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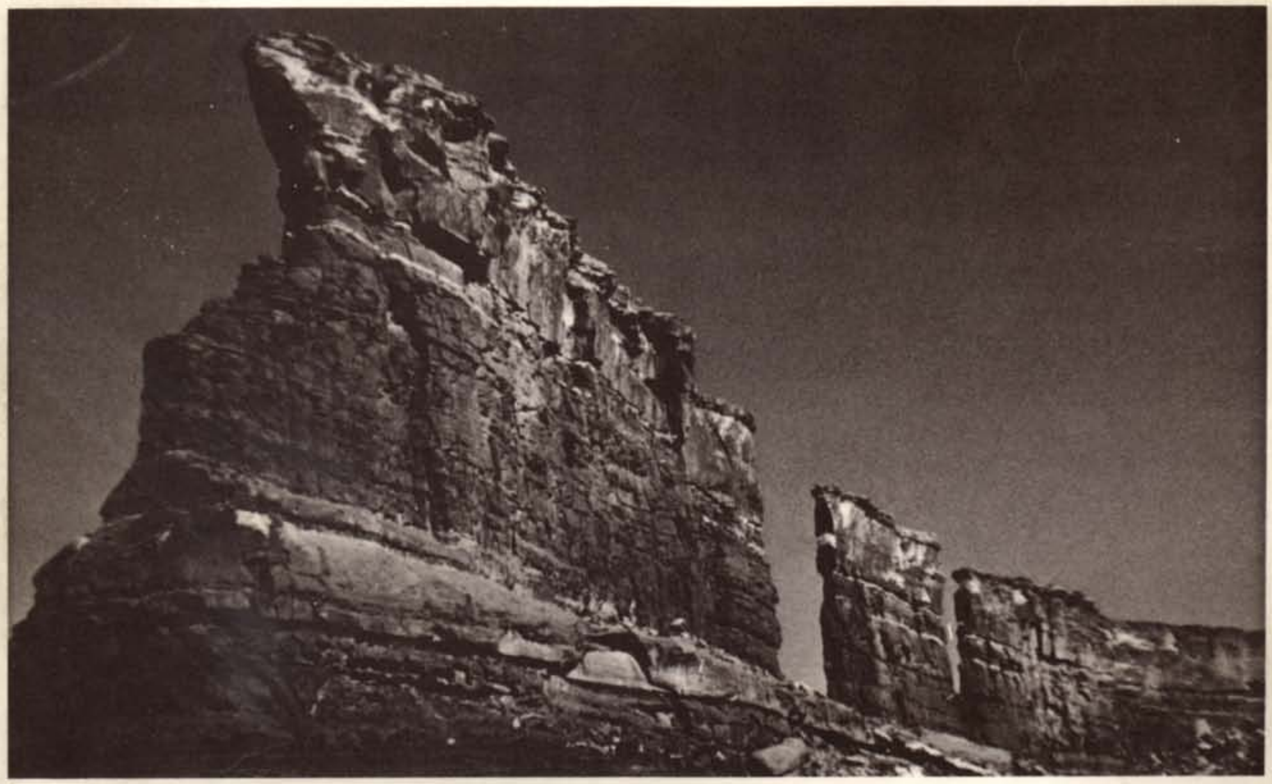

Utah Geology

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DEPOSITIONAL SYSTEMS AND DISPERSAL PATTERNS IN URANIFEROUS SANDSTONES OF THE COLORADO PLATEAU

by Robert G. Young[1]

ABSTRACT

In the Colorado Plateau, sandstone-type uranium deposits are present in at least 24 different formations ranging in age from Pennsylvanian to Pliocene. Some uranium deposits formed in their respective host sandstones soon after the sandstone was deposited, but other deposits were introduced much later along fractures or collapses.

Host sandstones were formed in fluvial, eolian, deltaic, strand-plain, barrier beach, bay-lagoon-estuary, and tidal plain environments. Most important are fluvial sandstones which are entirely of floodplain origin and belong to four depositional systems - humid region fan, braided stream, coarse-grained meanderbelt, and fine-grained meanderbelt. Sandstones of the eolian sand dune system are important in a few areas.

Major uranium producing units in the Colorado Plateau are the Triassic Chinle Formation, containing uranium in sandstone of braided stream and meanderbelt systems; the Jurassic Entrada Sandstone, containing uranium in sandstone of the sand dune system; and the Jurassic Morrison Formation, containing uranium in sandstones of the humid region fan, braided stream and meanderbelt systems.

The three most important uranium-bearing depositional super-systems (Monument Valley, Four Corners and San Juan) resulted from uplifts in the old Mogollon highland in southern Arizona and southern New Mexico. Where debris-laden streams from the uplift crossed the higher floodplains north of the uplift, they spread to form humid region fans of coarse sediment. Farther north they rejoined to form braided streams which soon began to meander as they flowed across the lower floodplains toward the distant sea. Not long after deposition of the host sandstones, uranium deposits began to form near the margins of the humid region fans and in the braided stream and coarse-grained meanderbelt sandstones just beyond the fan margins.

The advantage of identifying depositional systems in uranium-bearing sandstones is that one may be able to project ore trends and possibly locate new uranium districts.

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INTRODUCTION

General

Uranium occurrences are found in nearly all parts of the Colorado Plateau, the moderately elevated and deeply dissected physiographic province including much of northwestern New Mexico, northeastern Arizona, eastern Utah, and western Colorado (Fig. 1). In contrast to the widespread occurrences, economic uranium deposits discovered to date have been restricted to some 25 localities, principally in the southern two-thirds of the province.

Uranium occurrences are present throughout much of the stratigraphic sequence, and host rocks range in age from Pennsylvanian to Pliocene (Wood, 1956). Of the 28 uranium-bearing sedimentary formations, 24 are clastic, 3 are limestone, and 1 is coal (Table 1). The uranium in these deposits, which are commonly referred to as sandstone type deposits, coats sand grains, fills interstitial spaces, or replaces earlier minerals. The rocks are either friable or cemented but are not metamorphosed.

Most of the uranium deposits are believed to be epigenetic, formed during or within a few million to 10 million years following deposition of the host unit. A few of the uranium deposits are apparently supergene, occurring within or immediately adjacent to faults and collapses. Most such supergene occurrences are almost directly above or below uranium deposits in another more productive unit or are in a position where they likely were overlain by such a unit prior to its removal by erosion. A study of these widespread occurrences suggests that, given the proper set of geologic conditions, almost any sedimentary rock can host uranium deposits.

The importance of the Colorado Plateau as a uranium-producing province is underscored by the fact that it has accounted for 70 percent of past United States uranium production and contains at least 51 percent of the uranium ore reserves and 40 percent of the potential uranium resources of the U.S. (Hetland, 1976; U.S ERDA, 1976). Approximately 95 percent of past U. S. production has been from sandstone-type host rocks, and at least 95 percent of the reserves and 79 percent of the potential uranium resources of the U. S. are contained in sandstones and conglomerates. Percentages for uranium in sandstone-type hosts in the Colorado Plateau are still higher, approximately 98 percent.

Purposes of Study

The major purposes of this study are 1) to identify the depositional systems, depositional environments, dispersal patterns, and facies of uranium-bearing sandstones of the Colorado Plateau and 2) to develop a predictive sedimentary model for the occurrence of uranium deposits within the fluvial systems. Neither time nor space permit an exhaustive discussion of all depositional systems recognized; hence, only those of Triassic and Jurassic sandstones, in which the bulk of the province's uranium deposits have been found, will be addressed here.

Previous Work

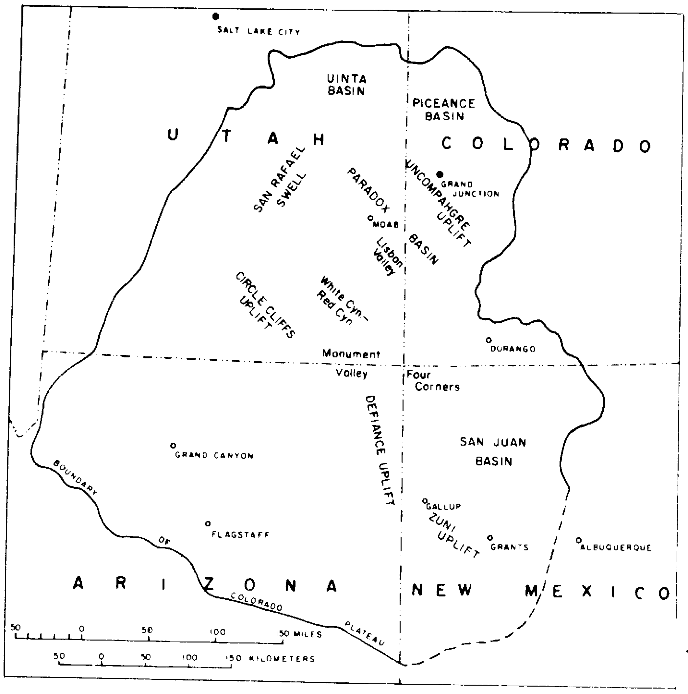
Literature concerning sandstone-type uranium deposits in the Colorado Plateau is voluminous. Most of these papers deal primarily with such facets as lithology, distribution, structural features, origin and chemistry of the host rock; depositional environments, dimensions, controls, age and nature of uranium deposits; and theories on nature and origin of mineralizing solutions. Some of the more pertinent reference works are those by Brookins (1975); Granger(1968) Fischer (1960); Fischer and Hilpert (1952); Hilpert (1969); Moench and Schlee (1967); Santos (1963); Squires (1969) and Wood (1968).

In order to discover additional sandstone-type uranium deposits, it is imperative that a depositional model be developed that will explain most, if not all, relationships noted by geologists in their autopsies of prolific uranium-producing fluvial sandstones. Some attempts at such modeling include those of Fischer (1974) and Rackley (1975).

DEPOSITIONAL SYSTEMS, ENVIRONMENTS AND FACIES

Definitions and Classification

The concept of depositional systems as defined by Fisher and others



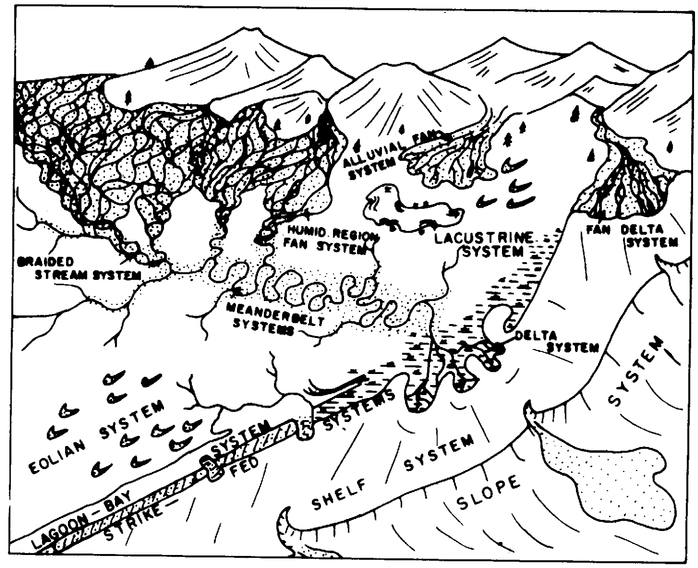


Figure 2. Idealized sediment dispersal system

← Figure 1. Location map of Colorado Plateau

Table 1. Uranium-bearing sedimentary units in the Colorado Plateau

Age	Formation-Member	Depositional System	Environment	Lithofacies	Locality
Pliocene	Bidahochi Fm.	Fine-grained meanderbelt	Interchannel		40 Miles North of Holbrook, Ariz.
Miocene	Browns Park Fm.	Braided stream	Channel	Planar bedded conglomeratic ss.	Near Lay, Colo.
Eocene	Uinta Fm.	Coarse-grained meanderbelt	Channel	Conglomeratic ss.	South of Ouray, Utah
	Wasatch Fm.	Coarse-grained meanderbelt	Channel	Conglomeratic ss.	North of Thompson, Utah
Paleocene	North Horn Fm.	Coarse-grained meanderbelt	Channel	Conglomeratic ss.	West of Ferron, Utah
Cretaceous	Fruitland Fm.	Fine-grained meanderbelt	Channel	Fine-grained ss.	10 miles NW Farmington, N. Mex.
	Williams Fork Fm.	Fine-grained meanderbelt	Interchannel	Coal	South of Skull Creek, Colo.
	Toreva Fm.	Fine-grained meanderbelt	Channel	Fine-grained ss.	Northwest of Black Mesa T.P., Ariz.
	Dakota Ss.	Barrier bar	Beach	Fine- to medium-grained sandstone	North of Pruitt, N. Mex.
	Cedar Mtn. Fm.	Braided stream	Channel	Conglomeratic ss	7 Miles N. of Naturita, Colo.
Jurassic	Morrison Fm. Brushy Basin M.	Humid region fan	Channel	Conglomeratic ss.	Jackpile SS. Paguate, N. Mex.
		Coarse-grained meanderbelt	Channel	Conglomeratic ss.	Pete Mine, Monticello, Utah
		Fine-grained meanderbelt	Interchannel	Carbonaceous ms.	Cedar Mtn. Area, Utah
	Westwater Canyon Member	Humid region fan	Channel	Arkosic ss.	Grants Mineral Belt Belt, N. Mex.

(continued)

Table 1. (continued)

Age	Formation-Member	Depositional System	Environment	Lithofacies	Locality
Jurassic	Salt Wash Member	Humid region fan	Channel	Coarse-Grained ss.	Uravan Mineral Belt, Colo.
		Braided stream	Channel	Conglomeratic ss.	Uranium Peak Meeker, Colo.
		Coarse-grained meanderbelt	Channel	Coarse-Grained ss.	Thompson Area, Utah
		Fine-grained meanderbelt	Channel	Carbonaceous ms.	Last Chance, Utah
	Bluff Ss.	Eolian sand dune	Transverse dune	Fine-grained ss.	Northwest Carrizo Mts., N. Mex.
	Summerville Fm.	Tidal flat	Intertidal	Fine-grained ss.	Haystack Butte, N. Mex.
	Curtis Fm.	Non-delta associated strandplain	Beach	Fine-grained ss.	W. of Skull Creek, Colo.
	Todilto Ls.	Restricted bay	Lagoon center	Algal ls.	Grants Mineral Belt, N. Mex.
	Entrada Ss.	Eolian sand dune	Transverse dune	Fine-grained ss.	North of Rifle, Colo.
	Carmel Fm.	Tidal flat	Intertidal and supertidal	Sandstone and mudstone	Saucer Basin, Utah
Jurassic-Triassic	Navajo Ss.	Eolian sand dune	Transverse dune	Fine-grained ss.	North of Rifle, Colo.
Triassic	Kayenta Fm.	Braided channel	Channel	Fractures in medium grained ss.	10 Miles NW. Naturita, Colo.
	Wingate Ss.	Eolian sand dune	Transverse dune	Fine-grained ss.	Temple Mtn., Utah
	Chinle Fm. Petrified Forest Member	Fine-grained meanderbelt	Channel	Carbonaceous ms.	Cameron, Ariz.
	Chinle Fm. Moss Back M.	Coarse-grained meanderbelt	Channel	Med.- to coarse-grained ss.	San Rafael Swell, Utah
	Monitor Butte M.	Coarse-grained meanderbelt	Channel	Coarse-grained ss.	San Rafael Swell, Utah
	Shinarump M.	Coarse-grained meanderbelt	Channel	Conglomerate and coarse-grained ss.	Monument Valley, Ariz.
	Moenkopi Fm.	Tidal flat	Intertidal	Fine-grained ss.	Torrey, Utah
Permian	Kaibab Ls.	Carbonate shelf		Cherty breccia	Temple Mtn. Utah
	Cutler Fm. Undivided	Fan delta	Distal fan	Arkosic lenses	Big Indian Wash, Utah
	White Rim Ss.	Eolian sand dune	Transverse dune	Fine-grained ss.	San Rafael Swell, Utah
	De Chelly Ss.	Eolian sand dune	Transverse dune	Fine-grained ss.	Monument Valley, Ariz.
	Coconino Ss.	Eolian sand dune	Transverse dune	Fine-grained ss.	Orphan Lode, Ariz.
	Rico Fm.	Delta associated strandplain	Beach	Med.-grained ss.	Cane Crrek, Utah
Pennsylvanian	Supai Fm.	Coarse-grained meanderbelt	Channel	Med.-grained ss.	30 Miles N. of Peach Spgs., Ariz.
	Hermosa Fm.	Carbonate shelf		Fractured ls.	13 Miles SW, Naturita, Colo.
	Weber Qtzite	Eolian and strandplain	Transverse dune and beach	Fine-grained ss.	7 Miles SW. Elk Springs, Colo.

