangeable determined on a 1N ammonium acetate extract.

The major problem encountered may instead relate to the small amount of soil-size material in the spoils. If the disturbed geological materials (spoils) are extremely coarse textured and support limited vegetation, then leaching will occur. Coarse textured materials are quite efficient in reducing surface evaporation and increasing water available for plant growth or groundwater recharge. Corey and Kemper (1968) found that evaporation losses from a fallow soil in a semiarid climate (Fort Collins, Colo.) could be reduced five-fold if a one-inch gravel mulch were used. Comparable results were reported by Linden (1970), who found that a one-inch gravel mulch over a non-vegetated sandy loam soil in eastern Colorado resulted in accumulation of about 11 inches (50%) of the total precipitation over a two-year period, whereas fallow treatments accumulated only 2.8 inches of water. Fairbourn et al. (1972) indicate a water harvesting efficiency of 66-87% of natural precipitation falling on a gravel-covered catchment surface in the Great Plains. These studies indicate that coarse spoils containing a low percentage of soil-size material would be an effective water-collecting system and percolation of the water can be expected if the spoil does not have sufficient water-holding capacity within the rooting zone to retain precipitation for eventual transpiration. The percolation of water through the spoils could pose water quality problems as the analysis (Table 1) shows that some of the materials contain fairly high concentrations of soluble salts.

In some arid and semiarid areas, production of native vegetation is greater on sandy soils than on medium and fine textured soils (Heerwagen, 1958; Tomanek, 1964), and sandy or stoney soils support a more mesic plant community (Hillel and Tadmore, 1962; Branson et al., 1964; Turner, 1971). One reason for this is that infiltration rates are greater on sandy soils (Rauzi et al., 1968); this results in less runoff and thus more available moisture on-site for plant growth. A second reason is that less moisture is held per unit of depth in sandy soils so less moisture is lost to surface evaporation (Taylor, 1960; Alizai and Hulbert, 1970).

Following this reasoning, the disturbed geological materials might have a more favorable plant-soil moisture relationship than the nearby fine textured soils. An obvious limit on this reasoning is that sufficient water-holding capacity must be present within plant rooting depth or water will be lost to percolation. Also, seedling establishment can be more difficult on coarse textured materials as the water available to the limited root system of young seedlings will be less in coarse textured materials than in finer textured.

Published information on the relationship between soil texture or coarse fragments in soils and productivity of vegetation in the Piceance Basin is limited to the study of Medin (1959, 1960) who found that production of mountain mahogany was greater on soils developed from sandstones than from soils developed from shales, however the yield data overlapped considerably. Soil depth (A + B horizon) was the most significant factor positively correlated with production of mountain mahogany within the sandstone or shale derived soils. Surface stoniness was negatively correlated with annual production of the shrub.

On coal mine spoils from the Mesaverde Formation near Hayden, Colo. (6,500 feet elevation, 16-17" average annual precipitation) which contain about 30% soil-size material (clay loam) and seeded to alfalfa and introduced grass species, forage yields were comparable to yields on fine textured soils in the same area (Berg and Barrau, 1973).

This discussion has been based on the assumption that weathering in terms of years will have little effect on the particle size breakdown of these spoils. This assumption needs to be checked in formal weathering studies as are being carried out by Campbell.

Soil Fertility Considerations

Salinity

In terms of plant growth, the soluble salt concentrations in the soil-size material (Table 1) would present slight to severe problems in seed germination and plant establishment (Richards, 1954). This would depend in part upon the species (Hayward and Wadleigh, 1949) and variety seeded (Dewey, 1960; Knipe, 1968). Considerations for establishment of vegetation by sprinkling are covered in the section on water requirements (Chapter 7). The discussion on salt leaching from spent shales for plant growth (Chapter 6) would also be appropriate on spoils.

Nitrogen

No determinations for plant available nitrogen were made, however, plant available nitrogen is usually very deficient on subsoil and spoil material. The discussion on nitrogen in the spent shale section (Chapter 6) would also be appropriate for spoil material. As with spent shales, maintenance application of N will probably be required over a period of years.

Phosphorus

Four of the five samples tested were very low in plant available phosphorus. The discussion on phosphorus in the spent shale section (Chapter 6) would also be appropriate for spoil material. In field studies on a very phosphorus-deficient argillaceous limestone spoil (near Fort Collins) containing 40% soil-size material (silty clay), we found that nitrogen fertilization plus moderate to extremely high rates of phosphate broadcast on the surface were relatively ineffective in herbaceous seedling establishment on unmulched spoil. However, there was an excellent plant growth response to 4-6" deep spot placement of nitrogen and phosphorus by certain planted woody species and annual weeds growing nearby.

Potassium

The potassium level in these spoils is adequate for plant growth by soil test standards. A caution is added in that the less-than-2-mm spoil material used in the soil test represents only a small percentage of the spoil mass. However, the relatively high levels of potassium in the surface soils and experience in other semiarid areas indicate that potassium will not be a problem.

pH

The pH of the spoils is what would be expected in these highly calcareous materials and should not be a limiting factor in growth of plant species adapted to the area. The pH of 8.8 in sample 4 may indicate a material high in exchangeable sodium. This is known to result in dispersion of soils which contain expanding clay minerals. The discussion in Chapter 6 on sodium in spent shales is also appropriate for spoil.

Micronutrients

Micronutrients were not determined in the samples. Future work should assess the availability of plant micronutrients and certain other elements such as selenium.

Greenhouse Study

Bulk samples of spoils resulting from drill site disturbance on sandstone and limestone were collected in the fall of 1972. These spoils are characterized in Table 1 as samples 4 and 5.

Spoil passing a 1/2-inch square sieve was used in the greenhouse study. The four fertility treatments were: no fertilizer; nitrogen (N) supplied as ammonim nitrate at the rate of 100 ppm N; phosphorus (P) supplied as monocalcium phosphate at the rate of 50 ppm P; and the combination of N and P at the above rates. A productive soil fertilized with N and P was used as a standard against which to compare growth of grass on the spoils.

Each treatment was mixed into 2000 grams of spoil and then placed in 1/2-gallon polyethylene-lined cartons. Tall fescue was seeded on 5 January 1973 and the spoil watered to field capacity. After 53 days growth in a greenhouse the plants were cut off, oven dried, and weighed. Three replications were used on all treatments. Table 2 shows the average yields for the fertility treatments.

Table 2. Grass yields in grams per pot as influenced by fertility treatments on spoils created by drill site disturbance in the Piceance Basin.

	Fertility Treatment			
Growth Medium	None	N	P	NP
Sandstone spoil	.24	.21	1.03	3.5
Limestone spoil	.34	.87	.42	3.8
Soil				5.1

The results show that the spoils are deficient in both N and P. With N plus P fertilization, the grass yield on the spoils approached the yield on a productive soil. Although it is difficult to extrapolate from greenhouse work to field conditions in a semiarid climate, the magnitude of the yield response to N plus P indicates that these elements will be limiting under field conditions. Fertilization with N and P is extensively discussed in Chapter 6 on spent shale and the same discussion would be appropriate on fertilization of these spoils. In brief, it appears that fertilization is feasible; however, long-term N fertilization may be required if vegetation is established directly on the spoils.

Vegetation Establishment on Spoils

Much of the establishment information in Chapter 3 of this report will also be applicable to the spoils. The probable coarse nature of the spoils would limit use of some machinery commonly used in rangeland seeding and shrub seeding and planting.

Because of climatic and spoil differences, the research and knowledge on establishment of vegetation on coal mine spoils in the eastern United States (Frawley, 1971) will have only limited application to what apparently will be the vegetation establishment problems on spoils from the geological materials in the lower Evacuation Creek member of the Green River Formation. Fine-textured spoils, rather than coarse-textured, appear to be the major problem in revegetation work reported on in Wyoming (May et al., 1971), Montana (Hodder, 1970), and Idaho (U. S. Forest Service, 1971). Hodder (1970) suggests analysis of cores taken from the overburden to predict the characteristics of individual stratum in a reclamation program. Similar sampling schemes have been used in planning reclamation of coal mine spoils in the eastern U.S. (Grube et al., 1973).

The probable success in revegetation of cut and fill slopes along New Mexico highways without irrigation has been related to soil texture. The ratings from good to poor are: sandy loams, loams, deep sands, clayey soils, gravelly soils (Lohmiller, 1971). Thus, the probable physical and chemical nature of the spoil materials indicates that intensive revegetation practices will be needed to insure stands of desired species. The practice might include irrigation, and probably should include mulching as well as fertilization. The lack of soil-size material in the spoils could result in percolation of water through the spoil materials; this water could pose pollution problems by dissolving salts in the spoil.

An alternative would be to cover the spoil with soil. If such an approach were used, a soil survey should be made before disturbance to determine the extent of soil suitable for covering spoil and also plan for the soil handling.

SOILS OF THE OIL SHALE STUDY AREA

Available Mapped, Chemical, Physical, and Engineering Soils Data

Available Mapped Soil Data

Mapped soils information, which identifies the kind of soil, depth to bedrock, depth to watertable if <60 inches, complexity and degree of slope, stoniness, and other soil and soil related features is essential before reliable predictions can be made about soil behavior when subjected to various uses. In addition, soil maps are needed to show the geographical extent and areal distribution of soils before reliable interpretations can be made with respect to erosion, sediment yield, runoff, site suitability, and other uses. The availability and detail of soil maps is of primary importance for evaluating the fertility, water needs, and conservation practices associated with revegetation activities.

Detailed soil maps: Except for a soil survey of the Little Hills Experiment Station and a few isolated surveys made for the purpose of developing ranch plans, there is essentially no detailed soil survey information available for the oil shale study area. Data from the Little Hills Survey is discussed in a later section.

General soil maps: A general soil map, compiled at a scale of 1:250,000 is available for the entire study area. A map was compiled from the Rio Blanco, Garfield, and Mesa County General Soil Maps, which were published by the Soil Conservation Service, USDA, July, 1972. The map accompanies this report. A legend identifying the Soil Associations by number and name is shown in Appendix Table 5.

The general soil map was prepared by drawing boundaries around portions of the landscape having similar relief, geology, and vegetation. The mapping units on a general soil map are called "soil associations." A soil association is a landscape that has a distinctive proportional pattern of soils. It normally consists of one or more major soils and at least one minor soil, and the association is named for the major soils. Soils in one association often occur in other associations, but in a different pattern or extent.

A general soil map showing soil associations is useful for comparing different parts of an area, or for locating large tracts of land that are suitable for various uses. Such a map, however, is not suitable for on-site planning for a small area because the soils in any one association usually differ in degree and complexity of slope, drainage, texture, stoniness, infiltration, and other characteristics that affect management.

Thus it must be remembered that the description of soils in this report is generalized in accordance with the requirements imposed by map scale. The discussion can only describe soils in a general way with respect to the needs associated with revegetation and stabilization of disturbed lands.

A narrative description of all soil associations found in the oil shale study area is given in the Appendix. The narrative descriptions include the number of the association for identification, name of the association, general description of the elevations at which the associations occur, annual precipitation and other general climatic information, and the extent and general nature of the soils found.

It should be pointed out that the general soil map was compiled based on limited field investigations. This map is a "first approximation" of the kinds, distribution, and extent of soils found in the oil shale study area.

Field Characterization Data Available

Field and laboratory characterization data for soils found in the oil shale study area are very limited. Some field descriptions are shown in a tabular form in Appendix Table 2, Appendix 2.

Laboratory Data Available - Chemical and Physical

Medin, studying the "Site Factors Influencing Mountain Mahogany," obtained some soil chemical and physical data from samples of 116 surface soils, 9 subsoils, and 8 parent material samples. These samples were all collected within an area of one square mile in the upper drainage of the Dry Fork of Piceance Creek. The samples were described as being derived from shale and sandstone. The data of Medin appear to indicate that the sandstone derived soils are mainly sandy loam and loam textured, while the soils developed from shale are mainly silt loams, silty clay loams, and clay loams. The sandstones described by Medin are probably the same material described as sandstone-siltstone by Campbell in the geology section of this report. It appears that the shale described by Medin is probably limestone (marlstone) as described by Campbell. Medin's data indicate that most of the soils have a low soluble salt content, are relatively high in organic matter, and have a very high lime content. Most of the soils are deficient in plant available phosphorus with the soils derived from shale having less available phosphorus than those derived from sandstones. Water infiltration rates of the surface soil materials are moderate to rapid (0.5 to 5.0"/hr) in the soils derived from shales. Soil pH is high, which reflects the high lime content of the soil. Analysis of the subsoil and parent materials does not indicate any accumulation of soluble salts with depth. The deepest sampling made by Medin was 35 inches. It appears likely that salts could be moved deeper than this, but because of shallow sampling, this was not detected.

Soil chemical and physical data collected during the course of this study are shown in Appendix Table 5. Soluble salt concentrations in the soils appear to be low, however some analyses of parent materials (geologic material as reported by Berg in this report) range from low to high. The available data suggest a wide variation in the chemical and physical properties of soils found within the oil shale study area. A detailed or more comprehensive soil survey and soil sampling effort is needed for identification of the chemical and physical features that are important for evaluating the use and management of the land.

Available Interpretive Soil Data

Limited soil interpretive data for some soils found in the soil associations of the oil shale area is available from the Soil Conservation Service, USDA, or from the author. The data are in the form of a first draft and are subject to change. Considerable characterization and interpretive information is lacking with respect to many of the soils found in the oil shale study area.

Classification of Soils

Identification of Soil Taxonomic Units

The goal of this section is to identify the taxonomic classes of soils proposed to be present in the oil shale study area, so that the relationships of the soils to one another and to the whole environment can be understood better, and to develop the principles set forth in soil classification that help us to understand soil behavior and soil response to management or manipulation.

The soils are classified using the new "Soil Taxonomy" which has been adopted for use by the National Cooperative Soil Survey. This is a hierarchical system consisting of 6 major categories. Each category defines soils at a particular level of abstraction. For example, the Order category which is the highest and broadest category is useful for studying or comparing soils in very large areas such as countries and continents. At the lowest category, the soil series defines soils very specifically and is used in detailed soil surveys so that soil interpretations can be used in managing fields, farms, and in specific engineering work. Very few soils in the oil shale study area have been described at this level of detail.

Table 1 shows the classification of soils found in the oil shale study area. As can be noted from Table 1, most soils of the study area are classified only at the higher categories. This means that only general statements can be made about the development, use, and management of these soils. Soil Association #92 is the only association for which there is detailed information available concerning the characteristics and behavior of individual soils.

Definition of Soil Taxonomic Classes

This section defines the taxonomic categories and classes of soils found in the study area. An attempt is made to interpret these units with respect to those behavioral characteristics important for evaluating soil suitability for revegetation and stabilization purposes.

Interpretations of soil taxonomic classes with respect to soil moisture: Names of soils at the Order, Suborder, and Great Group category levels include an identification of the soil moisture regime. The soil moisture regime as defined here, refers to the presence or absence either of groundwater or of water held at tension <15 bars in the soil or in specific horizons for various periods of the year. Water held at a tension of >15 bars is not available to keep mesophytic plants alive. The soil moisture regime is estimated by considering the moisture condition in the "soil moisture control section." In general, the soil moisture control section is roughly defined as that section of the soil which lies approximately between 4" and 12" depth if the particle size class is fine-loamy, coarse-silty, fine-silty, or clayey. The moisture control section extends from a depth of 8 to 24 inches if the particle size class is coarse-loamy, and from 12 to 35 inches if the particle size class is sandy.

From the data available if appears that soils in the study area would fall into all particle size categories. The soil moisture regime of a soil is considered important because of its importance in understanding and predicting the amount of soil development, important with respect to the amount, nature, and distribution of organic matter, and helps in predicting the base status of soils and the amount of leaching that takes place. The most important, however, is related to the potential for growing different plants.

The soil moisture regimes presently defined in Soil Taxonomy are: Aquic, Aridic and Torric, Ustic, and Udic.

The aquic moisture regime implies a reducing regime that is virtually free of dissolved oxygen because the soil is saturated by groundwater or by water of the capillary fringe. For those soils having an aquic soil moisture regime (Fluvaquents in Soil Association #132), this implies that the entire soil is saturated with water. The duration of the period that the soil is saturated is not exactly known. These soils are very young waterlaid deposits that are found in wet places on flood plains. The water table is at or close to the surface most of the year unless artificial drainage has been provided.

The terms "aridic" and "torric" are used to identify the same moisture regimes, but in different categories of the taxonomic classification. In the aridic (torric) moisture regime the moisture control section in most years is 1) dry in all parts more than half the time (cumulative) that the soil temperature at a depth of 50 cm is above 5°C; and 2) never moist in some or all parts for as long as 90 consecutive days when the soil temperature at a depth of 50 cm is above 8°C. There is little or no leaching in these moisture regimes, and soluble salts will accumulate in the soil if there is a source for them. Many of the soils in this moisture regime either have physical properties that keep them dry, such as a crusty surface which retards infiltration of water, or they are shallow over bedrock. Soils having a "torric" soil moisture regime are deficient in moisture for plant growth for most of the growing season. Soils in the oil shale study area with this soil moisture regime include the Haplargids, Camborthids, Natrargids, Torrifluvents, Cryorthents, and Torriorthents. See Table 1 which indicates in which Soil Associations these soils are found. Weathering of geologic materials exposed in this environment would be extremely slow.

The concept of the ustic soil moisture regime is that moisture is limiting, but moisture is present at a time when conditions are suitable for plant growth. The ustic soil moisture regime as it applies to the oil shale study area implies that the soil moisture control section is dry in some or all parts for more than 90 cumulative days in most years. But it is not in all parts for more than half the time that the soil temperature is >5°C at a depth of 50 cm. Also, it is not dry in all parts for as long as 45 consecutive days in the 4 months that follow the summer solstice 6 or more years out of 10. The annual soil moisture condition in soils having this soil moisture regime can generally be described in the following manner: The period from roughly late September through mid-February to late April is a period of surplus moisture (where precipitation exceeds evapotranspiration). It is during this period that some leaching could occur. During the period late April to mid- or late June, evapotranspiration exceeds precipitation. There is sufficient moisture for plant growth but very little leaching occurs. From mid- or late

June to late September is a period of moisture deficiency. Growth and/or establishment of plants is extremely limited during this period. Soils in the oil shale study area having this soil moisture regime are the Argiustolls, Ustifluvents, and Ustorthents. See Table 1 which indicates in which soil associations these soils occur.

The udic soil moisture regime implies that in most years the soil moisture control section is not dry in any part for as long as 90 days cumulative. In general, the udic soil moisture regime is common to soils found in climates that have well-distributed rainfall or have sufficient rain in the summer that the amount of stored soil moisture is approximately equal to or exceeds the amount of evapotranspiration. Leaching can occur at some time in most years. The annual moisture status of soils having this soil moisture regime is as follows: From about mid-September to early December is considered a recharge period. From early December to late April is considered a surplus period. Leaching could occur during this period when the soil is not frozen. From late April to mid-September is a period of utilization. Very little leaching would occur during this period. Soils in the oil shale study area having this soil moisture regime are the Cryoboralfs and Eutroboralfs. The Argiborolls, Cryoborolls, Haploborolls, and Paleborolls have either an ustic or udic soil moisture regime, or rather are considered more moist than typical for the ustic regime, but drier than typical for the udic. Table 1 indicates the soil ssociations in which these soils occur. Most of the soils listed have a favorable soil moisture situation throughout the growing season in most years.

Interpretation of soil taxonomic classes with respect to soil temperature: The temperature of a soil is one of its most important properties. Within limits, temperature controls the possibilities for plant growth and soil formation or development. Temperature controls biotic activity and also the rate at which many other soil forming processes take place. For example, a horizon as cold as 5°C is a thermal pan to the roots of most plants.

The soils of the Piceance Basin are included in the Cryic, Frigid, and Mesic soil temperature regimes. The temperatures cited are mean annual soil temperatures at a depth of 50 cm (20 inches).

Soils of the cryic soil temperature regime are very cold soils and have a mean annual soil temperature higher than 0°C (32°F) but lower than 8°C (47°F). The mean summer temperature (June, July, and August) is lower than 15°C (59°F) if the soil has no organic surface horizon and lower than 8°C (47°F) if the soil has an organic surface horizon. Soils found in this soil temperature regime are the Cryoborolls, Cryoboralfs, Cryorthents, and Paleborolls. Some of these soils also have frigid temperature regimes described below. Geologic materials exposed to this type of temperature regime would weather very slowly. Decomposition of organic matter is relatively slow because of the low biological activity. Soils having this temperature regime normally are characterized as having a cool and short summer period.

The frigid soil temperature regime is warmer in the summer than the cryic regime, but its mean annual temperature is lower than 8°C (47°F) and the difference between the mean winter and mean summer soil temperature is more than 5°C (9°F) at a depth of 50 cm or at a bedrock or bedrock-like contact, whichever is shallower. Soils of the study area that have this soil temperature are Argiborolls, Haploborolls, Paleborolls, Eutroboralfs, and Ustifluvents. The Torrifluvents and Fluvaquents may have either a frigid or a mesic temperature regime. The mesic temperature regime is defined below.

The Mesic soil temperature regime is characterized as soils with a mean annual soil temperature of 8°C (47°F) or higher, but lower than 15°C (59°F). Soils of the study area having this soil temperature regime are the Argiustolls, Haplargids, Camborthids, Torriorthents, and Ustorthents. As stated above, some Torrifluvents and Fluvaquents may occur in this temperature regime. Soil forming materials subjected to this environment would weather at a moderate rate.

General description of soil taxonomic units: In order to avoid redundancy and to develop clarity in the understanding of the nature of soils found in the oil shale study area, a general description will be given for the soils at the Suborder level. The Suborders are Borolls, Ustolls, Boralfs, Argids, Aquents, Fluvents, Orthents, and Orthids.

The borolls are soils having moderately thick to thick surface horizons, moderately high to high levels of organic matter, and high base saturation. The surface soils are characterized as being friable, having good structure - which reflects conditions favorable to water infiltration - and having good plant growth and root development. They are not generally short of available moisture in the root zone. The general fertility level of these soils is high. These soils represent areas that contain materials suitable as a source of topsoil. Landscapes on which these soils occur are generally characterized as being stable with respect to erosion and sediment yield unless the areas are disturbed.

Soils in the ustoll suborder are similar to the borolls, except that they are generally warmer and drier. Drought is frequent and in some years may be severe. During drought, wind erosion becomes a serious problem. These soils have a moderately thick surface horizon containing a moderate amount of organic matter, and are high in base status. They are generally characterized as having a friable surface horizon with good structure. Infiltration of moisture is generally good. Landscapes on which these soils are found are generally characterized as being fairly stable with respect to erosion and sediment yield.

The boralfs are characterized as having an organic horizon at the surface with a thin mineral surface horizon below. The surface soils are generally slightly acid to neutral. Landscapes on which these soils are found are typically characterized as being stable with respect to erosion and sediment yield. The occurrence of "raw" organic matter because of low biological activity caused by cool conditions. The fertility status of the surface soils would generally be considered as being fair.

The argid soils are characterized as having thin, light-colored surface horizons low in organic matter but high in base status. These soils are dry for long periods of time. Because of the low organic matter and depending upon the texture, some soils in this group take up water slowly and most rainfall runs off. Water and wind erosion are hazards on these soils. Except for a low nitrogen supplying ability, these soils generally have a moderate to high fertility status. The Natrargids, which are shown to occur within the study area (see Table 1), are soils having particular physical and chemical characteristics and need to be discussed separately as a class. These soils are characterized as being slowly permeable and soluble salts are commonly present in the subsoil or immediately below the subsoil. Most of the soils in this category are characterized as being fine-textured, i.e. having a high clay content. These soils offer particular problems with respect to plant growth, subsidence problems if soluble salts and/or gypsum are leached out, and may contain high shrink-swell clays.

The aquents are characterized as having very little soil development. These are wet soils located on floodplains of streams where the soil is saturated for some period of the year. Most of the soils are found in recent sediments. Thus, landscapes on which these soils are found are characterized as being unstable, i.e. depositional erosion from flooding occurs. Vegetation found on these soils includes those vegetative types that tolerate permanent or periodic wetness. Soils classified as aquents are generally low in general fertility status, particularly nitrogen. Wetness and flooding are hazards associated with these soils.

Fluvents are similar to the aquents except they are not wet. They are, however, subject to flooding. The soil materials are alluvial sediments that for the most part come from eroding soils or streambanks and may contain appreciable amounts of organic matter. These soils are highly stratified and their chemical and physical properties are highly variable with depth. Soils in this category or the materials in which they form could be a valuable source of plant growth medium for covering spent oil shale or coarse geologic materials.

Soils in the orthent category represent upland areas where little or no soil development is present. They represent areas of recent erosional surfaces. The erosion probably is geologic. These soils have a very low organic matter content and have a low fertility status. Landscapes on which these soils occur are characterized as being relatively unstable with respect to water erosion and sediment yield.

The orthids are similar to the argids except they do not have a strongly developed subsoil. They are either chronologically younger than the argids, or because of slope, parent material, or climatic conditions, or a combination of these, soil development has been retarded. If the latter is the case, this suggests that the soils occur on active erosional surfaces and the degree or severity of droughtiness and erosion hazards would be great. These soils may have a horizon of soluble salt accumulation. These soils have thin, light-colored surface horizons low in organic matter.

It must be remembered that the foregoing discussion is based upon definitions which describe the central, or "model" concept of these taxonomic classes. Soils of the study area may or may not conform to the central concept. Determining the Subgroup, Family, and Series is necessary for further or more precise interpretations. And this cannot be done unless a detailed soil survey is made to identify and characterize the soils in the area.

Table 1. Soils of the oil shale study area classified according to current classification.

Order	Suborder	Great group	Sub-group	Family	Series	Soil Associations where these classes occur
Mollisols	Borolls	Argiborolls	--	--	--	52, 53, 116, 143
		Cryoborolls	--	--	--	50, 53, 97, 98, 130
		Haploborolls	--	--	--	52, 54, 97, 116
		Paleborolls	--	--	--	130
	Ustolls	Argiustolls	--	--	--	54
Alfisols	Boralfs	Cryoboralfs	--	--	--	49, 98
		Eutroboralfs	--	--	--	55
Aridisols	Argids	Haplargids	--	--	--	59, 93, 96, 100
		Natrargids	--	--	--	100
	Orthids	Camborthids	--	--	--	59, 93, 96, 100, 143
Entisols	Aquents	Fluvaquents	--	--	--	132
	Fluvents	Ustifluvents	--	--	--	132
		Torrifluvents	--	--	--	82
	Orthents	Cryorthents	--	--	--	97, 98
		Torriorthents	--	--	--	59, 96, 99
		Ustorthents	Typic	Clayey, mixed, calcareous, mesic, shallow	Chipeta	92
		Ustorthents	Typic	Loamy, mixed, calcareous, mesic, shallow	Persayo	92

Note: Soils of the Rock outcrop and Badland areas have not been classified. There is little or no soil development. The soils are extremely shallow in these areas. Outcropping of geologic bedrock materials is a dominant characteristic of these areas.

Adequacy of Existing Soils Data for Evaluating Soil Behavior Related to Activities Associated with Proposed Oil Shale Development

The collection of soils data has revealed that the amount of soil data available for the oil shale study area is very limited. The general Soil Association Map which accompanies this report is adequate for developing a general overview of the diversity of soils found within the area and for defining relatively large blocks of land where soils offer certain opportunities and/or constraints relative to activities that will be associated with revegetation of disturbed lands. Unfortunately, much of the soil data which were used in the development of these general soil maps were both limited in scope and obtained in areas outside of the study area. Thus, a certain amount of caution must be applied to the interpretations, particularly if the information is being applied to small geographic areas.

The detailed soils information which is available is extremely fragmentary. Based on information available, the following discussion attempts to analyze some behavioral characteristics of soils found in the study area as they relate to some of the major types of activities associated with revegetation and stabilization of disturbed areas.

Erosion

A summary of the soils data presented indicates that most soils, except those on the floodplains, are situated on steep slopes; most soils have a very thin surface layer (6 inches or less), are quite variable in total depth; percent ground cover is small; texture is quite variable. The steepness of the slopes, lack of ground cover, thin surface layer, as well as shallowness of some soils, present major problems associated with erosion. Soil losses generally increase as slopes increase. For comparison, in general it is estimated that soils without cover on a slope of 1% might lose 5 tons of soil per acre annually, soils on 10% slope may lose 50 tons, and soils on a slope of 20% may lose 100 tons. Many soils in the study area are located on slopes of 10% or greater. Loss of topsoil results in a depletion of plant nutrients and reduces infiltration and water-holding capacity. Disturbances such as roads, waste piles, excavations or any other activity which exposes bare soil can lead to serious erosion problems. Erosion on road cuts and other disturbances as influenced by soil texture would be less on the soil materials derived from sandstone versus those derived from the limestone-siltstone materials. Because of the apparent susceptibility to erosion as indicated by the factors mentioned above, a detailed soil survey is needed establishing guidelines for the purpose of minimizing erosion hazards.

Suitability of Soils as a Source of Construction Materials

Interpretations of existing data indicate that many soils found in the study area are not suited as a source of sand and gravel. Materials suitable for roadfill appear to be confined to a few soils; however information is lacking for a large number of soils.

Physical data available from the study by Medin and data collected during this study indicate that the fine fraction (<2 mm size) of these soil materials range from good to excellent for use as subgrade or subbase materials, range from poor to good as base material directly under bituminous pavement, range from being reasonable stable to stable for embankments, and are good to excellent for fill less than 50 feet high and fair to good for fill more than 50 feet high. Information presented in the descriptions of Soil Associations, however, indicates a wide range of soil textures can be found, and thus it appears that there may be finer textured soils not reflected in the existing laboratory data which could be both plastic and expanding. It should also be pointed out that the data presented indicate a large percentage of >2 mm size particles in those soils. This affects the compactibility and the stability of materials. Existing data is not adequate for making confident predictions about the suitability of soils as construction materials or for other engineering uses.

Soil Stability

Soil stability in relation to engineering uses is dependent on a number of characteristics, one of which is slope. In general, soils on steep slopes are less stable than those on gentle slopes because of sliding. The stability of soils on steep slopes is affected partly by composition of soils and partly by whether the layers dip downslope or into the hill. In situations where materials dip down the slope with an impervious layer where water reaches this layer to lubricate this zone, landslides can occur.

Stability of the soils on slopes is also a function of the fine materials that can bind soil particles. Existing data indicate that many of the soils contain considerable amounts of gravel size fragments and a high sand content. On these soils, slopes of greater than 2:1 would not be advisable. Those soils with a higher "fines" content (loams, clay loams, silty clay loams, silt loams) may be stable on slopes of 1:1.

In areas where colluvial clays are present, sliding would be a more serious problem than with sandy material.

The type of clay present in the fine fraction of soil is a very important factor in soil stability. There is little or no data available with respect to the expansion characteristics of clays found in soils of the study area. Mineralogical characterization of selected soils is needed for determining this factor as it relates to soil suitability for engineering uses.

Subsidence or settling of soils is related principally to the compactability, moisture holding properties, and change in thickness of materials. Settlement is irregular if the thickness and/or compactability of materials varies. Moisture holding properties important in soil stability as related to engineering uses are 1) the liquid limit -- the amount of moisture at which soil material ceases to behave as a viscous liquid, 2) plastic limit -- the moisture content at which the material ceases to act as a plastic solid, and 3) shrinkage limit -- the moisture content below which further drying produces no shrinkage. These properties depend on the amount and type of clay. Soils which are plastic tend to shift under pressure. Existing data are not available to adequately define the plasticity and shrinkage limit of the major soils of the study area.

The density and stability of soils can be increased by compaction. It is difficult to compact silty soils and those high in micaceous materials and soils containing 5% or more of organic matter, or soils having a high rock content. It appears that many soils in the study area contain relatively high percentages of >2 mm size fragments which reduces their compactibility.

Suitability of Soils for Vegetative Growth

The data of Medin and laboratory analyses of soils collected during this study indicate that a large number of surface soils are relatively high in organic matter, low in soluble salts, have low to high water-holding capacity, have rapid to slow infiltration rates, are high in lime content, and generally low to moderately deficient in available phosphorus and high in available potassium. In general, a large number of soils appear to be well suited for plant growth unless moisture is limiting. In addition, some of the soil parent materials, particularly the materials associated with the Fluvent soils, appear to be a potential source of material for use as a plant growth medium. Data provided by Berg (in this report) suggest that disturbed overburden and spent shale may not be highly desirable as mediums for plant growth. It appears that it would be desirable to stockpile soil materials for further use in stabilization of disturbed areas. A detailed soil survey can aid in determining the potential amount of these materials available at various locations. Estimates based on existing data would be grossly inaccurate.