(1969) comprises " . . . assemblages of process-related sedimentary facies. As such they are the stratigraphic equivalents to geomorphic or physiographic units." Depositional systems are informal rock-stratigraphic units characterized by assemblages of facies which are generally linked by inferred depositional environments and associated processes. Some examples are fan delta, humid region fan, sand dune and tidal flat systems. Recognition of such depositional systems in ancient deposits is based on Holocene analogs. Because depositional systems are genetic they do not necessarily coincide with formal stratigraphic nomenclature. Genetically-related facies make up a depositional system, whereas formal lithostratigraphic units may include only one facies or as many as several depositional systems. In cases where deposits of two or more depositional systems are intermixed it is common practice to apply to them a geographic name such as the Monument Valley fluvial system, thus creating an informal super-system.

The geometry, lithologic character and areal distribution of terrigenous clastic facies provide insight into the nature of basin-fill deposits containing valuable mineral and energy resources (Brown, Cleaves, and Erxleben, 1973). Most studies using the depositional system approach have been directed toward the predicition of petroleum accumulations but Smith (1974) used it in a study of Permian copper deposits in fluvial-deltaic systems. Fisher and others (1970), Dickinson (1976), and Galloway (1977) have extended the application to prediction of uranium deposits in Tertiary fluvial-deltaic, strand plain-barrier bar, lagoonal, and deltaic systems in the Texas Gulf Coast. In applying the depositional system concept to uranium-bearing sandstones of the Colorado Plateau, the writer has compiled a classification of clastic deposition systems for fluvial and eolian environments (Table 2).

A variety of terrigenous clastic depositional systems may exist within basins such as those in which the Triassic and Jurassic sediments of the Colorado Plateau accumulated. These may range, during the course of basinal filling, from piedmont, valley, floodplain, eolian and lacustrine to deltaic, shelf, slope and basin systems (Brown, Cleaves, and Erxleben, 1972) These clastic systems can be related to an idealized sediment dispersal system, as shown in Figure 2.

If a route were plotted seaward from a highland source in such a basin, it would traverse a number of depositional environments. In the piedmont area adjacent to the mountain front, alluvial fans might form a narrow belt of coarse debris. In adjacent areas of the mountain front, meandering and/or braided streams may flow across a zone of low hills and narrow valleys. As these streams debouch from the valleys onto a broad floodplain, they may continue as braided and/or meandering streams in somewhat confined belts or they may spread laterally and combine with other similar streams to form a broad depositional plain or humid region fan consisting largely of coarse clastic debris dropped by the overladen anastamosing streams. This humid region fan would have an imperceptible seaward slope, might be as much as 200 or 300 miles across and extend an equal or greater distance laterally. Near the distal margin of the sand sheet, the scattered distributaries would again recombine to form a few large braided streams. Changes in bedload and/or gradient would soon cause the braided streams to become meandering streams which might ultimately become distributaries on a delta. Other agents of transport then might further distribute the load carried to the sea. Marine currents would carry much of it into shelf and slope environments, and longshore currents would convey additional amounts into strandplain, barrier beach, lagoonal and tidal flat environments.

Depositional Systems Containing Uranium

In the Colorado Plateau, uranium has been reported from at least 24 different sandstone units that represent 11 different depositional systems (Table 3). Twelve of the most productive host sandstones belong to fluvial systems and 7 belong to eolian systems. Occurrences in deltaic tidal flat, barrier beach and other clastic systems are relatively unimportant and in many localities appear to be secondary accumulations derived from stratigraphically higher or lower uranium deposits in other systems by groundwaters circulating through fractures, collapses or permeable sediments. For this reason only fluvial and eolian depositional systems will be discussed here.

Fluvial Systems: As suggested in Table 2, fluvial environments can be separated into two tertiary environments (valley and floodplain) on the basis of position in the sediment transport system. In some modern basins, streams may flow through valleys in low hills adjacent to the mountain front before emerging onto the floodplain. However, the depositional records of ancient beds are most fragmentary in near-source areas, and basinal deposits of the Colorado Plateau are no exception. As a consequence, there are no known occurrences of uranium in mountain front valley deposits in this region.

Floodplain deposits, unlike valley deposits, are relatively well preserved and constitute the bulk of fluvial deposits in most basins. In the Colorado Plateau it is possible to classify floodplain deposits into four depositional systems, based on position within the transport system. The majority of uranium-bearing sandstones in this region belong to one or more of these systems. Results of this study indicate that 3 of the uranium-bearing fluvial sandstones belong to humid region fan (sand sheet) systems, 4 to braided stream systems, 6 to coarse-grained meanderbelt systems and 6 to fine-grained meanderbelt systems. Obviously some sandstones belong to more than 1 system.

Eolian Systems: Eolian systems would appear to be unlikely hosts for uranium because of a dearth of organic matter but significant uranium occurrences nave been recorded in at least 7 different eolian sandstones in the region. All of these sandstones belong to sand dune systems.

GEOLOGY AND DEPOSITIONAL SYSTEMS OF URANIUM-BEARING SANDSTONES

Of the 24 known sandstone-type uranium host formations on the Colorado Plateau, 1 is Pennsylvanian, 3 are Permian 5 are Triassic, 8 are Jurassic, 4 are Cretaceous and 6 are Tertiary in age. The most productive units are the Chinle Formation of Triassic age and the Entrada Sandstone and Morrison Formation of Jurassic age.

Nearly all these units exhibit many of the criteria proposed by Grutt (1971), Fischer (1974) and other investigators as guides to uranium favorability of a sandstone. Some of the more important favorable criteria are:

1. Presence of uranium.
2. A Triassic, Jurassic or Tertiary age
3. Presence of tuffaceous sediments in the overlying sections.
4. Feldspathic, arkosic, quartzose or tuffaceous sandstones
5. A sandstone-shale ratio ranging from 1:1 to 4:1.
6. Red to tan sandstones that show bleaching.
7. Presence of reductants such as carbonaceous material or hydrogen sulfide
8. Presence of pyrite
9. Dips of less than 5 degrees.
10. Presence of hematite or limonite staining.
11. Formation in fluvial, marginal marine or eolian depositional environments.

Table 2. Classification of colluvial, fluvial and eolian depositional systems.

Depositional Environment			Depositional system	Primary subdivision	Facies
Primary	Secondary	Tertiary			
Continental	Colluvial	-	Landslide	-	Rock debris - bimodal with cobbles and boulders imbedded in finer matrix. Unstratified to poorly stratified.
			Talus	-	Rock fragments - any size and shape, unsorted, unstratified, usually coarse and angular.
	Fluvial	Piedmont	Alluvial fan	Proximal fan	Gravels - poorly sorted, lack fabric, no stratification, bound by clay, silt and sand.
				Medial fan	Interbedded sand and gravel - gravel clasts imbricated, sand parallel laminated and may show antidune cross stratification, sorting poor.
				Distal fan	Sand and gravelly sand - fair sorting, parallel laminae, cross stratification, imbricated gravel clasts.
			Fan delta	Proximal fan	Same as for alluvial fan.
				Medial fan	Same as for alluvial fan.
				Distal fan	Same as above but built into standing body of water. Progradational deltaic features and destructional bars.
			Clastic wedge (fan or bajada)	Proximal fan	Same as for alluvial fan.
				Medial fan	Same as for alluvial fan.
				Distal fan	Same as for alluvial fan.
		Valley (Mountain front)	Braided stream	Channel	Sand and gravel - poor to moderate sorting, gravel clasts imbricated, large to medium scale cross bedding, parallel laminae, ripple bedforms, both floor and bar deposits present, multistoried body with intraformational scours.
			Meanderbelt	Channel	Sand - fine to coarse grained, fair to moderately well sorted, medium to large scale planar and trough cross bedding, fills, scours, channel floor, channel bar and point bar deposits present.
		Floodplain	Humid region fan (sand sheet)	Proximal fan	Sand and gravel - multistoried body with numerous intraformational scours, poor to moderate sorting, medium to large scale cross bedding and some planar bedding, includes both channel floor and channel bar deposits.
				Medial fan	Very similar to proximal fan above but less gravel and a few thin mud partings present at base of some scours.
				Distal fan	Sand - fine to coarse grained, moderately well sorted multistoried, medium to large scale cross bedding and considerable planar bedding, sand bodies thinner and separated by tongues of mud.
			Braided stream	Channel	Sand - fine to coarse grained, moderate to good sorting, large to medium scale cross bedding, parallel laminae, ripple bed forms, both floor and bar deposits present, multistoried body with intraformational scours.
			Coarse-grained meanderbelt	Channel	Sand - fine to coarse grained, good sorting, fills scours, medium to large scale planar and trough cross bedding, consists of channel floor, channel bar, point bar and chute cutoff deposits.
				Interchannel	Sand, silt and mud - includes laminated muds of swales; coarse to fine, trough cross bedded sand of natural levees; sand and silt of crevasse splays; laminated and mud-cracked silt and mud of floodbasins; sand and organic mud of abandoned channels, and organic silt and mud of swamps.

(continued)

Table 2. (Continued)

Depositional Environment			Depositional system	Primary subdivision	Facies
Primary	Secondary	Tertiary			
Continental	Fluvial	Floodplain	Fine-grained meanderbelt	Channel	Sand - fine to medium grained; medium to large scale planar and trough cross bedding, scour at base. Contains deposits of channel floor, channel bar, point bar and chute cutoff.
				Interchannel	Sand, silt and mud as in coarse-grained meanderbelt.
	Eolian	Desert	Sand dune	-	Sand - fine to medium grained, steeply dipping cross bedding sharply truncated by parallel deflation surfaces, frosted grains, sorting fair to good.
		Beach	Sand dune	-	Same as desert above.
		Plain	Sand dune		Same as desert above.
			Loess plain	-	Silt and very fine sand - massive, structureless, may show columnar structure.

Table 3. Uranium bearing depositional systems in the Colorado Plateau

Second Order Depositional Systems	Third Order Depositional Systems	Fourth Order Depositional Systems	Number Of Each
Fluvial	Piedmont	Fan delta	1
	Floodplain	Humid region fan	3
		Braided stream	4
		Coarse-grained meanderbelt	6
		Fine-grained meanderbelt	6
Eolian	Desert	Sand dune	7
Barrier beach	Littoral marine	Independent with distant strike feeding	1
		Destructive sands of fan delta	1
Tidal plain	Tidal flat	Intertidal	2
		Sabkha	1

Because most of the important uranium deposits in the Colorado Plateau occur in the Chinle, Entrada, and Morrison, the following discussion of geology is limited to these units. This is not intended as a detailed discussion, but rather as a summary of the more salient features of each formation.

Chinle Formation

The Chinle Formation, present throughout much of the Colorado Plateau is one of the most extensively exposed continental Triassic formations in the world. It is a predominantly fluvial unit composed largely of red, purple, gray and variegated tuffaceous mudstone and siltstone interbedded with sandstone and conglomerate (Stewart, Poole and Wilson, 1972). The Chinle reaches its greatest thickness in northeast Arizona and thins northward to a feather edge on the flanks of the ancestral San Luis-Uncompahgre uplift along the eastern edge of the Colorado Plateau (figure 3). The Chinle is generally considered to be of Late Triassic age but the basal member may be Middle Triassic.

The Chinle is commonly divided into 6 members which are, from the base upward, the Shinarump, Monitor Butte, Moss Back, Petrified Forest, Owl Rock and Church Rock Members. The sequence is most complete in northeast Arizona, but when traced into adjacent areas the formation thins and several of the units wedge out or become indistinguishable. Additional local members such as the Gartra Member along the northern edge and the Aqua Zarca and Poleo Sandstones along the eastern margin of the province have different provenances and are less widespread. Figure 4 shows a possible correlation of the lower members of the Chinle in this region. Uranium has been produced from the tuffaceous Monitor Butte, Moss Back and Petrified Forest Members, primarily in those localities where the subject member forms the base of the formation.

Members: The Shinarump Member consists of fluvial sediments formed in braided and meandering streams in shallow valleys on an irregular erosional surface which existed to the north of the rising Mogollon highland. In the southernmost exposures of the Shinarump in northern Arizona, these sediments are mostly lenticular beds of conglomerate, sandstone, siltstone and mudstone, with abundant fragments of carbonized plant debris and small amounts of silicified wood. Farther north in the White Canyon-Red Canyon area of Utah, conglomerates are mostly absent but fine-grained sandstones, carbonaceous mudstones, and coals are more abundant. Still farther north, in the San Rafael Swell of Utah, the member is largely variegated tuffaceous mudstone with some carbonaceous mudstone and an occasional fine-grained sandstone lens. Thicknesses of the Shinarump range from a maximum of about 250 feet (76.2 m.) in some deep channels in the Monument Valley district to zero along its northern pinchouts.

The Monitor Butte Member unconformably overlies the Shinarump, and consists primarily of red to greenish gray tuffaceous mudstone and siltstone with

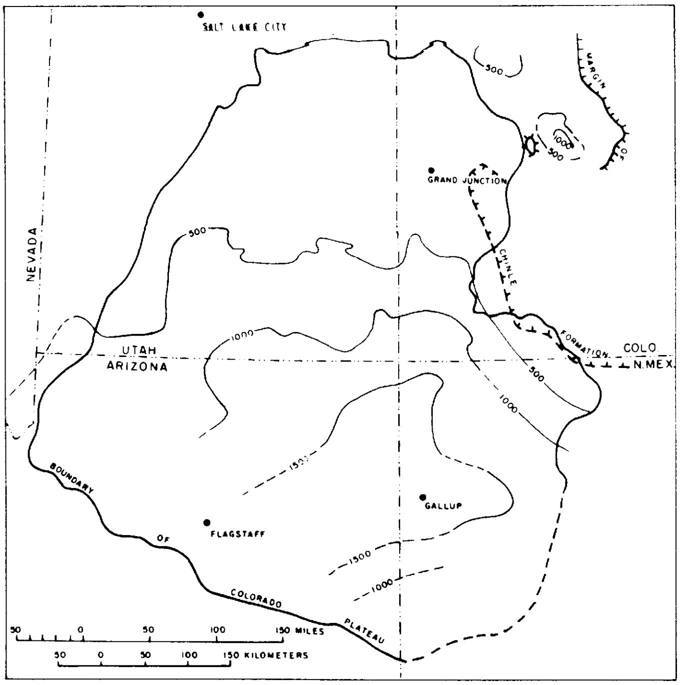


Figure 3. Isopach of Chinle Formation in Colorado Plateau, modified from Stewart and others, (1972) (Isopachs in feet).

some light brown to gray fine- to coarse-grained sandstone lenses throughout. In many localities in northeast Arizona and southeast Utah it has a basal coarse-grained to conglomeratic sandstone unit of floodplain origin which either blankets the Shinarump or is restricted to the flanks of topographic highs formed by partly eroded Shinarump channel-fill deposits (Young, 1964). The Monitor Butte is as much as 200 feet thick in northern Arizona but thins northward to a pinchout in eastern Utah. Near the wedgeout the member consists largely of variegated mudstone with some channel-fill sandstones formed in coarse- and fine-grained meander belts.

The Moss Back Member (and its probable correlative, the Poleo Sandstone Lentil in north-central New Mexico) is a fine- to coarse-grained and conglomeratic sandstone unit formed in a loose network of braided and meandering streams draining northwestward across the Colorado Plateau. It fills shallow valleys in an erosional surface carved into underlying members, most commonly the Monitor Butte. It ranges up to 150 feet (45 m.) thick, consists of subrounded clear quartz grains and rare black accessory grains, has a calcareous cement, and contains tuffaceous debris and abundant carbonaceous trash (Stewart and others, 1972). Its provenance was mainly one of granitic rocks and volcanic activity.

The Petrified Forest Member disconformably overlies the Monitor Butte and interfingers with the Moss Back. The lower portion of the member is composed of blue, gray, and white mudstone and tuffaceous siltstone with some lenticular sandstones in the lower part in the Cameron, Arizona area. The upper part consists of grayish red, pale reddish brown, and pale reddish purple mudstone, siltstone and sandy siltstone. Silicified wood is abundant in some zones. Thicknesses of the member range from zero along its northern edge to as much as 1200 feet (366 m.) in northeastern Arizona.