Soils as they Reflect Landscape Stability-Instability in the Study Area

Although many soils in the study area appear to be shallow and weakly developed, the data available would seem to indicate that at the present time surface conditions are fairly stable over much of the area. A gross estimate indicates that approximately 60-70% of the area is comprised of soils which reflect a moderate to high degree of surface stability. This implies that alteration or disturbance of surface conditions could result in large changes in sediment yield and runoff.

SUMMARY

Overburden

Limited stratigraphic data on the overburden above the commercial oil shale indicate that the overburden consists of 36% to 67% sandstone, 7% to 22% siltstone, 7% to 36% limestone (marl), and 2% to 27% shale. The shale is locally subeconomic oil shale. The standstones and siltstones are composed of quartz, feldspar, and rock fragments cemented by calcite. The majority of the rock fragments are volcanic in origin. The limestones are 90% to 95% calcium to calcium-magnesium carbonate which contain 5% to 10% quartz, feldspar, and clay. The shales consist of 50% to 66% clay minerals, 10% to 46% calcite or dolomite, and 1% to 30% quartz, feldspar, and micas.

The physical property studied was the development of fine particles in fresh broken, in crushed, and in naturally weathered overburden rocks. Too many fine particles will produce a highly erodible material, and not enough fines produces a material that will not hold adequate water for plant growth. Fresh broken samples of all overburden rocks tended to be coarse grained with 80% to 95% between 4 and 256 mm, and only 1% to 5% less than 1 mm. Crushing reduced the grain size, producing 10% to 20% more fines than fresh samples. These fines, produced by crushing, are smaller than the minimum closure of the crusher jaws, thus relect the friability of the rocks. Natural weathering had produced 20% to 50% fines less than 1 mm in many rock types. Rates and amounts of weathering on fresh overburden in unknown and is now being researched.

Spoils

The predicted physical and fertility characteristics of spoils determined by very limited sampling indicate that intensive revegetation practices will be required to insure stands of desired species. The lack of soil-size particles might be a major problem in vegetation establishment and maintenance on some of the spoils. Nitrogen and phosphorus are deficient for plant growth on the spoils. Fertilization can correct this deficiency, although long-term nitrogen fertilization probably would be required. Salinity may be a problem in plant establishment on spoil from some strata. This could be overcome by careful leaching. Ground water salinity problems may be posed by water percolation through salty spoils.

The alternative to establishing vegetation directly on spoils is to cover the spoil with soil. If this is considered, a soil inventory and handling plans must be made before disturbance starts. Long-term land use and management of disturbed areas are not discussed in this analysis but obviously require careful consideration and commitments before land disturbance.

Soils

Information available suggests that soils of the area vary widely in characteristics such as depth, texture, structure, stoniness, moisture regime, temperature regime, organic matter, and in their chemical nature. The existing mapped, chemical and physical data are not adequate for defining the extent, distribution, chemical and physical properties of soils, except in a very general manner.

The information obtained in this study does suggest that there are opportunities as well as some serious constraints posed by soils with respect to rehabilitation. A detailed soil survey plus laboratory characterization of soils is needed before reliable interpretations and recommendations can be made.

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APPENDEX I

GEOLOGIC DATA

By

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Petrology of Selected Samples of the Evacuation Creek Member
John A. Campbell

Sample Location	Rock Type	Size				Mineralogy % by volume					
		Range mm	Median mm	Mode mm	Sorting	Quartz	Feldspar	Rock Fragments	Other	Carbonate	Clay
1. Cow Creek, CC-13	Sandstone	0.13 to 2.5	0.35	.25 to .35	Well	17	9.6	40.0	0.7	31.3	1.3
2. Cow Creek, CC-15	Conglomeratic sandstone	0.13 to 2.5	0.35	.25 to .50	Mod. Well	13.7	2.7	53.9	1.0	31.0	0.0
3. Piceance Creek, PC-6	Sandstone	0.063 to 0.60	0.15	0.13 to 0.18	Well	18.7	13.3	21.3	0.0	13.7	33.0
4. Piceance Creek, PC-9	Limestone	0.008 to 0.30	0.44	0.31 to .044	--	7.5	2.0	0.0	0.0	90.5	0.0
5. Cow Creek, CC-14	Dolomitic limestone	.008 to .035	.012	.008 to .016	--	3.0	1.0	0.0	1.0	95.0	0.0
6. Piceance Creek, PC-3	Dolomite	.008 to .07	.012	.008 to .016	--	3.0	0.5	0.0	1.0	95.5	0.0
7. Cow Creek, CC-6	Shaly Siltstone	.008 to .25	.023	.016 to .031	--	18.7	5.0	0.0	1.0	9.0	66.3
8. Cow Creek, CC-11	Shaly Siltstone	.008 to 0.20	.033	.016 to .031	--	23.0	5.7	0.0	1.3	9.0	61.0
9. Corral Creek, OC-1A	Shale	.004 to .08	.013	.008 to .016	--	1.0	0.5	0.0	0.0	46.0	52.5

Measured Stratigraphic Section
Evacuation Creek Member, Green River Formation
Piceance Basin, Colorado
Sec. 15,16,22, T1N, R97W
Lower Piceance Creek
Measured and described by L. D. Milliken

Thickness	Distance above base	Description
15'	990'	Fine calcareous sandstone; lt. brown; friable; mod. resistant.
20'	975'	Calcareous siltstone; lt. tan to buff; moderately non-resistant.
20'	955'	Alternating beds of fine calcareous sandstone and bedded off-white to lt. tan calcareous siltstone (3' to 4' each); sandstone is massive and more resistant than the siltstone.
30'	935'	Calcareous siltstone; thin-bedded; manganese staining on bedding and fracture surfaces.
30'	905'	Fine calcareous sandstone; massive, friable; tan, some low angle cross-bedding present; resistant.
30'	875'	Very calcareous silty mudstone; bedded; lt. gray; non-resistant.
50'	845'	Fine to very fine sandstone, slightly calcareous in places; yellow-brown to lt. tan; semi-friable; moderately non-resistant.
5'	795'	Silty mudstone, non-calcareous; well-lithified, gray-brown.
14'	790'	Very fine, non-calcareous sandstone with some fine sand; tan, massive.
20'	776'	Thin-bedded, very calcareous mudstone; lt. gray; moderately non-resistant. LP-1D
90'	756'	Very fine, slightly calcareous sandstone with some thin, interbedded silts. One 6" layer of limestone, perhaps algal, with crystal calcite present. (Sample PC-9)
10'	666'	Inter-layered thin-bedded siltstone and more massive very fine sandstone, both calcareous and resistant.
40'	656'	Very thin-bedded dolomitic shale; brittle, chocolate brown (kerogenic). LP-1C
70'	616'	Fine, moderately calcareous sandstone; massive; resistant; brown.

The below section of alternating sandstone and "marlstone" was measured and logged as sandstone and marlstone by John R. Donnell, 1961, U. S. Geol. Survey Bull. 1082-L, Section 60. Details and description of lithologies are from field investigation by L. D. Milliken, 1972, as are the previously described lithologic descriptions and measurements.

Thickness	Distance above base	Description
168'	546'	Fine sandstone; moderately calcareous; massive and very resistant; orange-brown. (Sample PC-8) LP-1B
82'	378'	"Marlstone";predominantly lt. brown dolomitic shale, not as rich in kerogen as lower lying "marlstones"; silty near the base and top. (Sample PC-7)
35'	296'	Fine calcareous sandstone; yellow-brown; friable and relatively non-resistant. (Sample PC-6)
60'	261'	"Marlstone"; chocolate to lt. brown dolomitic shale with thin sandy layers. (Sample PC-5)
43'	201'	Very fine sandstone, calcareous; massive and moderately resistant; tan to lt. gray; oxidized iron nodules. (Sample PC-4)
82'	158'	"Marlstone"; lt. to dk. brown dolomitic shale, thin-bedded; keogenic; sandy in the upper 20'. (Sample PC-3) LP-1A
76'	76'	Fine calcareous sandstone, eyllow-brown, moderately resistant. (Sample PC-2)

Section started at base of first thick (10 feet or more) sandstone above Mahogany Marker, ended at highest local point on present erosion surface.

Sec. 29,31,32, T1S, R99W
Dry Fork, Corral Creek
Measured and Described by L. D. Milliken

Thickness	Distance above base	Description
50'	540'	Section continues in very fine sandstone, slightly calcareous, with interbedded fine sand and minor silts; tan to lt. tan; moderately resistant.
40'	490'	Very fine sandstone with interbedded silts, calcareous at bottom to only slightly calcareous at the top; more resistant where sand is calcareous. CG-1D
20'	450'	Very fine calcareous sandstone grading upward to a very calcareous siltstone; bedded in the upper 5'.

Thick- ness	Distance above base	Description
2'	430'	Fine to medium calcareous sandstone; 1/4 to 1/2 mm. biotite flecks present; very resistant.
23'	428'	Very fine calcareous sandstone with some silts; lt. tan, some organic material present; more massive than bedded (Sample OC-7B).
20'	405'	Lt. tan very fine sandstone to siltstone; slightly calcareous; moderately resistant.
7'	385'	Massive, fine sandstone; yellow-brown; calcareous, friable (Sample OC-6B).
8'	378'	Calcareous, buff-colored siltstone.
35'	370'	Bedded mudstone (calcareous) and limestone; tan to lt. gray; moderately non-resistant; non-fossiliferous.
10'	335'	Well-lithified calcareous siltstone; buff-colored; non-fossiliferous (Sample OC-5B).
15'	325'	Thin-bedded non-fossiliferous, lt. gray limestone.
3'	310'	Thin to very thin-bedded, fossiliferous, calcareous mudstone; lt. brown; non-resistant.
7'	307'	Lt. gray bedded limestone; non-resistant; non-kerogenic.
10'	300'	Grades up to a calcareous siltstone, lt. tan. CG-1B
10'	290'	Lt. buff-colored calcareous mudstone; non-kerogenic.
55'	280'	Thin-bedded mudstone; calcareous; shaly character of rock decreases upward as does brittleness, fossil content, and color intensity. The change from brittle, kerogenic, shaly calcareous mudstone to kerogen-poor muddy limestone is a marked topographic change. (Sample OC-3B) CG-1A
15'	225'	Same as below with thin (1 mm - 3 mm) layers of iron-rich material every 3" to 4" throughout the section, (Sample OC-2B); kerogenic.
15'	210'	Very thin-bedded, fossiliferous, calcareous mudstone or muddy limestone. CG-1C
20'	195'	Fossiliferous dark brown dolomitic shale, thin-bedded, resistant (Sample OC-1B).
10'	175'	Same as below, again with black cap layer.
10'	165'	Very thin-bedded dolomitic shale, chocolate brown fresh (high kerogen content); resistant; capped by a very resistant black dolomitic shale.
3'	155'	Thin-bedded limestone, gray, minor kerogen; capped by a dk. brown to black, very resistant dolomitic shale.
4'	152'	Interbedded thin calcareous shale and mudstone with some silt-size grains present. Non-resistant to very resistant depending on amount of kerogen present.
3'	148'	Thin-bedded limestone, grades into a tan calcareous siltstone.
22'	145'	Slightly calcareous interbedded siltstone and very fine sandstone; bedding increases vertically; one 1.5' bed of limestone present at 131'.
5'	123'	Alternating thin beds of siltstone and fine sandstone; iron modules present; semi-friable where sandy. (Sample OC-4A)
10'	118'	Siltstone grading up to fine sandstone, lt. yellow-brown to orange-brown; calcareous; biotite and K-feldspar present; mod. non-resistant.
5'	108'	Non-calcareous siltstone; buff colored.
33'	103'	Very thin-bedded, micro-crystalline limestone, weathers lt. gray, lt. brown to dk. brown fresh, (Sample OC-2A); 2 2" layers of black dolomitic shale present.
10'	70'	Very thin-bedded calcareous shale; lt. gray on outcrop, lt. to dk. brown fresh; capped by a very resistant 2" layer of black dolomitic shale. (Sample OC-1A)
10'	60'	Very fine to fine calcareous sandstone, semi-friable; tan; relatively non-resistant.
50'	50'	Mixed sandstone and siltstone, section covered so no detail was recorded.

Section started at base of first thick (10 feet or more) sandstone unit above Mahogany Marker, ended at highest local point on present erosion surface.

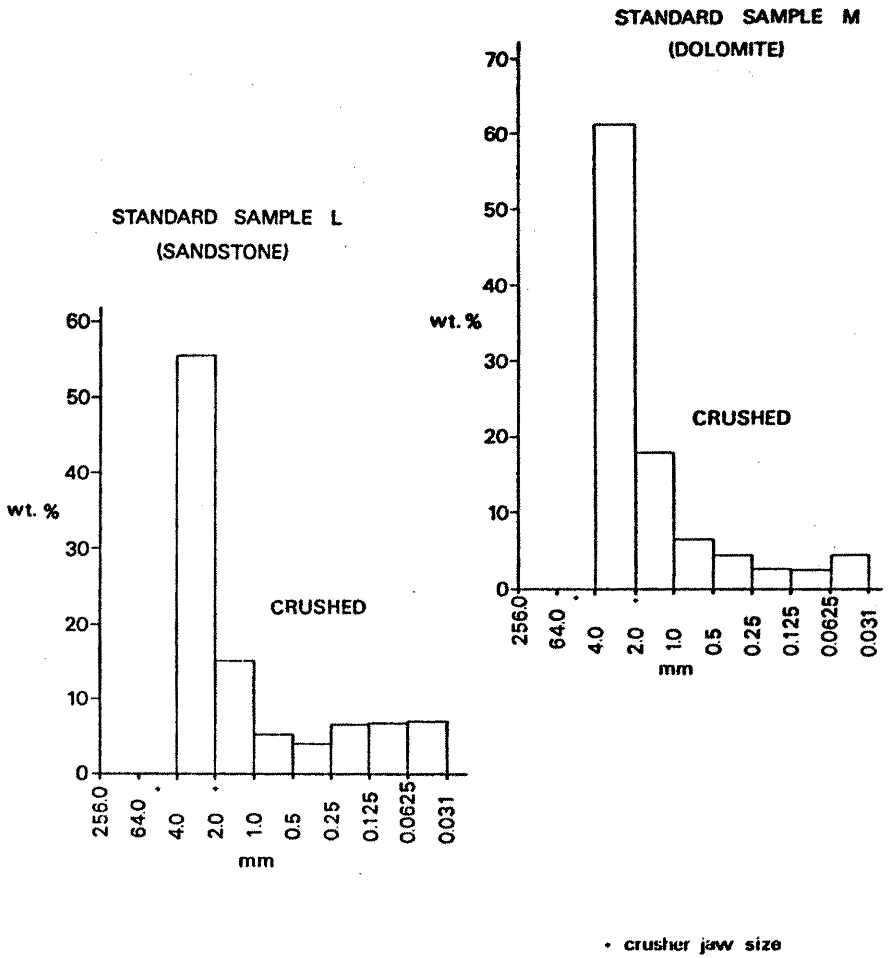
Sec.13,24, T4S, R95W
Cow Creek
Measured and described by L. D. Milliken

Thick- ness	Distance above base	Description
40'	.675'	Very fine sandstone, non-calcareous, semi-friable; tan; mod. resistant.

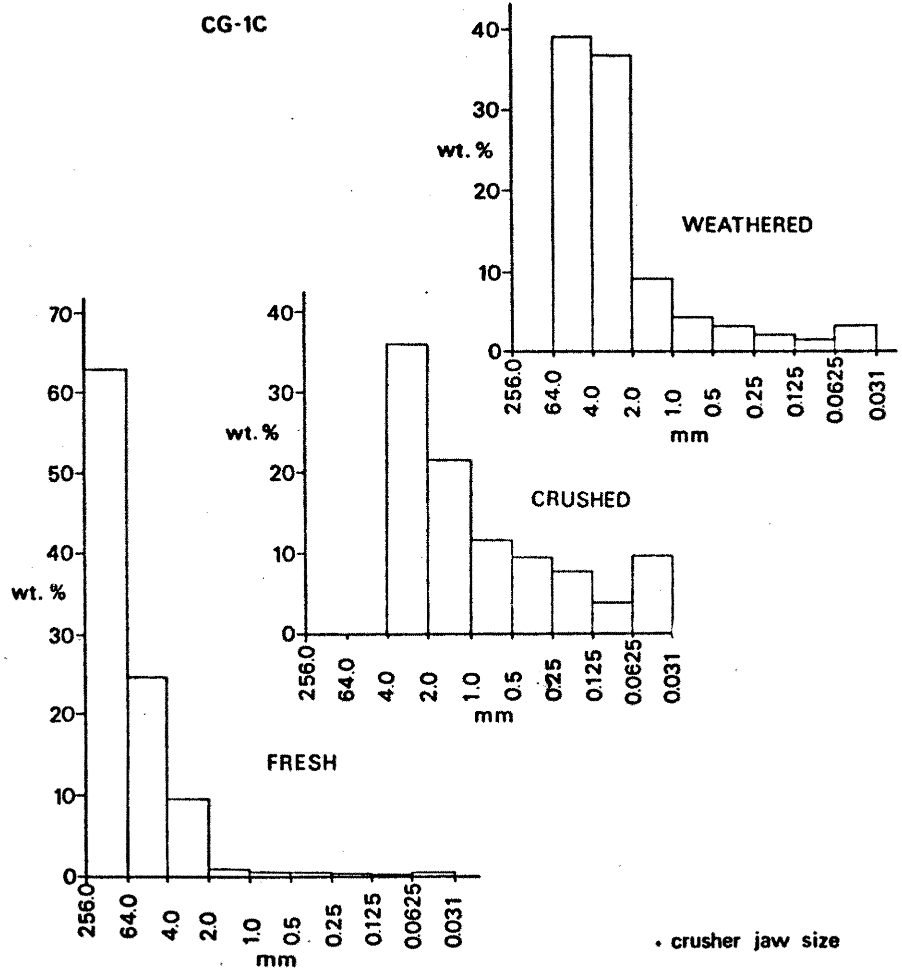
Thick-ness	Distance above base	Description
55'	635'	Primarily slightly calcareous siltstone with interbedded calcareous mudstone; gray to whitish; non-resistant.
20'	580'	Siltstone, slightly calcareous; grades upward to a calcareous mudstone, thin to medium bedded; gray; non-resistant.
15'	560'	Very fine sandstone with interbedded silts, slightly calcareous; semi-friable where sandy; massive to coarse bedded.
5'	545'	Compact, slightly calcareous siltstone, gray, little organic matter; semi-shaly fracture.
25'	540'	Fine sandstone, slightly calcareous to calcareous in places; some medium sand lenses present; semi-friable; tan to grayish; mod. resistant.
10'	515'	Calcareous small pebble conglomerate, very well-lithified; gray-brown. (Sample CC-15)
5'	505'	Fine to medium calcareous sandstone, friable; little organic matter; moderately resistant.
5'	500'	Limestone above grades into a calcareous mudstone/siltstone; lt. gray; minor organic matter; mod. non-resistant.
35'	495'	Gray, thin-bedded limestone; minor organic matter present; becomes less reactive with HCl near top (more dolomitic?). (Sample CC-14) mod. non-resistant.
20'	460'	Very fine sandstone, slightly calcareous, with interbedded silts; slightly bedded; semi-shaly fracture; organic content variable with some organic material replaced by $CaCO_3$. Mod. non-resistant.
10'	440'	Fine to medium calcareous sandstone with a thin interbedded granular to small pebble conglomerate. Conglomerate is well-lithified & resistant; calcareous. (Sample CC-13)
6'	430'	Very fine calcareous sandstone, tan, fairly non-resistant.
1'	424'	Calcareous mudstone to siltstone.
3'	423'	Calcareous shale, gray, non-resistant.
5'	420'	Calcareous siltstone to very thin-bedded calcareous shale or muddy limestone. (Sample CC-12)
40'	415'	Very fine calcareous sandstone with some interbedded silts; low organic content; friable; relatively non-resistant.
15'	375'	Lt. gray calcareous siltstone w/ some very fine sands; shaly fracture; very little organic content.
10'	360'	Dolomitic mudstone, low organic content, gray, non-resistant. (Sample CC-11)
2'	350'	Very fine sandstone to siltstone, slightly calcareous, non-resistant; shaly fracture; low organic content.
23'	348'	Massive, slightly calcareous, fine sandstone; low angle cross-bedding present; semi-friable; very little organic matter. (Sample CC-10)
15'	325'	Massive, slightly calcareous, very fine sandstone, tan; non-friable; smooth, rounded outcrop, fairly resistant.
15'	310'	Siltstone, non-calcareous, grading up to a non-calcareous, very fine sandstone; moderate resistance.
25'	295'	Non-calcareous siltstone, gray, moderate organic content, non-resistant with a shaly fracture. (Sample CC-9)
15'	270'	Interbedded siltstone, very fine sand, fine sand, some calcareous layers in fine sand; dominantly silts in lower 8', half silts and half sands in upper 7'; sands are yellowish, non-calcareous, friable; siltstone is gray, thin-bedded, non-calcareous, with moderate organic content.
5'	255'	Friable medium sandstone, slightly calcareous, with a 4" very calcareous layer. (Sample CC-8)
5'	250'	Very fine slightly calcareous sandstone, lt. brown, high organic content. (Sample CC-7)
10'	245'	Very fine sandstone grading up to a siltstone, non-calcareous, moderate organic content. (Sample CC-6)
8'	235'	Slightly calcareous very fine sandstone, buff-gray; organic and carbonate content increase vertically; moderately resistant.
7'	227'	Slightly calcareous very fine sandstone changing to siltstone, high organic content, yellow-brown, very soft and non-resistant. (Sample CC-5)
10'	220'	Massive medium calcareous sandstone, lt. tan, well-lithified. (Sample CC-4)
50'	210'	Very fine sandstone grades vertically to fine sandstone, slightly calcareous; some low angle cross-bedding present; iron nodules; very resistant (ledges and overhangs).

Thickness	Distance above base	Description
25'	160'	Very fine slightly calcareous sandstone, perhaps dolomitic; alternates massive to faintly thin bedded, organics decreasing vertically.
10'	135'	Very fine calcareous sandstone, tan, rounded outcrop, organic content up to 1+%.
5'	125'	Very fine slightly calcareous sandstone with interbedded silts; 2 1" layers of well-lithified v. calcareous fine sandstone (Sample CC-3) present.
5'	120'	Very fine non-calcareous sandstone; lt. tan.
5'	115'	Lt. gray, non-calcareous siltstone when fresh, v. calcareous on weathered surface; increased organic content.
5'	110'	Similar to below only more very fine sand and somewhat more calcareous.
5'	105'	Thin interbedded layers of silt, very fine sand, and fine sand; all non-calcareous; lt. tan to gray with some dk. brown iron nodules; weathers smooth with occasional thin ledges.
10'	100'	Fine sandstone, changes from very calcareous to slightly calcareous vertically; very compact and resistant, sub-choncoidal fracture in places; tan. (Sample CC-2)
15'	90'	Interbedded layers of varying thickness of fine and medium sandstone with some siltstone. Mostly non-calcareous, alternating friable and compact; wavy bedding. Approx. % sand to silt: 75:25
25'	75'	Very fine calcareous sandstone; scattered lens of silt (lt. gray) in tan sandstone; weathers blocky, very resistant.
15'	50'	Interbedded fine sandstone (slightly calcareous) and calcareous mudstone. Sandstones are tan, mudstones lt. gray; iron nodules, probably oxidized pyrite present; little organic material; rocks are relatively non-resistant.
5'	35'	Interbedded fine and very fine sandstones with siltstone, both slightly calcareous, higher organic and biotite content in coarser sand. (Sample CC-1)
20'	30'	Fine sandstone, slightly calcareous where fresh, very calcareous on weathered surfaces; tan to lt. gray, minor organic material and some biotite flecks present; some silt and clay-size particles present.
10'	10'	Very fine sandstone, slightly calcareous, with some silt-size particles present; compact, massive, contains dark organic material; blocky, rounded outcrop; lt. brown.

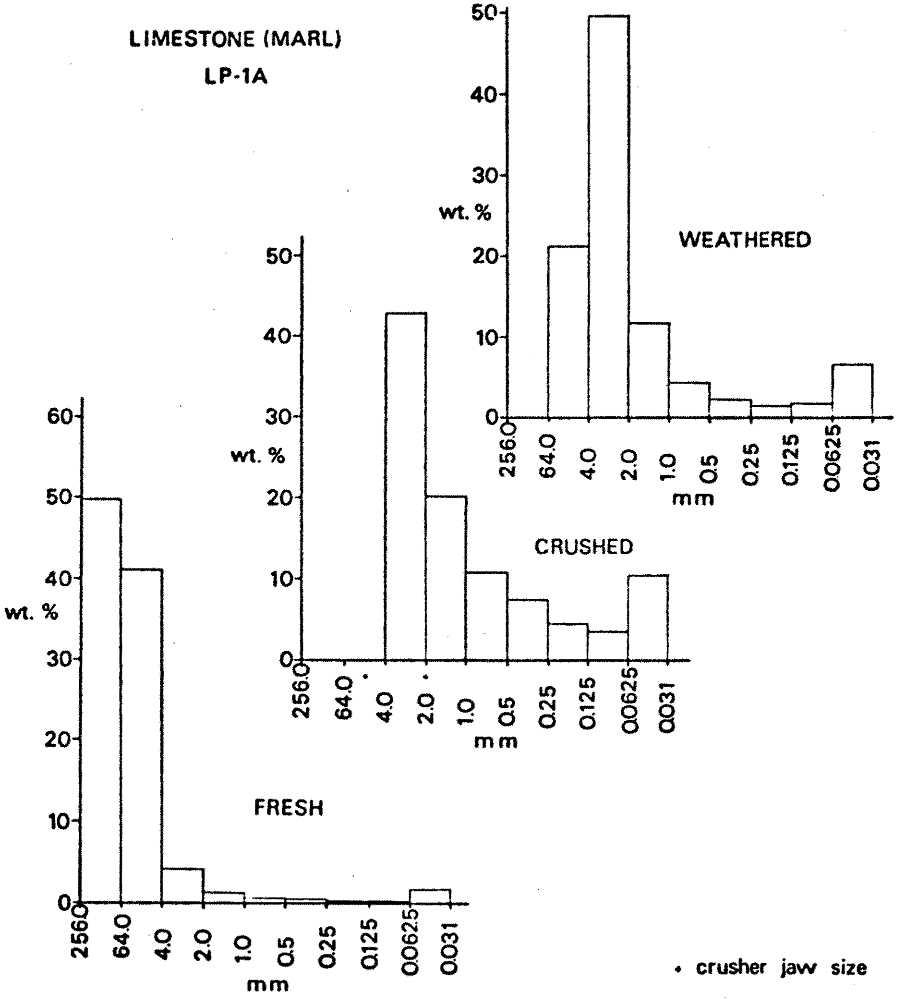
Section started at base of first thick (10 feet or more) sandstone unit above Mohogany Marker, ended at highest local point on present erosion surface.



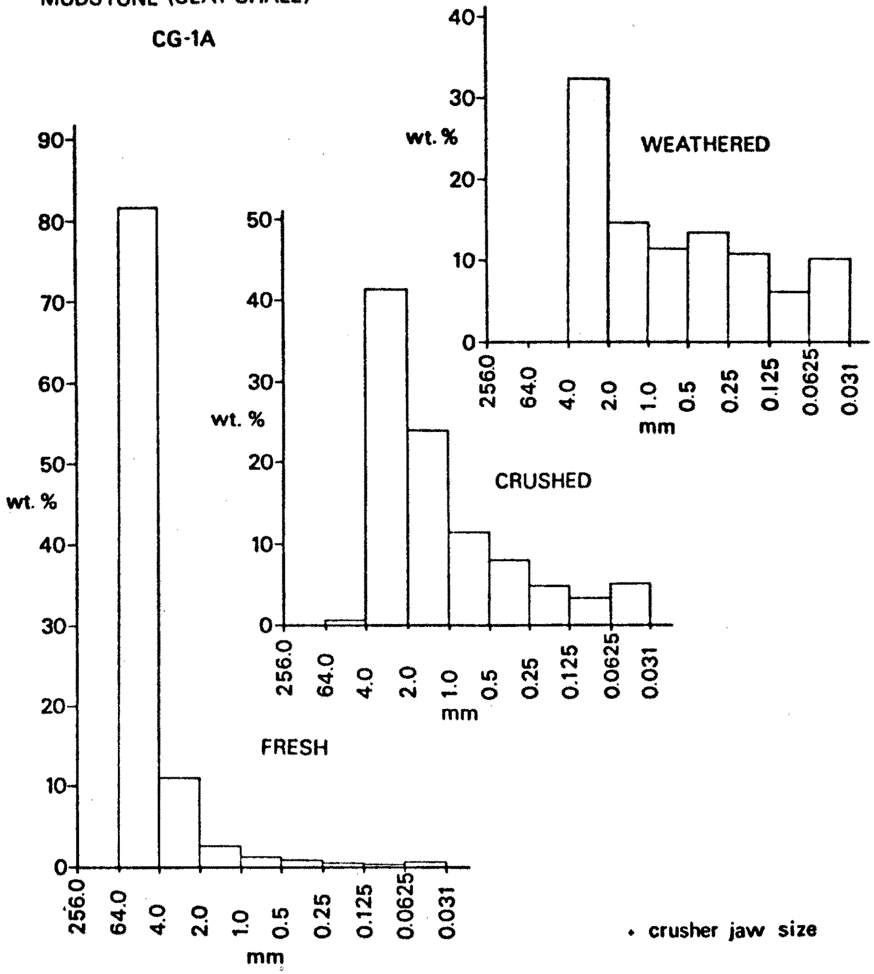
LIMESTONE (MARL)
CG-1C



LIMESTONE (MARL)
LP-1A

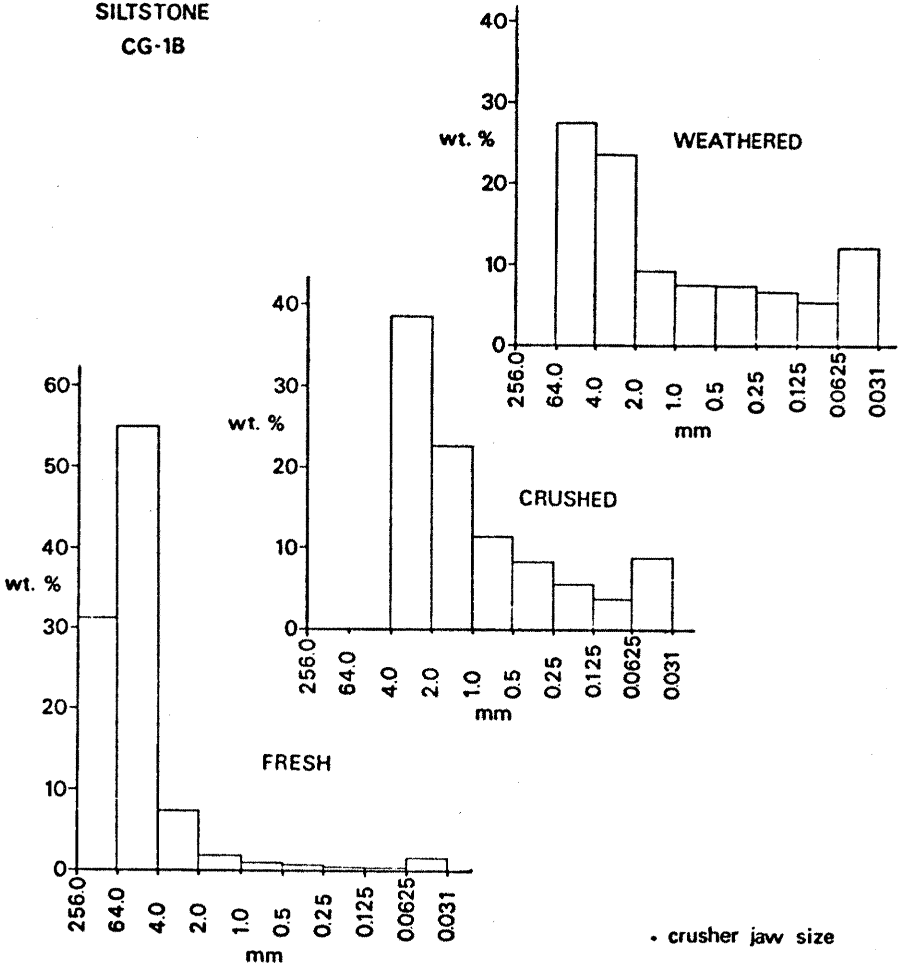


MUDSTONE (CLAY-SHALE)
CG-1A



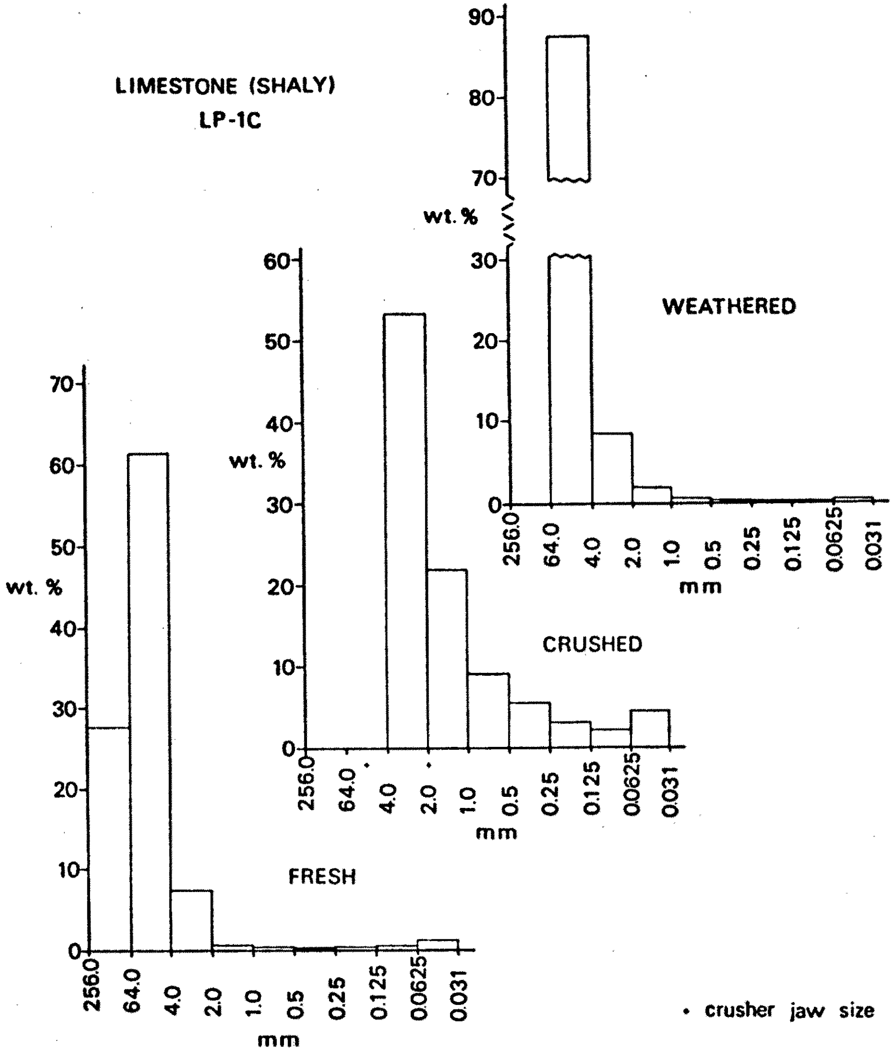
• crusher jaw size

SILTSTONE
CG-1B

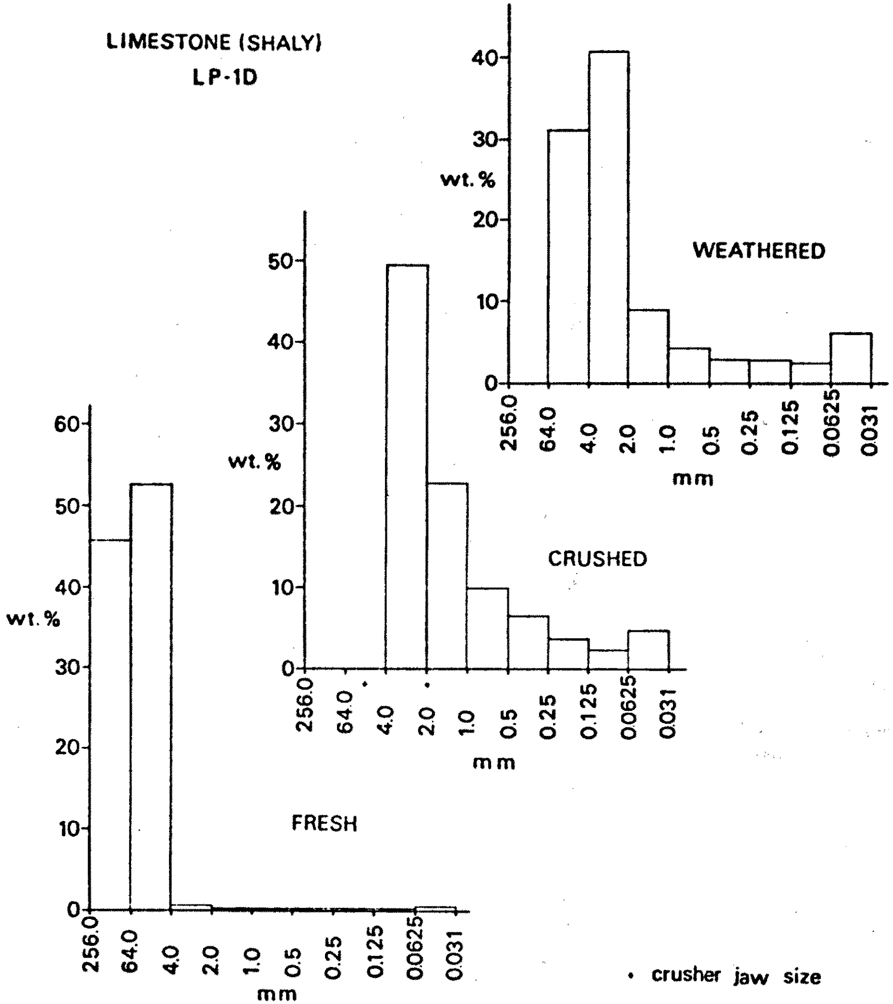


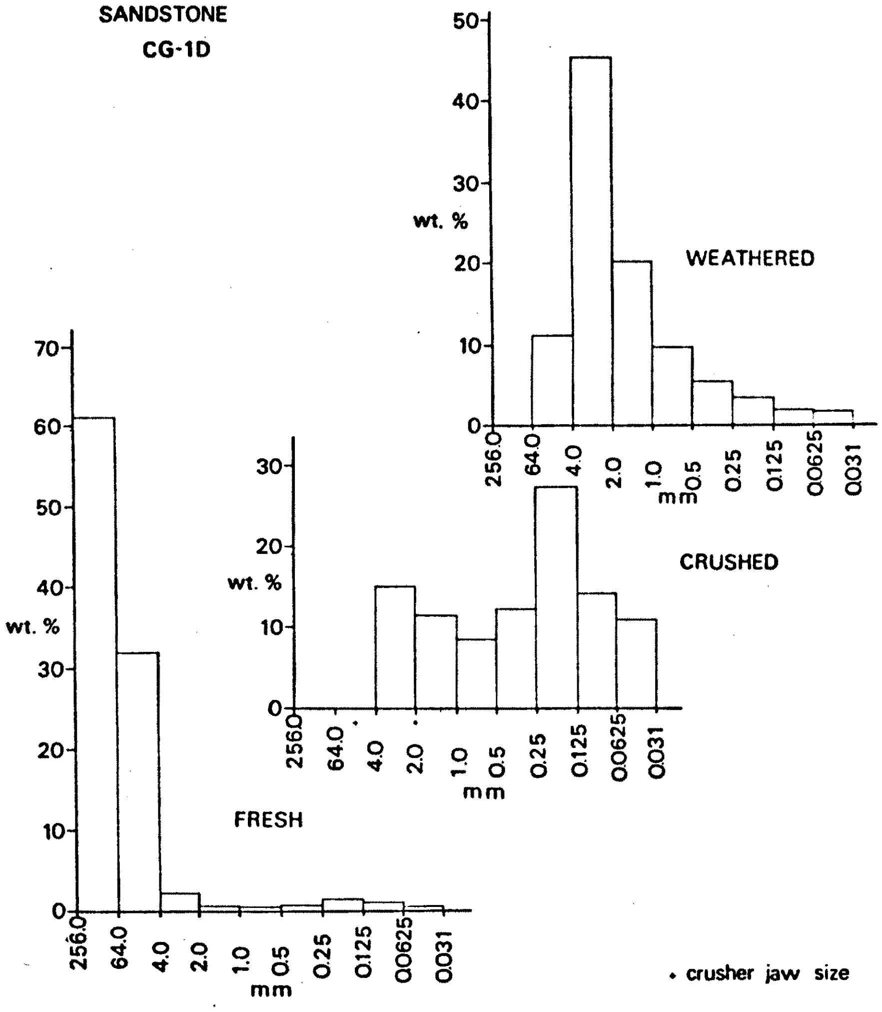
• crusher jaw size

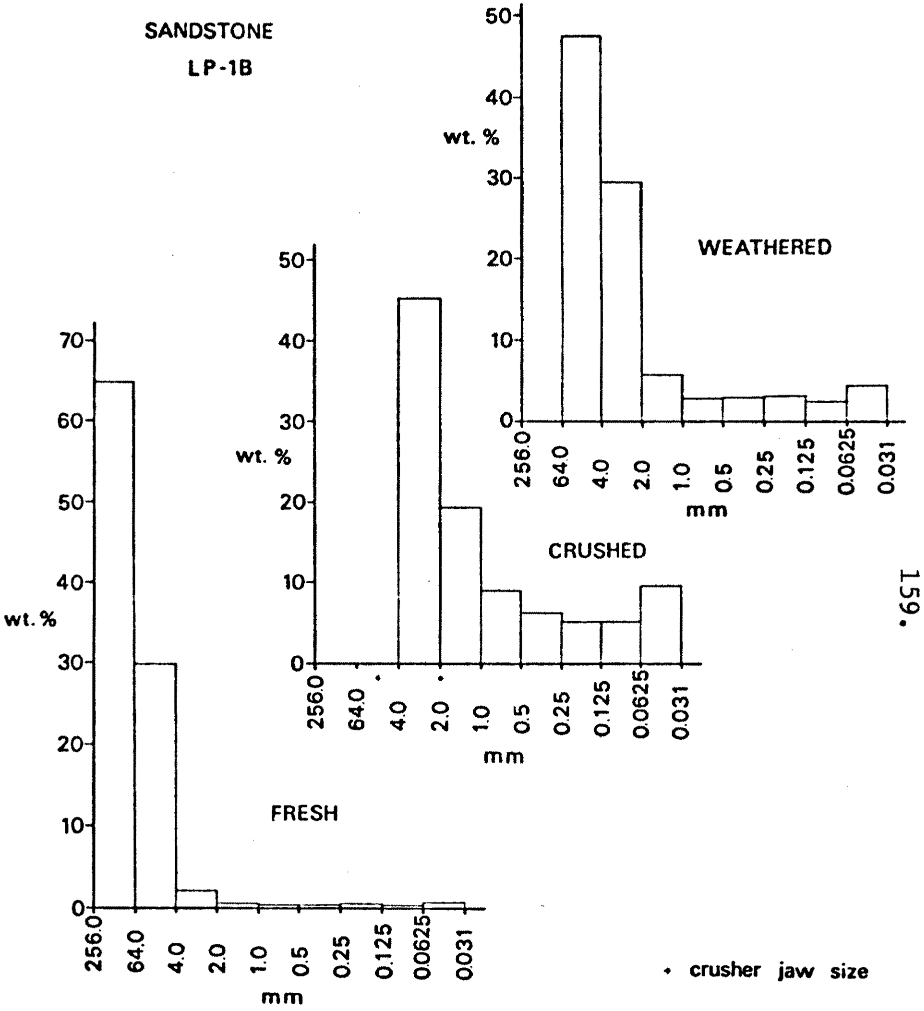
LIMESTONE (SHALY)
LP-1C



LIMESTONE (SHALY)
LP-1D




SANDSTONE
CG-1D
WEATHERED
CRUSHED
FRESH
wt. %
mm
256.0
64.0
4.0
2.0
1.0
0.5
0.25
0.125
0.0625
0.031
0
10
20
30
40
50
60
70
• crusher jaw size


SANDSTONE
LP-1B
WEATHERED
CRUSHED
FRESH
wt. %
mm
256.0
64.0
4.0
2.0
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0.5
0.25
0.125
0.0625
0.031
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10
20
30
40
50
60
70
• crusher jaw size

APPENDIX 2

Narrative Descriptions of the Soil Associations

The following Soil Assoxiation descriptions were obtained from personnel of the Soil Conservation Service, USDA. The descriptions were written for the development of County General Soil Maps from which the map that appears in this report was taken. The map and the descriptions are based on very limited field data. All of the descriptions are tentative and are subject to revision.

In addition, it should be pointed out that the following descriptions define the "average" soil composition found within an association. Thus, the composition of soils will vary somewhat from one location to another within an association. As a result, the descriptions may not accurately describe the relative composition of soils in a given area within an association. Because of this the information cannot be used for soil suitability interpretations for small geographic areas. The information is useful, however, in developing an overview concerning the variability and/or homogeneity of soil conditions in various areas, and for evaluating in a general way the opportunities and/or constraints that soils offer with respect to various activities. A detailed soil survey is needed before final planning or management decisions are made.

A narrative description of each association, listed by number and name, follows.

#49: Cryoborolls - Rock outcrop Association

This association is composed of the area widely known as the Cathedral Bluffs. Elevations range from about 7200 to 8500 feet. Annual precipitation ranges from 15 to 20 inches, about two-thirds occurring as winter snow. Summers are cool and short, with a frost-free season of 40 to 65 days.

About 50% of the association consists of shallow to moderately deep, light colored, calcareous soils over shale. They have a shaley-channery loam or fine sandy textured surface and a clayey subsoil with varying amounts of rock fragment. Rockland areas of high cliffs and bluffs of Greenriver shale make up about 25% of the association. About 15% of the association will consist of shallow to deep, will drained, slowly permeable soils under aspen and scattered coniferous forested areas. They have a surface litter, underlain by dark loamy or stony loam acid surface layers and brownish colored, clayey subsoils. Depth to bedrock ranges from 10 to more than 60 inches. The remaining 10% of the association is soil inclusions consisting of some shallow to deep, cobbly or stony loam to sandy loam textured soils throughout. Also found are small areas of dark colored moderately deep to deep clayey soils that are almost stone free in the more gentle sloping drainageways as well as scattered small slightly saline-alkaline areas. This assocaition is used primarily for scenic and recreational value.

#50: Cryoborolls - Cryoboralfs Association

Elevations range from 7000 to about 8200 feet. Annual precipitation ranges from 15 to 20 inches, about two-thirds occurs as winter snow. Summers are cool and short with a frost-free season of 40 to 65 days. About 50% of this association consists of moderately deep to deep, well drained soils with dark loamy surface layers and brownish clayey subsoils. A lime zone often occurs below 20 inches. Depth to bedrock ranges from 20 to more than 60 inches. About 45% of the association consists of shallow to deep, well drained, slowly permeable soils under coniferous and aspen forest, having a surface litter, dark loamy or stony loam acid surface layers and brownish colored, medium to clayey subsoils. Depth to bedrock ranges from 20 to 40 inches. The association also has about 5% inclusions that consist of small areas of very shallow rocky soils, wet soils in narrow swales and valley bottoms, as well as areas of gullied land, rockland, and rock outcrops. This association is used primarily for grazing, wildlife, and recreation. The areas of forest timber are too small and scattered for timber production.

#52: Argiborolls - Vanda Association

Elevations range from 6000 to 7000 feet. Annual precipitation ranges from 15 to 20 inches, three-fourths occurring as winter snow. Summers are moderate with a frost-free season of 75 to 100 days. About 65% of the association consists of deep, well drained, moderately fine to fine textured, gently sloping to sloping, moderately permeable soils of unnamed series developed in thick deposits of reddish brown Eolian materials. About 25% of the association consists of the Vanda soil series. Vanda soils are deep, well drained, calcareous, fine clayey textured grayish colored soils derived from exposed areas of Mancos shale. About 10% of the association is made up of inclusions consisting of small areas of loamy to clayey recent alluvium along drainages, small wet and poorly drained soils, areas of shallow to moderately deep soils over shale or sandstone, as well as shallow stony colluvial soil areas. This association is one of the most intensively farmed areas. Dry land grains and hay are the major crops. Considerable parts of this area are under irrigation and provide good pasture for cattle and sheep. There is considerable wildlife in the area but hunting is somewhat limited due to the high concentration of population. The area also provides excellent fishing along the White River and most of its tributaries.

#53: Argiborolls - Cryoborolls Association

This association is made up of approximately 65% Argiborolls and 35% Cryoborolls. These soils occupy the sloping to steeply sloping mountain slopes, upland mesas, and benches. They occur at elevations ranging from 6500 to 8500 feet. The average annual precipitation varies from 16 to 20+ inches in this zone. The soils are moderately deep to deep. The surface is normally loamy in texture, varying from a very fine sandy loam to a loam and having a relatively high organic matter content. The sub-surface soil horizons are loamy to clayey in texture, varying from a heavy loam to silty clay and clay. Stone is quite prominant in some soils of this association. Some areas have as much as 50% stones in a soil profile. The soils of this association are developing from quite contrasting geologic materials. These materials include limestone, shales and sandstone.

#54: Argiustolls - Haploborolls Association

The major portion of this association consists of large areas making almost a large circle around the Piceance Creek Basin. Elevations range from about 6200 to 7800 feet. Annual precipitation ranges from 12 to 15 inches; about two-thirds occurs as winter snow. Summers are moderate, with a frost-free season 85 to 110 days. About 55% of the association consists of shallow to moderately deep, well drained, channery medium to moderately fine textured soils over shale. They are light in color, calcareous throughout, and low in organic matter content. About 35% of the association is made up of dominantly moderately deep to deep, well drained, soils with a thin dark surface layer. They also are channery - gravelly medium to moderately fine soils that are calcareous. The remaining 10% of the association is comprised of inclusions. They consist of areas of deep colluvial-alluvial soils of medium and moderately coarse textures with various amounts of gravel to stones; areas of Rock outcrops and shale bluffs, and areas of severe erosion or gullied land. This association is used principally for grazing and recreation. This is part of the main deer winter rangelands. These areas also contain the main oil shale formation as well as natural gas.

#55: Eutroboralfs - Rock outcrop - Haploborolls Association

The major portion of this association comprises the lower mountainous portion of the Piceance Creek Basin. Elevations range from about 6000 to 7500 feet. Annual precipitation ranges from 12 to 15 inches; about two-thirds occurs as winter snow. Summers are moderate, with a frost-free season of 90 to 120 days. About 45% of the association consists of shallow and moderately deep, well drained, calcareous, medium to fine textured soils with varying amounts of channery shale and sandstone. They are generally light colored throughout but may have dark surfaces. Twenty-five percent of the association is made up of Rock outcrop of shale and sandstone of the Bridger formation. Twenty percent of the association consists of moderately deep to deep, well drained, calcareous, gravelly cobbly medium and moderately coarse textured, light to dark colored colluvial and alluvial soils. There is 10% inclusions within the association. They consist mainly of areas that are saline-alkaline, have fluctuating watertables or are moderately deep reddish-brown, medium to moderately fine textured wind deposited soils. Small gullied areas are also found within this association. This association is used primarily for grazing and recreation. These areas are the main winter deer range. The area is also used for oil and natural gas production.

#59: Camborthids - Torriorthents - Haplargids Association

Soils of this association are derived mainly from shale or sandstone of the Williams Fork and Iles formations. Elevations range from 5600 to 6800 feet. Annual precipitation ranges from 10 to 15 inches, two-thirds occurring as winter snow. Summers are warm with a frost-free season of 110 to 140 days. About 45% fo the association consists of very shallow to moderately deep, well drained, gravelly to stony medium textured, calcareous, light colored soils over shale and fine sandstone. About 30% of the association consists of moderately deep to deep, well drained, medium to fine, silty, textured soils with varying amounts of rock fragments. They also are calcareous, light colored and often slight to moderate saline-alkaline in reaction. Another 15% of the association consists of moderately deep to deep medium to moderately fine textured, calcareous, reddish-brown wind deposited soils on the flatter mesas and uplands on northerly slopes. The remaining 10% of the association consists of inclusions. These are made up of Rock outcrops, highly saline-alkaline areas, gravelly-cobbly coarse textured outwash deposits, and gullied land areas. This association is used principally for grazing and wildlife range. These areas also are used for oil, natural gas, and coal production.

#64: Rock Outcrop Association

Elevations range from about 7000 to 8800 feet. Annual precipitation ranges from 15 to slightly over 20 inches, about two-thirds occurring as winter snow. Summers are cool and short with a frost-free season of 40 to 80 days at the lowest elevations. About 60% of the association consists of a multiple series of steep vertically uplifted fault rock materials. Shallow to deep, well drained soils with dark loamy, acid surface layers and brownish clayey subsoils, that are often cobbly or stony throughout, make up about 25% of the association. These soils occur under coniferous and aspen forested areas. They also have a vegetative surface litter and often have a lime zone below 40 inches. Depth to bedrock ranges from 10 to more than 60 inches. About 10% of the association consists of well drained, moderately deep to deep soils with dark loamy or stony loam surface layers and a brownish or reddish colored clayey subsoil. Depth to bedrock is more than 20 inches. There also are about 5% of other soil inclusions within the association. They consist of small outcroppings of Bentonite clay deposits, areas of deep, dark colored, gravelly and cobbly medium textured alluvial outwash soils as well as small areas with moderate to high saline-alkaline conditions and eroded gullied lands. This association is used primarily for grazing in accessible areas as well as being used by wildlife. The area also has a fairly good recreational and scenic value. There has been some mining of the Bentonite clay deposits for local area use. The timber areas are too small and inaccessible for timber production. The timber species common to the association are mainly pinon, Douglas fir, and engelman spruce in the higher elevations and juniper at the lower limits.

#82: Fluvents Association

Elevations range from 5000 to 5900 feet. Annual precipitation ranges from 8 to 12 inches, one-half occurring as snow. Most of this association is under irrigation. Summers are moderate to hot with a frost-free season of about 115 days on the east and up to about 160 days at the Utah State Line. About 30% of this association consists of deep and moderately deep, well drained to somewhat poorly drained, moderately fine to sandy soils. Medium and moderately fine textured soils will make up about 50% of these, the moderately coarse textured soils 30%, and the sandy soils 10%. Areas of these soils will have fluctuating watertables and may be saline-alkaline in reaction. Inclusions which make up about 10% of the association are wet, bog or marsh-like areas, coarse textured river gravel bars, and gravelly to stony medium to moderately coarse textured outwash materials as well as some small gullied areas. This association is used largely for hay production and irrigated pasture. Wildlife also use this for winter range and habitat. Cottonwood and willow is the dominant tree vegetation.

#92: Chipeta - Persayo - Badland Association

The soils of this association are derived almost entirely from the Mancos Shale formation. Elevations range from 5200 to 6000 feet. Annual precipitation ranges from 8 to 12 inches, two-thirds occurring as summer rains. Summers are moderately hot with a frost-free season of 130 to 150 days. About 85% of the association consists of very shallow and shallow, well drained, shaley moderately fine to fine saline-alkaline soils of the Chipeta and Persayo series. The Chipeta series will make up about 60% of the association and the Persayo about 25%. About 10% of the association consists of moderately deep to deep medium to fine textured, light colored soils that severely eroded into gullied land areas. The remaining 5% consists of inclusions. These are small areas of rock outcrop, deep, fine textured, highly saline-alkaline alluvial bottoms, and small areas of gravelly-cobbly outwash deposits on terrace breaks and fans. This association is used primarily for oil production. The area also has some limited grazing. Vegetation is very sparse

#93: Haplargids - Camborthids Association

Soils of this association are derived mainly from shale or sandstones of the Wasatch formation. Elevations range from 5500 to 6800 feet. Annual precipitation ranges from 12 to 15 inches, two-thirds occurring as winter snow. Summers are warm with a frost-free season of 100 to 130 days. About 60% of the association consists of shallow to moderately deep, well drained, light colored, loamy textured soils that are often gravelly to stony and calcareous throughout. They also may contain varying amounts of gypsum. About 30% of the association consists of moderately deep to deep, silty and loamy textured with scattered rock fragments. They also are calcareous and contain varying amounts of gypsum. The remaining 10% of the association consists of soil inclusions. They are made up with small areas of deep, dark, loamy alluvial soils of narrow valley bottoms, moderately deep to deep, loamy to fine sandy loam textured calcareous, reddish-brown Eolian deposited soils on the flatter mesas and upland terraces, areas with high saline-alkaline reaction, and areas of shaley badlands or rock outcrops and cliffs as well as some eroded gullied land spots. This association is used principally as grazing and wildlife range. Some natural gas wells also have been developed within these soil association units.

#96: Haplargids - Torriorthents - Rock outcrop Association

The soils of this association are derived mainly from shale and sandstone of the Mesa Verde formation. Elevations range from 5200 to 6200 feet. Annual precipitation ranges from 8 to 12 inches, two-thirds occurring as summer rains. Summers are moderately hot with a frost-free season of 120 to 145 days. About 40% of the association consists of shallow to deep, well drained, mediu- and moderately fine textured, often gravelly and cobbly, calcareous, light colored, moderately developed soils. About 30% of the association is moderately deep and deep, well drained to somewhat excessively drained, moderately fine to moderately coarse textured, calcareous, soils often with thin dark surfaces, from shale and fine sandstone. Another 20% of the association consists of Rock outcrops of shale and sandstone. The remaining 10% of the association is made up of inclusions. There are areas of saline-alkaline soils, coarse gravelly-cobbly outwash deposits, and areas of moderately deep to deep, medium textured wind deposited soils, as well as small severely eroded gullied areas. This association is used largely for grazing as well as coal and natural gas production.

#97: Cryoboroll - Haploboroll - Cryorthent Association

Cryoborolls make up about 55%, Haploborolls about 30%, Cryorthents about 10%, and minor soils about 5% of the association. Cryoborolls are deep, well drained, moderately steep soils with thin silty clay loam surface layers and silty clay subsoils. They overlie soft shale at a depth of 40 to 60 inches. The Haploborolls are moderately deep, well drained, moderately steep soils. They have loam surface layers and silty clay loam subsoils. Depth to shale is 20 to 40 inches. Cryorthents are shallow, well drained, moderately steep soils. They are clayey soils and overlie shale at a depth of 10 to 20 inches. Deep, poorly drained, clayey soils are included. They occupy nearly level to sloping drainageways. The area is used almost entirely as native rangeland.

#98: Cryoboralfs - Cryoborolls - Cryorthents Association

Elevations range from 8000 to 9000+ feet. Annual precipitation is above 20 inches, about three-fourths occurs as winter snow. Summers are short and cool with a frost free season of about 20 to 40 days. About 65% of this association consists of shallow to deep, will drained, slowly permeable soils occurring mainly under coniferous or aspen forest. They have surface litter, dark colored loam or stony loam, acid and leached surface layers and brownish or reddish colored clayey often stony subsoils. Depth to bedrock ranges from 10 to more than 40 inches. Slopes range from gently rolling to very steep. About 20 percent of the association consists of moderately deep to deep, well drained, medium to moderately coarse textured soils of open grassland parks or brushy slopes with a southern exposure. These soils are permeable, dark colored and occasionally have reddish colored moderately developed subsoils below 40 inches. Depth to bedrock is more than 20 inches. The association also contains about 10% of deep dark colored, wet, loamy soils along streams and in open swales. There is about 5% inclusions within the association consisting of areas with leached, acid surface in the open areas, soils with strong calcareous subsoils, and areas of rockland or rock outcrops. This association is the main watershed area for the White River. The area is used for timber production, grazing, recreation, and wildlife.

#99: Torriorthents - Rock outcrop Association

The soils of this association are derived mainly from the Greenriver shale formation. Elevations range from 5100 to 6400 feet. Annual precipitation ranges from 8 to 10 inches, two-thirds occurring as summer rains. Summers are moderately hot with a frost-free season of 120 to 150 days. About 80% of the association consists dominantly of very shallow to moderately deep with some deep, well drained to somewhat excessively drained, silty medium and moderately fine textured, gravelly or channery, calcareous, light colored soils. Fifteen percent of the association consists of Rock outcrop of steep cliffs and bluffs. The remaining 5% of the association consists of inclusions. These mainly are saline-alkaline areas, coarse gravelly-cobbly deposits and severely eroded gullied areas. This association is used largely for grazing and some wildlife habitats.

#100: Natrargids - Haplargids - Camborthids Association

This association is made up of approximately 45% Natrargids, 30% Haplargids, and 25% Camborthids. These soils occupy the gently sloping to steeply sloping mesas and benches. The average annual precipitation varies from 4 to 12 inches in this zone. The soils in this association are moderately deep to deep. The surface soil is normally loamy in texture, varying from a very fine sandy loam to a silty clay loam. The sub-surface soil horizons are finer textured, varying from a clay loam to clay. The soils of this association are relatively high in total soluble salts and high in pH value. The Natrargids have a high sodium salt content and are characterized by puddled soils and surface "slick spots." Some areas of this association are considered to be somewhat poorly drained and have a high seasonal watertable. A gravel and cobble strata in the Haplargids is commonly encountered at depths of below 30 inches. The soils of this association are developing from shale and sandstone derived alluvial materials.

#116: Haploboroll - Argiboroll Association

This association is made up of about 60% Haploborolls, 30% Argiborolls, and 10% minor soils or inclusions. These soils occupy the moderately steep to steep outwash slopes, terraces, and fans below the higher lying mountains and foothills. They occur at elevations ranging from 6000 to 7500 feet. The average annual precipitation varies from 15 to 18 inches. The Haploborolls consist of moderately deep to shallow, well drained, dark colored, moderately to slowly permeable soils. They have loam to clay loam surface layers overlying loam, clay loam or clay sub-surface layers. The soils are frequently stony, both on the surface and scattered throughout the profile. The depth to bedrock varies from <20 to 40 inches over semi-consolidated and consolidated bedrock. The Argiborolls consist of moderately deep and deep, well drained, dark colored, slowly permeable soils. These soils have loamy surface textures overlying clay loam to clay sub-surface layers. These soils are normally stone free and are 40 to 60 inches in depth overlying semi-consolidated and consolidated bedrock. The minor soils range from very shallow to deep, grayish to black in color and frequently occur in areas near rock outcrop exposures or in a drainway with a high watertable condition. The soils of this association are therefore quite variable in color, texture, and depth. The less sloping areas of this soil association are extensively irrigated. These areas are primarily used for hay, irrigated pasture, oats and some corn is grown for ensilage.

#130: Paleborolls - Cryoborolls Association

Elevations range from about 7000 to 8200 feet. Annual precipitation ranges from 15 to slightly over 20 inches, about three-fourths occurs as winter snows. Summers are cool and relatively short with a frost-free season of 35 to 60 days. About 50% of this association consists of deep to moderately deep, cobbly and stony soils mainly under oakbrush cover. They have dark loamy surface layers and reddish brown to brown clayey subsoils with a lime zone occurring below 20 inches. Shallow cobbly to stony, calcareous soils over shale or fine sandstone make up about 40% of the association. They will have dark loamy surface layers and light colored clayey subsoils. Depth to bedrock is less than 20 inches. About 10% of the association is made up of inclusions consisting mainly of small areas of very shallow clayey slicked off soil on decomposing shale, rockland and rock outcrop areas, as well as small severely eroded badland spots. This association is used principally for grazing, wildlife, recreation, with scattered small valley bottoms where water is available producing grass hay. Oil and natural gas production has been developed in part of the unit - north and east of the town of Meeker.

#132: Ustifluvents - Fluvaquents Association

These are the main drainage soils of the Piceance Basin. Elevations range from 5800 to 6500 feet. Annual precipitation ranges from 12 to 15 inches, two-thirds occurring as winter snow. Summers are moderate with a frost-free season of 95 to 125 days. About 70% of the association consists of deep and moderately deep, well drained to somewhat poorly drained, calcareous silty, medium to fine textured and generally saline-alkaline soils. They are usually light colored but may be dark. Twenty percent of the association consists of deep, poorly drained, moderately coarse to moderately fine textured, calcareous and generally saline-alkaline soils. They are light to dark in color. The remaining 10% of the association consists of inclusions. They are areas of non saline-alkaline alluvial soils, shallow and moderately deep colluvial gravelly to stony medium textured soils, as well as small areas of wet, highly alkaline soils and gullied land. This association is used principally as grass pasture and some hayland. This area is also used as a major portion of winter deer range.