The upper members of the Chinle (Owl Rock and Church Rock) are best developed in the southern part of the Colorado Plateau but are present in nearly all Chinle outcrops in the province. They consist primarily of variegated mudstone with an occasional lens of limestone or sandstone. Their combined thickness is more than 700 feet (213 m.) in parts of northeast Arizona and they thin to a feather edge on the old San Luis-Uncompahgre highland.

Depositional Systems of the Chinle Formation: It was observed above that uranium is present in the four lower members of the Chinle and that these members are separated by disconformities that prove diastems of some magnitude between adjacent members. The fluvial depositional systems making up each uranium-bearing member of the Chinle in the region are grouped as a super system named for the locality in which it is best developed. The super system making up the Shinarump Member is the Monument Valley fluvial system, that of the Monitor Butte Member is the White Canyon fluvial system and that of the Moss Back Member is the Lisbon Valley fluvial system.

The Monument Valley fluvial system: consists of channel-fill sandstones and tuffaceous and carbonaceous mudstones deposited in shallow channels of northwest-flowing streams (figure 5). The Monument Valley system consists of three depositional systems - braided stream, coarse-grained meanderbelt and fine-grained meanderbelt. The braided stream system, recognized primarily in Monument Valley, Utah and Arizona, consists of single or multistoried coarse-grained scour-fill sandstone of the channel facies. Farther north in the White Canyon and San Rafael districts of Utah, where sediments become finer and valleys broader, the coarse-grained and fine-grained meanderbelt systems become dominant. Sediments are still confined to broad valleys but consist of coarse- to fine-grained sandstones interbedded with carbonaceous mudstones of various channel and interchannel facies. Possible equivalents of the Shinarump in the northern part of the Colorado Plateau are primarily coarse- to fine-grained sandstone lenses indicating that meanderbelt systems dominated that area. Uranium deposits are essentially confined to the braided stream and coarse-grained meanderbelt systems.

The Monument Valley system has been partly removed by pre-Monitor Butte erosion, and remaining deposits are preserved only in paleo-depressions and paleovalleys. As a result, knowledge of the dispersal pattern for this system is fragmentary. Most of the ancient streams flowed northward through the Four Corners area until they reached the White Canyon area. Here they turned westward and then northwestward through and around the San Rafael Swell and left the Colorado Plateau. Other ancient streams in the Four Corners area flowed northward toward the growing salt anticlines but turned to flow northwestward in rim synclines on the southwest flanks of such structures as the Dolores, Lisbon Valley, Cane Creek, Moab and Salt Valley salt anticlines. Some of these streams continued northward until they reached the southwest flank of the northwest-trending Uncompahgre uplift. Here they turned northwest and ultimately reached the western edge of the Colorado Plateau. Some streams that encountered

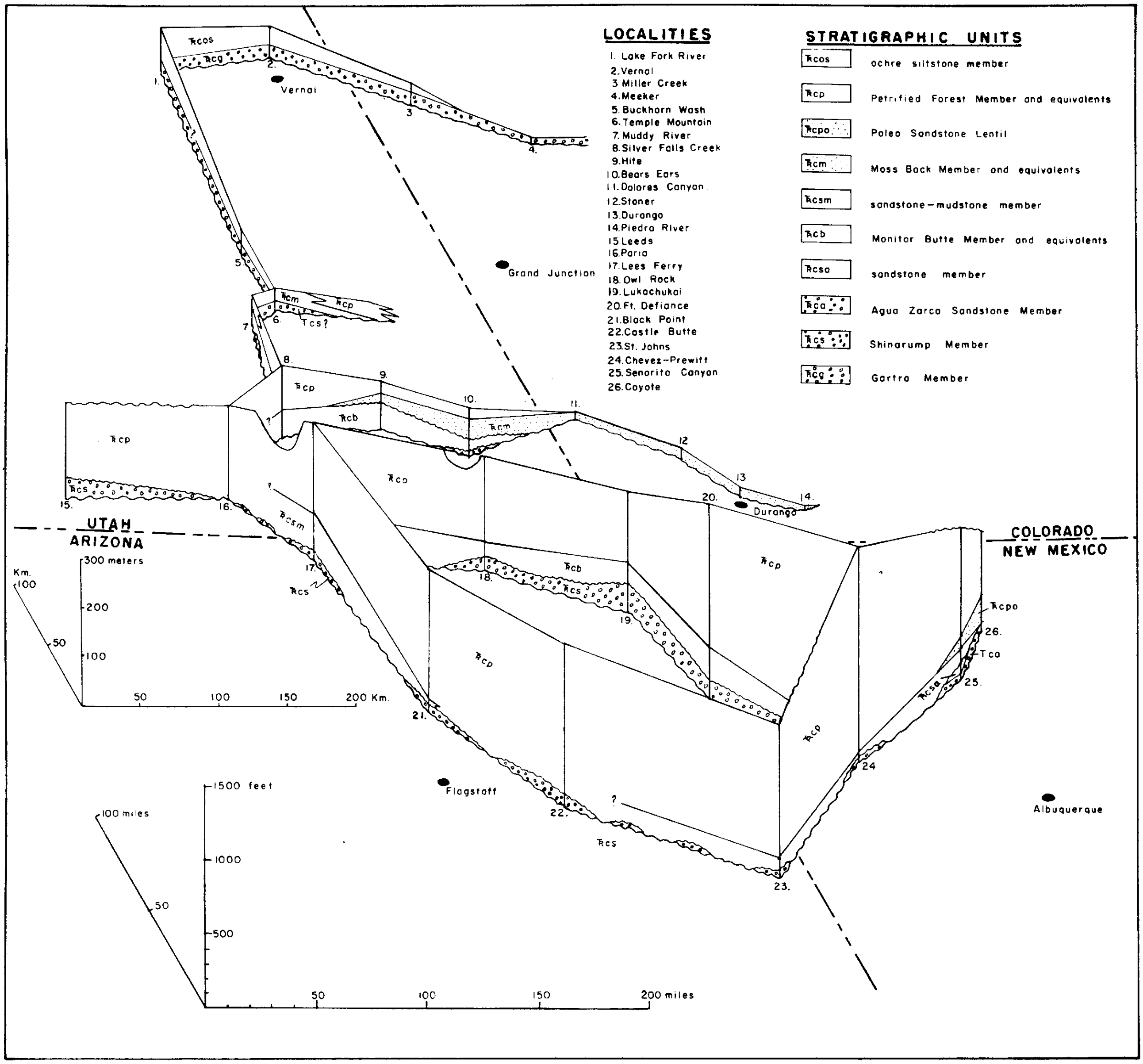


Figure 4. Fence diagram of lower members of Chinle Formation, modified from Stewart and others, 1972.

the salt anticlines appear to not have continued northward but were deflected westward and southwestward to join other streams in the White Canyon-Red Canyon area and the San Rafael Swell.

White Canyon Fluvial System: The dominant element in the Monitor Butte Member is the White Canyon fluvial system representing the deposits of another north-flowing stream system carrying detritus resulting from an orogenic pulse in the Mogollon highland. This fluvial super-system can also be separated into four depositional systems.

In its southernmost exposures the base of the member is composed of a coarse-grained blanket-like braided sandstone of a humid fan system. In southern Utah the blanket-like sandstone becomes confined to braided stream channels and becomes progressively finer northward. Both coarse- and fine-grained meanderbelt systems are represented. Where the upper part of the member is present, it consists of tuffaceous mudstones and fine-grained sandstone lenses of the fine-grained meanderbelt system, formed as uplift waned in the source area. Within the White Canyon fluvial system uranium deposits are rare and are restricted to the coarse-grained meanderbelt system.

Lisbon Valley Fluvial System: The only recognizable depositional system in the Moss Back Member is the Lisbon Valley fluvial system representing the deposits of a northward flowing network of streams carrying sediment from the highlands to the south (figure 6). Two depositional systems, braided stream and coarse-grained meanderbelt, are present but they are not separated here. The Moss Back represents the initial deposits of an uplift in the source area and the Petrified Forest represents the waning stages, hence the Petrified Forest mudstones are probably the products of the fine-grained meanderbelt environment. In this super-system, uranium deposits are known only in the braided stream and coarse-grained meanderbelt systems.

Economic Geology: The Chinle Formation has been productive of uranium in a number of districts but principally in the Camerson (Arizona), Monument Valley (Arizona and Utah), White

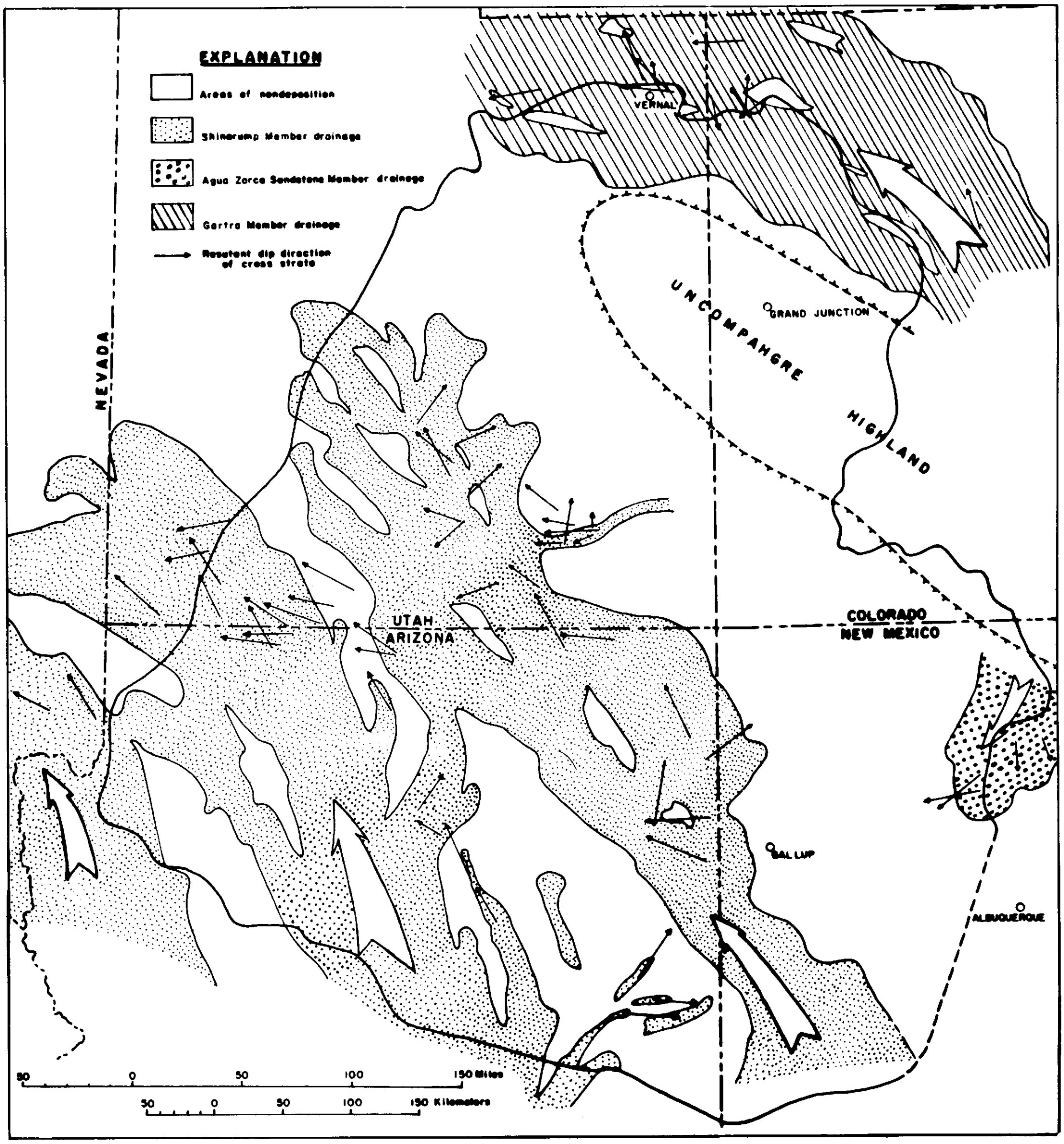


Figure 5. Monument Valley fluvial system and dispersal pattern, modified from Stewart and others, (1972).

Canyon-Red Canyon (Utah), Lisbon Valley (Utah), Seven Mile-Inter River (Utah), and San Rafael Swell (Utah). To date the Chinle has produced about 42,000 tons U_3O_8 and 21,000 tons V_2O_5. Present $30 per pound reserves are calculated at 9,200 tons U_3O_8 and the formation is assigned a resource potential of 140,000 tons U_3O_8 (Hetland, 1976).

In most of the districts uranium occurs on bends or at confluences of paleostream channels carved into underlying Triassic or Permian strata. It is almost invariably confined to favorable carbonaceous sandstone lenses near the base of the Chinle in the lower part of the Shinarump, Monitor Butte or Moss Back Members.

Ore bodies are closely-spaced, lenticular and generally concordant with bedding. The bodies range in size from a few tons to several million tons. Ore minerals are primarily uraninite and coffinite but varying amounts of vanadium, copper and molybdenum minerals are also present. Calcite is the most common cementing material.

The source of the uranium is uncertain, but it may have been derived from uranium-rich granitic detritus in the sandstones, from uranium-bearing surface or groundwaters moving basinward from a granitic source area, or from leaching of tuffaceous mudstones in overlying beds. Reductants were probably supplied by decaying vegetation or possibly by hydrocarbons escaping from petroleum accumulations.

Entrada Sandstone

The Entrada Sandstone of Late Jurassic age is another widespread unit on the Colorado Plateau (figure 7). In its type area in the San Rafael Swell, it consists of even-layered red earthy sandstone and siltstone reflecting a tidal flat origin similar to that of the underlying Carmel Formation, into which it grades. The lithology of the Entrada changes eastward into a clean eolian sandstone exhibiting large-scale cross bedding and prominent horizontal bedding planes. The formation is about 800 feet thick on the west side of the San Rafael Swell, but thins eastward to a wedge-out just east of the Colorado Plateau.

In some localities the Entrada is subdivided into various members or combined with an underlying correlative

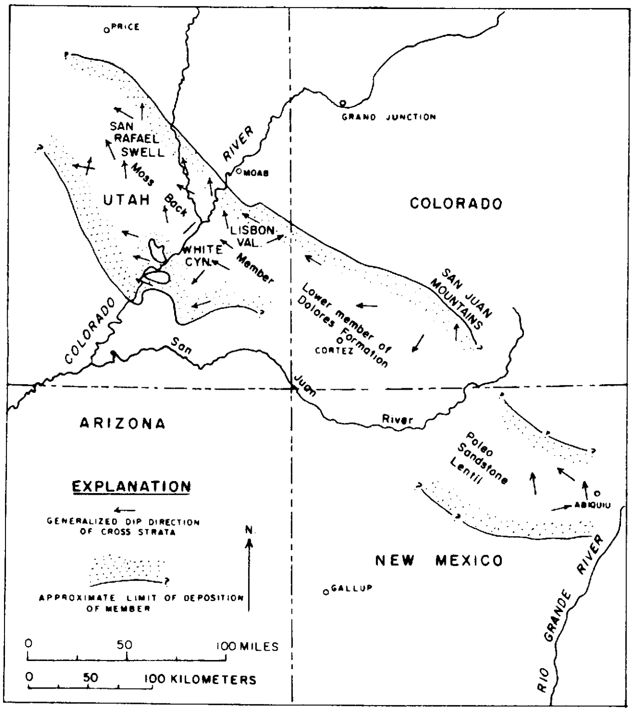


Figure 6. Lisbon Valley fluvial system and dispersal pattern, modified from Stewart and others, (1972).