#133: Ustorthents Association

Soils of this association are derived from shale and sandstone of the Williams Fork or Iles formation. Elevations range from about 5800 to 7000 feet. Annual precipitation ranges from 12 to 15 inches, about two-thirds occurring as winter snow. Summers are moderate, with a frost-free season of 100 to 125 days. About 90% of the association consists of shallow to deep well drained soil derived mainly from fine sandstone materials. They have thin dark surface layers, light colored subsoils, and are moderately fine to moderately coarse textured throughout with varying amounts of gravel and stone fragments. The remaining 10% of the association is comprised of inclusions. These consist of areas of rock outcrops, deep, sandy loam alluvial soils relatively free of stone fragments, small areas of moderately deep to deep reddish Eolian deposited soils. Also found are small areas of gullied lands or slicked off shale badlands. This association is used principally for grazing and wildlife range. Coal deposits are also found in this association.

#143: Camborthids - Argiborolls Association

Elevations range from 6400 to 7200 feet. Annual precipitation ranges from 15 to 20 inches, two-thirds occurring as winter snow. Summers are moderate with a frost-free season of 70 to 95 days. About 70% of the association consists of moderately deep to deep, well drained, moderately fine to fine textured soils over shale. They are grayish in color and generally calcareous throughout. Another 25% of the association consists of deep and moderately deep, well drained, medium and moderately fine textured alluvial bottoms that are often saline-alkaline. Small areas of poorly drained soils are also found. There are small areas of gravelly-stony colluvial soils on sloping to steep slopes and outwash fans. Small areas of very shallow soils on shale or raw shale outcrops are also scattered throughout the association. This association is used to produce dryland small grains as well as range for sheep, cattle, and wildlife.

Appendix Table 1. Site characteristics of selected soils found on the Little Hills Experiment Station.

Profile No.	Elevation	Physical Position	Ground Water	Slope	Aspect	Parent Material	Est. Annual Precip.	Internal Soil Drainage	Taxonomic Class. of Soils	Vegetation
(1)	6200	Alluvial fan	None	13%	North	Colluvial-alluvial from limey fine sandstone	13"	Rapid	Ustorthent	Pinon Juniper Serviceberry
(2)	6200	Mountain slope	None	65%	North	Reworked very limey sandstone	15"	Moderate	Typic Haplustoll	Pinon Juniper Serviceberry
(3)	6200	Mountain slope	None	65%	North	Reworked very limey sandstone	15"	Moderate	Typic Haplustoll	Pinon Juniper Serviceberry
(4)	6400	Narrow upland valley	None	9%	North	Limey reworked oil shale	14"	Moderate to rapid	Typic Haplustoll	Pinon Juniper Serviceberry
(5)	6800	Rolling upland	None	7%	North	Reworked limey oil shale	14"	Moderate	Lithic Argiustoll	Pinon Juniper Serviceberry
(6)	6800	Rolling upland	None	13%	North	Residual on Green-river shale	14"	Moderate	Lithic Ustorthent	Pinon Juniper
(7)	6800	Rolling upland	None	14%	North-east	Residuum on soft Bridger sandstone	14"	Moderate	Lithic Ustorthent	Pinon Juniper Serviceberry
(8)	6700	Mountain slope	None	50%	South	Greenriver shale	14"	Moderate	Lithic Ustorthent	Pinon Juniper Serviceberry

(continued)

Appendix Table 1. (continued)

Profile No.	Elevation	Physical Position	Ground Water	Slope	Aspect	Parent Material	Est. Annual Precip.	Internal Soil Drainage	Taxonomic Class. of Soils	Vegetation
(9)	6700	Mountain slope	None	45%	North	Greenriver shale	14"	Moderate	Lithic Haplustoll	Large Pinon Juniper Serviceberry Snowberry
(10)	6900	Gently sloping mesa	None	3%	Northwest	Limey shaley sandstone	14"	Moderate	Ustorthent	Pinon Juniper Serviceberry
(11)	6900	Gently sloping	None	3%	Northwest	Limey shaley sandstone	14"	Moderate to 36"	Aridic Argiustoll	Pinon Juniper Serviceberry
(12)	6900	Gently sloping mesa	None	5%	Northwest	Loess	14"	Moderate	Typic Camborthid	Sagebrush Grass
(13)	6800	Mountain slope	None	16%	North	Limey Bridger	14"	Moderate	Lithic Haplustoll	Pinon
(14)	7000	Upland valley	None	6%	North	Alluvium-sandy from Greenriver	15"	Moderate to rapid	Haplustoll	--
(15)	6300	Colluvial slope	None	13%	West	Colluvium from Bridger	13"	Moderate to rapid	Haplustoll	Sagebrush Needlebrush
(16)	6300	Mountain slope	None	60%	West	Fractured Bridger sandstone	13"	Rapid	Ustorthent	Pinon Juniper, some Serviceberry
(17)	6600	Mountain	Some ground water seep	95%	East	Bridger sandstone	15"	Moderate	Camborthid	Douglas Fir

Appendix Table 2. Some physical and morphological characteristics of selected soils on the Little Hills Experiment Station.

Profile No.	Hori-zon	Depth in Inches	Color (Moist)	Texture	Structure	pH Field Test	% Rock*
(1)	A_{11}	0-2½	Dark grayish brown	Gravelly sandy loam	Weak granular	8.4	32%
	A_{12}	2½-7½	Dark grayish brown	Gravelly sandy loam	Weak granular	8.8	52
	C_1	7½-11	Dark yellowish brown	Gravelly sandy loam	Weak subangular blocky	7.5	22
	C_2	11-19	Dark yellowish brown	Gravelly sandy loam	Massive	8.5	51
	C_3	19-26	Dark brown	Gravelly sandy loam	Massive	8.5	30
	C_4	26-33	Dark brown	Gravelly sandy loam	Massive	8.6	35
	C_5	33-40	Dark brown	Gravelly sandy loam	Massive	8.6	40
	C_6	40-60	Brown	Gravelly sandy loam	Massive	8.6	51
(2)	A_1	0-4	Dark yellowish brown	Gravelly loam	Weak granular	8.5	35%
	B_1	4-12	Dark yellowish brown	Gravelly loam	Weak subangular blocky	8.4	35
	C_1	12-15	Dark yellowish brown	Gravelly loam	Massive	8.4	35
	C_2	15-25	Yellowish brown	Very gravelly loam	Massive	8.6	55
	B_{1b}	25-40	Dark brown	Very gravelly loam	Weak subangular blocky	8.6	51
	C_{ca}	40-55	Yellowish brown	Loam	Weak subangular blocky	8.8	70
(3)	A_1	0-6	Very dark brown	Gravelly loam	Weak platy and granular	8.4	30%
	B_1	6-14	Brown	Gravelly sandy loam	Very weak sub-angular blocky	8.6	45

(continued)

Appendix Table 2. (continued)

Profile No.	Horizon	Depth in Inches	Color (Moist)	Texture	Structure	pH Field Test	% Rock*
(3) (con't)	B_2	14-32	Dark yellowish brown	Very gravelly	Very weak subangular blocky	8.6	55%
	C_{ca}	32-46	Dark brown	Very gravelly sandy loam	Very weak subangular blocky	8.4	70
	IIB_{1b}	46-55	Dark brown	Very stony sandy loam	Very weak subangular blocky	8.6	70
(4)	A_{11}	0-6	Dark brown	Loam	Weak platy and granular	8.3	5%
	A_{12}	6-10	Dark grayish brown	Very fine gravelly sandy loam	Weak subangular blocky	8.3	55
	B_{11}	10-16	Dark grayish brown	Gravelly loam	Weak subangular blocky	8.3	60
	B_{12}	16-31	Very dark grayish brown	Sandy loam	Weak subangular blocky	8.3	40
	C_{1ca}	31-55	Very dark grayish brown	Gravelly sandy loam	Weak subangular blocky	8.3	49
	C_{2ca}	55-60	Very dark grayish brown	Gravelly sandy loam	Massive	8.4	45
(5)	A_1	0-5	Very dark grayish brown	Loam	Weak platy and granular	8.3	30%
	B_1	5-10	Very dark grayish brown	Loam	Weak subangular blocky	8.3	30
	B_2	10-23	Very dark grayish brown	Loam	Weak subangular blocky	8.3	30
	C_1	23-25	Very dark grayish brown	Loam	Weak subangular blocky	8.4	60

(continued)

Appendix Table 2. (continued)

Profile No.	Horizon	Depth in Inches	Color (Moist)	Texture	Structure	pH Field Test	% Rock*
(5) (con't)	R	25+	Very dark grayish brown	Loam	Weak subangular blocky	8.3	Bedrock
(6)	A_1	0-5	Very dark grayish brown	Gritty loam	Very weak granular	8.4	25%
	C_1	5-12	Brownish yellow	Coarse gravelly loam	Weak subangular blocky	8.6	75
	C_2	12-18	Brownish yellow	Coarse gravelly loam	Weak subangular blocky	8.6	80
	R	18+	Brownish yellow	Consolidated bedrock	Massive	---	--
(7)	A_1	0-6	Dark yellowish brown	Very stony sandy loam	Weak granular	8.4	55%
	C_1	6-13	---	Fractured sandstone	Fractured rock	---	95
	R	13+	---	Bedrock	Bedrock	---	99
(8)	A_1	0-4	Grayish brown	Stony loam	Very weak granular	8.3	60%
	R	4+	---	Solid shale	Bedrock	8.6	--
(9)	01	1-0	. . . . Loose pine needles.				
	A_{11}	0-5	Very dark brown	Gritty loam	Very weak platy and granular	6.8	30%
	A_{12}	5-9	Dark brown	Gritty loam	Weak subangular blocky	6.8	45
	B_{21}	9-13	Dark yellowish brown	Gravelly loam	Weak subangular blocky	6.8	40

(continued)

Appendix Table 2. (continued)

Profile No.	Horizon	Depth in Inches	Color (Moist)	Texture	Sturcture	pH Field Test	% Rock*
(9) (con't)	B_{22}	13-19	Very dark grayish brown	Gravelly loam	Weak subangular blocky	8.4	65%
	R	19+	---	Fractured shaley limestone	Fractured rock	---	--
(10)	A_1	0-3	Dark brown	Stony loam	Weak platy and granular	8.0	55%
	C_1	3-11	Dark grayish brown	Very stony loam	Very weak subangular blocky	8.2	80
	R	11+	---	Sandy shale	Bedrock	---	--
(11)	A_1	0-7	Dark brown	Gravelly loam	Weak platy and granular	7.6	5%
	B_{2t}	7-14	Brown	Clay loam	Moderate subangular blocky	7.8	5
	B_{3ca}	14-24	Brown	Silt loam	Weak subangular blocky	8.2	10
	C_1	24-35	Brown	Gritty loam	Massive	8.2	20
	R	35+	---	Bedrock	Bedrock	---	--
(12)	A_1	0-3	Dark brown	Loam	Weak platy and granular	8.2	None
	B_{21}	3-10	Dark brown	Clay loam	Weak subangular blocky	8.2	None
	B_{22}	10-25	Dark brown	Silt loam	Weak subangular blocky	8.4	None
	C_{ca}	25-29	Dark brown	Silt loam	Weak subangular blocky	8.4	None

(continued)

Appendix Table 2. (continued)

Profile No.	Hori- zon	Depth in Inches	Color (Moist)	Texture	Structure	pH Field Test	% Rock*
(12) (con't)	C_1	29-55	Dark brown	Silt loam	Weak subangular blocky	8.6	None
	C_2	55+	Dark brown	Silt loam	Loose	---	None
(13)	A_1	0-3	Dark brown	Stony loam	Weak platy and granular	8.0	55%
	C_1	3-11	Dark grayish brown	Very stony loam	Very weak sub-angular	8.2	80
	R	11+	---	Sandy shale	Bedrock	---	--
(14)	A_{11}	0-2	Very dark grayish brown	Gritty loam	Very weak platy and granular	8.3	35%
	A_{12}	2-7	Very dark grayish brown	Gritty	Weak subangular blocky	8.0	5
	B_2	7-27	Very dark grayish brown	Loam	Moderate sub-angular blocky	8.0	20
	A_{1b}	27-40	Very dark brown	Loam	Weak subangular blocky	8.0	35
	C_1	40-58	Very dark grayish brown	Gravelly loam	Weak subangular blocky	8.0	25
	C_{cab}	58-65	Dark grayish brown	Gravelly loam	Moderate sub-angular	8.0	40
(15)	A_{11}	0-7	Very dark grayish brown	Sandy loam	Weak granular	8.0	20%
	A_{12}	7-14	Dark brown	Sandy loam	Weak granular	8.0	15
	B_{21}	14-19	DArk brown	Sandy loam	Weak subangular blocky	8.2	20

(continued)

Appendix Table 2. (continued)

Profile No.	Hori-zon	Depth in Inches	Color (Moist)	Texture	Structure	pH Field Test	% Rock*
(15) (con't)	B_{22}	19-27	Dark yellowish brown	Sandy loam	Weak subangular blocky	8.4	20%
	C_{ca}	27-58	Dark brown	Loam	Weak subangular blocky	8.4	24
	C_1	58-60	Dark brown	Sandy loam	Massive	8.6	30
(16)	A_1	0-3	Dark yellowish brown	Stony sandy loam	Very weak platy and granular	8.2	45%
	C_1	3-10	Brown	Very stony sandy loam	Massive	8.2	75
	C_2	10-24	Brown	Very stony loam	Massive	8.4	90
	C_3	24-36	Brown	Very stony loam	Massive	8.4	85
(17)	01	1-0	. . . . Organic layer			8.4	--
	A_1	0-3	Very dark brown	Gritty loam	Moderate granular	8.6	35%
	A_2	3-6	Yellowish brown	Sandy clay loam	Single grain	8.6	55
	B_2	6-16	Dark yellowish brown	Silt loam	Weak subangular blocky	8.6	60
	C_1	16-23	Dark yellowish brown	Stony clay loam	Massive	8.4	60
	C_2	23-34	Dark yellowish brown	Stony clay loam	Massive	8.4	70

*Rock content consists mostly of flat gravels.

Appendix Table 3. Site characteristics of selected soils in the oil shale study area.

Profile No.	Elevation	Physical Position	Slope	Aspect	Parent Material
1.	7,000	Upland	5%	NE	Limestone
1A.	7,000	Upland	5%	NE	Limestone
2.	7,000	Ridgetop	5%	S	Sandstone
3.	7,000	Upland	20%	S	Limestone
4.	7,000	Upland	10%	S	Limestone
5.	7,000	Upland	10%	S	Limestone
6.	6,000	Flood-	5%	SE	Alluvium
6A.	6,000	plain	5%	SE	Alluvium
6B.	6,000		55%	SE	Alluvium
7.	7,000	Upland	25%	E	Limestone
8.*	8,500	Upland	5%	NE	Sandstone
8A.	8,500	Upland	5%	NE	Sandstone

*This soil appears to be typical of the soils on the Divide between the Piceance Basin and the Colorado River.

Appendix Table 4. Chemical and physical properties of selected soils in the oil shale study area.

Profile No.	Soil Depth	Vege-tation	pH	Conductivity mmhos/om^3	% Lime	Texture	Location
1.	0- 7"	Big Sage	7.6	0.41	2.0	Silty	T1S, R99W
1A.	7-14"	Big Sage	7.9	0.38	1.7	clay	Sec. 32
						loam	
2.	0-14"	Pinon Juniper	7.0	0.33	0.6	Clay* loam	T1S, R99W Sec. 32
3.	0- 8"	Pinon	8.0	1.00	32.0	Clay loam	T1S, R99W Sec. 32
4.	0-10"	Bare	8.3	0.80	41.8	Silt loam	T1S, R97W Sec. 33
5.	0-10"	Pinon	8.2	0.80	35.6	Silt loam	T1S, R97W Sec. 33
6.	0- 6"	Big Sage	8.3	1.00	22.5	Fine	T2S, R97W
6A.	6-12"	Big Sage	8.4	1.00	16.6	sandy	Sec. 28
6B.	12-18"	Big Sage	8.3	1.60	17.1	loam	
7.	0- 8"	---	8.1	1.00	8.6	Silt loam	T4S, R95W Sec. 18
8.	0- 6"	---	6.5	0.70	1.7	Sandy loam	T6S, R95W Sec. 29
8A.	6-13" bedrock at 13"	---	6.5	0.70	1.0	Silt loam	T6S, R95W Sec. 29

*80% of surface covered with sandstone fragments.

Appendix Table 5. Names of soil associations found in the oil shale study area listed by association number (taxonomic and descriptive names are included).

No.	Name of Association	Description
49	Cryoboralfs - Rock outcrop	Cold, deep to shallow, well drained, gently sloping to steep soils and rock outcrop and rock slides on high mountain slopes.
50	Cryoborolls - Cryoboralfs	Cold, moderately deep and deep, well drained, moderately steep and steep soils on mountain slopes.
52	Argiborolls - Haploborolls	Cool, dominantly deep and moderately deep, well drained, moderately steep and steep soils on mountain slopes.
53	Argiborolls - Cryoborolls	Cool and cold, deep and moderately deep, well drained, sloping to steep soils on upland mesas and benches.
54	Argiustolls - Haploborolls	Cool, dominantly moderately deep and deep, well drained, sloping to steep soils on mountain slopes.
55	Eutroboralfs - Rock outcrop - Haploborolls	Cool, shallow and moderately deep, well drained, steep soils and rock outcrop on mountain slopes.
59	Camborthids - Torriorthents - Haplargids	Warm, dominantly shallow, well drained, steep soils on hills, breaks, and canyons.
64	Rock outcrop	Rock outcrop and cold, very shallow and shallow, somewhat excessively drained, steep and very steep soils on mountain slopes.
82	Fluvents	Warm, deep, well drained, nearly level soils on flood plains and low terraces.
92	Chipeta - Persayo - Badlands	Warm, shallow, well drained, gently sloping to steep soils and shale outcrop on upland breaks.
93	Haplargids - Camborthids	Warm, deep, well drained, nearly level and gently sloping soils on mesas and terraces.

(Continued)

Appendix Table 5. Continued.

No.	Name of Association	Description
96	Haplargids - Torriorthents - Rock outcrop	Warm, deep to shallow, well drained, gently sloping to moderately steep soils and rock outcrop on mesas, benches, and canyons.
97	Cryoborolls - Haploborolls - Cryorthents	Cold and cool, deep to shallow, well drained, gently sloping to steep soils on benches and mountain slopes.
98	Cryoboralfs - Cryoborolls - Cryorthents	Cold, deep to shallow, well drained, sloping to steep soils on mountain slopes and mesas.
99	Torriorthents - Rock outcrop	Warm, shallow, well drained, sloping to steep soils and rock outcrop on breaks and canyons.
100	Natrargids - Haplargids - Camborthids	Warm, deep and moderately deep, well drained, gently sloping to moderately steep soils on mesas and benches.
116	Haploborolls - Argiborolls	Cool, moderately deep and deep, well drained, moderately steep and steep soils on colluvial - alluvial slopes, terraces and fans.
130	Paleborolls - Cryoborolls	Cool and cold, deep to shallow, well drained, sloping to steep soils on mountain slopes.
132	Ustifluvents - Fluvaquents	Cool, deep, well to poorly drained, nearly level and gently sloping soils on flood plains and low terraces.
133	Ustorthents	Cool, shallow and moderately deep, well drained, moderately steep and steep soils on mesas and breaks.
143	Camborthids - Argiborolls	Cool, deep and moderately deep, well drained, gently sloping to moderately steep soils on uplands and in valleys.

Chapter 6

CHARACTERISTICS OF SPENT SHALE WHICH INFLUENCE WATER QUALITY, SEDIMENTATION AND PLANT GROWTH MEDIUM

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INTRODUCTION

The development of an oil shale industry in the Piceance Basin will require the disposal and stabilization of spent shale and overburden spoils at a scale unprecedented in the history of mining. As estimated in this chapter, a projected 250,000 barrel per day industry will produce more than 100 million tons or about 80 million cubic yards of spent shale per year. Utilizing the proposed disposal sites, approximately 5500 acres of spent shale material will require stabilization during a twenty year period.

The magnitude of the spent shale disposal problem indicates that the nature of the spent shale material must be thoroughly evaluated to permit safe disposal pile design, efficient yet permanent stabilization, and minimize environmental problems. The objective of this chapter is to identify the physical, chemical, and hydrological characteristics of spent shale materials derived from current retorting processes. Emphasis is placed on identifying potential problems in stabilizing spent shale piles including potential erosion and leaching problems, and a consideration of spent shale as a plant growth medium.

PHYSICAL, CHEMICAL, AND HYDROLOGICAL CHARACTERISTICS OF SPENT SHALE

Spent Shale

The solid wastes from the oil shale retorting processes have been called spent shale, burned shales, shale ash, processed shale, retort ash, retorted shales, waste products, and similar names. Spent shale in this report will be used as generic term for the solid waste products generated by retorting oil shales. Where important, spent shales will be identified by the retorting process used, for example, TOSCO II spent shales. Although the spent shales from pilot and experimental plants have been characterized, the precise nature of spent shales from commercial plants is unknown. From studies of existing spent shales it is known that spent shale characteristics will vary with the mineral content of the raw oil shale, the temperature at which the shales were retorted, and the nature of the retorting process.

Many retorting processes have been patented in the last century, but only a few processes are presently considered to be candidates for commercial use. Three of these, the TOSCO, the Union Oil Underfeed Retort, and the Bureau of Mines Gas-Combustion Process, are considered the most likely methods for first generation retorting plants. The in-situ method has also been extensively studied and may ultimately become a commercial method. A fourth method, the paraho method, will be tested at the USBM plant at Anvil Point in the near future. This method is a modification of a limestone kiln process.

All retorting processes have one fundamental characteristic--they heat the oil shale until the organic matter is vaporized. This pyrolysis temperature, which ranges from 800° to 1000°F, is the only practical means known for producing shale oil (Schramm, 1970). The products are shale oil, some gases, and spent shale.

TOSCO Process

A semiworks 1,000 tons per day unit was operated on Parachute Creek near Grand Valley, Colorado from 1965-1967 and again in 1971-1972. This plant achieved rates of 3,000 tons per day in 1972. The essential feature of the TOSCO II process is the solid to solid heat transfer which is accomplished by preheated (1200°F) ceramic balls. Finely crushed oil shale is preheated in a dilute phase fluidized bed, then fed continuously into a horizontal rotation kiln along with previously heated ceramic balls. The balls and shale equilibrate at a temperature above 900°F which is adequate to cause thermal decomposition of the organic matter in the oil shale without burning. The vapors are condensed and fractionate into gas, naptha, oil, and heavy residuum. The balls are recovered by passing the kiln discharge over a trommel screen and are reheated and recycled. The spent shale is routed to disposal by a screw conveyor. Specific reports on the TOSCO process are Lenhart (1969) and Hutchins, Kreck, and Legatski (1971).

A significant advantage of this process is the ability to retort fine particles. Shale feed for the TOSCO II process is crushed to less than 1/2 inch size. All of the TOSCO spent shales are finer than 1/2 inch and 85 percent or more are smaller than 2 mm in diameter. Processed shale from the TOSCO II process has a bulk density of about 70 lbs./ft^3. When processing 35 gal/ton oil shale, the spent shale is 81 percent by weight of the raw shale feed (Spec. Comm. of Gov's. Oil Shale Adv. Comm., 1971).

Union Oil Company Underfeed Retort

A demonstration plant was operated from 1955-1956 at the confluence of the forks of Parachute Creek and reached a maximum of 1,200 tons of shale per day. The Union Oil Company process uses internal combustion heating in a continuous vertical refractory-lined retort, which is underfed with shale, and has a downward-flow of air and combustion gases (Carver, 1964). The unique feature of this retort is a "rock pump" used to push the shale upward into the bottom of the retort. As the shale is pumped upward, it is heated by hot gases pulled down past the rock by blowers. These hot gases result from the burning of residual carbon from the spent shale at the top of the retort and have temperatures of approximately 2000°F (Berg, 1956). After heating the incoming oil shale to the retorting temperatures and being cooled in the process, the gases along with the shale oil condensed on the cool incoming shale are withdrawn from the bottom of the retort. The spent shale at the top continues upward and becomes shale ash as the residual carbon is burned off. The spent shale in the form of a clinkered ash spills over a disposal chute at the top of the retort, and is cooled by the cold air drawn into the chute.

The Union Oil Company retort has a tolerance for fine particles, but a small percentage of the feed must be removed and disposed of with the spent shale. Spent shale residue amounts to 62.8 percent by weight of the raw shale feed (Berg, 1956). Most of the material is smaller than 10 inches and has a bulk density of approximately 70 lbs./ft^3 (Spec. Comm. of Gov's Oil Shale Adv. Comm., 1971).

Bureau of Mines Gas-Combustion Process

The research on this process was carried to the point of showing that it had possible commercial applications during the early 1950's at Anvil Points near Rifle, Colorado. Additional work by the Colorado School of Mines Research Foundation was conducted from 1964 to 1968. In this process all heat exchange takes place in the refractory-lined retort with the crushed shale flowing down while the gas rises through the shale bed. Combustion of part of the product gases and some residual carbon on the spent shale provides heat for retorting. Matzick et al. (1966) notes that the carbonate decomposition tends to limit the maximum shale temperatures to about 1600°F, several hundred degrees below the fusion temperature of the mineral portion of the shales.

The gas combustion process works best on materials in the one-to-three-inch particle size and has a low tolerance for fine materials. Therefore, plans for utilizing this process might include a briquetting plant for materials of less than 3/16 inch in diameter. The briquetting plant could utilize shale oil as the binding material. The waste products at the Anvil Points plant are pilot research results and include large clinkers and unretorted or partially retorted oil shale from unsuccessful runs. Specific reports on the gas-combustion process include Matzick et al. (1966), Ruark et al. (1969), and Ruark et al. (1971).

The processed shale from the Bureau of Mines gas combustion process consists of a soft friable material with small rocks less than three inches in diameter in a matrix of soil sized particles. The bulk density of the spent shale ranges from 60 to 80 lbs./ft^3, and amounts to 75 to 80 percent by weight of the raw shale feed (Spec. Comm. of Gov's. Oil Shale Adv. Comm., 1971).

Physical Characteristics of Spent Shale

TOSCO II Process

The physical characteristics of the TOSCO II process, as determined from pilot plant residues, are summarized in Table 1. Of particular significance is the large proportion of silt sized particles in the material.

Culbertson, Nevens, and Hollingshead (1970) investigated the physical characteristics of shale from the Colony Mine below the Mahogany Marker as retorted in the TOSCO pilot plant and shale from above the Mahogany Marker at the Bureau of Mines plant retorted at 932°F. The particle size analysis used only a Tyler screen sieve analysis so the particle size can only be generalized, but the indications are that their samples had a much larger mean particle size than the TOSCO materials analyzed by Ward et al. (1971). The summarized results of particle size found by Culbertson et al. are as follows:

Particle Size	TOSCO Sample Above Marker	Sample Below Marker
	Weight %	Weight %
>2.38 mm	12.1	9.6
2.38 - .053 mm (Sand)	54.2	44.4
< .053 mm (Silt & Clay)	33.7	46.0

Table 1. Summary of Physical Characteristics, TOSCO II Process

Physical Characteristics	Schmehl and McCaslin (1973) Ave. of 3 Samples	Ward, Margheim and Lof (1971)
Particle Size		
>8 mm	0.0%	0.0%
2-8 mm	14.0%	0.0%[2]
<2 mm	86.0%	100.0%[2]
2.0 - .05 mm (Sand)	12.1%[1]	31.7%[2]
.05 - .002 mm (Silt)	60.0%[1]	68.3%
<.002 mm (Clay)	13.9%[1]	0.0%
Maximum size particle		<0.476 cm
Minimum size particle		>0.00077 cm
Solids density		2.49 g/cc
Bulk density		1.30 g/cc
Porosity		0.47
Permeability		2.50×10^{-10} cm^2
Field Moisture capacity	20.4% H_2O	
Saturation moisture content (by weight)		0.38
Saturation moisture content (by volume)		0.47

[1] Data obtained by special analysis of two of the original samples -- Agronomy Department, CSU, October 18, 1972.

[2] Approximate conversion from sieve sizes to USDA soil separates.

Union Oil Company Process

Ward et al. (1971) listed the physical properties of a sample of Union Oil Company oil shale residues as follows:

Physical Properties

Bulk density	1.80 g/cc
Solids density	2.71 g/cc
Porosity	0.33

USBM Gas Combustion Process

Some of the physical properties of spent shale residues from the Anvil Points pilot Gas-Combustion Process are summarized in Table 2.

Table 2. Summary of Physical Characteristics, USBM Gas Combustion Process

Physical Properties	Schmehl and McCaslin (1973) Ave. of 3 Samples	Ward, Margheim and Lof (1971)
Particle Size		
>8 mm	34.3%	34.2%[2]
2-8 mm	27.0%	22.3%[2]
<2 mm	38.7%	43.5%[2]
2.0 - .05 mm (Sand)	17.0%[1]	36.1%
.05 - .002 mm (Silt)	15.6%[1]	7.4%
<.002 mm (Clay)	6.1%[1]	0.0%
Maximum size particle		< 3.81
Minimum size particle		> .00077
Solids density		2.46 g/cc
Porosity		0.41
Bulk density		1.44 g/cc
Permeability		3.46×10^{-9} cm^2
Field Moisture capacity (<2 mm fraction)	19.8% H_2O	

[1] Data obtained by special analysis of original samples--Agronomy Department, CSU, October, 1972.

[2] Approximate conversion from sieve sizes to USDA soil separates.

Other Retorting Processes

Information is not available as to the physical properties of spent shale from other retorting processes such as the Petrosix Process (Cameron, 1965), which is similar to the gas combustion process except that a separate furnace heats a stream of circulating gas.

Color of Spent Shales

The color of spent shales ranges from a buff, or light yellow, to black depending on the amount of carbon remaining. Schmehl and McCaslin (1973) mention that spent shales may cause lethal temperatures for germinating seeds, because unshaded spent shale in a glass house reached temperatures of 140 to 150°F at about one-half inch depth. They recommended a light-colored surface mulch until the surface is shaded by plants.

Ward et al. (1972) reported that temperatures within the TOSCO spent shale piles remained relatively constant at 20-24°C (68-75°F), throughout the duration of the rainfall experiment, but the dark color of the spent shales caused surface temperatures of 77°C (170°F), which would have been lethal to germinating seeds.

Hydrologic Characteristics of Spent Shale

Compaction and Stabilization of Spent Shale

Disposal of spent shale and other waste products from a single commercial scale 50,000 bbl/cd oil shale industry amounts to 52,700 tons/cd and is a major undertaking. Even with maximum compaction (100 lbs /ft^3) this amount of waste material required 14,240,000 cubic yards, or 8,827 acre-feet, of disposal area annually.[1] Culbertson, Nevens, and Hollingshead (1970) comment that it is very unlikely that any group of products could be developed to utilize the spent shale from even a single commercial sized oil shale plant.

As noted in previous sections, the dry processed shale from most retorting processes weighs about 70 lbs /ft ^{3}. Compaction to 100 lbs /ft ^{3} has the obvious advantage of reducing the volume to 70 percent of the initial volume. It also has the additional advantages of reducing the permeability and erodibility of the spent shales.

A Special Committee of the Governor's Oil Shale Advisory Committee (1971) reported that:

> "With 10 weight percent water, and a practical level of compaction, the dry density (excluding the weight of water) can be increased to the range of 85 to 90 pounds per cubic foot. With an increase in water content to 20 percent, the optimum for achieving high compacted density, and with intensive compactive effort, a dry density of close to 100 pounds per cubic foot can be obtained."

The U.S. Department of Interior (1973) estimated 20 percent by weight water requirements for compaction but did not specify the degree of compaction attainable other than to show it as the basis for table preparation. For slurry deposited fills, they indicate the slurry could contain 50 percent solids and that with time the material would dewater to 70 to 80 percent solids and be relatively stable. For slurry deposited fills behind dams, the USDI (1973) estimates that:

> "The moisture content of the processed shale in the dam should reduce to about 20 percent by weight or less through drainage and desiccation. Compaction to a dry density of about 90 pounds per cubic foot could be reached."

Non-Wetability of Spent Shales

Both Ward et al. (1971) and Schmehl and McCaslin (1973) commented on the

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[1] Calculation based on TOSCO II process retorting 35 gal/ton oil shale with 100 percent of Fischer assay recovery, and spent shale 81 percent by weight of raw shale.

resistance to wetting of the TOSCO II spent shale. Schmehl and McCaslin (1973) found they could wet the spent shale by stirring in water and that once wetted it would rewet. Ward and Reinecke (1972) reported:

> "...freshly placed oil shale residue (TOSCO) is fairly hydrophobic. When contacted with water for a long period of time, however, percolation into the residue bed will begin to occur. Once saturated and redried, it will immediately become saturated again when contacted with water unless its capillary structure is disturbed. If the capillary structure is disturbed, it will again be hydrophobic."