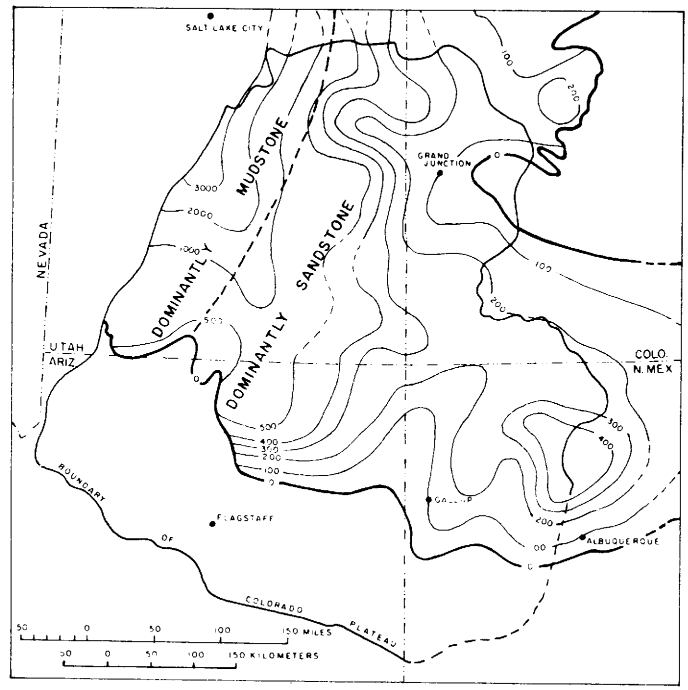


Figure 7. Isopach of Carmel Formation and Entrada Sandstone in Colorado Plateau and adjacent areas. (Isopachs in feet).

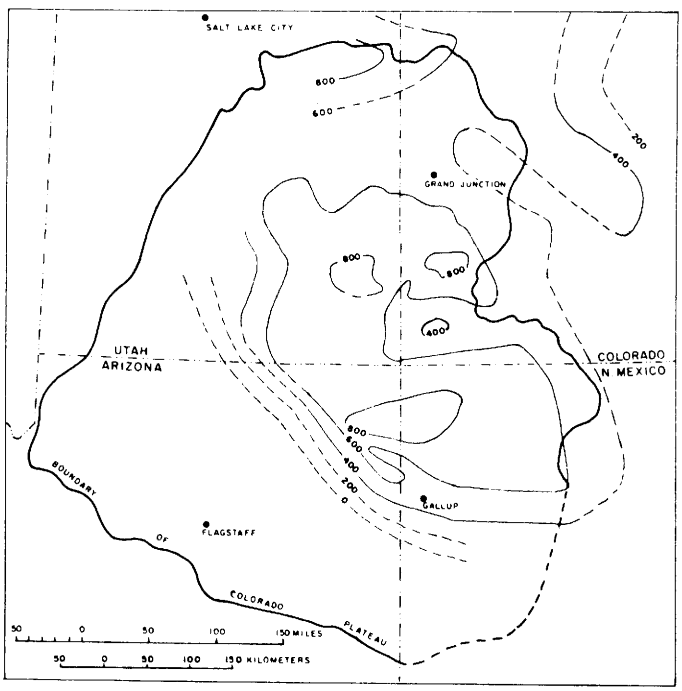


Figure 8. Isopach of Morrison Formation in Colorado Plateau, modified from Craig and others, (1955)(Isopachs in feet).

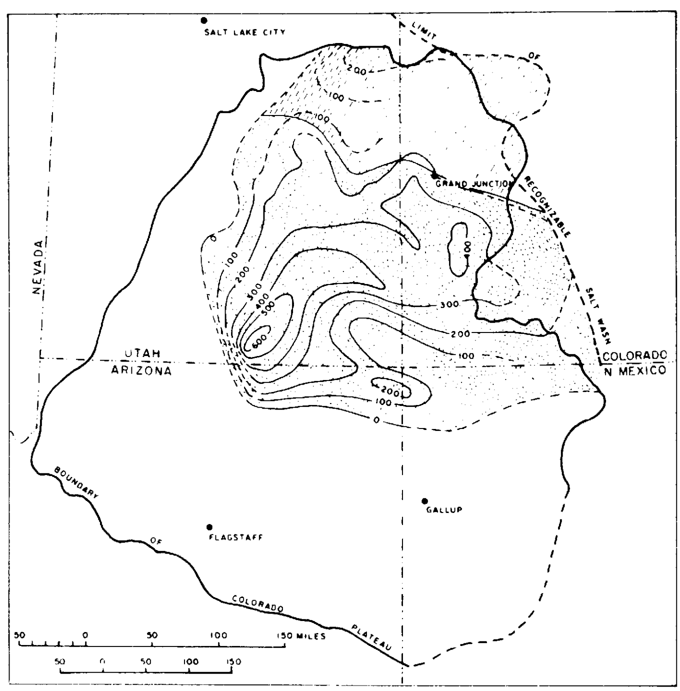


Figure 10. Isopach of Salt Wash Member of Morrison Formation in Colorado Plateau, modified from Craig and others, (1955). Stippled pattern denotes humid region fan and braided stream systems. Dashed pattern indicates coarse- and fine-grained meanderbelt systems. (Isopachs in feet).

of the Carmel Formation to form a single unit. The lower contact of the eolian facies of the Entrada is gradational where it overlies the Carmel or its correlatives, but where these units are absent the contact is a pronounced disconformity. Throughout most of the Colorado Plateau the Entrada grades upward into and intertongues with the overlying Summerville Formation; but, in the San Juan basin of northwestern New Mexico and southwestern Colorado, it is disconformably overlain by the Todilto (Pony Express) Limestone of restricted bay origin. Along much of the western edge of the region the Entrada is disconformably overlain by the littoral and neritic Curtis Formation.

Depositional Systems of the Entrada Sandstone: The Entrada is composed of two distinct depositional systems: an eolian sand dune system on the east and tidal flat mudstone system on the west (figure 7). Both systems contain uranium but the sandstone system is by far the more important.

The sand dune system is a thick wedge of fine- to medium-grained cross-bedded sandstone produced by sand dunes migrating generally eastward from a broad tidal flat bordering a shallow inland sea in central Utah in Late Jurassic time. Near its eastern margin it appears to have been somewhat reworked by streams and it is here that uranium deposits occur.

The tidal flat system is a series of red sandstones, siltstones and mudstones with some interbedded gypsum. The presence of gypsum indicates a sabkha or supratidal origin. Uranium in this system is generally related to collapses produced by solution of gypsum.

Economic Geology: The Entrada has been a producer of uranium-vanadium ores at a number of localities in western Colorado. Most important of these are the Rifle and Durango-Rico-Placerville (Roscoelite belt) districts. Production from the Entrada has been about 387 tons U_3O_8 and 9,000 tons V_2O_5. Thirty dollar per pound reserves are estimated at about 300 tons V_3O_8 and the potential resources at 4,000 tons U_3O_8.

Ore occurs as one or more tabular layers parallel to formational contacts but in places solution fronts cut sharply across bedding to form prominent roll ore bodies. At Rifle, where the ore extends into the underlying Jurassic Navajo Sandstone, there are three ore layers, possibly parts of the same roll front that is S-shaped in plan view. Each layer is accompanied by one thin layer of finely disseminated grains of galena and clausthalite and by a second layer containing a micaceous chrome-bearing mineral (Fischer, 1960). Ore minerals are principally micaceous vanadium-bearing silicates with varying amounts of secondary uranium and uranium-vanadium minerals.

The source of uranium is unknown, but the uranium could have been derived from the overlying Morrison Formation or from solutions migrating laterally through the sandstone from a distant source. The precipitant for the uranium is also unknown, but the proximity of a small breached oil reservoir at Rifle and the somewhat petroliferous overlying Pony Express Limestone in the Roscoelite belt suggest a petrolic reductant.

Morrison Formation

The Morrison Formation of Late Jurassic age, one of the most widespread fluvial units on the Colorado Plateau (figure 8), is the major uranium producing formation in the U.S. It covers more than half of the Plateau but has been eroded from the major upwarps.

In the Colorado Plateau the Morrison consists of somewhat tuffaceous claystones, mudstones, siltstone, sandstones and conglomerates, and ranges from 500 to 1000 feet (152 to 304 m.) thick. Ledge-forming sandstones and conglomerates are pale brown, orange, yellow and gray, whereas finer-grained slope-forming strata are reddish brown, greenish gray and purple.

In the Colorado Plateau the Morrison has been subdivided into 4 members which are, from the base upward, the Salt Wash, Recapture, Westwater Canyon and Brushy Basin Members (figure 9). The 3 lower members are restricted to various portions of the region, but the Brushy Basin Member is present nearly everywhere Morrison rocks are recognized (Craig and others, 1955).

Members: The Salt Wash Member is restricted to the northern two-thirds of the Colorado Plateau where it forms a large fan-shaped coarse clastic wedge (figure 10). Along the western and northern margins of the coarse clastic wedge it interfingers with and grades into the overlying Brushy Basin, and in northeastern Arizona it intertongues with the Recapture Member.

The Salt Wash is composed predominantly of interstratified units of sandstone and mudstone but the ratio of these lithologies varies from place to place. In south-central Utah, near the thickest point of the sand sheet, the Salt Wash is as much as 600 feet (183 m.) thick and consists almost entirely of quartzose sandstone. As the unit is traced northward and eastward it thins to an average thickness of about 200 feet (61 m.) and tongues of mudstone appear in the section. In the eastern portion of the sand sheet 2 prominent mudstone units split the sandstone beds into 3 wedges, to which the terms "lower", "middle:," and "upper" rims have been applied. Along most of the periphery of the sand sheet the sandstones disappear by interfingering with and grading into mudstone, but in places along the northern and eastern margins the sandstones may continue toward the northeast as narrow channel-fill bodies marking the courses of meandering streams draining the broad floodplain.

The sandstones are grayish yellow, pale orange, or white, fine-to medium-grained and contain a few lenses of pebbles. They commonly exhibit medium- to large-scale cross bedding, have sharply scoured bases, and contain scattered concentrations of carbonized logs and fine carbonaceous trash. Individual lenses range from a few inches to 20 feet (6 m.) or more in thickness and may combine to form multistoried bodies more than 100 feet (31 m.) thick.

Mudstones range from silty to sandy and vary from pale reddish brown to grayish red and light greenish gray. The greenish gray color is characteristic of bleached zones beneath sandstone beds.

The Recapture Member is restricted to the southern one-third of the region (figure 11). Throughout most of this area it is the basal unit of the Morrison, but in the Four Corners area it intertongues with and overlies the Salt Wash. Limited studies indicate a southwestern source for Recapture sediments (Hilpert, 1969).

The Recapture generally consists of interstratified pinkish gray to light brown sandstone and pale red to dark red silty and sandy mudstone. Along its southwestern margin it intertongues with and grades into the eolian Cow Springs Sandstone. Throughout northeastern Arizona and northwestern New Mexico it ranges from 200 to 300 feet (61 to 91 m.) in thickness, attaining a maximum of about 680 feet (207 m.) in northeastern Arizona.

The Westwater Canyon Member disconformably overlies the Recapture (Green 1975) and is essentially restricted to the southern one-third of the Colorado Plateau (figure 12). It attains a maximum thickness of more than 300 feet (91 m.) near Todilto Park northwest of Gallup, New Mexico, from where it grades northward into the Brushy Basin Member in southwestern Colorado. It thins westward and southward to a featheredge that passes near Cow Springs, Arizona and along the southern margin of the San Juan

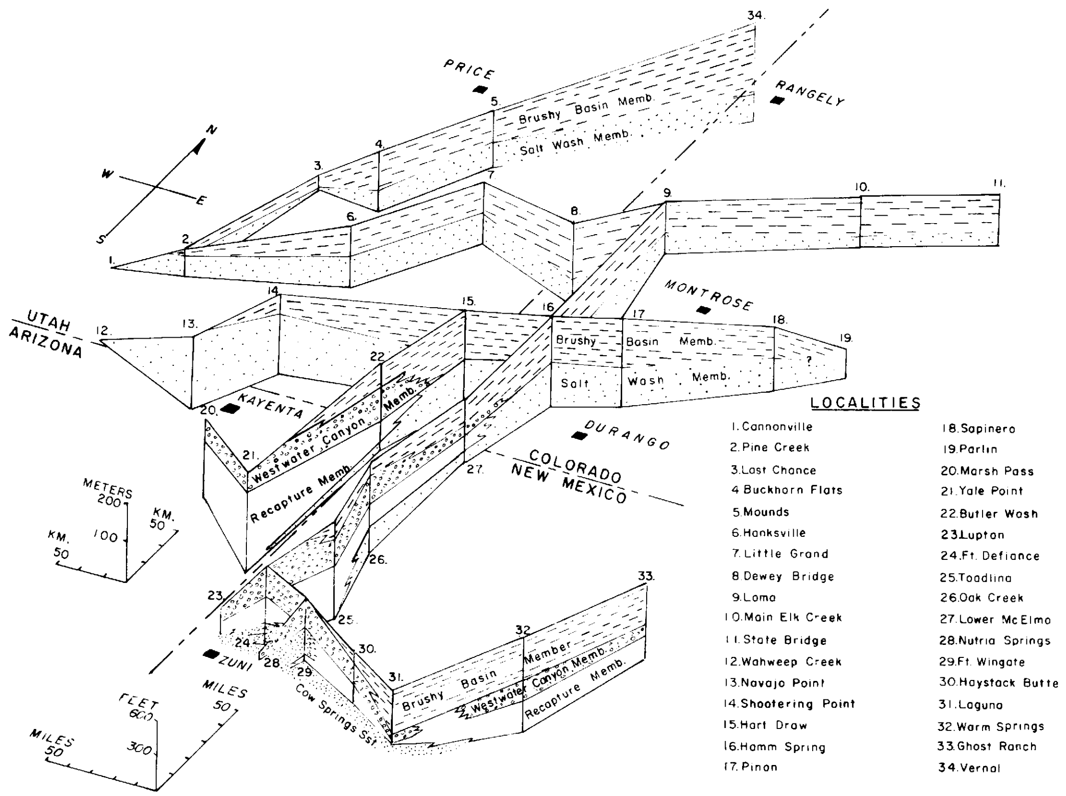


Figure 9. Fence diagrams of Morrison Formation, modified from Craig and Dickey, 1956.

basin. It ranges from 100 to 250 feet (31 to 76 m.) thick throughout most of the San Juan basin.

The Westwater Canyon Member in New Mexico is largely a gray or reddish brown, medium- to coarse-grained, moderately well-sorted, subarkosic to arkosic sandstone interbedded with mudstone. The sandstone generally consists of many lensing cross-laminated beds, each as much as 20 feet (6 m.) thick, which exhibit deeply scoured bases. Locally the sandstone contains stringers and layers of quartz, feldspar, granite, quartzite, and chert pebbles. A conglomeratic sandstone phase occurs in an area near Gallup, New Mexico. Plant debris is common in the sandstone and consists of fragments of carbonized and silicified logs or limbs. local concentrations of finer carbonaceous debris, and a fine-grained black to brown material that coats sand grains and fills intergranular spaces.

The mudstone is generally green or yellow and occurs in discontinuous layers ranging from less than 1 foot to 40 feet (0.3 to 12 m.) in thickness. In general, mudstones are more prominent near the top of the member, and become dominant where the Westwater Canyon Member intertongues laterally with the Brushy Basin.

Cross-stratification, heavy mineral, and pebble-size distribution studies (Craig and others, 1955; Cadigan, 1967; Dodge, 1973; Flesch, 1974) of Westwater Canyon Member sediments suggest a probable source area to the south and southwest in the ancient Mogollon highland. Mapped sedimentary trends show strong north to northeast components in western portions of the area covered by the Westwater Canyon Member and east to southeast components in the Grants mineral belt and eastern San Juan basin (figure 13).

The Brushy Basin Member which occurs throughout most of the Colorado Plateau is the most widespread of all members of the Morrison (figure 14). Pre-Cretaceous erosion removed it from the southwestern margin of the province and more recent erosion has eroded it from major uplifts. It ranges in thickness from zero along the southern edge of the Colorado Plateau to about 400 feet (122 m.) in southwestern Colorado and to as much as 600 feet (183 m.) near Vernal, Utah (Craig and others, 1955). Variations in thickness are due to intertonguing with other members and to the influence of growing structural features.

The Brushy Basin consists primarily of greenish variegated silty and sandy mudstone, but does contain some carbonaceous mudstone in eastern Utah. The mudstone generally contains abundant montmorillonite derived from devitrification of volcanic ash. Interbedded with the mudstone are lenses and layers of sandstone similar to those of the members with which it intertongues. In the northern half of the region some sandstone lenses at or near the base of the Brushy Basin are similar to those of the Salt Wash. One of these is the so-called Christmas Tree Conglomerate. Along the southern margin of the San Juan Basin there are two thick uranium-bearing sandstone wedges near the base of the member: the Poison Canyon Sandstone of the Ambrosia Lake area and the Jackpile Sandstone of the Laguna area.

The Poison Canyon Sandstone in its type area is about 50 feet (15 m.) thick, and is lithologically identical with the Westwater Canyon Member from which it is separated by a 15- to 25- foot thick (5 to 7 m.) mudstone (Hilpert and Freeman, 1956). The Poison Canyon extends northward and eastward several miles before pinching out into the Brushy Basin. The writer has traced the Poison Canyon westward to where the intervening mudstone is absent and it rests disconformably on the Westwater Canyon Member. For this reason some workers consider the Poison Canyon Sandstone to be a part of the Westwater Canyon Member. The Poison Canyon reaches a thickness of about 110 feet (34 m.) near Coolidge, New Mexico (figure 15).

The Jackpile Sandstone is a yellowish gray to white, fine- to coarse-grained

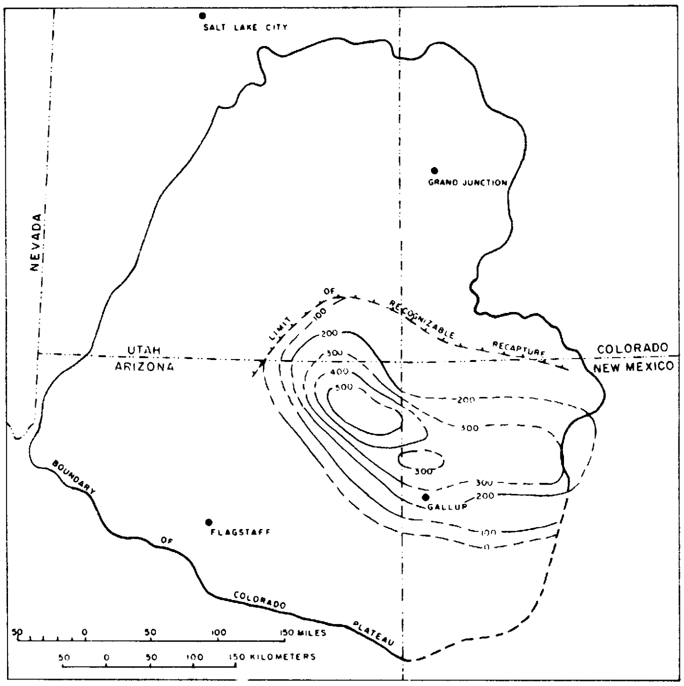


Figure 11. Isopach of Recapture Member of Morrison, modified from Craig and others (1955) Isopachs in feet.

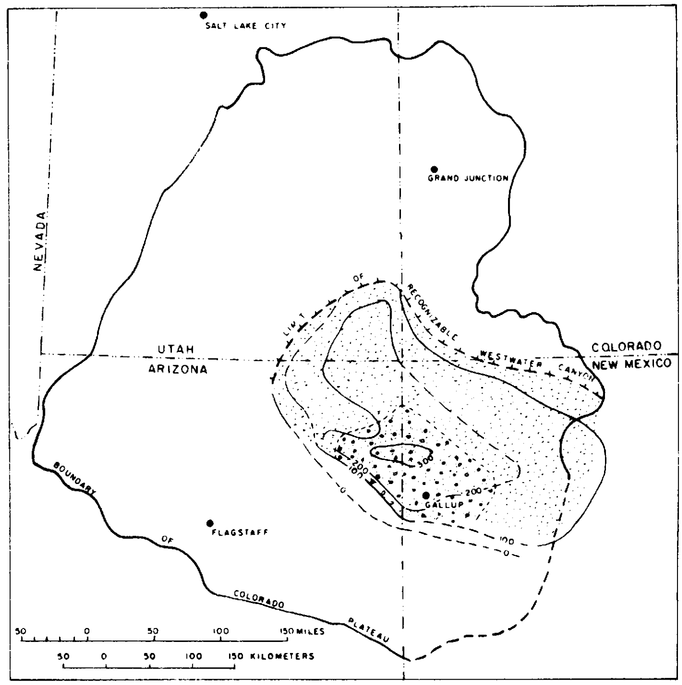


Figure 12. Isopach of Westwater Canyon Member of Morrison Formation, modified from Craig and others (1955). Stippled pattern denotes humid region fan and braided stream systems. Larger dots locate conglomeratic phase. (Isopachs in feet).

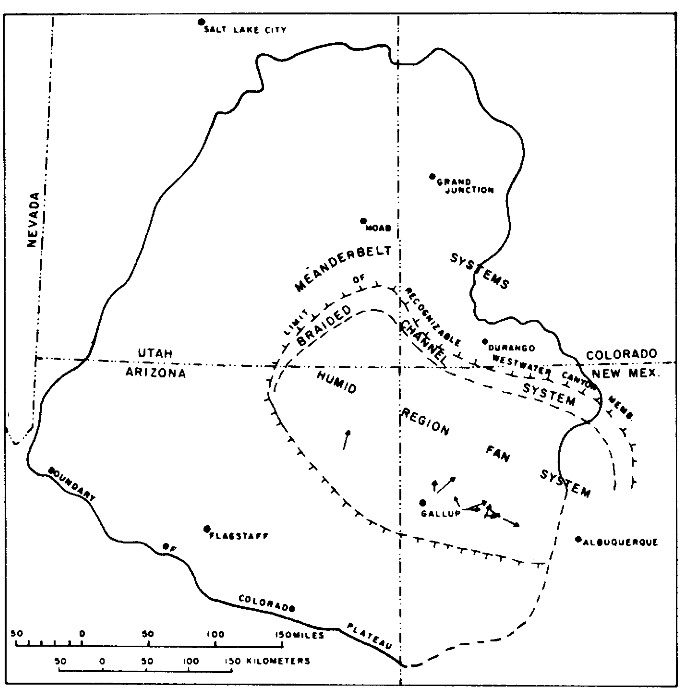


Figure 13. Sedimentary trends and depositional systems in Westwater Canyon Member of Morrison Formation, modified from Craig and others (1955).

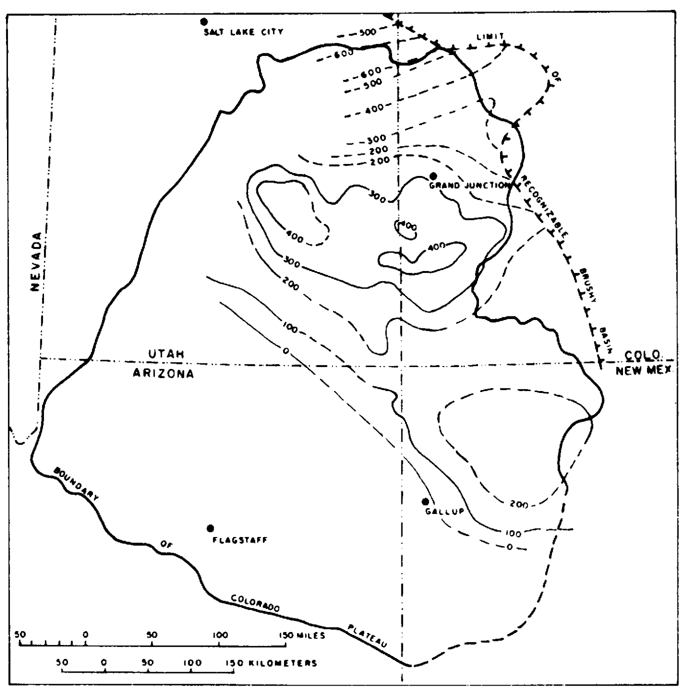


Figure 14. Isopach of Brushy Basin Member of Morrison Formation, modified from Craig and others, (1955). (Isopachs in feet).

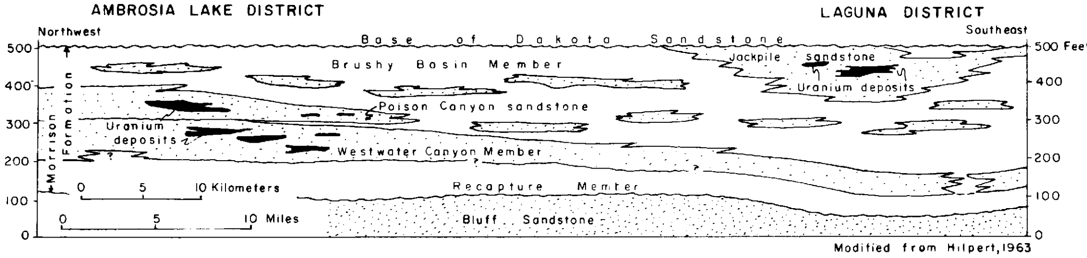


Figure 15. Cross section of Morrison Formation along southern margins of San Juan basin, New Mexico.

fluvial sandstone with minor conglomerate filling a northeast-trending pre-Cretaceous structural depression. It is a sandstone body some 13 miles (20 km.) wide, more than 30 miles (45 km.) long, and as much as 200 feet (61 m.) thick (Schlee and Moench, 1961; Moench and Schlee, 1967).

Depositional Systems of Morrison Formation: The Morrison Formation of the Colorado Plateau is composed of 4 fluvial and fluvial-eolian depositional super-systems each recording a period of uplift and subsequent erosion in the old Mogollon highland of southern Arizona and southern New Mexico. These super systems include the Four Corners fluvial-eolian system and the San Juan, Haystack Butte and Laguna fluvial systems.

The Four Corners Fluvial-eolian system constitutes the Salt Wash and Recapture Members of the Morrison and a part of the Cow Springs Sandstone. This system represents the products of wind and stream sediments transported northward and northeastward from the old Mogollon highland during or following a period of pronounced uplift of that source area. The eolian sands accumulated relatively close to the mountain front, but the stream-transported debris was spread far to the north, some of it eventually reaching the sea nearly a thousand miles away.

Four fluvial depositional systems can be recognized within the Four Corners fluvial-eolian super-system: humid region fan, braided stream, coarse-grained meanderbelt and fine-grained meanderbelt systems (figure 16). Most of the large streams appear to have emerged from the mountains in northwestern Arizona, from whence they spread over the upper part of the floodplain to form the thick sheet of coarse-grained multistoried sandstone characteristic of the Salt Wash in its southern habitat. As the anastamosing streams reached the distal edge of the humid region fan, they coalesced to form a few large northeast-flowing streams. At first they were overladen and their courses were braided, but they eventually flowed more swiftly and meandering commenced. Salt Wash sediments of the northern portion of the Colorado Plateau formed on the lower floodplain dominated by meandering streams.

The Four Corners system is thickest at the apex of the humid region fan in south central Utah. From here braided streams spread northward and northeastward as shown on figure 16. Near the eastern margin of the fan the dispersal pattern is controlled by growing structures such as the salt anticlines of the Paradox Basin and the adjacent Uncompahgre uplift. Sandstones are thicker and stream channels may turn abruptly to follow the flanks of structures. This might be explained by the existence of rim synclines on the flanks of salt anticlines, but such features are lacking on tectonic folds.

The bulk of the uranium deposits in the Four Corners system are found near the margins of the humid region fan deposits and in braided stream sandstones. A few are present in coarse-grained meanderbelt sandstone beds.

In the southeastern portion of the region, a large sand dune field occupied the area just northeast of the Mogollon highland and effectively blocked any large streams from draining directly into the lowlands from the uplift. However, small streams draining from the dune areas joined with those flowing eastward from the edge of the humid region fan to supply mostly fine clastics to the strongly oxidizing environment of the southeastern quarter of the Colorado Plateau. These coarse- and fine-grained meanderbelt deposits form the Recapture Member and the eolian sand dune deposits form the Cow Springs Sandstone.

The San Juan fluvial system comprises the Westwater Canyon Member and the correlative portion of the Brushy Basin Member. It was produced by streams draining northward and northeastward from the Mogollon highland during and following a second uplift of the source area in Morrison time. The focus of this uplift appears to have been farther east than the first uplift, because major sediment-bearing streams appear to have been located in the upper floodplain near Gallup, New Mexico. From here these streams spread across the southeastern portion of the Colorado Plateau.

Humid region fan, braided stream, and coarse- and fine-grained meander belt systems are also recognized within the San Juan super-system (figure 13). The humid region fan system constitutes the bulk of the Westwater Canyon. The fan forms a broad sheet of multistoried arkosic sandstone covering much of the San Juan basin and extending northward into southeastern Utah and southwestern Colorado. Along the distal margins of the fan, the streams reunited to form larger braided streams flowing northward and northeastward. Farther north they formed meanders. Deposits of the braided stream and meanderbelt systems constitute that part of the Brushy Basin correlative with the Westwater Canyon.

The San Juan super-system is thickest in the Gallup, New Mexico area, which is also the apex of the humid region fan or sand sheet. From the apex some streams drained nearly due north, others flowed northeast and east and a few found their way toward the southeast (figure 13). With the exception of the southeast-flowing streams all appear to have followed the gentle basinward slope. Those that tended to flow southeastward were apparently controlled by a series of shallow folds produced by buckling of limestone in the underlying Todilto as the result of hydration of anhydrite to form gypsum. Little is known about sedimentary trends beyond the margins of the fan, but isolated measurements indicate meandering channels trended generally northward.

Nearly all the large uranium deposits of the San Juan super-system are near the distal margins of the humid region fan sand sheet. A few occur in sandstones of the braided stream and coarse-grained meanderbelt systems.

The Haystack Butte super-system constitutes the Poison Canyon Sandstone and the correlative mudstone unit of the

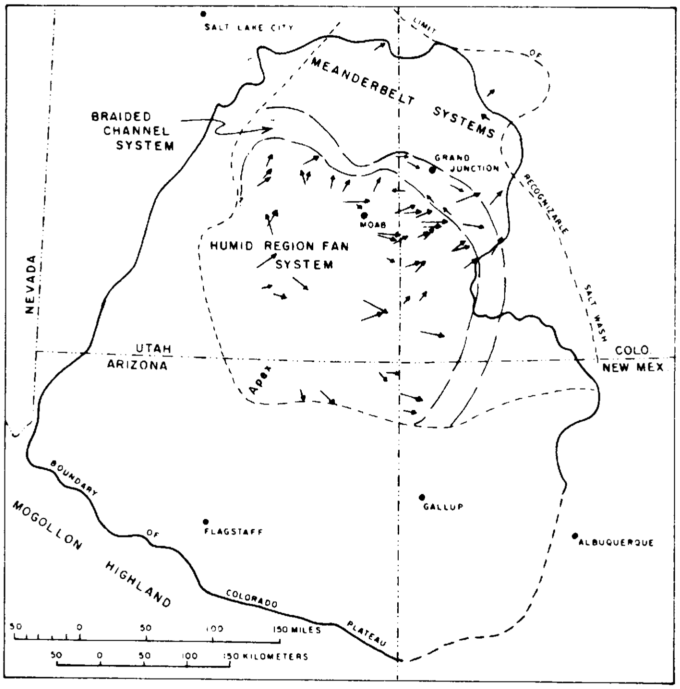


Figure 16. Depositional system and dispersal pattern in Four Corners fluvial-eolian system.

Brushy Basin Member of the southern San Juan basin. The most prominent depositional system recognized in the Haystack Butte super-system is the humid region fan system which consists of a multistoried coarse-grained arkosic sandstone deposited by streams entering the region in an area near Gallup. It appears to have formed in response to a third, but lesser, uplift in the source area during Morrison time. Braided stream and meanderbelt systems are present beyond the distal margins of the fan, where they constitute the correlative portion of the Brushy Basin mudstone.

Nearly all the uranium deposits in the Haystack Butte system are clustered near the distal margins of the fan. A few occur in braided stream and coarse-grained meanderbelt systems.

The Laguna super-system constitutes the Jackpile Sandstone and the correlative mudstone unit of the Brushy Basin in the area between Laguna and Cuba, New Mexico. Most of the recognizable Jackpile Sandstone is formed by the humid region fan depositional system. The Jackpile consists of a multistoried sandstone deposited in a northeast-trending structural depression by streams draining the Mogollon highland, to the south, and probably represents a fourth orogenic pulse in the source area. The correlative mudstone units of the Jackpile Sandstone are formed by braided stream and meanderbelt systems.

The exceptionally large uranium deposits of the Laguna system also tend to occur near the distal margins of the humid region fan. None have been recorded in other systems.

Economic Geology: The Morrison Formation is the most important host formation in the Colorado Plateau. Uranium has been produced from all 4 members but production from the Recapture has been negligible. The Department of Energy (DOE) does not record production or estimate reserves and resource potential for each member but does have total figures for the formation. As of January 1, 1977, the Morrison had produced approximately 150,000 tons U_3O_8 and 195,000 tons V_2O_5. Thirty dollar per pound reserves are estimated to total 333,000 tons U_3O_8 with 350,000 tons V_2O_5, and $30 per pound potential uranium resources are estimated at 863,000 tons U_3O_8 (US ERDA, 1976).