A modification on the TOSCO II process at the Parachute Canyon experimental plant results in a moistened spent shale which eliminates the initial wetability problems outlined above.

Schmehl and McCaslin (1973) reported that they encountered no difficulty in wetting USBM gas combustion process spent shale. However, the samples they worked with had been exposed for some time and the wetability of the fresh residue needs to be tested.

A possible analogy to the non-wetability of some spent shales may be the non-wettable soils sometimes found in wildland areas in most states of the western United States and also reported in Florida, New Zealand, and Australia (DeBano et al. 1967). The non-wetability is apparently associated with organic matter and the non-wettable region may be in or on the soil surface (Scholl, 1971) or deeper in the profile (DeBano et al. 1967). In the latter case, the water repellency is apparently induced by organics volatilized during wildfires and condensed on cooler soil deeper in the profile. DeBano et al. (1967) report that non-wetability can be found on both burned and unburned watershed areas, but that it is more pronounced on burned areas.

DeBano (1966) induced non-wetability in a soil by burning <u>Ceanothus crassifolius</u> (a shrub) litter over it in a container that was heated from the top. Non-wetability was shown to be a function of temperature and period of exposure to the temperature by DeBano et al. (1967), whose data indicate non-wetability was destroyed after 10 to 15 minutes exposure at 800 to 900°F. However, non-wetability was increased when the exposure was for a shorter period of time.

An increasing resistance to wetting of water repellent soils was reported by Scholl (1971) as the soil water content decreased from near field capacity to the wilting point. When the soil became even drier, the wetability increased. This was believed to be caused by cracking of clays. DeBano (1969) found that wetability of a water repellent soil increased with decreasing soil moisture content.

Non-wettable soils may or may not have an analogy in spent shales produced by certain retorting processes. However, investigations on the rewetability of spent shales after drying and disturbance appear to be needed in view of the conflicting reports of Schmehl and McCaslin (1973) and Ward and Reinecke (1972), and the importance of rewetting in infiltration and runoff relationships if spent shale is used as a plant growth medium.

Water Relationships of Spent Shale

The water relationships of spent shale stabilization and revegetation, or pollution potential, has only recently received any attention by researchers. The water relationships of spent shale disposal are also highly related to the retorting and disposal method utilized, and considerable research is needed to define the minimum water requirements for achieving compaction and stabilization with vegetation.

Water holding capacity of spent shales: The water holding capacity of soils or soil-like materials is complex, but the principal factors are texture, structure, and organic matter content. Since spent shale initially has no structure, and the organic matter content is in a form of carbonaceous material on the surface of the individual particles, the most important factor to water holding capacity is particle size. If the soil size materials are defined as particles of less than 2 millimeters, the range for spent shales would be from approximately 25 to 100 percent of the total volume of spent shale depending upon the retorting method used.

For the Bureau of Mines Gas-Combustion Process, Schmehl and McCaslin (1973) reported ranges of from 24 to 48 percent soil size materials, and Ward et al. (1971) reported an average of 43 percent soil size particles. But these samplings obviously did not include any of the large clinkers found in the waste piles at the Bureau of Mines Anvil Points experimental retort facility. The TOSCO type spent shales are much more uniform and Schmehl and McCaslin (1973) reported 80 to 89 percent soil size materials. Ward et al. (1971) in a sieve analysis of TOSCO spent shale residues indicated that 100 percent of the materials passed through a No. 8 U.S. Standard Sieve (2.38 mm), which would indicate all soil size materials.

Utilizing the soil textural triangle (U.S. Department of Agriculture) the fines in spent shale would be classed as a silt loam. Haugan (1967) found that wet shale ash is non-plastic and similar to loess.

Ward et al. (1971) listed the saturation moisture capacity as 38 percent by weight and 47 percent by volume for the TOSCO spent shale residue with a bulk density of 1.30 g/cc. In the subsequent snow experiments on spent shale piles, Ward and Reinecke (1972) found that the compaction of surface layers was reduced to 1.20 g/cc and the saturation moisture content was reduced to 43 percent by volume (approximately 36 percent by weight).

Schmehl and McCaslin (1973) reported field moisture capacities ranging from 18.5 to 22.2 percent water for TOSCO process spent shales and from 18.8 to 22.1 percent for the <2 mm fraction of spent shale materials from the gas combustion process. Since medium textured soils generally have field capacities of about one-half the saturation percentage, the results agree.

If these limited results are compared with moisture constants for silt loam soils, the saturation moisture contents are average; but the field moisture capacity of some samples would be less than the one standard deviation range of from 20.6 to 35.4 percent by weight reported by Broadfoot and Burke (1958). This is consistent with the lack of organic matter, structure, and clay size particles in spent shale.

Infiltration and percolation characteristics: Infiltration, or the intake of water into the soil surface, is highly related to the subsequent percolation, or downward movement through the material. The infiltration capacity cannot exceed percolation capacity, since no more water can enter than is being moved through the profile. Only a small amount of information is available on the percolation and infiltration rates of spent shale material.

Ward et al. (1971), working with TOSCO II spent shales not previously wetted, reported rainfall study permeabilities of 3.46 x 10^{-9} cm^2 for U.S. Bureau of Mines, and 2.5 x 10^{-10} cm^2 for TOSCO spent shales. In the subsequent snowmelt studies, Ward and Reinecke (1972) reported TOSCO spent shales as having permeabilities of 4 x 10^{-10} cm^2. If this intrinsic permeability is converted to mm/hr for water at 20°C (68°F) (Todd, 1964), the equivalent permeability rates would be 12.7 mm/hr for USBM and between 1 and 1.5 mm/hr for TOSCO spent shales.

Infiltration studies by Gifford on TOSCO II spent shale piles (about four months old) with slopes of 19-23° had infiltration rates at the end of thirty minutes of approximately 1.5 inches (38 mm) per hour. In the same study, spent shale piles (nine months old) with one hundred percent grass cover and 22-25 percent initial soil moisture had infiltration rates at the end of thirty minutes in the range of 1.28 to 1.82 inches per hour (33 to 46 mm/hr).

Meiman (1973)[1/] reported average infiltration rates for one-hour periods on a number of spent shale types and conditions. One-hour infiltration for the old USBM Anvil Points spent shale pile was approximately 3-4 cm/hr (1.2 - 1.6 in/hr). One-hour infiltration on the TOSCO II spent shales varied according to the surface moisture conditions. Spent shales with moist surfaces or mulch covers had rates of 2 to 2.5 cm/hr (0.8-1.0 in/hr) while spent shales which had been allowed to dry and become salty with an exposed surface, approached zero infiltration rates.

Rauzi et al. (1968) reported infiltration rates of from 0.95 to 1.17 inches per hour during the second thirty minutes for silt loam soils under range in poor and fair condition, whereas infiltration rates were nearly doubled under good range conditions. They concluded that the total weight of vegetal cover was more important than texture, structure, or percent of bare ground exposed in influencing infiltration rates. A gravel mulch has also been shown to greatly influence infiltration rates and decrease runoff and erosion rates. Kincaid et al. (1964), working in semi-arid areas of varying cover density, found the percent gravel content, both on the surface and for the top one-fourth inch of soil, to be directly related to infiltration rates when vegetative cover was absent or sparse. A three-year study in Texas concluded that surface covers of straw (two inches) or gravel (one inch) increased water intake and essentially eliminated erosion (Adams, 1966).

Erodibility of Spent Shales

Natural sediments are the products of disintegration or decomposition, or both, of mineral rock. Physical properties of sediments depend on a number of factors such as the composition of the parent rock, texture and structure of the original formation, topography, type of weathering, and climatic factors. The mining, crushing, and retorting of large quantities of oil shale can be

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[1/] Personal communication

viewed as a tremendous acceleration of this process that, in effect, is producing 58,960 tons (38.7 acre-feet at 70 lb/ft^3) 50,000 bbl/cd) of potential sediment per day for each commercial oil shale plant (USDI, 1973). Therefore, the potential for accelerated erosion is obvious, much of the spent shale material will be of the readily eroded soil-size particles of less than 2 mm.

The erosion potential of man-made spent shale piles is as yet undefined and will require studies from a number of perspectives to establish the disposal system with the least environmental effects. One of the more important questions to be answered is the final particle size of spent shale and whether the material will be shale ash or not. From the standpoint of erosion, the calcined or fused and clinkered product from the current USBM or Union Oil Company retorts have the definite advantage of larger size particles. The work of Culbertson et al. (1970) also shows that the cementation of shale ash can produce stable piles with high cohesive strengths and very low permeabilities. On the other hand, the TOSCO type spent shales are finely divided; and, since the heat of retorting does not reach the minimum temperature of about 1150°F for lime formation, it shows no cementation.

Ward et al. (1971) studied the erosion potential of TOSCO spent shales on approximately 68 tons in a pile 80 feet long with a twelve foot top width and a slope of 0.75 percent. All of the sediments collected during the rainfall experiments were smaller than 0.074 mm and had a mean size of 0.0317 mm. This project definitely established that there could be considerable erosion, even on very flat slopes, for exposed piles of TOSCO type spent shales.

The USDI (1973) discusses a 45° (100 percent) slope for a tolerable depth of 100 feet. The erosion potential of these steep slopes is high for any material, and very difficult to vegetate.

Heley (1973) proposed a 4:1 (25 percent) slope face with horizontal benches at approximately 25 foot intervals for TOSCO II spent shale. These dimensions were based on a proposed compacted density of 85 lbs/ft^3 in the interior of the pile and 90 lbs/ft^3 near the slope face.

Chemical Characteristics of Spent Shale

Oil shale is a sedimentary organic-inorganic matrix deposited by ancient deep stratified inland seas. Deposits were laid down under reducing conditions of saline water. Therefore, saline minerals are a natural part of the oil shale environment.

Chemical analysis of spent shales have all shown them to be highly saline, highly alkaline, and there is a definite potential for high concentrations of Na, Ca, Mg, and SO_4 in the runoff or leachate from spent shale residues (Schmehl and McCaslin, 1973; Ward et al., 1971; Culbertson et al., 1970).

Salinity of Spent Shale

Interest in the pollution potential of spent shale disposal is so recent that the only published results on salinity are from limited research at Colorado State University by Schmehl and McCaslin (1973); Ward, Margheim, and

Lof (1971); Ward and Reinecke (1972); and a single analysis of Union Oil Company spent shales reported by the Special Committee of the Governor's Oil Shale Advisory Committee (1971). To the extent possible, the results of the Experiments on salinity and water soluble ion extraction are converted to a common basis for comparison purposes in Table 3.

Conductivity determinations of the saturation extract from spent shale samples analyzed by Schmehl and McCaslin ranged from 9.0 to 22.0 mmhos/cm at 25°C and averaged 17.8 for TOSCO spent shales and 14.3 for those from the Bureau of Mines gas combustion process. The conductivity of 1:10 spent shale to distilled water extract by Ward et al. (1971) ranged from 1.4 to 11.0 mmhos/cm at 25°C. The answers are not comparable because of the wide variation in the amount of water used for extraction by the two research groups. Richards (1954) warns that the higher the moisture content used for conductivity analysis, the less representative it will be of the solution to which plant roots are exposed in the soil. He also notes that high dilution extracts for salinity measurement containing large amounts of sulfate or carbonate salts are highly affected by moisture content, while those containing mostly chloride salts are little affected. Therefore, interpolation of the results from Schmehl and McCaslin (1973) to a common spent shale water ratio would be expected to give much lower results for soluble salts than the data from Ward et al. (1971).

Available analysis of water soluble ions were standardized to parts per million for 1,000 grams of spent shale to a liter of water (1:1 ratio) for comparison purposes (Table 3). This conversion is questionable in light of the widely different methodology used in the original analysis. It does, however, serve to point out the wide range in results, and the need for analyzing a large number of samples using standard methods.

Soluble Na is the principal water-soluble cation (687 to 21,000 ppm) reported. Schmehl and McCaslin (1973) reported that one sample contained sodium to the extent of 74 percent of all water-soluble cations. Without much doubt, the potential for Na pollution would be considered the most serious for Colorado river waters. The pollution potential for spent shales would also be much higher if shale containing Nahcolite and Dawsonite in appreciable quantities were being retorted since they are completely decomposed during retorting and would release large quantities of Na_2O and Na_2CO_3.

Spent Shale Leaching Studies

The pollution potential from leaching salts out of spent shale piles is a function of local precipitation amounts and timing, evapotranspiration rates, amount and type of vegetation, as well as the height, slope, roughness, degree of wetting and compaction, retorting method used, and place or method of disposal for spent shales. The prediction of the water pollution potential is, therefore, probably impossible until after the retorting and disposal methods for a commercial oil shale industry are more clearly defined.

The relative hydrophobicity and impermeability of unwetted spent shales and the cementation reactions of shale ash have led some environmental reports to essentially ignore the problem of pollution from leaching. But because of the large volumes of spent shale disposal and the essentially unlimited supply of soluble salts available, a large water pollution potential exists. This is

Table 3. Results of Salinity and Water Soluble Ion Extraction of Available Spent Shale Samples

	TOSCO Process			Union Oil Company	Bureau of Mines Gas Combustion	
		Ward, Margheim and Löf (1971)				
Item	Schmehl and McCaslin (1973)	Blender	Shaker	Ward, Margheim and Löf (1971)	Schmehl and McCaslin (1973)	Ward, Margheim and Löf (1971)
Conductivity (mmhos/cm @ 25°C)	17.8[1]	1.7[2]	1.6[2]	11.0[2]	14.3[1]	1.4[2]
pH of Extracts						
Saturation paste	9.2				8.7	
1:5 (Shale:water)	9.5				9.1	
1:10 (Shale:water)		8.4		9.9		7.8
Concentration of Water Soluble Ions (Parts Per Million)[3]						
Ca^{++}	176	1,140	1,020	3,270	189	420
Mg^{++}	158	270	310	910	198	35
Na^{+}	1,328	1,650	2,060	21,000	687	2,250
K^{+}	24	320	100	6,250	170	720
$CO_3^{=}$	29				5	
HCO_3^{-}	26	200	200	280	13	380
CL^{-}	40	76	58	330	27	130
$SO_4^{=}$	3,476	7,300	7,750	62,300	2,653	6,000
	5,257	10,956	11,498	94,340	3,942	9,935

[1] Solution from spent shale saturated with water (approximately 40 percent by weight).

[2] 100 grams of spent shale that passed a No. 40 sieve in one liter of distilled water.

[3] Standardized to 1,000 grams spent shale to 1 liter of water equivalent saturation.

particularly true for slurry deposited spent shales, disposal areas that could be affected by the ground water table, and unstablized spent shale piles.

A number of physical factors affect the rate of salt dissolution and removal from spent shale piles. The velocity of water through the spent shale can affect the dissolution by limiting the time water is in contact with the salts. Particle size and retorting temperatures both have important effects on the infiltration and percolation characteristics of spent shales. Thus, the combination of slow percolation rates and great depths for the spent shale piles will insure maximum salt concentration of the leachate. Another important effect known as "piston flow" is the replacement of one fluid by another without mixing taking place (Nelson and Biggar, 1961). As leaching water percolates downward, an interface tends to develop between the low-salt leaching water and displaced saline solution because of the density difference. The greater the density difference, the less mixing tends to occur. This effect is one reason for the extremely high initial salt concentrations from leaching previously unwetted spent shale columns that are reported later in this section.

The study of leachability of spent shales has two principal functions: (1) To determine the potential pollution of the aquifers; and (2) To determine the best method for removing sufficient soluble salts to permit vegetation establishment and growth. Ward et al. (1971) did a limited leaching study on a single sample of TOSCO spent shale, and Schmehl and McCaslin (1973) studied a sample of TOSCO spent shale that was pretreated to insure wetting in six column lengths to determine if salts could be removed by leaching. Considering the array of possible leaching problems, the limitations of available data emphasize the need for additional research.

The leaching study by Ward et al. (1971) was conducted to determine the quantities of dissolved solids leachable by simple percolation. It consisted of a single 12,500 gram sample of TOSCO spent shale compacted1/ in a plastic column 120 cm in length (47.2 in.) and 10 cm (3.97 in.) in diameter. The sample was leached by tap water with a constant head of 2 cm. The first leachate took two weeks to move through the column and a total of 42 days were required to collect 4.6 liters of leachate. The results of this experiment are shown in Table 4. The initial leachate from this column had a conductance of 78.1 mmhos/cm at 25°C and a salt concentration of >130,000 ppm for Na, Ca, Mg, SO_4, and Cl ions. The salt concentration is equivalent to approximately 13 percent salts in the solution and is over 27 times the maximum permissable salt concentration for irrigation waters of 5,000 mg/liter TDS (FWPCA, 1968). After passing 4560 cc of tap water through the column, the conductance of the leachate had dropped to 3.9 mmhos/cm, and the salt concentration was about 6,200 ppm.

Ward et al. (1971) did not determine the remaining salts in the column nor state the saturation capacity of the column of spent shale. If, however, we assume that the 12,500 grams of TOSCO spent shale was compacted to 1.30 g/cc, we can assume a volume of 9,615 cc in the column. If we also assume that the porosity is approximately equal to the saturation capacity of the column, or (9,615 x .47) = 4,520 cc, we can conclude that a total volume of 9,080 ml of water could leach the excess salts from 9,615 cc of dry spent shale.

1/ Compacted to bulk density of 1.30 g/cc and a porosity of 47 percent.

Table 4. Experimental Results of a Percolation Experiment Conducted on TOSCO Spent Oil Shale (After Ward et al. 1971)

Volume of leachate sample (cc)	Total Volume of leachate (cc)	Conductance of sample (umhos/cm @ 25°C)	Concentration (mg/l) of sample				
			Na^+	Ca^{++}	Mg^{++}	SO_4^{--}	Cl^-
254	254	78,100	35,200	3,150	4,720	90,000	3,080
340	594	61,600	26,700	2,145	3,725	70,000	1,900
316	910	43,800	14,900	1,560	2,650	42,500	913
150	1,060	25,100	6,900	900	1,450	21,500	370
260	1,320	13,550	2,530	560	500	8,200	205
125	1,445	9,200	1,210	569	579	5,900	138
155	1,600	7,350	735	585	468	4,520	138
250	1,850	6,825	502	609	536	4,450	80
650	2,500	5,700					
650	3,150	4,800					
650	3,800	4,250					
760	4,560	3,850					
	∞*	1,800	86	64	118	740	11

* These are extrapolated values and were not actually observed. These extrapolated values are probably accurate to within ± 6%.

Ward et al. also extrapolated the leaching study results to a steady state condition whereby the conductance was estimated at 1.8 mmhos/cm and the salt concentration at slightly over 1,000 ppm. This value is approximately equal to that for a normal soil that is high in gypsum.

Schmehl and McCasling (1973) studied a sample of TOSCO II spent shale that was pretreated to insure wetting in columns of 6, 12, 18, 24, 30, and 36 inches in length. The material was compacted to 74 lb/ft^3 (1.18 g/cc). The water saturation capacity in the column was 2.5 in. per six inches of column or 41% by volume. They found that the conductivity of the leachate was less than 4 mmhos/cm after passing 10 inches of water through the 36 inch column. Passing 15 inches of water through the 36 inch column removed 82 percent of the salts present. The soluble salts remaining in the 36 inch column of spent shale after leaching with 20 inches of distilled water shows a conductivity of the saturated extract of 1.77 as compared to 26.0 mmhos/cm for the same sample before leaching.

These limited leaching studies suggest that the soluble salts can readily be removed from TOSCO spent shale by leaching. Salt removal is more efficient in longer columns because of contact time. Very long contact times utilizing unwetted spent shales, would produce very high initial concentrations of salts and would be typical of any percolation waters that move through large piles of unwetted spent shale.

Chemical Characteristics of Process Water

In addition to oil, the retorting of a ton of oil shale may produce up to 10 gallons of water with the average range two to five gallons (USDI, 1973). This water contains dissolved minerals, organic materials and has a pH of about 8.8 (Cook, 1971). The organic material consists of amines, acids, bases, and neutral compounds that give the water a dark color and a bad odor (Hubbard, 1971). The inorganic components are mostly ammonium, sodium, bicarbonate, carbonates, sulfate, and chloride ions. Table 5 lists the kinds of minerals found in three oil shale waste waters. These constituents can be removed, but there are no economically recoverable by-products, and the purified water is very expensive. The most practical solution seems to be to use the retort water for moistening the spent shale. By this means, the 1 to 5 percent solids and other products may be held in the spent shale dumps.

The by-products of oil shale production are generally not directly related to water pollution other than the process water from retorting and refinery waste water from upgrading shale oil. A 50,000 bb/cd of upgraded shale oil industry is estimated to produce from 150-350,000 gals/cd of process water and approximately 100,000 gals/cd of refinery waste water (USDI, 1973). The assumption is made that this water would be utilized for wetting the spent shale. The process of upgrading shale oil for this plant was also estimated to produce sulfur (43 ton/cd), ammonia (138 ton/cd), and coke (855 tons/cd).

THE USDI (1973) also indicates that there would be an annual disposal requirement of about 248 tons for chemicals used in the upgrading of shale oil for each 50,000 bbl/cd plant. The chemicals would be iron catalyst, iron oxide, and char which are solids, and monoethanolamine (MEA), which is a solid liquid mixture that is not water soluble. The USDI (1973) states that these chemicals can be disposed of in the spent shale piles without significant environmental problems.

Table 5. Chemical Components in Three Oil Shale Waste Waters

	Concentrations g/l		
Component	Water 1[1/]	Water 2[2/]	Water 3[3/]
Ammonia	12.4	4.8	2.4
Sodium	1.0	3.1	.5
Carbonate	14.4	19.2	20.8
Carbon, Total	18.5	6.4	6.7
Chloride	5.4	13.4	1.8
Nitrate	Trace	Trace	Trace
Nitrogen, Total	10.2	5.4	3.0
Sulfate	3.1	4.5	1.2
Sulfur, nonsulfate	1.9	.3	1.0

1/ Separated from gas combustion retort oil.

2/ Separated from an oil produced by in situ retorting.

3/ Separated from an oil produced in a 150-ton batch retort.

SPENT SHALE DISPOSAL

In view of the physical, chemical, and hydrological characteristics of spent shale, and the tremendous quantities to be produced, it is obvious that the development of an oil shale industry will depend upon the development of satisfactory methods for stabilizing the spent shale disposal areas, and preventing both present and future environmental degradation. Disposal and stabilization must be accomplished with three primary objectives in mind: (1) design of the pile and stabilization of the surface to protect against erosion by either wind or water; (2) location and/or design of the pile to prevent leaching and chemical pollution of surface and ground waters; and (3) design of the pile to prevent mechanical failure and subsequent erosion of the leading face. This suggests that spent shale disposal piles should be located in areas where the natural terrain affords some degree of protection and natural containment with respect to climatic and hydrologic processes.

Projection of an oil shale industry to 1980 assumes that the industry will have a production capacity of 250,000 bbl/cd. This would be distributed between public and private land with the federal lease tracts C-a and C-b supporting 100,000 and 50,000 bbl/cd plants respectively, while a 100,000 bbl/cd industry would be developed on private land. Spent shale disposal requirements, based on proposed disposal areas for C-a and C-b and best estimates for the private sector would amount to 1.3 million acre/feet of spent shale and overburden spoils over a twenty year period. Disposal of this material in the proposed disposal areas would create 5500 acres of spoil surface requiring stabilization and revegetation. The twenty-year disposal requirements are shown in Chapter 7, Table 3.

Potential Pollution Problems

Three potential pollution sources or mechanisms are recognized. The first of these is the indirect effect of removing fresh water from the Colorado and White Rivers. Since a one million bbl/cd industry would require from 105-156,000 acre feet of water per year (USDI, 1973), withdrawal of this amount will, in effect, reduce the amount available for dilution of downstream salt loads in the Colorado River. It is estimated that salt loads at Hoover Dam would be increased by 8 to 12 mg/l if this amount were withdrawn. Utilization of existing ground water and treatment of any excess process water to be released should help to reduce this effect.

The second potential pollution source is the release of saline groundwater into natural water ways. The drilling and limited testing of a number of wells in the basin indicate the presence of large quantities of saline groundwater below the Mahogany Zone (USDI, 1973), and lesser quantities of higher quality water above the Mahogany Zone. The development of underground mines in the Mahogany Zone, for example Tract C-b, will require de-watering of the mine and disposal of any saline water which moves into the mine from the leached zone. Direct release of mine water into the stream channels would create a serious pollution problem. Although little is known about specific volumes to be disposed, it is assumed that much ground water can be utilized in spent shale disposal. Surplus water may require treatment before release.

The third source of potential pollution, and of most concern to this report, is the potential for leaching salts from the spent shale disposal areas and eventual release to surface or ground waters. As previously discussed, spent shales contain large quantities of soluble salts which are easily removed by leaching. Control of pollution will essentially require disposal of spent shale in such a manner as to restrict movement of water into and through the pile. A number of possibilities are considered.

Surface Disposal With Compaction

The most probable method of spent shale disposal will be to pile the material in canyons or other natural depressions in the terrain. Projected areas of spent shale disposal are based on disposal in the steep sided canyons of the region. This has a number of advantages including, (1) permitting deep piles with some protection from the elements; (2) a comparatively short face to stabilize, and (3) the bulk of the pile can be hidden from public view. Obvious disadvantages include the fact that the pile lies across the natural drainage ways and may require special measures to route the natural flow through or around the pile.

In this situation, the problem of preventing pollution becomes one of either preventing water intake into the pile or preventing movement through the pile, or both. The obvious method of reducing water movement through the pile is to compact the pile to greater densities, hence, lower permeabilities. As previously reported, unconsolidated spent shales have bulk densities from 70-80 lbs/ft^3 and porosities of about 47 percent. By compacting the spent shale to 90 and 100 lbs/ft^3 porosities can be reduced to 42 and 35 percent respectively, and permeabilities reduced accordingly. This has the added advantage of reducing the storage volume required for disposal. Approximately 10 percent by weight of water must be added to compact to 90 lbs/ft^3 and about 20 percent by weight to compact to 100 lbs/ft^3. Although the permeabilities of the compacted shale are not known, they would be very small (Ward, et al. 1971).

The primary problem is the disposition of natural rainfall on the surface of the pile. This can best be managed by considering the water balance of the basin. Since the Piceance Basin ranges from near 5000 ft. to over 8000 ft. in elevation, the water balance varies considerably from a zone of severe deficiency at the lower elevations to a zone of surplus at the upper elevations. The variation in water available for recharge to the spent shale pile is illustrated in Figures 1 and 2. At the 6000 ft. elevation a severe deficiency occurs from March through mid-December. This means that natural rainfall occuring during the summer months will go into the spoil surface where it is either evaporated or used by plants with little or no movement below the root zone, while any surplus water during the winter months would go to recharge the soil water storage in the root zone. The primary source of pollution here would be that caused by the occasional intense thunderstorm where a proportion of the rainfall would directly flow off the surface carrying any loose spent shale particles and any salts accumulated at the surface.

At the 8000 ft. elevation a different situation occurs. Here a greater proportion of precipitation occurs as snow during the winter months which slowly melts and soaks in the spoil surface, increasing the probability for deep percolation and leaching. A period of water surplus occurs from mid-November through April, while a severe deficit occurs during the summer months. This indicates that, at the upper elevation, a water surplus occurs during the winter, of which a portion will be available for deep percolation. Calculating the total water excess for the six months with a net surplus (November - April) gives a total surplus of 4.78 inches. Assuming a four inch soil water storage capacity in the root zone which must be satisfied before deep precolation can occur, gives a net surplus of 0.78 inches. This is a relatively small quantity but, with time, will eventually move through the spent shale pile and create a source of salt pollution.

The data and calculations presented are estimated mean values based on the best information available. Because of climatic variation, individual storm characteristics, and the tendency for snow to be redistributed into natural depressions, the actual relationships for each disposal pile must be determined individually through field observations.

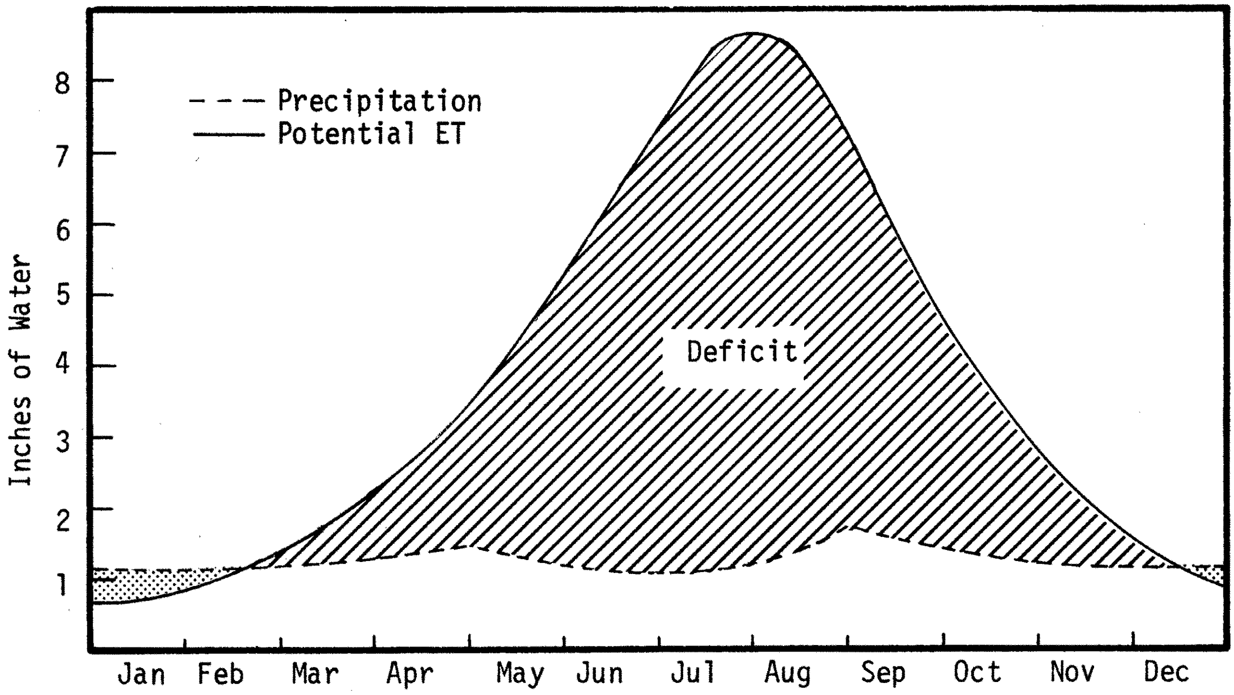

Figure 1. Water balance for the Piceance Basin at 6000 feet elevation.

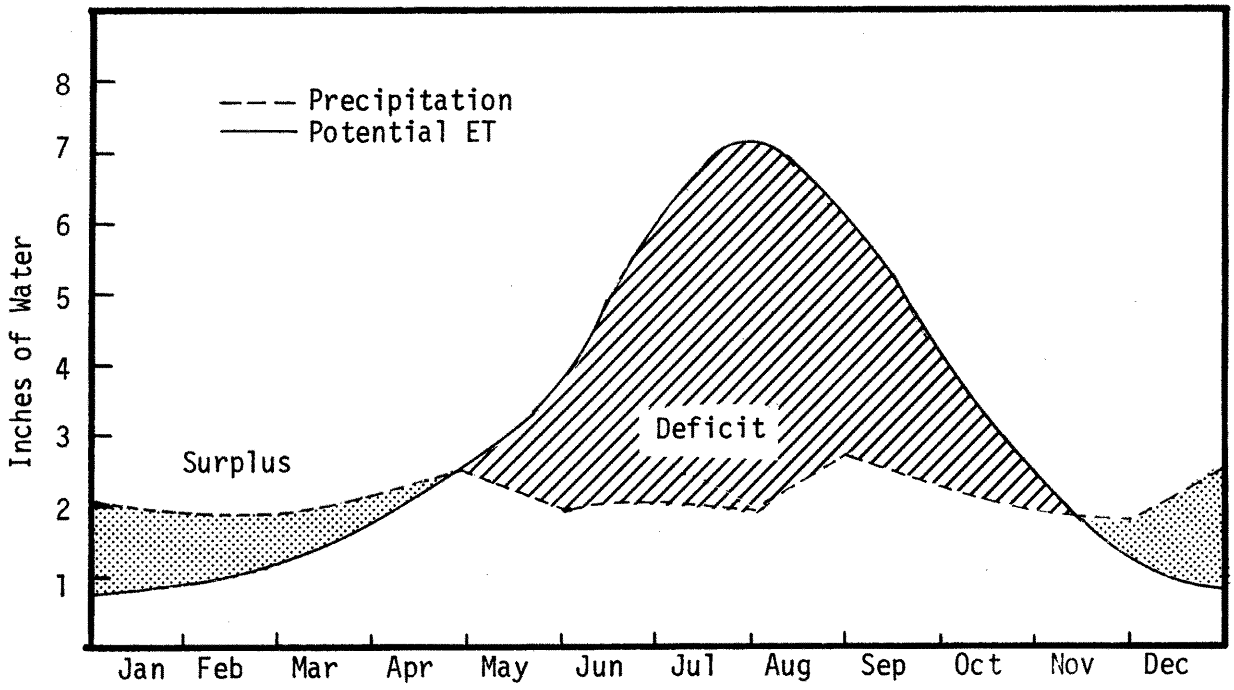

Figure 2. Water balance for the Piceance Basin at 8000 feet elevation.

Another possibility which has not been previously discussed, is to seal the surface of the spent shale pile and, in effect, create a water harvesting area. This would not only prevent water from moving through the pile, but would also provide a source of high quality water for the industry or revegetation purposes. This would require protecting the surface of the pile from runoff erosion, protecting the channels to carry the maximum probable storm event, and providing a storage reservoir to hold the anticipated runoff.

Disposal in Mined-out Areas

Returning the spent shale to the mined-out area is perhaps the most logical method of disposal, and will certainly be utilized. However, a considerable lag will occur between the beginning of mining and the ultimate disposal of spent shale in mined-out areas. For example, it is estimated that after approximately sixteen years of production on Site C-a, the mined-out area would be sufficient for backfilling into the pit.

During the development period, all spent shale disposal will, of necessity, be at off-site areas so as not to interfere with the mining operation. Ultimately the pits or underground mines will take a portion of the spent shale. Calculations show that this could vary from about 50 percent for slurry deposited fill to 95 percent for highly compacted fills. This would depend upon the amount of oil extracted from the shale, the degree of by-product recovery, and the degree of compaction of the spent shale and other solid waste products.

The pollution potential from these disposal areas would be approximately the same as for the piles previously discussed, unless disposal is by slurry conveyence.

Slurry Deposits

Slurry methods are popular in waste disposal because they are inexpensive and the methodology is presently used in many mill tailing disposal systems. The USDI (1973) suggested slurry deposits in the dry canyons west of Cathedral Bluffs would be a feasible method of spent shale disposal for tract C-a. Since tract C-a is projected as a 100,000 bbl/cd plant, the general volume relationships and disposal area relationships can be estimated. The specific technology for slurry disposal is not yet known, although best estimates are that a slurry mix of equal volumes of water and spent shale will work. Approximately half of the water used in the slurry mix would be recovered and recycled in the slurry transport process. This suggests that the water would aquire a very high salt content as it was used and re-used. More recent studies suggest that a slurry of spent shale will not de-water as quickly as assumed, but may contain as much as 100 percent by weight water in the disposal site (Colony Development Corp. comments on the USDI (1973) impact statement).

The implications of slurry disposal on water pollution potential are important. A number of sources of pollution are possible. First, there is a constant danger of a holding pond failure due to either flooding or accident. The volumes of the slurry produced by a 100,000 bbl/cd industry will be tremendous and will require a correspondingly large tailing pond system. A failure in this system would create an enormous mud flow which would be very difficult to control. This indicates that the design and construction of the water control system and tailings ponds is critical for a stable system. Secondly, seepage through the retaining structure or into the underlying geologic material from the saturated tailings, will pose a continuous pollution problem. Dewatering by natural evaporation will be difficult because of the high salinity and the continuous daily additions to the basins. It appears that the nature of the hazards associated with slurry disposal make it the least desirable of the disposal methods.

Erosion Control Problems

All spent shale surface disposal areas will be vulnerable to both wind and water erosion until stabilization is accomplished through vegetation or other means. Erosion is inevitable on fresh spoil banks, as it is on any bare soil. The degree of erosion will depend upon the amount and intensity of rainfall, the steepness and length of slope, extent of freezing and thawing, and how the water is concentrated on the surface (USDA, 1968). Therefore it is essential that all aspects of the spent shale disposal system be planned to minimize erosion.

Quantification of erosion rates and sediment loads for any area is difficult because sediments, unlike other pollutants, are readily available under natural conditions. Natural erosion rates in the Piceance region have been mapped as yield class 3 or 0.5 to 1.0 acre-feet per square mile per year (Upper Colorado Region State-Federal Inter-Agency Group, 1971). This is equivalent to 1.25 to 2.50 tons/acre per year. The environmental goal for an oil shale industry would then be to maintain or decrease this level of erosion.

Estimating Erosion Potential

The rates and severity of erosion are primarily controlled by four variables: precipitation factors, topographic factors, soil factors, and vegetal factors. Considerable research has been done on the inter-relationships of these factors, and a number of prediction equations utilizing these factors have been developed. Unfortunately, most of these equations are based on agricultural plots in the Eastern United States and have not been tested or modified for western or mountainous conditions. The methodology does, however, provide a number of useful relationships for the various factors. Within certain limits, estimates of the erosion potential of spent shales may be determined.

Most erosion equations are basically factorial approaches similar to that developed by Musgrave (1947), but modified by subsequent research or field measurements for particular situations. Since there are no specific methods for predicting the erosion of spent shales, three different methods were examined for applicability in spent shale disposal. These include (1) the basic erosion equation of Musgrave (1947); the Universal Soil Loss Equation (Wischmeier and Smith, 1965); and the Forest Service, Southwestern Region method (Anderson, 1969). Of these three the Universal Soil Loss Equation was selected because of the greater experience in its use and the range of conditions to which it has been applied. As presented by Wischmeier and Smith (1965) the soil loss equation is:

$$A = R\ K\ L\ S\ C\ M$$

in which:

A = soil loss in tons per acre
R = rainfall factor
K = soil erodibility factor
L = slope length factor
S = slope gradient factor
C = cropping factor
M = erosion control factor

The precipitation factor R is based on the energy available in the 2-year 30-minute storm for the region. Since rainfall energies in mountainous regions are variable depending on raindrop size, the rainfall factor for the Piceance Basin was estimated using the ratio of the 2-year 30-minute storm for an area with known rainfall factors to the equivalent storm for the Piceance Basin. The rainfall factor used for the Piceance Basin is 22.

The soil erodibility factor is expressed as the soil loss in tons/acre for each unit of rainfall erosion index for the area, and a bare soil condition with a 9 percent slope and a 73 foot slope length. This factor is usually based on field measurements. Since sufficient erosion data for spent shales is not available, the erodibility factor used is based on reported erosion rates for similar soils. Wischmeier and Smith (1965) report Erodibility factors for silt loam soils ranging from .28 to .69. Anderson (1969) gives a value of .41 for deep medium textured slowly permeable soils of the southwest. Since this corresponds to a medium silt loam, it is used as the erodibility index (K) for TOSCO spent shales. This value should be confirmed by field measurements.

The slope and slope length factors are determined using the relationships recommended by Wischmeier and Smith (1957) where:

$$S = \frac{0.43 + 0.30s + 0.043s^2}{6.613}$$

where: s = the slope of the surface (percent)

and $$L = \left(\frac{sl}{73}\right)^{0.5}$$

where: sl = the slope length in feet

The cropping and management factor (C) and (M) are related to the effectiveness of the vegetation cover as a deterent to soil erosion and also to the effect of cultural practices such as terracing and contouring. This cropping factor will vary from a maximum of 1.0 for a bare soil with cultivation up and down slope, to as low as 0.003 for a total ground cover of 95 percent. Anderson (1969) presents a table of vegetation cover coeficients. The management factor (M) will vary from a maximum of 1.0 for contour planting on slopes greater than 24 percent to about 0.25 for strip cropping and terracing on slopes less than 12 percent.

Based on the estimation of these factors and relationships, the potential soil loss from TOSCO II spent shales and varying degrees of cover are shown in Table 6.

Table 6. Potential soil loss rate for TOSCO II spoil assuming a slope length of 73 feet using the Universal Soil Loss Equation.

Percent Slope	Erosion Rate in tons/acre/year		
	Bare Soil	50% Cover	90% Cover
5	4	.48	.08
10	11	1.32	.22
20	32	3.8	.64
30	66	7.9	1.32
40	111	13.3	2.22
50	168	20.2	3.36

Rehabilitation of Spent Shales

The erosion estimates in Table 6 should be used with caution since the factors used have not been determined specifically for spent shales but estimated using known soils data. However, the relationships presented should be representative of conditions for the Piceance Basin and demonstrate the need for stabilizing the surface of the spent shale piles as soon as possible after disposal, either by revegetation or other means. Since the disposal of spent shale will be a continuous process once the retorting begins, it is apparent that the top surface of the spoil pile will be bare for many years as disposal proceeds while the face of the pile can be revegetated as soon as disturbances are eliminated. Erosion from the top surface will have to be controlled by some interim measure while the pile is being formed. Such measures might include construction of debris basins or other retaining structure downstream from the pile, or construction of temporary drainage control structures on the top surface of the pile. In addition, storm flows or other channel flows originating above the disposal pile will have to be routed around or under the pile by special drains from both the erosion control and pollution control objectives. Management practices to control erosion may not be compatible with pollution control objectives and must be considered from both viewpoints.

The erosion estimates in Table 6 are based on a standard slope length of 73 feet. Since erosion rates increase with slope length, the length of the face of the pile should be considered. Using the estimated pile depth of 1200 feet and a face slope of 25 percent as proposed by Heley (1973), gives a face slope length of about 5000 feet. Reducing the slope to 20 percent increases the slope length to about 6100 feet. Unbroken slopes of this magnitude would pose a serious erosion threat and some consideration should be given to breaking the slope using contour terraces or lateral drainageways.

A number of other possibilities should be considered in stabilizing the face of the spoil pile. For example, covering the face of the pile with a mantle of natural soil material would have the advantages of providing a better seed bed, reducing the leaching requirements for plant survival, and, depending upon the nature of the soil, reducing the erosion potential. Similarly, a large proportion of rock material piled on the face of the spoil bank would provide a resistant pavement and possible improved moisture relationships for natural vegetation. These possibilities should be tested on field plots for the specific disposal situations planned.

Other Disturbed Areas

The erosion potential of other disturbed areas is similar to that for spent shale piles, and should receive the same intensity of planning, design, and revegetation. This amounts to the development of a careful watershed management plan for the entire Piceance Creek Basin to prevent erosion, water pollution, and other environmental quality degradations to the extent possible. Table 3 in Chapter 7 indicates an estimated 3250 acres for mining facilities connected with the hypothetical 250,000 bbl/cd oil shale industry. Of this area, 1000 acres are for utility corridors and roads which will require careful erosion control and revegetation of the borrow areas and right-of-ways. The 820 acres to be utilized for plants, shale storage, and other uses will require water control planning.

Table 3 in Chapter 7 also shows 980 acres for overburden disposal. The USDI(1973) suggested disposal of the overburden(Federal tract C-a) in Water Gulch. The disturbed overburden materials will probably be coarse textured and permeable. The water pollution potential of these materials is comparatively low. The few samples of this material which have been tested were considerably lower in soluble salts than spent shales. The erosion potential of the overburden will also be comparatively lower, and mostly from the fine textured materials placed on top of the pile.

SPENT SHALE AS A MEDIUM FOR PLANT GROWTH

Salinity

Plant Growth

The spent shales are extremely salty in terms of plant establishment and growth. Schmehl and McCaslin (1973) reported that grass germination in a greenhouse study on unleached TOSCO spent shale was only 20% of that on soil, and that tall wheatgrass (*Agropyron elongatum*) on N and P fertilized but unleached TOSCO spent shale produced only 3% of the yield on N and P fertilized leached spent shale or a soil. The soluble salt analysis by Ward *et al.* (1971), when interpreted in terms of plant establishment and growth (Richards, 1954), is in general agreement with the work of Schmehl and McCaslin (1973).

Hutchins *et al.* (1971) state that no initial treatment other than fertiliziation was needed to obtain satisfactory germination and growth of grasses on TOSCO spent shale in greenhouse studies. This is in direct conflict with the studies mentioned above. The study (Schaal, 1973) referred to by Hutchins *et al.* (1971) was carried out in flats which were open to drainage and some leaching probably occurred when watering. The study of Schmehl and McCaslin (1973) was carried out in pots that were not open for drainage.

Sprinkler irrigation has been used in field studies where vegetation has been established on spent shales (Hutchins *et al.*, 1971; USDI, 1973, Vol. I, p. 57-66). The irrigation had resulted in leaching of sufficient salt from the root zone so that germination and growth were not restricted (Berg, 1973b). However, in a 1972 field study[1], germination and growth of several herbaceous species seeded in TOSCO spent shale was restricted due to insufficient sprinkling to leach salt from the rooting zone.

Leaching patterns of soluble salts from TOSCO spent shale have been demonstrated under laboratory conditions by Ward *et al.* (1971) and Schmehl and McCaslin (1973). Limited information is available on salt leaching from TOSCO spent shale under field conditions (Berg, 1973a and b). The salts are readily leachable, however, Schmehl and McCaslin (1973) report a buildup of soluble salts in leached spent shale in pots during their greenhouse study, but believe this may have been from salt that was not initially leached from spent shale due to channeling of leach water. Schmehl and McCaslin (1973) found that 15 inches of leachate through a 36" column of spent shale removed 82% of the soluble salts. Ward *et al.* (1971) found that the electrical conductivity (a measure of salt concentration) of the leachate from a 120 cm (47") column of TOSCO spent shale was reduced 16-fold after 40 cm (15.7") of water had leached through. These leaching requirements on spent shale appear smaller than the leaching requirement of 4 to 6 feet of water to reclaim a saline silty clay loam soil near Grand Junction, Colorado to a depth of 50 inches (Amemiya *et al.*, 1956) and a leaching requirement of four feet of water to reclaim a saline soil in Utah to a depth of four feet (Reeve *et al.* as reported in Richards, 1954).

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[1] Personal observation

The data do not allow a direct comparison of leaching requirements for the TOSCO spent shale and the soils, but the data is in better agreement if the water hold-up in the spent shale columns is included. This would be about 20 inches for the work of Schmehl and McCaslin (1973) and 24 inches for the work of Ward et al. (1971). Thus, it appears that three to four feet of water leached through a two to four-foot deep rooting zone in spent shale would be the minimum required to reduce the salts to levels found in productive soils.

It is known that some species [e.g. fourwing salt bush (Atriplex canescens), saltgrass (Distichlis stricta)] are much more tolerant to soluble salts than other species, thus consideration could be given to use of such species in the revegetation work. However, on certain sites this is not compatible with the objective of restoration to a condition equal to or better than that before disturbance. The salt tolerance of some of the woody species such as Gambel's oak and serviceberry is unknown. Varying degrees of salt tolerance have been found within some species (Richards, 1954; Dewey, 1960). Thus, seed source may be an important consideration in revegetation with species that may not be particularly tolerant to saline conditions.

The leaching in itself does not appear to pose a major problem if the infiltration rate of the spent shale is considered in design of the sprinkler system. Major problems posed by the leaching treatment are: (1) disposition of the leach water, and (2) resalinization of the leached zone by salt movement upward.

Disposition of Leach Water

One concept in disposal of spent shale is to compact the spent shale in lifts and then to leave a veneer of uncompacted spent shale (say, 3 to 4 feet thick) on the surface as a plant growth medium. The salt must be leached from the latter as discussed above. If this is done in place, consideration must be given to the fate of the leach water. The permeability of compacted TOSCO spent shale is described as "extremely slow" by Hutchins et al. (1971). This would imply that with moderate leaching rates (say, 1 inch/day) the uncompacted shale would become saturated with water at the interface with the compacted shale. This could lead to slumping on slopes. Drain tile might be considered to remove some of this water but if used it must be remembered that water will only enter such drains when free water is present (i.e. when the spent shale is saturated). Thus, even with installation of drainage tile, a slump hazard or the possibilities of water movement downslope along the compacted spent shale may be a possibility. Leaching rates comparable to the permeability of the compacted spent shale could also be mentioned. Here, several factors have to be considered: (1) Is the permeability sufficient to even consider leaching at this rate? (2) Will the water influence the stability of the pile? (3) If the compacted shale is already at field capacity, then through-leaching would occur.

Possible considerations are to adjust the water content when compacting spent shale so the leach water can be adsorbed without through-leaching. This would probably be considered only on those sites where evapotranspiration is sufficient so that percolation will not later occur due to natural precipitation.

Problems similar to those raised above would also occur on spent shale disposal sites at higher elevations where precipitation during certain periods exceeds evapotranspiration and percolation into, and eventually through, the spent shale may occur.

Alternatives to the leaching of salts from the rooting zone in spent shales would be to cover the spent shale with soil and/or geological materials. Soil cover to a depth of several feet should do away with the salt leaching requirement. A thin soil cover (say 4-6") would be a very shallow rooting depth and would require that salt be leached from 18 inches to several feet of the soil-covered spent shale to provide adequate water holding capacity. Covering the spent shale with geological materials (spoils) would be a possibility, however, these materials may be coarse textured (see Chapter 5 on disturbed overburden) and pose problems of water percolation into the spent shale. Nor would soil cover solve the problem of possible water penetration into the spent shale or a water buildup at the interface between the compacted spent shale and the soil cover. Such a buildup would depend on the balance between precipitation, runoff, and evapotranspiration and might not pose a problem at the lower elevations.

Possible resalinization of the leached zone in spent shale should be considered under two conditions: (1) when a water table exists within the zone of capillary rise, and (2) resaliniation when no water table exists. Salinization of non-saline soil cover over spent shales must also be considered.

A discussion by Gardner (1960) covers the first situation: "The rate of upward movement of water from a water table.....may be rapid enough to present a serious salinity hazard when the ground water is saline, even though the water table may be several meters below the soil surface. Some previous workers have concluded that upward movement did not take place when the water table was below 10 or 12 feet.....the theoretical limit of capillary rise is sufficiently greater than this..... Laboratory studies show that water can certainly move from water tables at least as deep as 7 meters at appreciable rates".

Resalinization from a water table would be dependent upon the depth to the free water and the texture and compaction of the soil material. Thus, capillary rise would be expected to be greater on the relatively fine textured TOSCO spent shale than on the USBM gas combustion process spent shale.

The second situation where resalinization is to be considered is where no water table exists. A discussion directly relating to this was not found in the literature, so the approach is indirect. Gardner (1960) presents a figure relating capillary conductivity to soil moisture tension in soils with sandy loam, loam and clay textures. This diagram shows that capillary conductivity decreases drastically when moisture tension increases from tensions near field capacity to tensions of 1 bar. Using a loam soil as an example, if the tension at field capacity is assumed to be 1/3 bar, the capillary conductivity is about .01 cm/day and decreases over ten-fold when the moisture tension is one bar. The point is that water movement upward by capillary rise is extremely slow in soils that are below field capacity. Countering this upward movement would be precipitation that would move the salts downward.

The limited information on salt concentrations in soils of the area (Medin, 1969; Ward et al., 1971; Heil, Chapter 5 of this report) indicates that the upland surface soils tend to be less salty than sub-surface materials. This is interpreted as, that over a period of time the net movement of salts in soils of the area where no water table exists is downward. Soils information is available on this in the area east of the Front Range (USDA, Soils Cons. Service, 1967, p 138-141) where upland soils developed on salty materials are non-saline to depths of 6 to 12 inches. However, the precipitation patterns are different in this area than in northwestern Colorado although total precipitation may be similar for certain areas. The problem needs further attention. In uniform textured material such as the TOSCO spent shale the question might be approached on a theoretical basis.

As another approach to predicting salt leaching, spent shale produced an estimated 50 years ago by a USBM project near Rulison was sampled. Two assumptions have to be made in dealing with the coarse textured (50% <2 mm, texture-loamy sand) black material sampled. One assumption is that the material is actually spent shale (it could be coal cinders) and the other is that the material was initially high in soluble salts. The pile sampled was small -- about 150 square feet and relatively thin (18-24"). There was a sparse plant population on the edges but no plants near the center. Four holes were dug and samples taken at six-inch intervals. Soluble salts were quite low in the surface horizon and increased slightly with depth, however, no salt concentrations approaching the soluble salt concentrations in unleached spent shales were found. The data indicate (if the assumptions are valid) that soluble salts have been leached from the material over a long time under an 11-inch average annual precipitation regime. This result is not unexpected in view of the coarse nature of the material and the lack of plant growth on it (see discussion in Chapter 5 on particle size considerations in disturbed overburden).

Fertility

Nitrogen

In greenhouse work, Schmehl and McCaslin (1973) showed that both nitrogen (N) and phosphorus were extremely deficient for grass growth on TOSCO spent shale. Later studies[1] showed that a similar situation existed for USBM gas combustion process spent shale. Other studies on the vegetative stabilization of spent shales (Hutchins et al., 1971; Schaal, 1973) indicate that N and P fertilization is needed.

In our work we find that 60 to 100 pounds of N/acre will often give good grass growth responses on mine spoils and mill tailings where other factors are not limiting. However, on very N-deficient materials this response will be less noticeable in a year's time. After several years the vegetative ground cover will decrease if legumes are not a major component of the stand.

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[1] W. R. Schmehl, Colorado State University, personal communication

The question broached but not answered in the following discussion is, how much more N will need to be added to N-deficient materials before they reach a level where they can maintain adequate N for plant growth?

Soils in Colorado with a moderate degree of development may contain 3,000 to 10,000 pounds of N in a three-foot profile (USDA, Soil Cons. Serv., 1967). Among other factors, the amount of N will depend upon climate, topographic position, aspect, and soil texture.

The build-up of soil N on N-deficient materials has been reviewed by Stevenson (1965) who states: "Information on the rate of nitrogen accumulation in soil during colonization by plants has come from studies of time sequences on the moraines of receding glaciers....., mud flows....., spoil banks....., sand dunes....., road cuts....., Indian mounds, and an abandoned fortress...... In general, the results show that the rate of nitrogen accumulation is rapid during the first few years, diminishes slowly, and reaches equilibrium in periods of time which vary from 110 to 1,500 years".

On all the materials and sites mentioned above, average annual precipitation was greater than in the Piceance Basin area. The systems where the N reached equilibrium in terms of 100 years appear to be those where legumes or other N-fixing plant species were major components of the vegetation.

A situation which may be closest to that in western Colorado (but with considerably more precipitation) is the work of Andrew and Rhoades (1948) on a road cut in calcareous glacial material near Lincoln, Nebraska. They found that there was an apparent 1,400 pounds N/acre accumulation over a 75-year period (this averages 19 pounds N/acre per year). The vegetation on the site when sampled was described as consisting of "big and little bluestem with some other grasses and leguminous and nonleguminous forbs".

Important sources of N accumulation are listed by Stevenson (1965) as being biological fixation and N in rainwater. Under biological fixation he lists: (1) blue green algae, (2) free living bacteria, (3) bacteria living in symbiosis. Blue green algae are mentioned as probably being important N fixers in the initial stages of soil formation as they are able to synthesize all of their biochemical requirements from CO_2, free N, water, and mineral salts. These algae also form symbiotic relationships with other organisms such as lichen fungi. Porter (1969) reports on rates of N fixation by algae, but points out that these were obtained under continuously moist conditions. He also states that the rates would be considerably less on semiarid rangelands.

Stevenson (1965) points out that under natural conditions the N-fixing capacity of free living bacteria such as Azotobacter are severely restricted due to their high requirements for energy which comes from carbon in organic matter. Copely (1971) reported that asymbiotic N fixation rates on a short grass prairie near Fort Collins were less than 50 $\mu g/meter^2$ per day (.0005 pounds/acre/day).

Symbiotic N fixation can account for substantial N additions to soils (Stevenson, 1965). Such relationships are commonly associated with legumes;

however, certain nonleguminous species also develop root nodules and fix N. Farnsworth and Hammond (1968) reported nodules on the roots of Artemisia ludoviciana and Opuntia fragilis in Utah and have recently reported N fixation by these species (Farnsworth and Hammond, 1972). They also report finding nodules on the roots of Chrysothamnus viscidiflorus (a rabbit brush). The significance of these species in supplying N under field conditions has not been evaluated. Copely (1971) found a fairly high level of N fixation on the native legume Oxytropis sericea, but stated that this source of N probably was not significant in the short grass ecosystem because of low densities of this and other legumes.

Stevenson (1965) cites Erickson's summarization of N in atmospheric precipitation for Europe and the United States as varying from .7 to 18.7 pounds per acre per year. Most reports were in the range of 4 to 7 pounds per acre per year.

Thus, natural additions of N to spent shale or spoil material might be expected to be several pounds per acre per year to several times this much, and considerably more if efficient N-fixing plants are established. However, the semiarid and arid climate and land use considerations severely limit the use of legume species for which seed is available.

The fixation of N by natural sources will probably be considerably less than required to maintain maximum ground cover on spent shale. Therefore, additions of fertilizer N will be required. Residual effects of relatively low N rates applied to rangelands are usually short lived (Cook, 1965; Bowns, 1972). Mason and Miltimore (1972) recently reported yield responses ten years after application of up to 450 pounds of N per acre on a beardless wheatgrass (Agropyron inerme) - sandberg bluegrass (Poa secunda) association in British Columbia (ave. ann. pttn. 11 inches, el. 1,300 feet). Thus, where leaching is not a factor, high N rates might be applied; however, N applied at the rate of 1,000 pounds per acre by Smith et al. (1968) resulted in killing of vegetation.

Fertilization with manure or sewage sludge may also be a possibility to consider in view of current disposal problems of these wastes. Here, transportation would be a major expense. Studies now underway, such as those of Mathers and Stewart (1971) on high rates of feedlot manure applied to soil, would be of interest if manure is considered. Studies have also been reported on use of sewage sludge on coal mine spoils (Sopper and Kardos, 1971; Hinesly and Jones, 1972) and mill tailings (Dean and Havens, 1971).

Rate and timing of N fertilization can have major effects on plant species composition. Carpenter and Williams (1972) have recently reviewed the literature on this as well as on the influence of fertilizers on palatability. The increase in palatability due to N fertilization could result in management problems from deer and rabbits. Smith (1971) reports that rodent damage to planted mountain mahogany was greater on fertilized portions of his plots than on unfertilized portions.

N losses from fertilized spent shales could be caused by leaching. For this reason N should not be applied until salts have been leached from spent shale.

This review indicates that a variety of problems and considerations emerge when a N fertilization program for spent shales or spoils is considered. The problems posed appear to be solvable.

Phosphorus

Satisfactory grass growth on leached TOSCO II spent shale was realized only when fertilized with nitrogen (N) and phosphorus (P) in the greenhouse study of Schmehl and McCaslin (1973). In this study, the addition of N alone resulted in very poor growth, while the combination of 100 ppm N and 200 ppm P resulted in grass yields comparable to those on a productive soil.

Schmehl (1971) states that the P rates needed to obtain maximum grass production in greenhouse tests on spent shales were higher than expected on the basis of soil tests.

No visible differences in plant growth response to rates of 200, 400, and 800 pounds P_2O_5/acre were visible two growing seasons after application on a demonstration plot on TOSCO II spent shale (Berg, 1973a).

It is obvious that fertilizer P will have to be applied if spent shales are to be used as a plant growth medium. The time to do this would be before seeding and possibly before salt leaching. At this time, relatively high rates of P could be mixed into the surface of the spent shale. The rates to be used have yet to be determined, but the 200-800 pound P_2O_5 rate mentioned above for the Colony test plot may be within the range.

An extensive body of knowledge is available on the reaction of fertilizer P in soils. The literature will now be used to discuss P fertilization on soils somewhat similar to the spent shales.

Nielson _et al_. (1956) reported alfalfa yield responses after four to six years on field plots where high rates of P (200, 400, and 600 pounds of concentrated triple superphosphate) had been applied to highly calcareous soils (lime content 40-55%). A response was also measured after 13 years on a study receiving 2,600 pounds of concentrated superphosphate. In these studies, the residual effect was in proportion to the amount of P initially added.

Stanberry _et al_. (1960) reported that alfalfa production on a calcareous sand from a single, initial P application of 66 pounds of P/acre was as effective as application of 22 pounds P/acre for each of three years.

The above studies indicate that application of the proper amount of P fertilizer to spent shales would be expected to have lasting effects. However, if the spent shale became deficient in plant available P, would surface application of P fertilizer be effective? Here we assume a cover of permanent vegetation is growing on the spent shale and additional fertilizer P cannot be mixed into the spent shale. (The usual recommendation on calcareous soils is to broadcast the P fertilizer and then mix it into the plowlayer as P has very limited mobility in most soils.)

Responses to surface application of P fertilizer on established alfalfa stands on calcareous clay loam and sandy loam soils have been reported by

Schmehl et al. (1955), and on a calcareous sand by Stanberry et al. (1960). Responses to surface applied P fertilizer on native grassland vegetation have recently been reported by Bowns (1972), and Wight and Black (1972). The studies indicate that broadcast application of P fertilizer would probably be effective on established vegetation on spent shale.

The very poor plant growth on unfertilized spent shale brings up the question of root growth into spent shale below the depth of P fertilizer incorporation. As P is known to be quite mobile within plants (Seatz and Stanberry, 1963), sufficient P should be translocated to supply roots below the fertilized zone.

The pollution potential of P fertilizer additions also needs to be mentioned. The solubility of fertilizer P in soils is limited; so much so that research on P fertilizers in soils centers on the limited solubility of various phosphorus compounds (Olsen and Flowerday, 1971). Olsen et al. (1950) reported movement of band applied solid P fertilizer to a depth of 3 inches but that most of the P was concentrated in the surface inch of soil. In contrast, liquid H_3PO_4 applied at the soil surface moved as deep as 12 inches but was largely concentrated in the top four inches of soil.

Little movement after initial reaction and movement into the soil would be expected. Pratt et al. (1956) determined the P content in an irrigated soil after 28 years of fertilization and found that little P penetrated beyond 24 inches, and 80% of the applied P remained in the top 12 inches of soil. During a four-year period, movement of P applied to an irrigated loamy fine sand was related to the rate of application (Stanberry et al., 1955). At the highest P rate (570 pounds of P/acre) P moved no deeper than 18 inches. Thus, leaching of fertilizer P should not be a problem on the spent shales. The only P pollution problem would apparently be from erosion of P fertilized spent shale by water or wind. Erosion has been discussed in a previous section.

A last item to be covered on P is that at the high temperatures that are generated by some retorting processes, most of the calcium and magnesium carbonates in the oil shales will be decomposed and converted to oxides. In time, the oxides will reconvert to carbonates. In this process it would seem that extensive carbonate surfaces would be created that would react with fertilizer P. Thus, the amount of P fertilizer required may in part be a function of the retorting temperature of the shale.

Other Plant Nutrient Considerations and Possible Ion Imbalances

Sodium: sodium analyses by Schmehl and McCaslin (1973), Culbertson et al. (1970), and Ward et al. (1971) show that spent shales contain large amounts of soluble sodium, which is often the most abundant soluble cation. As discussed in a previous section, the bulk of the soluble salts would have to be leached from spent shale used as a plant growth medium. Considered here are two possible effects that sodium, which remains after leaching, could have on plant growth in spent shale.

The first effect is physical, in that sodium adsorbed as an exchangeable ion is known to have a dispersing effect on soils. If this effect is strong enough, the physical characteristics of some soils can change so as to become nearly impermeable to water (Richards, 1954; Bernstein, 1962), and upon drying, dense crusts form that interfere with germination and seedling emergence (Wilcox and Durum, 1967). An index of the sodium hazard is the Sodium-Adsorption Ratio (SAR) which is a calculated value that can be determined on irrigation water or on the water soluble ions in a soil extract (Richards, 1954).

SAR values of 33, 25, and 28 for TOSCO spent shale and 8, 30, and 4 for samples of USBM gas combustion process spent shale were reported by Schmehl and McCaslin (1973). An SAR of 3 was reported for weathered spent shale from the Union Oil process (State of Colorado, 1971).

The common interpretation of SAR values for irrigation of soils in the Western U.S. are (Richards, 1954):

0 - 10 - low sodium hazard
10 - 18 - medium sodium hazard
>18 - high sodium hazard

Limitations of these interpretations are recognized but have not been defined by Richards (1954) who states that dispersion problems caused by sodium are not as severe on sandy soils or on soils which do not contain montmorillonitic (expanding lattice) clay minerals. As spent shales contain relatively small amounts of clay-size particles (content will vary with the retorting method used), and because the spent shales do not contain expanding lattice clay minerals (Schmehl and McCaslin, 1973) the sodium dispersion hazard is probably considerably less than the guide indicates. However, Ward et al. (1971) reported a decrease in permeabilities of 37 and 9% for USBM and TOSCO spent shales, respectively, when leached. Sodium is suggested as the reason for the decrease in permeability. The dispersing effect of sodium would be greatest when very low concentrations of soluble salts are present, as soluble salts will flocculate even sodium saturated soils. In summary, the effect of exchangeable sodium in dispersing fine-textured, intensively leached spent shales appears to deserve additional study.