The largest and most important known uranium deposits in the Morrison are those in the southern part of the San Juan basin in New Mexico. Most of the ore is in the Westwater Canyon Member and the Poison Canyon and Jackpile Sandstones of the Brushy Basin Member. The principal ore mineral is fine-grained coffinite which is associated with fine-grained, grayish black or brown carbonaceous material that coats sand grains or fills intergranular voids. Ore bodies are of two types: primary ore bodies that are tabular elongate or lensoid masses with long dimensions generally parallel to depositional trends, and redistributed (stack and roll-front) ore bodies. Ore bodies containing several million pounds U_3O_8 are common.

Elsewhere in the Colorado Plateau most of the Morrison uranium deposits are in sandstones of the Salt Wash Member. In the Uravan mineral belt and the LaSal, Lukachuki Mountains, Carrizo Mountains, Henry Mountains, Cottonwood Wash, Green River and Thompson mining districts, coffinite, uraninite, montroseite and numerous secondary uranium and vanadium minerals occur in association with carbonaceous trash in sandstone. Ore bodies are commonly tabular parallel to bedding and are elongate parallel to sedimentary trends. In many localities they display prominent solution-front "rolls". Ore bodies are generally smaller than those in the southern San Juan basin but a few may contain as much as 2 million pounds U_3O_8 and several times as much V_2O_5.

Small amounts of uranium have been mined from Brushy Basin sandstones just above the Salt Wash in several localities in Utah and Colorado. Somewhat larger deposits are reported in carbonaceous mudstone of the Brushy Basin in the San Rafael Swell district, Utah.

The source of the uranium in the Morrison has not been determined but could have come from volcanic ash in Brushy Basin mudstone or from granitic debris in the sandstones. Regardless of origin, the Morrison ore deposits appear to be of more than one age. Brookins (1975) has demonstrated, using K-Ar dating methods, that Westwater Canyon Member ore is 14 to 29 million years older than that of the stratigraphically higher Jackpile Sandstone.

USE OF SEDIMENTOLOGIC DATA TO PREDICT NEW TRENDS

Sandstone-Type Uranium Model

The model presented here is based on such factors as source and nature of the sediment type of depositional system, presence of a reducing environment, presence of a uranium source, thickness of host sandstone, sandstone-shale ratios, dip of the host and nature of ground waters.

The best model for sandstone-type uranium deposits is one in which a rising mountain mass with an exposed uranium-rich granitic intrusive core (50+ ppm U_3O_8) is subject to rapid weathering and vigorous erosion Nearby volcanic eruptions may supply pumice and ash in great quantities from

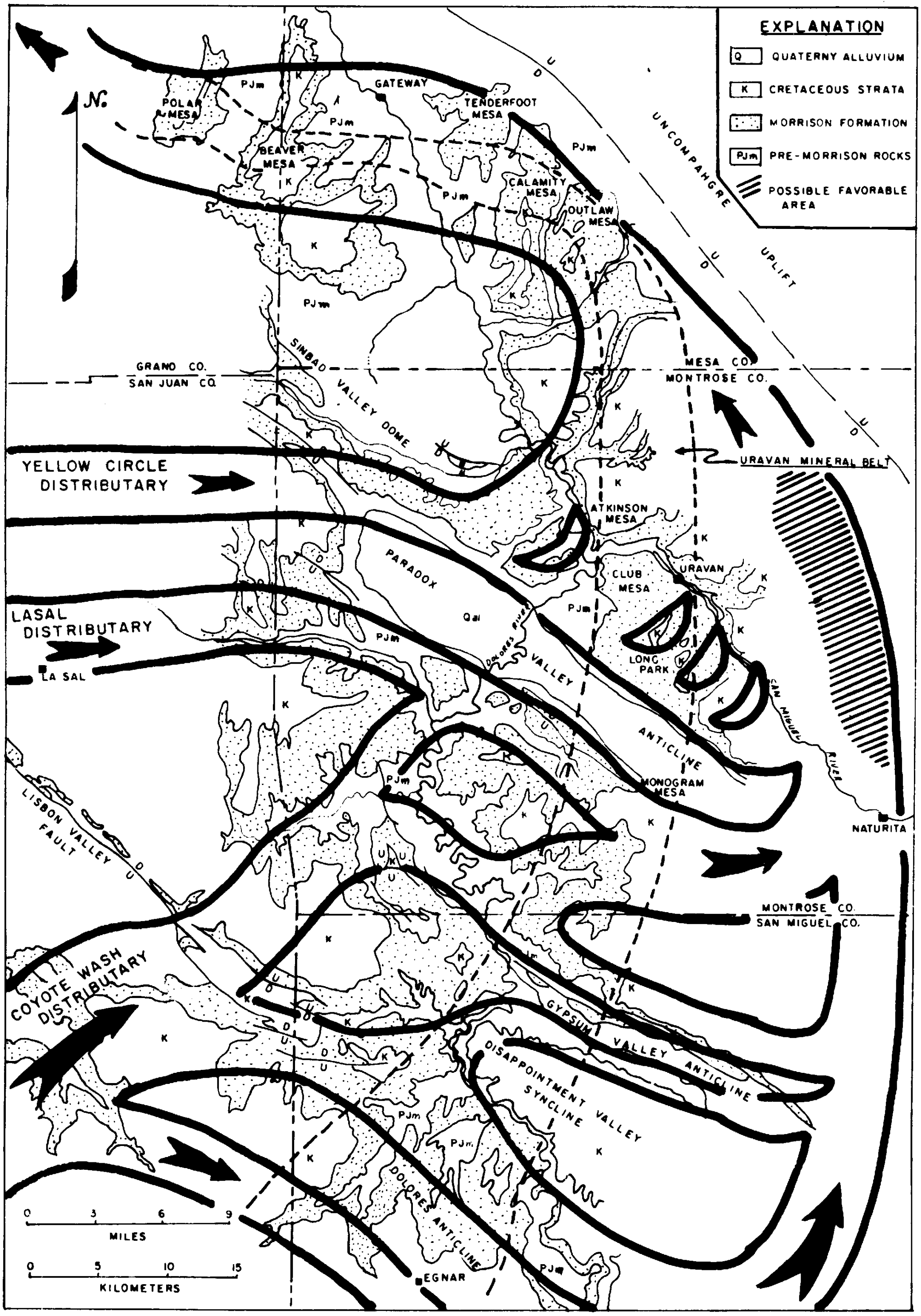


Figure 17. Distributaries and favorable areas in Uravan mineral belt of eastern Utah and western Colorado.

the same intrusive magma. The weathering debris and volcanic materials are transported basinward by wind and large rapidly flowing streams. As the streams emerge from the uplands onto the broad gently-sloping plain beyond, they are unable to transport their heavy bedloads and sand deposition begins. The streams split into innumerable shallow distributaries which alternately divide and rejoin to form a broad system of anastomosing streams. These streams constantly rework and spread the coarser clastics to form a huge fan-like sheet of sand with thicknesses ranging from several hundred feet to a feather edge. Conifers, cycads, ginkgos, ferns and other closely related plant genera grow in profusion on the foothills and on portions of the fan, indicating a warm humid climate. From time to time shifting channels destroy islands of vegetation and the plants are swept away only to become buried farther down the fan, along with other plant remains carried down by floodwaters from the mountains.

The sediments deposited on the fan

come finer with increased distance from the source, because of decrease in stream carrying capacities. On occasion large floods allow channels of coarse debris to reach the fan, but normally the sediment is fine-grained sand along the distal edge.

As the waters reach the distal edge of the fan they tend to recombine to form larger streams that continue across the lower floodplain. At first these streams carry a large load of finer sand, and they commonly are braided. As more streams combine, their carrying capacities are increased, channels become deeper and meandering begins. The fines, which have been in suspension to this point, now accumulate as overbank material during floodstage. As the humid region fan spreads from the source it commonly covers some of the earlier-formed braided stream and meandering channel deposits.

When the source area has been reduced to low hills, chemical weathering is intense, and the uranium and other metallic elements contained in the granitic rocks are released to be carried basinward by oxidizing surface and ground waters. As these waters percolate basinward through the sand sheet, they release additional uranium from volcanic and granitic debris in the sand and transport it basinward in solution. Where these solutions encounter buried organic material they may give up some of their solution load of metals to the local reducing environment, perhaps caused by hydrogen sulfide generated by sulfate-reducing bacteria feeding on the plant debris. Where clay pods are encountered some metals may be precipitated by ion exchange reactions. Most of the uranium-bearing waters follow the more permeable sand zones but eventually encounter the thinner and finer-grained sands of the fan margins where sandstones interfinger with lenses of mud (sand: mud ratios of 1:1 to 4:1 are ideal), and percolation rates decrease dramatically. Here the oxidizing solutions find the sands already filled with strongly reducing waters produced by decaying vegetation. Interaction of the solutions results in the deposition of the uranium.

Some of the uranium solutions manage to move through the sand sheet and into braided channel and coarse-grained meanderbelt sandstones where they encounter local reducing environments. Here the last of the uranium and other metals are removed from solution.

Extending a Salt Wash Trend

In order to demonstrate the use of depositional systems in predicting new trends or the extension of old ones, the writer has selected an example from the Salt Wash Member in eastern Utah and western Colorado (figure 17). The area of interest is near the eastern edge of the humid region fan system which constitutes the bulk of the uranium-bearing Salt Wash. There are several small mining districts in this portion of the fan, and all are characterized by small to medium-sized high grade uranium-vanadium ore bodies.. As mentioned in a previous section, the sedimentary trends and geometry of the host sandstone in this area were partly controlled by growing structural features; most are related to the movement of salt in the Paradox basin over which this edge of the fan was deposited.

The Uravan mineral belt forms a somewhat arcuate pattern discordant with structure and with the fan margin. During recent years, sections were measured and channel trends mapped to determine the reason for the discordance. In addition uranium trends were plotted and occurrences were recorded to determine where new ore trends might be found. Because most of the occurrences are in the upper rim of the Salt Wash member, most data were obtained from that unit. Directional data were plotted on a geologic base and an attempt was made to reconstruct the major distributaries of the upper or third rim sandstone.

One of the most significant results of the study was the discovery that, during deposition of the bulk of the upper rim sandstones, there were at least 3 major distributaries in this portion of the fan. Southernmost of these is the Coyote Wash distributary, which trended northeast through eastern Utah into at least 6 branches each following a depression (rim syncline) on the flank of a salt structure, then recombined to form a large north-flowing stream along the flank of the Uncompahgre uplift. The LaSal distributary, some 15 miles (22 km.) northwest of the Coyote Wash distributary, trended nearly east until it reached the southwest flank of the Paradox anticline. There, it turned southeast to follow a rim syncline.

The Yellow Circle distributary, approximately five miles north of the LaSal distributary, entered the area from the west, crossed the west end of the Paradox anticline and turned southeast to follow an old rim syncline on the northeast flank of that structure. Splits from the distributary turned abruptly toward the north in broad sweeping patterns at various places along this flank. There, they joined with other distributaries from farther south to form a very large northwest-trending stream. The rising Uncompahgre uplift prevented continuation of the stream north-eastward and caused it to turn northwest to parallel the large structure. Near the town of Gatewaterway, Colorado, it turned westward, crossed into Utah, and continued northwestward until it reached the Yellowcat area. Here it turned away from the northeast flank of the Salt Valley salt anticline, swung around the Yellowcat salt dome, and continued northeast across the nose of the Uncompahgre uplift. Near the Utah - Colorado state line it split into several lesser distributaries. Some crossed the Douglas arch and continued east and southeast across the Piceance basin. One major distributary turned southeast along the northeast flank of the Uncompahgre uplift and continued for at least 50 miles (75 km) in that direction.

This study points out the possibility of the occurrence of uranium deposits in those distributing segments which continued southeastward in the rim synclines and ultimately turned northward to regroup into the large distributary along the flank of the Uncompahgre uplift. These segments are at relatively shallow subsurface depths for many miles, and are exposed in a few places. There are a few exposures of thick favorable sandstone containing a few small ore bodies. This area warrants further investigation.

ACKNOWLEDGMENT

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EOLIAN SAND DUNES OF THE GREAT SALT LAKE BASIN

by Leslie E. Dean[1]

ABSTRACT

Sand dunes cover approximately 11 percent of the area in the Great Salt Lake Desert and along the coast of Great Salt Lake. Thirty-one dune fields were identified and mapped, and data concerning 11 variables for 169 dunes were gathered. Three sand lithologies are present: silica (quartz), gypsum, and oolite. Silica sands are generally found surrounding the Great Salt Lake Desert, gypsum sands are found within the Great Salt Lake Desert, and oolitic sand is found downwind from many beaches along the coast of present-day Great Salt Lake. Two predominant dune types are present: transverse dunes, found within the Great Salt Lake Desert, and parabolic dunes. The majority of dunes are stabilized by vegetation..

In this study, data was collected for eleven variables, including dune area, height, dune type, elevation above sea level, sand lithology, orientation of dune field and underlying slope, percentage of dune cover and vegetation cover, and grain size and sorting coefficient of the sand.

The results of the statistical testing indicate the dunes are of lacustrine origin and have been reworked by eolian processes.

INTRODUCTION

Extensive eolian deposits are found peripheral to the Great Salt Lake and within the Great Salt Lake Desert area of Utah (figure 1). The area studied encompasses, in part, the following Utah counties: Box Elder, Davis, Juab, Salt Lake, and Tooele, and is located within the northeastern part of the Great Basin section of the Basin and Range physiographic province.

The purpose of this study was to map and classify dunes and dune fields in the Great Salt Lake Basin, and to collect data to test whether the dunes are of eolian or lacustrine origin modified to some extent by the wind after exposure of the Bonneville Lake sediments.

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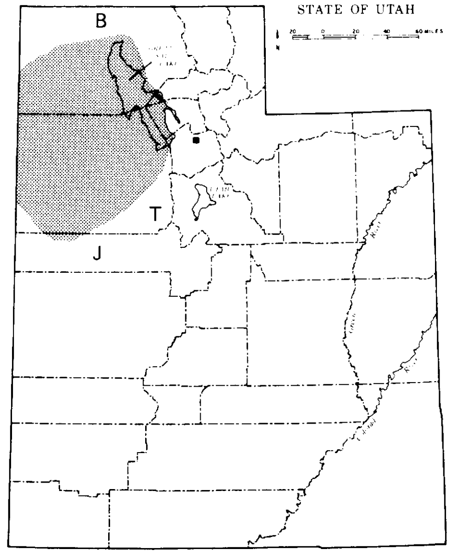

Figure 1. Index map

Definitions

For the purposes of this study, the following definitions are used: *Sand Dune:* a mound or ridge of eolian sand, that may or may not exhibit a slipface. In this study the lowest eolian structure considered to be a dune is limited to 1 meter in height. Some structures that appear to have been influenced by eolian processes in the past but are presently covered by coarse granular material (lag gravel) are also considered as dunes in this study. *Sand Dune Field:* a cluster of dunes, composed of similar lithologies, oriented in a similar direction, that are distinctly separated from all other clusters.

Field mapping of Dune Fields

Thirty one dune fields in the area were located on conventional aerial photographs, geologic maps, topographic maps, and by ground observation, and mapped on 1:250,000 scale base maps (figure 2, table 1). Conventional aerial photograph coverage was an invaluable source in areas, such as the Great Salt Lake beaches, where it was available. Satellite imagery was generally not suitable for this study because of its limited resolution.

The 1:250,000 scale Geologic Map of Utah, northwest, (Stokes, 1962) provided data on major field boundaries and lithologies, but many smaller fields were found to have been omitted. United States Geological Survey 1:24,000 and 1:62,500 scale topographic quadrangle maps provided data for some smaller field boundaries, but coverage does not exist for the entire area.

Several dunes were located by ground observation, some while enroute to other known fields. Individuals familiar with parts of the area provided additional data on some fields.

United States Government weapons testing made much of the study area inaccessible. In August, 1975, a visit was permitted to obtain data within the Dugway Proving Grounds. The visit was limited in scope by the amount of time allotted and to the areas for which access was permitted. Therefore, this part of the study area was not sampled in as much detail as the remainder.

The author believes that, while some smaller fields may have been overlooked, the sand dune fields within the study area have been adequately identified, described, and sampled to meet the objectives of this research.

An area mapped as silica sand west of the Newfoundland Mountains on the geologic map by Stokes (1962) was sampled at sites B-07 and 08, and found to have a predominant lithology of gypsum. The area northeast of Sapphire Mountain (south of Granite Mountain) within the Dugway Proving Grounds mapped as being an oolitic dune field, was sampled at site T-17 and found to have a predominant lithology of silica.

Review of Pertinent Literature

Eardley (1938), stated that the oolites found in some dunes were probably formed in shallow water. Agitation of the water and a high evaporation rate probably resulted in rapid deposition of calcium carbonate layers on available nuclei, particularly around fecal pellets of brine shrimp. Eardley and Stringham (1952) wrote that exposures of selenite-bearing clays could have been deflated to provide the gypsum.

Jones (1953) noted that a series of transverse dunes near Knolls is composed of 50 percent gypsum, 38 percent oolites, and minor amounts of quartz. He found oolites in the dunes around Knolls to be

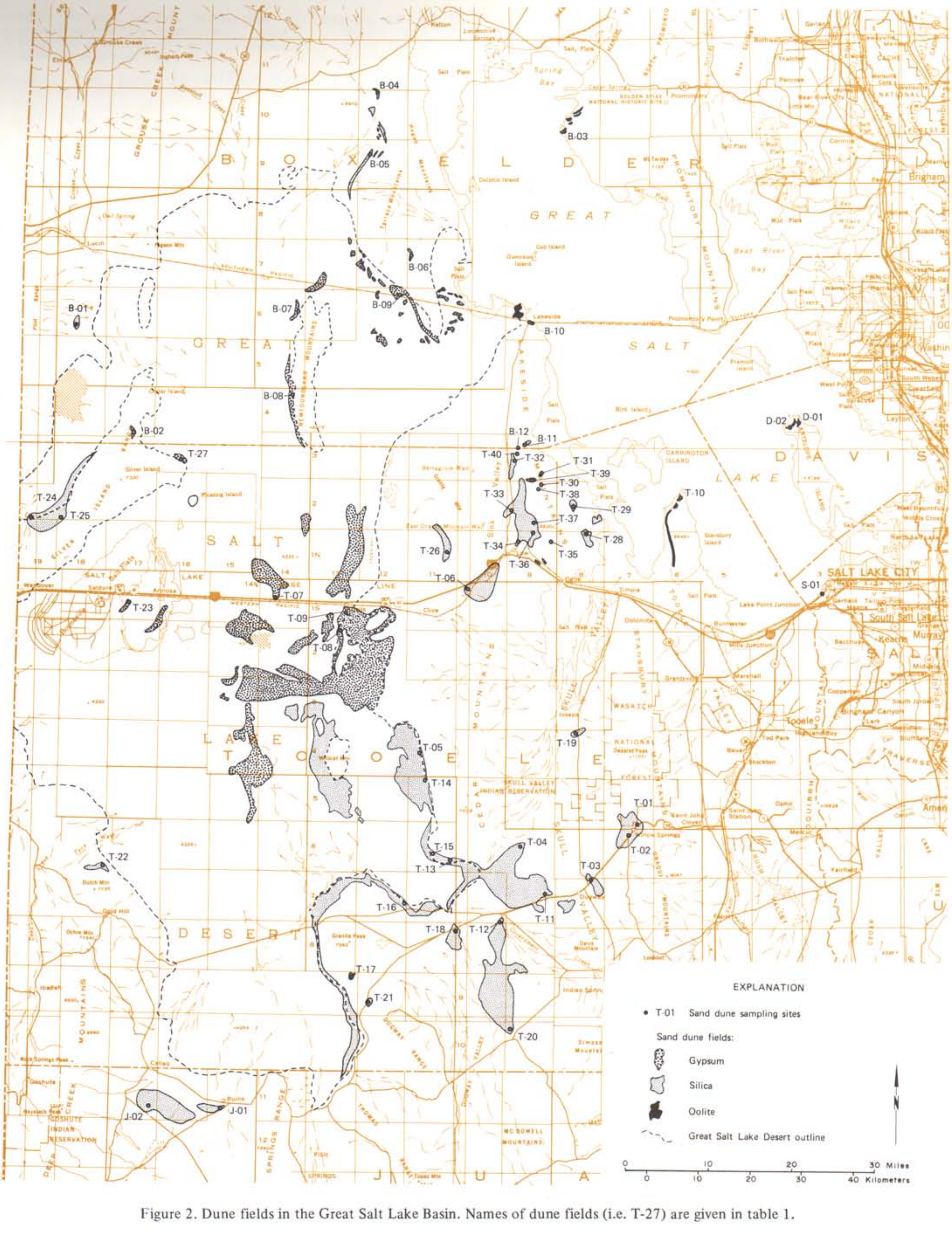

Figure 2. Dune fields in the Great Salt Lake Basin. Names of dune fields (i.e. T-27) are given in table 1.

Table 1. Sand dune fields and included sites; refer to figure 2 for boundaries of fields and location of sites. (B- Box Elder County; D- Davis County; J- Juab County; S- Salt Lake County; T- Tooele County.

Dune Field Name	Included Sites
1. Antelope Island	D-01 and 02
2. Buchanan	T-18
3. Callao	J-01 and 02
4. Cobb Peak	T-27
5. Ditto	T-12 and 20
6. Dove Creek Sinks	B-04
7. East Dugway	T-03
8. East Lakeside Mountains	B-11, T-28, 29, and 31
9. Gold Hill	T-22
10. Granite Mountain	T-16 and 21
11. Johnsons Pass	T-01 and 02
12. Knolls	T-08 and 08
13. Lakeside Mountains, Bonneville Level	T-30, 35 and 38
14. Lakeside Railroad Settlement	B-10
15. Lucin	B-01
16. Microwave	T-07
17. Newfoundland Mountains	B-07 and 08
18. North Wig Mountain	T-05 and 14
19. Promontory Ranch	B-03
20. Puddle Valley	T-06
21. Ripple Valley	T-26
22. Salt Mountain	T-19
23. Saltair	S-01
24. Sapphire Mountain	T-17
25. Silver Island Mountain	B-02, T-24 and 25
26. South Wig Mountain	T-13 and 15
27. Stansbury Island	T-10
28. Terrace Mountains	B-05, 06, and 09
29. VOR	T-23
30. West Dugway	T-04 and 11
31. West Lakeside Mountains	B-12, T-32, 33, 34, 36, 37, 39 and 40

generally smaller than those in present-day Great Salt Lake. Quartz sand was believed to be from Tertiary lacustrine sediments.

Teichert (1958) noted that sand dunes overlie Lake Bonneville sediments in the vicinity of Johnsons Pass (between the Stansbury and Onaqui Mountains). Here sand is composed of fine quartz grains, presumed by Teichert to have been blown in from the desert to the west.

Schaeffer (1961) noted that sand dunes composed of quartz and feldspar are accumulating along the west side of the northeastern extremity of the Leppy Range (south end of Silver Island Mountains). He found mound-shaped dunes composed largely of wind-blown silt on the north and northwest edges of Crater Island. On the northwest side of Donner-Reed Pass, between Silver Island and Crater Island, are linear sand deposits up to hundreds of meters long that trend northwest and are located at approximately the Gilbert level of Lake Bonneville (1296 meters). He concluded that poor sorting and rounding of the sand grains are indicators that these were beach sands that have a very local source and have had little reworking. Their mineralogical composition appeared to be that of the Crater Island stock to the north. Deposition appeared to have been influenced by a northwesterly current within Lake Bonneville.

Eardley (1962) suggested that the gypsum crystals that comprise dunes in the central part of the Great Salt Lake Desert may have originated in the desert surface clays. These crystals probably had been removed from the clays by wind ablation.

Doelling (1964) noted that dunes are found on the east side of Ripple Valley (west of the Grassy Mountains) near the south end of Puddle Valley, (between the Grassy & Lakeside Mountains) and along the west slopes of the Lakeside Mountains. Minor patches of dune sand are found near the tops of the Lakeside Mountains and along the east side of the range. Doelling found the Ripple Valley dunes to be composed of gypsiferous, calcareous, and quartzitic material. The dunes surrounding the Lakeside Mountains are composed almost entirely of quartz material. He postulated that some of these dunes are remains of Pleistocene Lake Bonneville beaches driven by prevailing westerly winds to the east edge of the valley and into protected areas. He further noted oolitic sand dunes at the settlement of Lakeside and at Strongs Knob. Most of the oolitic sand is irregular to sub-crescentic in shape and is generally found against the west side of an obstruction, indicating a westerly or southwesterly prevailing wind.

Stifel (1964) noted a group of dunes between the southern Terrace Mountains and the northern Newfoundland Mountains. The group is made up of approximately 80 dunes, most of which lie in a belt 6 kilometers long and 0.5 kilometer wide. Only one is barchan-shaped, and is 427 meters long from front to back, 1189 meters from horn to horn, and 9 meters high. The other dunes are roughly dome-shaped and may have been modified by water only a few meters deep. These dunes average 518 meters in length, 244 meters in width, and have crests 4 to 7 meters in height. Gypsum grains, 3.25 to -2.50 phi in diameter, comprise the greater part of the sand. These dunes are sparsely covered by phreatophytes and trend southeastward. Stifel stated that these dunes are possibly the erosional remnants of a former tabular body of sediment which covered the area, or may be mounds of material accumulated by currents on the floor of Lake Bonneville during its later stages. This is evidenced by small spit-like protruberances present on many of them.

Maurer (1970) noted that sizable accumulations of eolian quartz sand exist on the southern, western, and northern fringes of the Cedar Mountains. Both active and stabilized dunes are found. The active dunes form a north-northwest trend along the southwest border of the range. Certain areas contain transverse undulating ridges with barchans on the margins.

DATA COLLECTION

Methodology

Initially, 31 dune fields were identified, mapped (figure 2) and a dune representative of each field was chosen as a sampling site (figure 2; table 1). Sand samples were collected from a point midway up the windward slope of the dune (figure 3). Three 200-gram sand samples were taken from each dune: one sample from 1.0 meter below the surface, one sample 0.1 meter below the surface and one sample from the surface lag granules. An additional sample was collected from the slipface, if a slipface was present. At Dugway Proving Grounds, only one sample was collected at sites T-11 through T-18 (figure 2).

The data gathered for eleven variables were selected for their inherent value in describing the physical features

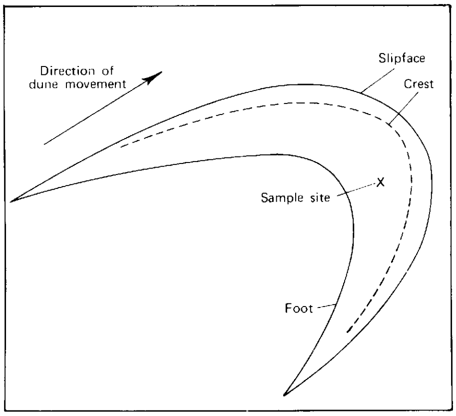

Figure 3. Parabolic dunes showing representative sample location.

of sand dunes. These variables include: area, dune height, dune type, elevation above sea level, lithology of the sand, orientation of the dune field, orientation of the underlying slope, percentage of dune cover, percentage of vegetation cover, the phi-standard deviation (sorting coefficient) of the sand, and the phi-mean grain size of the sand, (the logarithmic mean of the grain size obtained by using the negative logarithms of the class midpoints to the base 2.).

Variables for Dune Field Analysis

Dune Type

Two predominant dune types are found in the study area: parabolic (figure 3) and transverse. Most are parabolic. Isolated barchans occur on the western fringes of Wig Mountain in the southwest Cedar Range. The dunes were identified on convential aerial photographs, where available and by ground observations. Dunes were classified according to Melton (1940).

Parabolic dunes form when wind-blown sand interacts with vegetation. Unidirectional gentle-to-moderate winds (10-14 mph) and a substantial amount of sand are necessary to form the quantity of parabolic dunes found in the study area (Melton, 1940). Melton (p. 126-127) postulated that as a climate becomes increasingly arid, or if the ground water surface is lowered for some other reason, the vegetation cover may find itself unable to grow as rapidly as the wind exposes its roots. This causes a basin or "blow-out" to be formed in the sandy ground surface. The coarser sand will tend to accumulate on the leeward side of the basin, thus forming the crescent-shaped sand ridge and basin typical of the parabolic dunes in the study area. Most parabolic dunes are oval-shaped, with the "horns" of the crescent pointing toward the wind (figure 3). These dunes are recent in age and are indicators of increased climatic aridity in the Salt Lake desert. Parabolic dunes comprise the majority of dunes of every dune field in the study area except those west and south of the Cedar Mountains and west of Wildcat Mountain and Knolls (figure 2).

Transverse dunes appear to form where there is sparse vegetation and abundant sand. Melton (1940, p. 117-118) hypothesized that this dune type is formed by gentle winds blowing predominantly from one direction across a bare sand surface of substantial area and depth. This condition will produce a relatively evenly spaced series of long parallel sand ridges situated perpendicular or transverse to the direction of the prevailing wind. The windward side is gently sloping and subject to wind scour as the wind moves upward, toward the dune crest. The lee side is subject to sand deposition as grains, blown over the crest, fall and slide down the slipface, which is inclined at the angle of repose for loose sand (approximately 34°).

Barchans are isolated crescent-shaped hills which move across a relatively flat non-sandy surface in response to an unvarying wind direction (Melton, 1940, p. 115-116). In contrast to parabolic dunes, the horns of the crescent point with the wind, or downwind. As with the transverse dune, the windward slope is gentle and subject to wind scour; the leeward slope is a steep slipface. As these dunes move across the surface, the smaller dunes move more rapidly and may merge with one another to form transverse ridges. This process may be occurring in the study area.

Dune Lithology

Three lithologies are encountered in the study area: silica (quartz), gypsum, and oolite. Where the dominant constituent was not obvious in the field, microscopic examination was performed in the laboratory. The silica sands are generally found surrounding the Great Salt Lake Desert, and gypsum sands are found within the Great Salt Lake Desert. The oolite sands are found down-wind from many beaches surrounding present-day Great Salt Lake.

Silica sand is found in the predominantly parabolic dune fields. These dunes tend to be composed of moderately to poorly sorted material that appears to be of local origin, possibly from beaches deposited during various stages of Lake Bonneville. Transverse dunes, in contrast, may have moved some distance to reach their present locations and are consequently better sorted.

Gypsum sand, according to Eardley and Stringham (1952) and Jones (1953), may be concentrated from exposures of selenite-bearing clays in the Great Salt Lake Desert. Selenite clasts weather free and are concentrated by the wind.

Oolites (Eardley, 1938, and Jones, 1953) are probably formed in shallow water with a high evaporation rate. Agitation of the water results in rapid deposition of calcium carbonate layers on available nuclei. Oolites encountered in this study tend to be nearly spherical.

Dune-like structures located at the southern end of the Terrace Mountains and extending to the northern end of the Newfoundland Mountains, described as gypsum dunes by Stifel (1964), were sampled at sites B-07 and 09 (figure 2). These structures do not closely resemble dunes, but are composed of gypsum clasts, generally regarded as being of eolian origin. The 1.0- and 0.1-meter samples provided much coarser phi-means and higher phi-standard deviations than other gypsum samples taken from the study area. In the field it appeared that these gypsum structures may have been dunes of a previous dry cycle, modified by a minor rise in lake level, and again exposed. The surface material at these sites is very coarse, relative to other gypsum samples, and contains relatively smooth granules characteristic of a lacustrine environment. Gypsum dunes represented by sites T-07, 23, and 27 (figure 2), have sediment properties similar to those at sites B-07 and 09 and may have had a similar origin.