The nutritional effect of relatively large amounts of exchangeable sodium in relation to other cations also should be considered. Bernstein (1962) reviewed literature on plant growth as influenced by high levels of exchangeable sodium in soils and found that in general yields decline as exchangeable sodium increases. However, most of these results are confounded by the unfavorable physical effects due to exchangeable sodium.

To avoid the physical effect, Bernstein and Pearson (1956) stabilized a soil by addition of VAMA (vinyl-acetate-maleic copolymer), then treated the soil to obtain a range of exchangeable sodium percentages. Alfalfa yield fell as exchangeable sodium increased in both untreated and VAMA stabilized soils, however the yield reduction was not as drastic in the VAMA stabilized soils where yield decreased one-half with 40% sodium saturation. In contrast, beets yielded well until 40% sodium saturation was reached. These researchers indicated that tolerance to high exchangeable sodium is characterized by a high degree of translocation of sodium from the roots to the tops. Black (1957) indicates that the plant toxic effect of high sodium may be related to reduced calcium uptake in plants.

Hayward and Wadleigh (1949) mention a study by Bower and Wadleigh where beans were found to be very sensitive to exchangeable sodium, but Rhodes grass and beets were quite tolerant. Thus, a range in tolerance to relatively high concentrations of exchangeable sodium might be expected among species considered for revegetation on the spent shale. The good growth of species seeded to date on leached and N and P-fertilized TOSCO spent shale indicates that high concentrations of sodium are not a problem to these species on this material. Oil shales that contain larger amounts of sodium minerals may pose problems because a higher percentage of the cation exchange capacity on spent shale will be satisfied by sodium ions.

Boron: Schmehl (1971) and Berg (1973b) reported that excess boron might be a problem in plant growth on spent shales. Boron toxicity is a common problem reported in attempts to grow plants on ash from coal-fired power plants (Cope, 1962; Hodgson and Holliday, 1966). Richards (1954) notes that plant species differ markedly in tolerance to excessive concentrations of boron and lists alfalfa as among the more tolerant species. Plant available boron appears to leach readily from TOSCO spent shale (Berg, 1973b), however, this may not be the case with spent shales from retorting processes where fusing temperatures occur. In the latter case, boron might become available over a period of time as reported for fly ashes by Townsend and Hodgson (1973). Townsend and Hodgson (1973) have attempted to reduce concentrations of plant available boron in fly ash. They report that boron toxicity is long-term but its effects are lessened by inorganic and organic amendments which either reduce boron solubilities or increase the natural loss by leaching.

As indicated for sodium, the growth of some plant species on leached and N and P-fertilized TOSCO spent shale indicates that boron toxicity is not a major problem on this material. However, certain species considered for revegetation might be sensitive to this element. Possible boron toxicity from spent shales produced by other retorting processes needs to be explored.

Magnesium: rather high concentrations of magnesium were reported by Schmehl and McCaslin (1973) in extracts from some but not all spent shales tested. One sample of spent shale from the TOSCO process and one from the USBM gas combustion process were very high in soluble magnesium in relation to soluble calcium. Vlamis (1949) found a sharp reduction in lettuce and barley growth on a soil as calcium saturation of the cation exchange capacity (CEC) fell below 20% and the remainder of the CEC was dominated by magnesium. Walker et al. (1955) confirmed these results for some agricultural plants but found that some species native to serpentine soils (high magnesium content) grew well at this level and also at 2% calcium saturation, the lowest level in the study.

As mentioned for sodium and boron, the growth attained by certain species on leached and N and P-fertilized TOSCO spent shales indicates that no major problems with an excess of magnesium is anticipated on this material. However, some plant species may be sensitive to the relatively high amounts of magnesium in this and in spent shales from other retorting processes.

pH: freshly retorted spent shales will vary in pH with the retorting temperature and possibly with the amount of sodium carbonate minerals the oil shales contained. pH of retorted shales would be expected to decrease with time as CO_2 in the air would convert oxides to carbonates. pH's reported for spent shale have been determined largely on samples that had been retorted some time previously.

The range in pH for retorted spent shales reported by Schmehl and McCaslin (1972) was 8.6 to 12.1. Ward _et al_. (1971) reported a pH range of 7.8 to 9.9.

The effect of high soil pH _per se_ on plant growth is not well defined as it is usually associated with high sodium content as it will be on the spent shales. Black (1957) presents data of Bower and Turk where alfalfa yields were nil on a soil high in exchangeable sodium with a pH of 9.6. When the soil was leached with calcium chloride and then with water, the pH fell to 8.6 and plant growth was substantial.

Arnon and Johnson (1942) noted reduced growth of tomatoes, lettuce, and Bermuda grass grown in pH 9 nutrient solutions as compared to growth in lower pH solutions. It would appear that a pH between 9 and 10 is limiting to plant growth on the spent shales. This would probably vary with plant species and also with the availability of plant nutrients and possible effects of excess sodium and bicarbonate.

Extremely high pH spent shales such as the shale ash samples with pH values of 10.9 and 12 reported by Schmehl and McCaslin (1973) may present physical problems as well as chemical ones in that they may set up like the shale ashes reported on by Culbertson _et al_. (1970) and be physically unsuitable for plant growth.

Potassium: somewhat low levels of plant available potassium in two TOSCO spent shales were reported by Schmehl and McCaslin (1973). However, they found no response to fertilizer potassium in greenhouse studies. Other spent shales, including one TOSCO sample, tested high in potassium. No potassium deficiencies are anticipated in field studies, but if deficiencies do occur, fertilization should be no problem.

Bicarbonate: the possible plant toxicity of the bicarbonate ion has been discussed by Hayward and Wadleigh (1949). The effect is usually compounded by high sodium concentrations and high pH's. Bicarbonate can interfere with calcium uptake and plant species vary in tolerance to this ion.

Sulfate: Hayward and Wadleigh (1949) mention some situations where specific plant toxicities to high concentrations of sulfate ions have been found. However, sulfate is usually not considered to be toxic to plants unless concentrations are high enough to produce a salt effect rather than a sulfate ion effect _per se_.

Physical Considerations

A previous section in this chapter discussed the tremendous reduction in erosion potential as plant and litter cover becomes more dense on soils. Data are not available on ground cover potential on well managed native vegetation of the area as a function of soil texture, aspect, slope, and elevation. However, more cover cannot probably be expected than now exists on some of the sites. In other situations it is obvious that overuse has depleted the ground cover. Thus, a basic question posed in vegetative stabilization of spent shale is -- How much cover can be maintained under natural precipitation once a stand of adapted species has been established by leaching, fertilization, seeding, mulching, and sprinkler irrigation? This is a question we will investigate in phase II-A of this study.

The effect of aspect on plant species composition is rather obvious as pointed out by Cottle (1932). Klemmedson (1964) mentions that knowledge "of topographic influences seems, for the most part, to be confined to gross qualitative influences". Cottle (1932) cites work of Weaver in southeastern Washington where evaporation was only 64% as great on northeast as on southwest slopes. Further search of the literature would reveal additional information on aspect but would only confirm what we already know that south and west slopes are dry sites. Chapter 7 contains a diagram showing the profound effect aspect has on irrigation requirements.

The dark color is another factor to be considered in plant establishment on spent shales. Schmehl and McCaslin (1973) reported temperatures of 140 to 150° F at one-half inch depths in unshaded spent shales in greenhouse pots. Ward _et al_. (1971) measured a surface temperature of 77° C (170° F) on TOSCO spent shale in field studies. These temperatures are within the range reported by Schramm (1966) as lethal to seedlings on black coal wastes. Mulching and sprinkling will control temperatures for plant establishment on spent shales, but the effect of the black color on evaporation and possible heat effects on certain plant species where adequate vegetative and litter cover cannot be maintained to cover the spent shale surface need to be considered.

Steepness of slope of spent shale disposal piles is another factor that must be considered from both mechanical stability and vegetation establishment viewpoints. A discussion of the former is beyond the scope of this review. Slopes of 4-1 (25%) or less are favored from a revegetation standpoint as certain traditional soil preparation and seedling equipment can be used. The possibility of wildire also should be considered. Cook _et al_. (1970) state that grass fires on slopes of 3-1 (33%) can generate enough heat to kill grass.

Hand (1969) mentions that disposal problems may arise because spent shale is hot and because some spent shales contain combustible material. A discussion on the potential for spontaneous combustion of spent shales from the Green River Formation is contained in Volume I of the USDI (1973) impact statement. If a spent shale pile is warmer than normal soils within the area due to undissipated heat, plant adaptability problems might arise; also, the site would be drier than expected from the climate and topographic considerations because of greater evapotranspiration potential.

The effect of soil particle size on moisture relationships in soil and soil material has been discussed in Chapter 5 and will not be repeated here except to note that the spent shales produced by the various retorting porcesses range from silty material (TOSCO) to very coarse clinkered material (Union Oil process). These differences will have a profound effect on moisture relationships, species adaptability, and revegetation procedures. Spent shales that cement (Culbertson _et al_., 1970) would be unsuitable plant growth media (Haberman, 1973).

Compaction by vehicles, animals, or sightseers could result in drastic reduction in infiltration rates on the relatively fine textured TOSCO spent shale and this, in turn, could result in substantial runoff and erosion.

Overgrazing and overbrowsing of vegetation on spent shales and other disturbed areas could pose serious management problems. This problem has been encountered in revegetation of mine wastes in other places in Colorado. Management options might include seeding and planting of less palatable or non-palatable species, repellants, fences, and population control. Pocket gophers are a recognized problem in certain higher areas in Colorado (Turner *et al*., 1973).

Covering spent shale with soil or geological material would eliminate some but certainly not all of the problems posed in this review. Here again, density of plant and litter cover and erosion rates would be important considerations. Information on mill tailings that have been covered with soil and/or geological material in or near Colorado include the extensive uranium tailings stabilization work that was carried out in 1961 and 1962 by the A.E.C. on 40 acres of tailings and an inactive mill site at Monticello, Utah (ave. annual precipitation 14", elevation 7050'). In this work the tailings were graded to control runoff, to fill in pond areas, and to allow the tailings to be traversed by earth-moving machinery. Then the tailings were covered with an 8-12" layer of rock and soil and seeded to adapted grasses and legumes. (This work is detailed in a report of the U.S.A.E.C., 1963.) A follow-up report three years later indicates that the vegetation was well established, soil erosion was of a minor nature, and there was no evidence of transport or radioactive material from the site. The project involved movement of 350,000 cubic yards of material. Total cost was $190,000.

Some of the first stabilization work on Colorado uranium tailings was carried out by the Union Carbide Company in 1966 and 1967 on a former mill site about one mile east of Rifle (elevation 5400', ave. annual precipitation 11"). Here, approximately ten acres of tailings were leveled, drainage established around the pile, the sides were riprapped, the area covered with approximately 6" of earth, fertilized, seeded, fenced, and a sprinkling system installed (Beverly, 1968). In 1973 the area was supporting a good grass cover and blended in well with adjacent farmland. The area has received several sprinklings a year and has had a maintenance application of N fertilizer.

Uranium tailings at Gunnison, Naturita, Grand Junction, and Slick Rock, Colorado, and at Shiprock, New Mexico have been covered with soil. A tailings pile from the processing of gold ore at Colorado Springs was covered with soil a number of years ago. The Colorado Springs tailings were on a fairly steep slope, no maintenance was carried out after covering; as a result the cover has severely rilled and gullied.

At the Twin Buttes open pit copper mine south of Tucson, Arizona, the spoil from the overburden removed to get to the ore body has been piled into large dikes enclosing areas to be used for tailings disposal.

Aesthetics and long-term management have not been covered in this review. The need is obvious and these must be included in an acceptable spent shale disposal scheme.

CONCLUSIONS AND RECOMMENDATION

Conclusions

The chemical, physical, and hydrological characteristics of spent shale vary considerably according to the specific mining and retorting methods used. Spent shale materials from existing pilot plant retorting methods range from coarse clinkered ash (Union Oil Company) to a fine powdery ash with predominately silt sized particles (TOSCO II). Bulk densities average about 1.5 g/cc; specific gravities about 2.5 g/cc; porosities about 40%; and field moisture capacities about 20%. Water intake rates vary according to the specific condition of the surface with moderate infiltration rates (1-1.5 in/hr) on moist or mulched surfaces but near zero infiltration rates on dry exposed saline surfaces,for TOSCO spent shales.

The chemical content also varies, with large quantities of Na, Ca, Mg, and SO_4 readily leachable, and lesser quantities of other ions.

The untreated spent shale materials are highly erodable. The uniform texture and single grained structure create a serious erosion condition, especially on steep slopes. Treatments such as pre-wetting and compaction will reduce the hazard somewhat. However, it becomes increasingly apparent that a cover of soil or rock over the spent shale plus revegetation will be the most effective long term means of stabalizing spent shales.

Important physical considerations are particle size, color, and degree of slope. Infiltration rates on fine textured spent shales could be critical if reduced by compaction. Spent shales produced by a retorting process that results in spent shales that cement would be unsuitable for plant growth. Residual heat in spent shale piles would enhance evapotranspiration and make disposal sites drier than expected from climatic and topographic considerations.

Salt must be leached from spent shales if they are to support plant growth. Leaching should pose no particular problem if infiltration rates are adequate, however, disposal of several feet of leach water does pose a problem, as does resalinization of leached spent shales.

Plant available N and P are extremely deficient in spent shales; fertilization is feasible. The need for long-term N applications is a distinct possibility. Other plant nutrition problems are possible but difficult to evaluate. If plant nutrition problems arise, differences in tolerance among and within plant species would be expected.

Aesthetics and long-term management are not discussed in this review but must be included in the planning phases of any spent shale disposal program. Wildlife use on disposal areas will require careful management.

Recommendations

This review and summary of known characteristics of spent shale suggests many areas which require additional research and consideration by the organizations charged with rehabilitation of the spent shale piles. One of the most obvious deficiencies is the extent of information regarding the spent shale materials. All of the data and conclusions presented in this report are based on spent shale materials from pilot project plants and may not be representative of the spent shale materials from commercial scale plants. As a result planned restoration measures may require modification when the proposed plants become active. In addition, a number of other recommendations may be made:

1. Detailed water balances should be calculated for the specific disposal areas so as to determine the probability for leaching and pollution at each site. This would require the installation of good quality weather stations and collection and analysis of the data during the developmental phases of the various proposed plants.

2. A thorough analysis of erosion potentials and erosion control measures should be made at each site prior to disposal of spent shales. This should include recommendations on techniques for compaction, slopes, drainage, and surface erosion control.

3. The use of a soil cover on the spent shales should be tested and evaluated with respect to leaching requirements, water balance calculations, plant establishment, and potential erosion.

4. The use of coarse textured soil or rock on the face of the spent shale pile should be considered and tested with respect to plant water availability and erosion potential.

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Chapter 7

WATER REQUIREMENTS FOR STABILIZING AND VEGETATING SPENT SHALE IN THE PICEANCE BASIN

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INTRODUCTION

One of the important factors in the future development, and ultimate size, of an oil shale industry for the Piceance Basin of Colorado is the availability of water. This report is an attempt to provide planners with estimates of irrigation water requirements for the revegetating disturbed areas, and surface waste disposal areas for spent shale and overburden.

Because it is difficult to present water requirements in the abstract, water requirements are also projected as the 20-year and annual water requirements for a hypothetical 250,000 barrel per calendar day (bbl/cd) oil shale industry. This size industry is equivalent to projections for 1979 (USDI, 1973, Vol. I, p. III-9). Since previous water requirement estimates vary widely, this report provides a single estimate of the total water requirements for the projected 250,000 bbl/cd oil shale industry, based on the best available information.

The major assumptions are stated, and hopefully sufficient detail is provided for the planner to adjust the answers to the specific conditions desired. Persons desiring specific climatological data, technical details of the evapotranspiration methodology, or mining volumes calculations should request copies of the technical appendices from the Department of Earth Resources, Colorado State University.

After initiation of the project it quickly became apparent that the water requirements for stabilizing and revegetating waste product disposal areas had largely been ignored in earlier water requirement studies. More important, water requirements are a function of the specific mining, retorting, and disposal methods utilized by the industry. The only data available are from pilot research or prototype plants with maximum capacities of 833 bbl/cd (1,000 tons of 35 gal/ton shale per day). Therefore, this study concentrates on providing an evaluation of factors that affect water use, and in accurately determining the irrigation requirements for revegetation of the disturbed areas associated with an oil shale industry.

The climate of the basin is arid-steppe and is subject to dramatic changes within short distances, or over a short time span. To provide elevation zone planning data a regression analysis of monthly climatological data (temperature and precipitation) from nine immediate-area weather stations was used to develop monthly elevation zone estimates. A regression analysis of April-October class A pan evaporation for eight Colorado evaporation station from Climax (11,300 ft.) to Grand Junction 6ESE (4,710) was used to provide estimates of potential evaporation rates during the growing season.

In the initial stages of the evaluation, the Thornthwaite and Blaney-Criddle methods of estimating water use and irrigation water requirements were provided for the 5-8,000 ft. elevation zone. Because of limitations in these methods, the Jensen-Haise method of estimating evapotranspiration was modified to provide monthly water use estimates for specific vegetation types for both the winter (moisture accumulation period) and the growing season use. The modified Jensen-Haise methodology for the Piceance Basin uses linear regression techniques for estimating all elevation zone data. The methodology was also adapted to provide evapotranspiration estimates for different slopes, aspects, and temperature relationships. The complete study provides relatively simple equations that can be used to estimate evapotranspiration (or irrigation water requirements) for specific vegetation types growing on 0-50% slopes and 8 aspects. Because spent shale disposal areas will have higher than normal temperature relationships for a number of years, a temperature correction factor is provided that can be used to provide estimates of water use for sites that are warmer or colder than the regional averages.

Presentation of the water requirements, spent shale and overburden disposal data, and total land requirements for a hypothetical 250,000 bbl/cd industry is intended only as a framework for displaying the magnitude and variety of recognized problems.

NEED FOR REVEGETATION

Potential surface disturbances associated with a commercial oil shale industry are of such magnitude that stabilization, rehabilitation, and revegetation of the land surface are imperative. The major disturbances from an oil shale industry will be the result of: (1) surface disposal of spent shale and overburden; (2) storage areas for mined shale; (3) land areas for retorting plants and mine facilities; (4) road and utility rights-of-way and borrow areas; (5) floodwater-retarding structures (or debris basins and sediment traps) to protect plants, disposal areas, or downstream floodplains; and (6) urban areas and facilities associated with the oil shale industry population increase. This report is concerned only with the water requirements for stabilization and revegetation of spent shale and overburden materials, but the results are applicable to revegetation of other disturbed areas.

Disposing of at least 52,700 tons/cd of spent shale and other solid waste products for a 50,000 bbl/cd commercial scale oil shale retorting plant poses a major problem. Since the USDI (1973) and other reports project an oil shale industry of the 1,000,000 bbl/cd for the Piceance Creek Basin, the spent shale and other waste product disposal problem could ultimately exceed one million tons per calendar day. Because spent shale occupies more space than the mined out areas, a portion of the spent shale must be disposed of on the surface. For various reasons, surface disposal may be necessary for almost all of the spent shale and other solid waste products from an oil shale industry. Even if the spent shales are compacted in some of the deeper dry canyons of the basin, the areas requiring revegetation could approach one thousand acres per year for an industry of one million bbl/cd.

The extent of overburden disposal areas requiring revegetation is directly related to the extent of surface mining. The USDI indicates that Colorado leasing tract C-a is amenable to surface mining (USDI, 1973, Vol. III, p. III-10). They further estimate that the first 16 years of surface mining operation on this site would necessitate off-site disposal for some 256 million cubic yards of waste material. The mined-out area would then be sufficient to accomodate the spent shale and overburden from additional operations at this site. The surface area of the overburden is estimated at 980 acres after 16 years use of the Water Gulch disposal site (USDI, 1973, Vol. III, p. IV-15). Thus, an operation of this type would require the revegetation of approximately 50 acres/year.

Revegetation of these disturbed areas is difficult and the term "harsh site" provides a useful image of the problem. Brown, et. al (1971) define harsh sites as those denuded slopes that persist as dangerous erosion and runoff hazards due to environmental conditions. These sites may have high solar radiation loads, high variable wind speeds, high surface temperatures, or inadequate soil water levels in the root zone during the growing season. The relative magnitude of these variables is related to the aspect, slope, altitude, topography, depth of soil (or soil-like materials), exposure to prevailing winds, time of year, and the hydrologic conditions. For spent shale the physical factors of particle size, hydrophobic conditions, dark color, and the chemical factors of salinity and deficiency in nitrogen and phosphorus are important additional considerations. The most important factor for plant establishment and growth under all considerations, however, seems to be available water in the plant root zone.

Severe disturbances (such as the surface disposal of large volumes of hot, dark-colored spent shale into dry canyons) may result in drastic alterations of many microclimatic variables, creating a number of unforeseen revegetation problems. For example, snow accumulation would not be expected on the freshly-placed spent shale piles because of the high temperature of the spent shale.

Natural Revegetation

Restoration of disturbed areas by natural revegetation may be extremely slow for the lower elevation zones of the Piceance Creek Basin. Average annual precipitation varies from 9.12 inches at Rangely, Colorado (elevation 5,216 feet) to about 25 inches at the 9,000-foot level. Indications (from Chapter 3 of this report) are that natural revegetation is much too slow to be environmentally acceptable, except for the most favorable sites or relatively small disturbed areas. The disturbed areas associated with spent shale or overburden disposal will be large harsh sites which will require long periods for natural revegetation to take place.

Artificial Revegetation

Many of the disturbed areas in the Piceance Creek Basin will be on harsh sites. Ideally, species for revegetation must be both physiologically adapted to the specific environment and morphologically suitable for providing adequate ground cover. The generally xeric conditions, and other problems associated with harsh-site revegetation, necessitate the selection of native or adapted plants.

Since it seems unlikely that a satisfactory species or species mix can completely stabilize the spent shale disposal areas under the natural climatic regime, it appears necessary to modify the plant environment, at least initially, so that a vegetative cover can be rapidly established. This environmental modification will include: (1) irrigation to leach salts from the root zone to tolerable levels for the species selected, and (2) irrigation to supplement natural rainfall during the growing season to ensure the establishment of a successful vegetative cover.

Irrigation is recognized as necessary for intensive crop production in the Piceance Basin. At the higher elevations (and during the more favorable years at lower elevations) plant cover can be established without irrigation on disturbed areas, overburden materials, and leached spent shales. But non-irrigated areas may require a number of years to establish the desirable degree of vegetative cover for erosion control.

For spent shale disposal areas and other harsh sites, the combination of the high surface temperatures resulting from the dark color of some spent shales and the high salinity may inhibit the establishment of any appreciable plant cover without leaching, mulching, and irrigation for at least the initial establishment. Because of aesthetics and other environmental considerations, the public will probably protest any large areas of unvegetated spent shale. The alternative is to treat the spent shale disposal areas and other harsh sites with intense agronomic practicies to provide a rapid vegetative cover.

Research conducted to date indicates that spent shales can be used as a medium for plant growth (Schmehl and McCaslin, 1973, Bloch and Kilburn eds., 1973, and Berg-Phase II-A of this report). By leaching the spent shale profiles with several feet of water passed through a two to four-foot root zone, the salts can be reduced to levels found in productive soils (Berg, Chapter 6 of this report). Hutchins, et. al (1971) have indicated that sprinkler irrigation is a satisfactory method of establishing vegetation on spent shale piles. Because of the slopes involved and erodibility of spent shales, any other method of irrigation would probably be unsuitable for vegetation establishment.

The critical question will be whether an adequate plant cover for erosion control can be maintained under natural precipitation. Because the precipitation and vegetation of the area are in delicate balance, it may be necessary to provide standby irrigation systems to maintain vegetation on critical areas during drought periods.

Phase II-A of this study is specifically designed to investigate surface stability of spent shales and soil-covered spent shales under natural precipitation conditions after the initial vegetation has been established by irrigation and other intensive practices.

An unanswered question in the use of irrigation to establish adapted species on critical sites, is how long the irrigation should continue. Experience on the experimental plots at Anvil Points (phase II-A of this report) showed that a 60% ground cover could be achieved by September after spring seeding a mixture of native grass species and irrigating as needed. The 60% ground cover obtained is probably more than the Anvil Points site can support under natural rainfall conditions. As the study continues, irrigation will be stopped and the vegetation permitted to thin out, to determine the density which can be supported under natural rainfall.

In this report, water requirement projections are based on irrigating for two growing seasons after planting.

WATER REQUIRED FOR REVEGETATION

Evapotranspiration Estimation: The Jensen-Haise Method

Factors Affecting Evapotranspiration

Evapotranspiration (E_t) is a coined word used to describe the combination of evaporation from water surfaces, moist soil, and transpiration from plants. It is generally synonymous with consumptive use, and total use. In broad terms, it is the amount of water used by plants to produce a mature crop. Evapotranspiration includes three major forms of water loss: (1) transpiration losses and uses by plants; (2) interception losses of precipitation caught by vegetation and evaporated; and (3) direct evaporation from soil, ice, snow, and water surfaces not included in the other terms.

Transpiration from plants occurs in response to the same energy sources as evaporation from a water surface. The specific factors have been known for some time, but their evaluation is difficult because of interdependent effects. The most important climatic factors are solar radiation, wind movement, humidity, air temperature, atmospheric pressure, and precipitation form and amount. The most important nonclimatic factors are related to plant characteristics: size, spacing, leaf area, stage of maturity and the quantity and quality of available soil water.

In recent years the energy-balance concept has added greatly to the understanding of evapotranspiration. Energy balance is simply an accounting of the incoming and outgoing thermal energy for a vegetated surface, which provides a measure of the energy available for evapotranspiration. The energy budget equation may be written:

$$R_n + \text{advected energy} = A + G + E_t + \text{heat storage in the vegetation} + \text{photosynthesis (Chang, 1968)} \quad (1)$$

where R_n is net radiation, A is heat transfer to the air, G is heat transfer to the soil, and E_t[1] is evapotranspiration. By ignoring the relatively small components of advected energy, photosynthesis, and heat storage in the vegetation, the equation is reduced to:

$$R_n = A + G + E_t \quad (2)$$

which states that the net radiation is disposed of as heat flux to the soil, heat flux to the air, and used for evapotranspiration.

The soil heat component (G) of equation (2) is usually neutral for long periods of time, and is therefore often ignored. However, for spent shale disposal areas, soil heat can be an important energy source. Heat relationships for major surface spent shale disposal areas are unavailable simply because a commercial industry has never produced a large volume of spent shale. Heley (1973) reports that for the TOSCO II retorting technique processed shale[2] is cooled to about 200°F and moisture is added prior to transfer to the disposal areas. Plans call for the waste material to be distributed and compacted in 18-inch lifts on the surface of the embankment. The final internal temperature of the spent shale disposal areas is difficult to estimate because of the lack of information regarding the specific heat capacities for compacted spent shale, and the large energy inputs from solar radiation on the exposed black surface of most spent shales[3]. A preliminary evaluation indicates the long-term internal temperature of the spent shale disposal areas would exceed 100°F. Even after 10 yrs. the spent shale disposal areas may have surface temperatures averaging about 10°F higher than native soils in the region.

It is beyond the scope of this report to attempt an evaluation of the temperature relationships for spent shale disposal areas, but further investigations should be conducted to determine the probable temperature gradients, equilibrium temperatures, and the effect on air temperatures above the disposal piles. Certainly, snow will not accumulate on the surface of the disposal piles for several years, and the normal growing season for any vegetation will be considerably longer than in native soils.

Methods of Measuring and Estimating Evapotranspiration

A number of empirical methods are used to estimate consumptive use and irrigation water requirements for the standard irrigated farm crops. These methods all provide a good estimate of water use for the specific crop, or

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[1] Generally shown as LE, or latent heat of vaporization of water (about 590 cal/gm).

[2] Processed shale is the term utilized for the spent shale remaining from the TOSCO II process.

[3] The USDI (1973), p. I-48, indicates surface temperatures of 77°C (171°F) for TOSCO shale.

region, for which they were originally developed. Unfortunately, these formulas were developed to estimate agricultural growing season water use for flat irrigated fields, below 5,000-ft. elevations, within large areas of irrigated cropland, and for a strictly monocultural vegetation. These conditions minimize the effects of heat transfer, differences in the drying power of the air, and uneven wind currents.

In contrast to irrigated crop consumptive use, native vegetation evapotranspiration estimation requires estimates for the entire year. The Piceance Basin has elevation zones from less than 5,000 ft. to more than 9,000 ft., wide variations in topography, at least seven major vegetation types, many barren cliffs or canyons that create hot upslope winds, and the Basin is in the middle of a large area of water-deficient, sparse vegetation. These factors all emphasize the need for special evapotranspiration methodology. They also emphasize the impossibility for the generalized methodology to provide specific irrigation requirements for individual revegetation sites or years.

The Jensen-Haise method (1963) was chosen for this study because, with modification, it can be used to estimate annual evapotranspiration, and provide quantification of observed differences in water use for different slopes and aspects. It was also specifically developed for use in the arid or semiarid western United States. The Jensen-Haise method uses the evaporating power of solar radiation as the main parameter and modifies it by a linear formula using mean air temperature in °F. The Blaney-Criddle (1950) and Thornthwaite (1948) are two other commonly used equations for estimating E_t or consumptive use. These methods were tested and reported in the preliminary reports for this study.

The evapotranspiration estimates contained in this report are bookkeeping methods, and make no pretense toward theoretical elegance. The Jensen-Haise method was modified to provide annual estimates by elevation zones. The original equation is used only to estimate the April-October potential evapotranspiration for the 5,000-ft. elevation zone. Modifications were made to estimate E_t for elevation zones up to 9,000 ft. and to estimate losses during the November-March moisture accumulation period.

Estimated Evapotranspiration by the Modified Jensen-Haise Method

The Jensen-Haise equation represent an empirical relationship between the factors in the energy budget equation (1) as they relate to irrigated cropland conditions in the arid or semi-arid areas of the western United States. The equation estimates potential evapotranspiration (E_{tp}), which is the upper limit, or maximum evapotranspiration (E_t) that occurs over periods of 10 days or longer under given climatic conditions. This use rate is approximated by well watered alfalfa with 12 to 18 inches of top growth. Conditions for this high water use rate seldom occur in the Piceance Basin, except for short periods when water is readily available from the soil. The scattered vegetation (less than 100% ground cover), limitations in water availability, and a native vegetation largely adapted to xeric conditions all tend to limit water use to much less than potential. Water use by vegetation on spent shale and overburden disposal areas will probably be similar to that for native vegetation because many of the species planted will be native to the area, and because the plants will be allowed to mature and produce seed.

The ratio of water use by specific vegetation to potential evapotranspiration (E_{tp}) is called a plant water use coefficient (K_c) . This allows for differences in plant canopies, stages of growth, plant densities, and individual plant characteristics. The computed potential evapotranspiration rates are adjusted for growth stages and other factors for the desired period by applying the plant water use coefficient as follows:

$$E_t = K_c E_{tp} \qquad (3)$$

Different monthly coefficients are needed for each major vegetation type. Crop coefficients for irrigated pasture and native meadows are available from irrigation studies (Jensen and Haise, 1963; Pair et al. 1968; and Kruse and Haise, 1973). Monthly water use coefficients for the plant mixtures used in rehabilitating spent shale and other disturbed areas were adopted from those used for irrigated hay and pasture. The adjustments were made using the growth characteristics of western wheatgrass (Agropyron smithii) from research by Blaisdell (1958), and Hyder and Sneva (1963). This adjustment in K_c values results in reduced water requirement estimates for native grasses and other plants that are allowed to mature and produce seed rather than being harvested to maintain vegetative growth.

The special conditions for rehabilitation of spent shale and overburden areas require evapotranspiration estimates for the entire year. Therefore, the evaluation of evapotranspiration was conducted as:

$$E_t = E_{tw} + E_{ts} \qquad (4)$$

where

E_{tw} = Evapotranspiration for the November-March water accumulation period (mostly as snow).

E_{ts} = Evapotranspiration for the April-October growing season.

As previously noted, spent shale disposal areas have higher temperature relationships than normal regional soils, and therefore, tend to have higher air temperatures above the disposal piles. There are also large temperature differentials between north and south facing slopes during the daytime (Marlatt, 1973). To account for these differences a temperature correction factor (T_{cf}) was added to the basic Jensen-Haise equation. The T_{cf} provides a quick means of adjusting evapotranspiration for higher or lower than normal temperatures. Specific temperature correction factors are the departure of average mean monthly temperatures from regional elevation zone temperatures. For this report, temperature correction factors are incorporated in the elevation zone evapotranspiration equations, but the slope temperature effects are only available in Appendix E.

Slope or exposure climate is determined to a large extent by the amount of direct solar radiation and heat received on a specific slope and aspect. The basic Jensen-Haise equation was modified to account for these factors, but because of space limitations, this information is not included in this report.

Evapotranspiration varies with elevation primarily because of lower temperatures, and shorter growing seasons at higher elevations. Table 1 provides monthly elevation zone evapotranspiration estimates for spring planted and full season water use by revegetation areas. These estimates assume unlimited soil water supplies and normal temperature regimes. The monthly E_t estimates provided in Table 1 are linear, so interpolation can be used to estimate average monthly water use rates for any elevation in the basin. For planning purposes, the revegetation area water requirements for specific elevations can be estimated by the following equations:

$$\text{Spring Planting} \quad E_{tsp} = (46.45 - 3.86E_1 + 0.994T_{cf}) \qquad (5)$$

$$\text{November-March} \quad E_{tw} = (5.21 - 0.30E_1 + 0.092T_{cf}) \qquad (6)$$

$$\text{April-October} \quad E_{ts} = (41.10 - 2.54E_1 + 0.756T_{cf}) \qquad (7)$$

where E_1 = elevation of evaluation area in thousand feet.
T_{cf} = temperature correction factor (^{o}F).

For example, the water requirements for a spring planting at 7,200 ft. elevation on a spent shale disposal area, with average monthly air temperatures 5^{o}F higher than normal, are estimated as $E_{tsp} = 46.45 - 3.86(7.2) + 0.994(5) = 23.7$ inches evapotranspiration.

The user of these E_t estimates should remember that they are generalized for the Piceance Basin and specifically for the revegetation areas.

Table 1-. Estimated evapotranspiration (Inches) for spring planted and full season on irrigated revegetation areas.

	Elevation zone				
Month	5,000	6,000	7,000	8,000	9,000
	Inches	Inches	Inches	Inches	Inches
			Spring Planting[1]		
April	.84				
May	3.07	3.38	1.46		
June	4.20	3.25	3.54	4.08	2.07
July	7.49	6.01	4.68	2.87	2.88
August	6.28	5.79	5.30	4.58	3.13
September	3.83	3.47	3.12	2.77	2.41
October	1.44	1.39	1.33	1.27	1.22
Total[2]	27.15	23.29	19.43	15.57	11.71
			Full Season		
November	.74	.70	.66	.63	.59
December	.46	.45	.43	.41	.39
January	.48	.45	.42	.39	.36
February	.72	.65	.59	.52	.46
March	1.31	1.16	1.01	.86	.71
Subtotal[3]	3.71	3.41	3.11	2.81	2.51
April	2.09	1.87	1.66	1.43	1.22
May	4.82	4.23	3.64	3.05	2.46
June	6.46	5.91	5.35	4.80	4.24
July	6.73	6.18	5.64	5.10	4.55
August	4.24	3.91	3.58	3.25	2.92
September	2.70	2.45	2.20	1.95	1.70
October	1.36	1.31	1.25	1.20	1.15
Subtotal[4]	28.40	25.86	23.32	20.78	18.24
Total	32.11	29.27	26.43	23.59	20.75

[1] Planting dates assumed to be 14 days later per 1,000 ft. increase in elevation starting about April 22 at the 5,000 ft. elevation zone.

[2] $E_{tsp} = (46.45 - 3.86E_1 + 0.994T_{cf})$

[3] $E_{tw} = (5.21 - 0.30E_1 + 0.092T_{cf})$

[4] $E_{ts} = (41.10 - 2.54E_1 + 0.756T_{cf})$.

Water Requirements for Revegetating Disturbed Areas

Leaching Requirement - Spent Shale

Spent shale can be used as a plant growth medium if the salt content in the root zone is reduced to a tolerable level (Chapter 6). Leaching appears to be the only feasible method of reducing the salt content. The minimum leaching requirement seems to be three to four feet of water leached through the rooting zone. This amount of leaching water should reduce the salinity of spent shale to levels found in productive soils.

For this evaluation, it was assumed that the net leaching requirement for spent shale disposal areas would be 48 inches of irrigation water. It is further assumed that the leaching would be accomplished with sprinkler irrigation using very low application rates (about 0.10 inches/hour), and that the irrigation efficiency would be about 80%. Therefore, the gross irrigation requirement for leaching would be 60 inches, or 5.0 ft. of irrigation water per surface acre of the spent shale disposal area being rehabilitated

Decision makers are cautioned to note that there are a number of unsolved problems related to leaching spent shales for permanent vegetation establishment. There is also the alternative of covering the surface disposal areas with soil and/or overburden materials for revegetation (Chapter 6).

Irrigation requirement

The evapotranspiration estimates shown on Table 1 are monthly averages and do not provide for peak consumptive use. While this factor is beyond the scope of the present study, it should not be ignored in the design of the sprinkler irrigation system. Net irrigation estimation is based on average rainfall during the growing season, but in the Piceance Basin, precipitation variability is such that effective rainfall may be nonexistent during drouth periods. Therefore, in a given year the irrigation system may need to furnish the entire water requirement of the area being revegetated.

Under natural conditions, rainfall and soil water stored in the root zone are the sources of plant water requirements. In the rehabilitation of surface disposal sites and other disturbed areas, irrigation water is applied only to the extent required for prompt vegetation establishment. Effective rainfall is perhaps the most important factor in estimating the irrigation requirement. As noted in the Introduction, a regression analysis of elevation zone precipitation was developed in preliminary phases of this study. For irrigation evalutions, it was assumed that precipitation would amount to 80% of the predicted precipitation for the elevation zone, and that all precipitation would be 100% effective up to the available water holding capacity of the root zone. Specific irrigation water requirement evaluations were conducted for each elevation zone for spring planting and full season irrigation seasons, and are available on special request. Net irrigation requirements are all evaluated as $I_{net} = E_t - P_e$, where P_e is inches of effective precipitation.

Spring planting: irrigation design was based on daily irrigation water applications for 21 days for germination and establishment. During this period the rate of evaporation is assumed to be 90% of E_{tp}, and normal precipitation is ignored for scheduling purposes. A crop development curve similar to that shown for normal field crops in "Sprinkler Irrigation" (Pair et al., 1969) was used to develop K_c values. The grass-shrub vegetation mix is assumed to reach a maximum K_c value of 0.80 by the 90th day after planting.

The rooting zone for spring planted vegetation areas was assumed to be 18 inches, with 2.35 inches of available water holding capacity. Normal net irrigation application was assumed to be 1.00", and the sprinker irrigation efficiency was assumed to be 75%. For elevation zones 7,000 ft. and below the root zone (24 inches) should be irrigated to field capacity (3.16 inches) in the fall to prevent winter kill from drought. Irrigation evaluations for all elevation zones show precipitation effectiveness to average 48% of normal regional April-October precipitation, or $P_e = 1.48 E_1 - 4.45$ for estimating purposes.

Table 2 provides the estimated monthly irrigation requirements for spring planted 10-acre revegetation areas. Water requirements per acre are obtained by dividing by 10. Specific spring planted revegetation site water requirements may be evaluated as:

$$I_{wsp} = (56.53 - 5.93 E_1) /10 \tag{8}$$

where I_{wsp} is the first growing season gross irrigation water delivery requirement per acre.

Full season: irrigation design was based on estimated evapotranspiration (Table 1) and precipitation rates from the end of the first growing season (October) through the next growing season. The net irrigation water requirement (inches) was based on a 24 inch root zone with 3.16 inches available water holding capacity, and 1.50 inch net irrigation application. The sprinkler irrigation system was assumed to have a 75% efficiency.

Effective annual precipitation can be estimated from the equation $P_e = 2.63 E_1 - 5.37$, or in terms of total annual precipitation, it would be approximated by $P_e = 2.94 + 0.622P$, where P = annual precipitation (inches).

Table 2 provides the estimated monthly irrigation water requirements for full season irrigation of 10-acre revegetation areas by elevation zone. Per acre water requirements for specific elevations can be estimated by the equation:

$$I_{wf} = (57.44 - 6.08 E_1) /10 \tag{9}$$

Table 2-. Estimated irrigation water required (Acre-feet) for spring planted and full season irrigation of 10-acre revegetation areas on a horizontal surface.[1]

Month	Elevation zone				
	5,000	6,000	7,000	8,000	9,000
	Acre-ft.	Acre-ft.	Acre-ft.	Acre-ft.	Acre-ft.
			Spring Planted		
April	.93				
May	3.21	3.76	1.57		
June	4.07	2.67	2.99	4.53	2.09
July	6.53	4.53	2.70	1.48	1.07
August	5.92	4.92	3.92	1.56	
September	3.42	2.64	1.88	1.52	
October	2.80	2.43	1.96		
Total[2]	26.88	20.95	15.02	9.09	3.16
			Full Season		
April	.80				
May	4.66	3.03	1.08		
June	6.58	5.56	4.52	3.50	1.46
July	6.80	5.83	4.88	3.92	1.26
August	3.66	2.83	2.01	1.19	
September	2.17	1.51	2.39	.19	
October	2.37	2.20			
Total[3]	27.04	20.96	14.88	8.80	2.72

[1] Assuming a 75% irrigation efficiency using sprinkler irrigation.

[2] Horizontal surface $I_{wsp} = 56.53 - 5.93 E_1$

[3] Horizontal surface $I_{wf} = 57.44 - 6.08 E_1$

Note: Per acre irrigation requirements are obtained by dividing by 10.

where I_{wf} is the acre-ft. per acre gross irrigation water delivery requirement for the sprinkler irrigation system.

Most of the surface spent shale disposal areas will have some sloping faces, and preliminary indications are that a 25% slope will be acceptable. Therefore, Figure 1 is included in this report to show the estimated net effect on full season irrigation water requirements of 25% slope facings for revegetation areas at 7,000 ft. A simple ratio can be used to provide suitable estimates of irrigation water requirements (acre-ft.) for the various aspects at other elevation zones. Equations for estimating slope variations from 0-50% are available.

WATER REQUIREMENTS FOR A HYPOTHETICAL 250,000 BARREL PER DAY OIL SHALE INDUSTRY

The U. S. Department of the Interior (1973) predicts a commercial oil shale industry could begin about 1976 (under the most optimistic estimate), and by 1980 a productive capacity of 250,000 bbl/cd could be established (Vol. I, III-9). This production would consist of two 50,000 bbl/cd plants on private land, a 100,000 bbl/cd unit utilizing surface mining at leasing site C-a, and a 50,000 bbl/cd plant utilizing underground mining at leasing site C-b. While the timing of this developmental stage may be questionable, a summary of mining volumes, waste disposal problems, land requirements and total water required for a 20-year project life should be useful. Ideally, the evaluation should show the probable impact of the total projected industry, but the 20-year summary for the four initial industries is hopefully more understandable.

It should be recognized that at present there is no shale oil production, and that this report reflects only the technology of the early 1970's. Since no specific method of retorting has been announced, the TOSCO II process is used as the model for all retorting and spent shale disposal evaluations. This process gives oil yields of approximately 100% of Fischer assay, seems the most advanced technically, and the most information is available as to the water requirements for disposal, compaction, and revegetation.

In situ methods are ignored for this study because the available information on the methodology is not sufficient to permit any water requirements estimates.

Oil Shale Mining, Processing, and Disposal Relationships

The available mining and surface retorting technology for an oil shale industry is summarized by the USDI (1973). Chapter 4 of this report also provides an evaluation of mining techniques. Therefore, this report is confined to a summary of the mining and disposal volumes (acre-ft.), land requirements, and total water required.

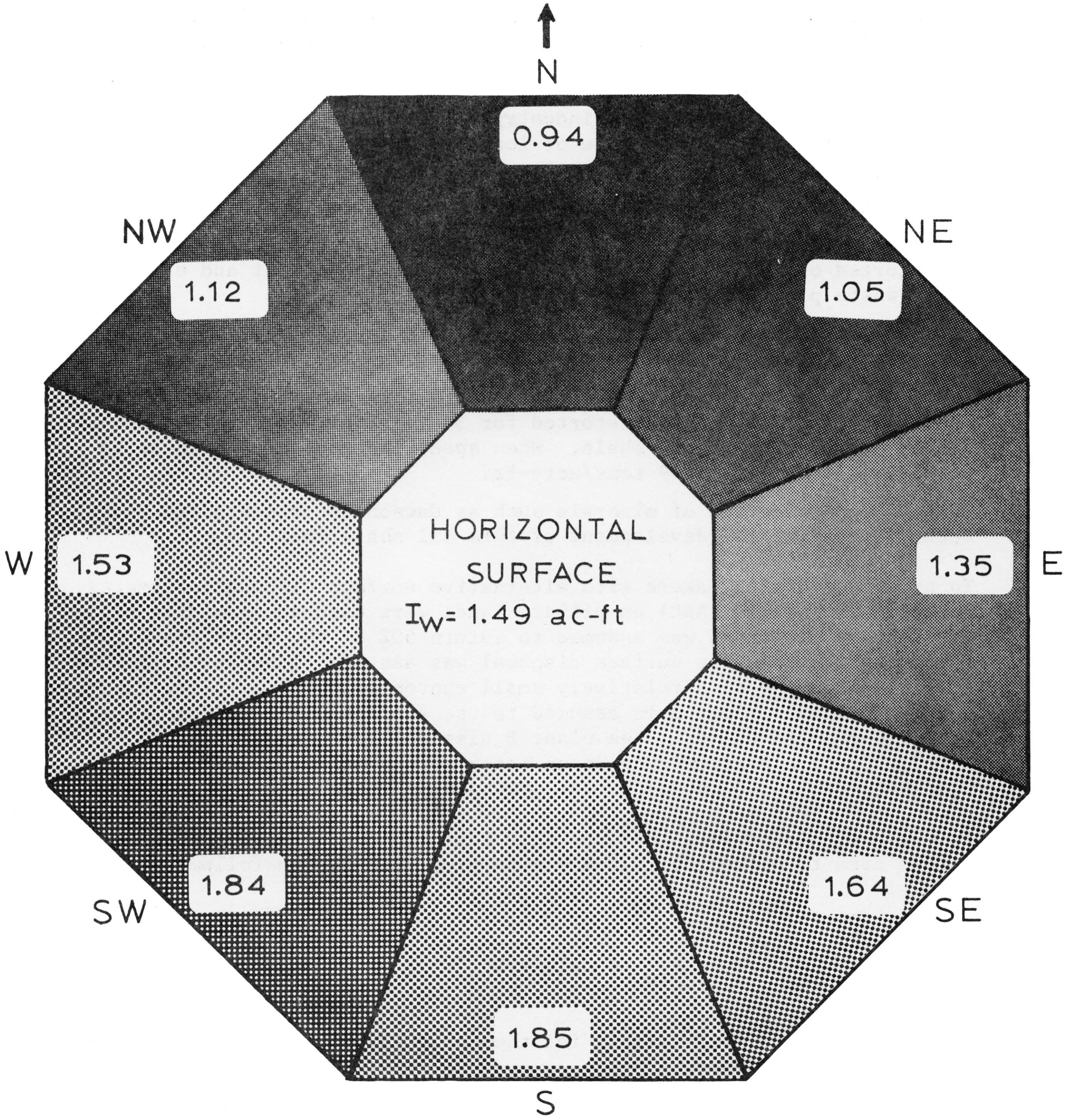

Figure 1. Estimated irrigation water required (Acre-feet) for full season irrigation on the horizontal surface and 25% slope facings of revegetation areas at 7,000 ft.

Table 3, provides some of the twenty-year mining and waste disposal relationships for the projected 250,000 bbl/cd of upgraded shale oil production capacity. Some of the basic assumptions used in developing the table are:

(1) 50,000 bbl/day oil shale industry will need to produce 53,500 bbl/cd of raw shale oil because of losses (7%) in upgrading.

(2) The retorting process would be 100% efficient in terms of Fischer assay oil grade.

(3) Dust losses in mining and crushing were estimated to be 1.3% of retorted oil shale, and the disposal of recovered dust and other solid waste products would amount to the same total.

(4) That 30 gal/ton oil shale weighs 2,904 tons/acre-ft., and 35 gal/ton oil shale weighs 2,821 tons/acre-ft.

(5) Spent shale and other solid waste materials amounts to about 84% by weight of the raw shale retorted for 35 gal/ton, and 86.6% by weight for 30 gal/ton oil shale. When spent shale is compacted to 95 lbs/ft.^{3}, it weighs 2,069 tons/acre-ft.

(6) No co-production of minerals such as dawsonite or nahcolite would occur in the initial development of this oil shale industry.

To provide decision makers with alternative surface disposal estimates, the two projected plants (A&B) on private lands were used to show different disposal systems. Plant A was assumed to return 50% of the spent shale to the mined out area, and the surface disposal was assumed to be at the 7,300 to 7,900 ft. elevation in a relatively small canyon (150,000 acre-ft. capacity) on the Roan Plateau. Plant B is assumed to use surface disposal for all spent shale and other solid wastes. The plant B disposal area was assumed to be at the 6-7,000 ft. elevation zone in an intermediate size canyon with a disposal capacity of 300,000 acre-ft. for depths of about 660 ft.

An evaluation of several canyons show that (up to the canyon's capacity) the surface area to be rehabilitated can be predicted by the following equation:

$$A_{ts} = 41.24 \, D_v^{0.57} \qquad (10)$$

where A_{ts} = surface area (acres) for the basically horizontal top surface of the disposal pile.

D_v = disposal volume of spent shale or overburden in thousand acre-feet (Acre-ft./1,000)

Table 3-. Twenty-year mining and waste disposal relationships for the projected 250,000 barrel per calendar day (bbl/cd) of upgraded shale oil production capacity.

		Private land		Federal land		
Item	Units	Plant A	Plant B	Tract C-a	Tract C-b	Total
Plant capacity	bbl/cd	50,000	50,000	100,000	50,000	250,000
Expected mining method		Underground	Underground	Surface	Underground	
Grade of shale retorted	gal/ton	35	35	30	30	
20-year mining volume						
Oil shale - retorting	Ac-ft	168,322	168,322	381,550	190,775	909,969
Oil shale - low grade	Ac-ft			47,420		47,420
Mine waste & overburden	Ac-ft			172,270		172,270
Total mined	Ac-ft	168,322	168,322	601,240	190,775	1,128,659
20-year waste disposal						
Spent shale and other solid waste products[1]	Ac-ft	190,490	190,490	457,690	228,845	1,067,515
Overburden (25-years)[2]	Ac-ft			215,339		215,339
Total waste disposal	Ac-ft	190,490	190,490	673,029	228,845	1,282,854
Estimated surface disposal	Ac-ft	95,200(50%)	190,490	524,800[3]	112,100[4]	827,300
Land requirements						
Surface facilities[5]	Acres	140	140	200	140	620
Mine development[5]	Acres	10	10	1,600	10	1,630
Storage-low grade shale[5]	Acres			200		200
Utility corridors & roads	Acres	200	200	400	200	1,000
Subtotal - facilities[5]		350	350	2,400	350	3,250
Spent shale & other waste						
Top surface	Acres	550	820	1,700	600	3,670
Sloping face (25%)	Acres	110	130	500	140	880
Total spent shale	Acres	660	950	2,200[6]	740[6]	4,550
Overburden				980[6]		980
Total land requirements	Acres	1,010	1,300	5,580	1,090	8,780

[1] Based on compaction to 95 lbs/ft^3

[2] Final compaction 114.3 lbs/ft^3 (17.5 ft^3/ton), or 125% of original volume.

[3] Based on off-site surface disposal of 80% of spent shale and 73.7% of overburden USDI (1973).

[4] Based on 40% surface disposal after first 3 years of production USDI (1973).

[5] USDI (1973) Vol. I, p. III-12.

[6] USDI (1973) Vol. III, Chapter IV, Section A - Land Impacts.

The sloping face (25% slope) of the disposal areas is significantly less (for equal volumes of storage) in large canyons. For evaluation purposes, the sloping face area can be estimated from the following equations:

$$\text{Small canyon} \qquad A_{sf} = 0.31\ D_v^{1.30} \tag{11}$$

$$\text{Intermediate canyon} \qquad A_{sf} = 0.40\ D_v^{1.10} \tag{12}$$

Where A_{sf} is the predicted surface area of the 25% sloping faces of the disposal pile.

Water Requirements for Spent Shale Disposal and Compaction

The USDI (1974) estimates that water requirements for spent shale disposal would amount to 20% by weight water. This estimate seems to be related to the use of slurry transport methods for disposal of part of the spent shale. The conclusion of Chapter 6 of this report is that slurry deposition methods have entirely too much potential for water pollution to be environmentally acceptable. Therefore, the calculations of water requirements for spent shale disposal are estimated at 13% by weight water for dust control and compaction to 95 lbs/ft^3 as recommended by Hutchins (1973). Heley (1973) in discussing processed shale disposal stated that moisture contents of 11-15% were found to be optimum for compaction with a segmented wheel on TOSCO II spent shale. This test program produced dry densities of 110 lbs/ft^3, so the 95 lbs/ft^3 used for evaluation purposes appears obtainable.

The use of lower amounts of water for dust control and compaction has the advantage of both saving water and in providing ultimate additional capacity within the spent shale pile for leaching and deep percolation waters. If we assume average compaction to 95 lbs/ft^3 (1.52 g/cc), initial wetting to 13% by weight water, and a field capacity of about 20% by weight water the spent shale disposal area would have an additional water storage capacity of about 1.25 inches per foot of depth with little potential for drainage from the pile. Coupled with the slow permeability rates of compacted spent shale this additional storage capacity could act to greatly reduce the potential for salinity pollution of the ground water aquifers.

Water requirements for overburden disposal were estimated at 2% by weight water for dust control.

Water Requirements for Vegetating Surface Disposal Areas

The design of surface disposal areas for spent shale has only recently received much attention, and many of the initial disposal plans have been abandoned because of environmental problems. Many of the disposal plans currently being considered will also be found to have unacceptable environmental features. Considerable research will need to be conducted on disposal methods, and environmental trade-offs to develop the least cost environmentally acceptable surface disposal systems. The most probable surface disposal areas now seem to be the smaller canyons close to the Roan Plateau or Cathedral Bluffs.

A disposal area planned to completely fill the upper reaches of a small canyon would have distinct advantages including (1) reduced surface runoff, hence reduced water control problems, (2) reduced need for sloping faces on the disposal piles or floodwater retarding structures, and (3) upper surfaces can be blended into the terrain. If the upper reaches of a canyon are completely filled it would also be possible to pass the limited surface runoff into adjacent canyons for ultimate disposal.

Because the specific location for disposal areas is not yet available, no attempt was made to estimate different water requirements for slope exposures. However, in general the sloping face of the disposal piles will have an average elevation of several hundred feet lower than the top surface. Irrigation requirements (Eq. 8 & 9) for the specific elevation result in higher water requirement estimates for the sloping faces of the disposal areas.

The water requirements for revegetating spent shale and overburden surface disposal areas are shown in Table 4. This evaluation assumes that the revegetation areas will be leached in the summer and fall (plus limited natural leaching in winter), be spring planted, and receive full irrigation for two years.

For the specific assumptions used in this evaluation, the revegetation water requirements would average 7.31 acre-feet/acre, with the leaching water requirement of 5.00 acre-ft/acre accounting for 68% of the total. Since the leaching water is not consumptively used, the potential always exists for this highly saline water to ultimately become a pollution source. This emphasizes the need for additional research on leaching spent shales for revegetation. This should include studies of off-site leaching and benefit-cost evaluations of providing soil and overburden materials to cover the disposal sites for revegetation. Evaluations should also be conducted on innovations like sealing the disposal areas and creating special watersheds for additional water supplies.

The above water requirements evaluation ignores the problem of higher than normal temperatures for the spent shale disposal areas. As shown by E_t equations (6 & 7) a one degree change in mean annual air temperature changes the annual water requirement for revegetation areas by 0.848 inches. The soil heat flux factor of the energy budget equation (1) may be a great deal more important to water requirements, because preliminary evaluations indicate this energy source to be greater than 10% of the normal solar radiation received. Specific energy budget evaluations will need to be conducted for long term heat dissipation from the spent shale piles, and additional research on plants adapted to the longer seasons of growth.

Table 4-. Estimated water requirements for revegetation of surface spent shale disposal areas by leaching, spring planting and full irrigation for two seasons.

Revegetation site	Elevation zone	Revegetation water requirement Ac-ft/acre	Estimated 20-year revegetation acres	Water requirements Acre-feet	
				Average Annual	Total 20-years
Private land:					
Plant A					
Spent shale					
Leaching requirement		5.00	660	165	3,300
Irr. for revegetation					
Top surface	7,900	1.91	550	53	1,050
Sloping face	7,600	2.27	110	12	250
Subtotal		1.97	660	65	1,300
Total plant A		6.97	660	230	4,600
Plant B					
Spent shale					
Leaching requirement		5.00	950	238	4,750
Irr. for revegetation					
Top surface	7,000	2.99	820	123	2,452
Sloping face	6,500	3.59	130	23	467
Subtotal		3.08	950	146	2,919
Total plant B		8.08	950	384	7,669
TOTAL PRIVATE LAND		7.63	1,610	614	12,269
Federal land:					
Tract C-a					
Spent shale					
Leaching requirement		5.00	2,200	550	11,000
Irr. for revegetation					
Top surface	6,200	3.95	1,700	336	6,716
Sloping face	6,100	4.07	500	101	2,035
Subtotal		3.98	2,200	437	8,751
Overburden					
Irr. for revegetation	7,500	2.39	980	117	2,342
Total tract C-a		6.95	3,180	1,104	22,093
Tract C-b					
Spent shale					
Leaching requirement		5.00	740	185	3,700
Irr. for revegetation					
Top surface	6,900	3.11	600	93	1,866
Sloping face	6,700	3.35	140	24	469
Subtotal		3.16	740	117	2,335
Total tract C-b		8.16	740	302	6,035
TOTAL FEDERAL LAND		7.18	3,920	1,406	28,128
Total for 250,000 bbl/day industry		7.31	5,530	2,020	40,397

Estimated 20-year Water Requirements for a 250,000 bbl/cd Oil Shale Industry

The 20-year and annual water requirements for a 250,000 bbl/cd oil shale industry are shown in Table 5. Water requirements for spent shale or overburden disposal and revegetation were developed specifically for this report. Other process water requirements are basically averages for the range of values shown in the USDI (1974) Environmental Statement (Vol. I, p. III-34), although some water requirements are estimated as a weight percent rather than using averages from the tables. Associated urban water requirements are ignored for this report, as are the irrigation water requirements for rights-of-way, plant sites, and other areas requiring revegetation.

The water requirements for spent shale disposal (33.7%), overburden disposal (1.3%), and revegetation (6.4%) total about 41.4% of the total process water requirements. Spent shale and overburden disposal for a 250,000 bbl/cd industry are estimated to use a total of 219,520 acre-ft. during a 20-year project life, or an average of 10,976 acre-ft. per year. This is equivalent to a continuous flow of 15.16 cfs, or 9.8 million gals/day. Revegetation water requirements for the same period amount to a total of 40,408 acre-ft. total, or 2020 acre-ft. per year, which is equivalent to a continuous flow of 2.79 cfs (1.8 million gallons/day).

The values shown in Table 5 are the best current estimates of water requirements for a specific scale of development. Additional research on any of the factors can provide improved estimates for specific conditions or situations.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

If spent shale is to be used as a plant growth medium irrigation will be needed to leach out salt and establish vegetation. Irrigation will also often be desireable to rapidly establish vegetation on soils and geological materials disturbed by oil shale development especially at the lower elevations.

For spent shale disposal areas on the surface, it was estimated that leaching will require five acre-feet of irrigation water per acre based on a net requirement of 48 inches leaching water and an 80% irrigation efficiency.

With normal precipitation, total irrigation requirements for spring planted and full season irrigation are essentially equal for each elevation zone (Table 2). For the assumptions used in this report, the gross irrigation requirement ranges from about 32.4 inches at the 5,000 ft. elevation zone to 3.2 inches at the 9,000 ft. elevation, with a decrease of 7.3 inches for each 1,000 ft. increase in elevation.[1]

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[1] Table 2 provides estimates of irrigation water required in acre-feet for 10-acre revegetation areas rather than in area inches.

Table 5-. Estimated 20-year and annual process water requirements (Acre-feet) for a 250,000 barrel per calendar day (bbl/cd) of upgraded shale oil production capacity.

	Private land			Federal land			Total	
Process requirements	Plant A	Plant B	Total	Tract C-a	Tract C-b	Total	Industry	%
Estimated 20-year water requirements: (Acre-ft.)								
Mining and crushing[1]	6,993	6,993	13,986	16,317	8,159	24,476	38,462	6.1
Retorting[2]	10,362	10,362	20,724	24,178	12,089	36,267	56,991	9.1
Shale oil upgrading[3]	36,500	36,500	73,000	73,000	36,500	109,500	182,500	29.0
Spent shale disposal[4]	37,763	37,763	75,526	90,733	45,366	136,099	211,625	33.7
Overburden disposal[5]				7,895		7,895	7,895	1.3
Power requirements[3]	17,520	17,520	35,040	35,040	17,520	52,560	87,600	13.9
Revegetation[6]	4,600	7,669	12,269	22,093	6,035	28,128	40,397	6.4
Sanitary use[3]	700	700	1,400	1,000	700	1,700	3,100	0.5
Total	114,438	117,507	231,945	270,256	126,369	396,625	628,570	100.0
Estimated average annual water requirements: (Acre-ft.)								
Mining and crushing[1]	350	350	700	816	408	1,224	1,924	
Retorting[2]	518	518	1,036	1,208	604	1,812	2,848	
Shale oil upgrading[3]	1,825	1,825	3,650	3,650	1,825	5,475	9,125	
Spent shale disposal[4]	1,888	1,888	3,776	4,537	2,268	6,805	10,581	
Overburden disposal[5]				395		395	395	
Power requirements[3]	876	876	1,752	1,752	876	2,628	4,380	
Revegetation[6]	230	384	614	1,104	302	1,406	2,020	
Sanitary use[3]	35	35	70	50	35	85	155	
Total	5,722	5,876	11,598	13,512	6,318	19,830	31,428	

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[1] Mining and crushing - estimated as 2% by weight water for dust control.

[2] Retorting - estimated as 3% by weight water for processing and cooling spent shale.

[3] Average for USDI (1973) Vol. I, p. III-34.

[4] Spent shale disposal - 13% by weight water for dust control and compaction.

[5] Overburden disposal - 2% by weight water for dust control.

[6] Water required for leaching spent shale, and revegetation of spent shale and overburden areas only. Other disturbed areas and rights-of-ways may also require irrigation for revegetation.

Spent shale disposal piles will probably have surface temperatures that are higher than undisturbed areas; so a temperature correction factor was included in the evapotranspiration equations to provide a means of estimating the higher use rates. Slope and aspect also have considerable effect on irrigation requirements. For instance, at 7,000 ft. the irrigation requirement would be about 18 inches on a horizontal surface, 11 inches on a 25 percent north slope, and 22 inches on a 25 percent south slope (Figure 1).

Specific conclusions from the study can be summarized as follows:

1. Approximately 60 inches of leaching water will be required in the revegetation process if spent shale is to be used as the plant growth medium. Less may be required for soil covered disposal areas.
2. Supplemental irrigation will be required during the establishment of a vegetative cover on the disposal sites, the amount depending upon the natural rainfall, elevation, slope and aspect, and heat load of the spent shale.
3. Of the estimated water required for a 250,000 barrel per calendar day industry (31,000 acre feet/year), a small fraction (6.4% or 2020 acre feet), is required in the revegetation of surface spent shale disposal areas.

Recommendations

1. Additional research is required on leaching methods and water requirements to determine minimum water requirements and most efficient leaching methods, if spent shale is to be used as a plant growth medium.
2. Additional study of the energy balance and heat exchange within the spent shale piles is essential to providing better water requirement and planting estimates.
3. Design of spent shale disposal areas should concentrate on water control to prevent erosion and provide for the maximum plant use of available water supplies.
4. The species mix for revegetation should include grasses, forbs, browse, and tree species to provide more complete cover, and through variations in rooting depth provide more complete use of available water supplies.
5. In the relatively "harsh" environment of the Piceance Basin, it will be difficult to maintain a desirable vegetative cover on the spent shale piles under natural precipitation regimes. Therefore, it is recommended that revegetation plans call for excluding all livestock use and careful wildlife management.

6. Temperature, precipitation, wind movement, and class A pan evaporation stations should be established in higher elevation areas of the Piceance Basin to provide planning data.

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