At the Lakeside Mountains (figure 2) sand dunes are not only found on the east and west sides of the range, but are also found near the tops of the mountains (figure 4). These higher elevation dunes were located on aerial photographs and field checked at sites T-30, 35, 38. They are composed of the same lithology as the dunes on either side of the range and are located at approximately the highest stabilized level of Lake Bonneville, which is approximately 1624 meters (5330 feet) in this vicinity. The phi-mean grain sizes for these dunes are generally the same as those for the dunes surrounding the mountain range at lower elevations. However, these Bonneville level dunes tend to be better sorted and exhibit smaller phi-standard deviations than dunes located at lower elevations. If these dunes had moved from a lower altitude to attain their present locations, their phi-mean grain sizes should be significantly higher, indicating finer grained material. It is probable that these dunes were derived from local beach deposits at the Bonneville level and have not moved far

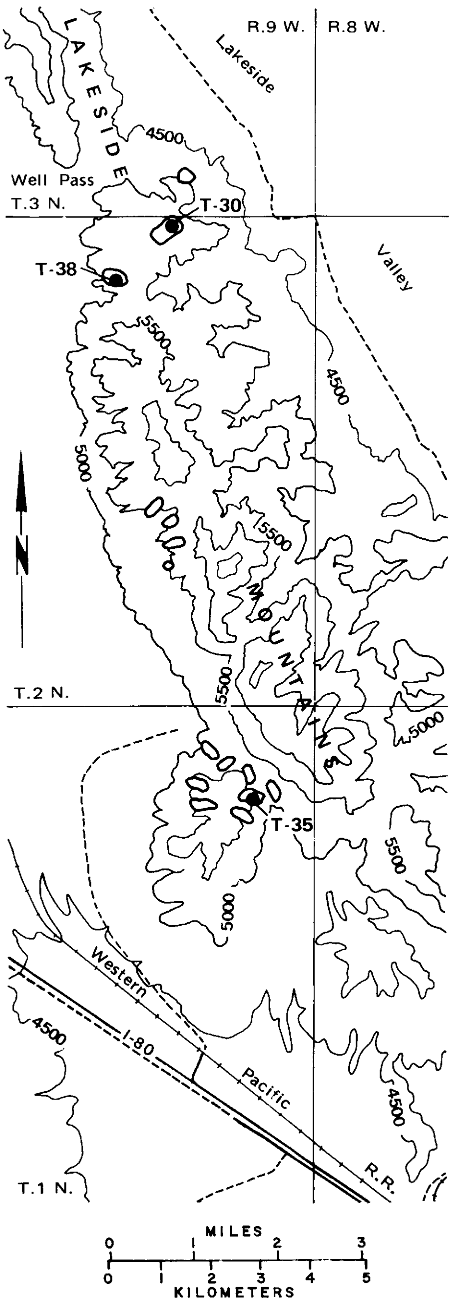

Figure 4. Map of southern Lakeside Mountains showing locations of dune fields.

to reach their present locations. The silica dunes at Johnson's Pass (sites T-01 and 02) are found at a similar elevation and exhibit similar statistical characteristics.

Mean Elevation

The average of the highest and lowest elevations within each dune field is expressed in meters above sea level. Large-scale and medium-scale topographic maps were used in measuring this variable.

Mean elevations of silica dune fields range from 1305 meters in the east Lakeside mountains to 1615 meters above sea level at Johnsons Pass. Gypsum sands are found from 1285 meters, at Cobb Peak, to 1295 meters at Knolls. Oolitic sands are found from 1285 meters at Saltair, to 1292 meters at Stansbury Island. Many fields appear to be located at well-defined former levels of Lake Bonneville.

Area of Dune Fields

The total area within the boundary of each field is expressed in square kilometers. A field includes all clustered dunes and interdune areas. Transparent overlays divided into square kilometers, scaled to the large- and medium-scale topographic maps, were used to measure the area.

The areas of silica dune fields range from 2 km^2 at Dove Creek Sinks to 114 km^2 at West Dugway. The areas of gypsum fields range from 8 km^2 at Cobb Peak to 389 km^2 at Knolls. Oolite fields range from 1 km^2 at Saltair to 13 km^2 at Stansbury Island.

Slope Angle

The mean slope of the terrain on which each dune field lies is expressed in degrees. To determine the slope, topographic maps were used to obtain the vertical and horizontal distances of each dune field. The tangent was determined according to the following formula: $\frac{V}{H} = T$ where V= vertical rise of slope beneath dune field; H= horizontal length of slope beneath dune field and T= tangent of slope angle. The tangent was then converted to its arc tangent by means of trigonometric tables.

The sub-dunal slope angles beneath silica dune fields range from 1° to 4°. The slope angles of gypsum fields are all 1° or less. The slope angles of oolite fields range from 1° to 2°.

Slope Orientation Azimuth

The azimuth toward which the slope faces is expressed in degrees clockwise from true north. Topographic maps were used to determine these azimuths.

The slope orientation azimuths of silica dune fields range, clockwise, from 10° at East Dugway to 330° at Silver Island Mountain. Slope orientations of gypsum fields range, clockwise from 120° at VOR to 360° at Cobb Peak. Slope orientations of oolite fields range from 10° at Lakeside Railroad Settlement to 320° at Stansbury Island.

Dune Field Orientation Azimuth

The azimuth from which the dune field is moving expressed in degrees clockwise from True North. If a field is stabilized, this angle represents the direction from which the field was moving when movement ceased. Aerial photographs, topographic maps, and ground observations were used to measure field orientation.

Figure 5a illustrates an outlined dune field with the general direction of the dune-forming or working wind indicated by arrows (Ives, 1946). The term "dune-forming wind" is used because prevailing winds in some parts of the study area are not the winds that appear to have been working the dunes. For example, the silica dunes near Dugway Proving Grounds are re-worked by a southwest wind, but the prevailing wind reported is either southeast or northwest. The southwest wind may be most prevalent during the drier weeks when the sand can be worked more easily. The farthest point upwind on the dune field in figure 5a is marked B and the two points most distant from B are marked A and C. Angle ABC is bisected to provide the mean direction from which the field is moving. Where fields in the study area are not favorably shaped for this type of analysis, the same geometric procedure is utilized employing individual dunes to calculate orientation for a field (figures 5b and 5c).

The field orientation azimuths for

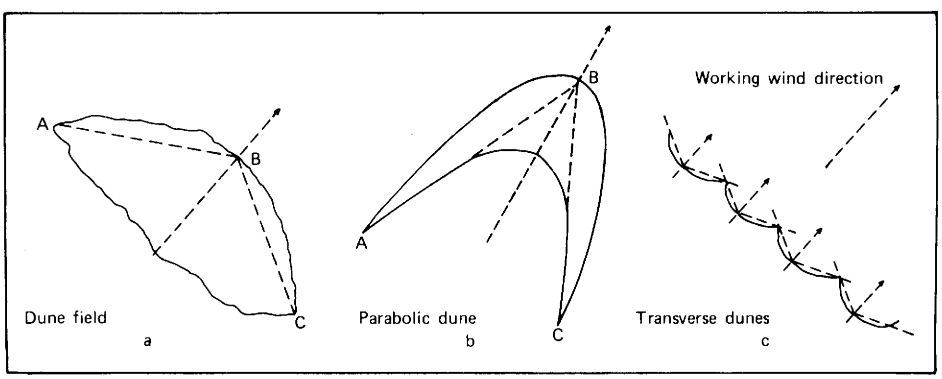

Figure 5. Determination of dune field orientation.

silica dune fields range, clockwise, from 117° at Lucin to 247° at Gold Hill. The orientation azimuths of gypsum fields range from 297° at VOR to 327° at Cobb Peak. The orientation azimuths of oolite dune fields range from 187° at Lakeside Railroad Settlement to 347° at Saltair.

Percentage of Field Covered by Dunes

The percentage is the portion of each field actually covered by dunes. The higher the percentage of dune coverage, the more closely spaced the dunes. The percentage was determined by random sampling, based on aerial photographs and ground observations.

The percentages of dune cover in silica dune fields range from 25 percent in Ripple Valley to 95 percent at Lucin and Johnsons Pass. The percentages of dune cover in gypsum fields range from 25 percent at Microwave to 90 percent at the Newfoundland Mountains. The percentages of dune cover in oolite dune fields range from 95 percent at the Lakeside Railroad Settlement to 99 percent at the Promontory Ranch.

Percentage of Field Covered by Vegetation

The amount of vegetation cover on the dunes on each field is inversely related to the amount of active dune surface within a field. Generally speaking, the higher the percentage of vegetation cover, the more stabilized the field. Aerial photographs and ground observations were the sources of these data.

The percentages of vegetation cover in silica dune fields range from 5 percent at North Wig Mountain to 99 percent at Gold Hill, Puddle Valley, Ripple Valley and West Lakeside Mountains. The percentages of vegetation cover in gypsum fields range from 5 percent at Knolls to 80 percent at Cobb Peak. The percentages of vegetation cover in oolite fields range from 90 percent, as at Promontory Ranch, Saltair, and Stansbury Island, to 95 percent at Antelope Island and Lakeside Railroad Settlement. Vegetation present includes bromegrass, bunch grasses, sunflowers, russian thistle, sagebrush, juniper, and psammophytic and phreatophytic species.

Dune Heights

The dune height, expressed in meters above the sub-dunal surface, was obtained in the field using a Brunton pocket transit and the geometric relationship described in figure 6.

Common dune heights in silica dune fields range from 1.8 meters at Lucin to 12.2 meters at West Dugway. Common dune heights in gypsum fields range from 1.8 meters at Microwave to 7.6 meters at the Newfoundland Mountains and Knolls. Common dune heights in oolitic fields range from 4.6 meters at Saltair to 10.7 meters at Lakeside Railroad Settlement.

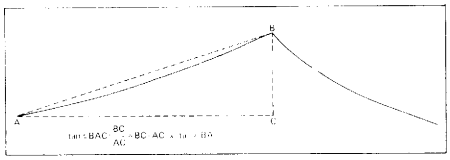

Figure 6. Determination of dune height.

Statistical Measures of Grain Size

Samples were drawn from representative sites within each field. Sample sites for the study are shown on figure 2. Data concerning each sample and data for all variables for each dune field are given in Dean (1976).

Each sample was dry sieved mechanically on a Cenco-Meinzer sieve shaker, using a shaker setting of 6, and a time of 10 minutes. One-half phi sieves, ranging from -1.0 to 4.0, were used. Phi-mean grain size, phi-standard deviation, phi-skewness, and phi-kurtosis were then computed for the 1.0-meter and the 0.1-meter samples from each site with a Nova II digital computer using the language BASIC.

Table 2 lists the averages of the phi-moment statistics for 169 sand samples collected for the study. Note that in order of increasing grain size or decreasing phi-mean, the lithologies are ranked as follows: silica, gypsum, and oolite. A significantly larger mean grain size is exhibited by the lag granules found at site B-07, west of the Newfoundland Mountains. These granules are characterized by a phi-mean of .30 and are the largest that were found in the study area.

The average phi-standard deviations range from moderately well sorted for silica and oolite sands to poorly sorted for gypsum sands, based on Folk's (1966) classification of sorting (table 3).

Hypothesis Testing

The data collected for these 11 variables suggest that certain probable relationships exist. The strength of these relationships was tested by the formulation of seven hypotheses described below.

To test the first six of these hypotheses, data obtained for 11 variables (including phi-mean grain size and phi-standard deviation; excluding dune type) at 57 sand sampling sites within 30 sand dune fields, have been correlated and the results summarized in table 4. Note that "r" represents the Pearson correlation coefficient, or strength of relationship, between paired variable. A coefficient of 1.0 would indicate a perfect correlation. Also, note that "r^2" represents the amount of variance explained in one variable by the other. Finally, "s" represents the significance level of "r", utilizing a one-tailed test of significance built into the program. If the level of significance of any of the correlated pairs of variables is smaller than or equal to .10, that hypothesis is rejected, i.e., a significant relationship does exist. Table 4 also lists separately the correlation coefficients for each lithology.

Hypothesis No. 1

It is accepted that when sand moves uphill, the larger sand grains tend to be left at lower elevations. The finer material, moved by gentler winds, may move toward the top and sometimes over an obstacle. To analyze the strength of this relationship in this study area, the following null hypothesis was tested:

There is no significant relationship between the phi-mean grain size of sand and the mean elevation of a field above sea level.

This hypothesis is rejected. A weak, but direct relationship is shown to exist. In this case, 6 percent of the variance in the dependent variable is explained by the independent variable. Phi-mean grain size should increase as sand moves upslope because the coarser, heavier material tends to be left at lower elevations. The fact that this relationship is not strong in this study area may indicate that these sands are located very close to the deposits from which they were derived and, therefore, have little relationship to each other.

Hypothesis No. 2

Previously conducted fieldwork has shown that as phi-mean grain sizes of sand samples decrease (as grain size increases), their phi-standard deviations increase. Possibly, more coarse material could be, or is, in the process of breaking down into finer material for transport. To analyze the strength of this relationship in the study area, the following null hypothesis was tested:

There is no significant relationship between the phi-mean grain size and the phi-standard deviation (sorting) of sand samples from the study area.

Table 2. Phi-moment statistical averages and ranges for sand dune fields.

Statistic	Total n=30	Silica n=20	Range*	Oolite n=5	Range*	Gypsum n=5	Range*
Mean	2.28	2.44	1.17 to 3.22 T-02 T-05	1.81	1.11 to 2.35 D-02 B-03	2.15	0.30 to 3.06 B-07 T-27
Standard Deviation	0.65	0.58	1.37 to 0.24 J-02 T-35	0.58	0.27 to 0.68 D-02 T-10	1.02	1.72 to 0.34 B-09 T-08
Skewness	0.02	0.03	-0.60 to 0.51 T-26 B-05	0.06	-0.48 to 0.31 T-10 D-01	-0.04	-0.71 to 0.50 T-08 B-08
Kurtosis	1.24	1.46	-1.17 to 11.71 B-02 T-26	1.55	-0.46 to 4.87 S-01 D-02	0.04	-1.39 to 3.25 T-23 T-08

* The site at which each value is located is indicated directly below the value.

Table 3. Scale for sorting.

Sorting Term	Phi-Unit Boundary
Very well sorted	.35
Well sorted	.50
Moderately well sorted	.71
Moderately sorted	1.00
Poorly sorted	2.00
Very poorly sorted	4.00

(Folk, 1966)

This hypothesis is rejected. An inverse relationship exists; 35 percent of the variance in the dependent variable is explained by the independent variable. As phi-mean grain size decreases, phi-standard deviations tend to increase. This indicates that sands which have phi-means in the higher phi-unit values (finer grained materials) have smaller phi-standard deviations from the phi-mean and are better sorted. While the unit weight of gypsum clasts are less than that for silica or oolite grains, gypsum grains or clasts are more wind resistant because of their shape. Therefore, it is probable that a given wind velocity could move a greater size range of gypsum grains, causing them to be more poorly sorted than either silica or oolite sands.

Hypothesis No. 3

In an area of sand devoid of vegetation, dunes should be formed with relative ease and possibly cover the entire devoided area. On the other hand, if vegetation exists, it appears that sand cannot easily move and the area of the potential field will be dimished. To analyze the strength of this relationship in the study area, the following null hypothesis was tested:

There is no significant relationship between the area that a dune field covers and the percentage of the field covered by vegetation.

This hypothesis is rejected. An inverse relationship exists. In this case, 34 percent of the variance in the dependent variable is explained by the independent variable. The strength of relationship is above average for this study area. Apparently, the larger the area of a field, the less vegetation cover is found and vice versa. This may be attributed to the fact that larger areas of sand have probably developed because relatively little vegetation was present to hinder movement.

Hypothesis No. 4

Dune fields covering large areas presumably have large and continuous supplies of sand. Therefore, dunes of greater height will be found in larger fields than in fields of smaller areal extent. To analyze the strength of this relationship in the study area, the following null hypothesis was tested:

There is no significant relationship between dune heights in a particular field and the area of that field, in the study area.

This hypothesis is accepted. In this study area it is not uncommon to find high dunes in a relatively small dune field, indicating that the dunes may be reworked beach deposits, originally deposited by lacustrine processes as high off-shore and beach bars. Now, eolian processes are reworking the surfaces of these structures and the dune field area has little relationship to dune heights.

Hypothesis No. 5

When a body of sand moving across relatively flat terrain encounters a slope oriented in an opposing direction, the sand should move over or around this slope by applying the principle of least work. To analyze the strength of this relationship in the study area, the following hypothesis is tested:

There is no significant relationship between a dune field orientation azimuth and the orientation azimuth of the slope on which the field is located.

This hypothesis is rejected. A direct relationship exists. In this case, 32 percent of the variance in the dependent variable is explained by the independent variable. The strength of relationship is above average for the hypotheses tested. When a body of sand, whether it is moved by eolian or lacustrine processes, encounters a slope of greater angle, the sand will proceed along a path of least work. In this study area, most dune fields are located on very gentle slopes. Any forward movement in these fields, in the same direction as the working winds, could be regarded as overrunning the obstacle, but when a greater slope angle is encountered, the field will attempt to bypass the obstacle. The body of sand will align itself nearly perpendicular to the slope on which it rests, as the working wind permits.

Hypothesis No. 6

When a moving body of sand encounters an upward slope of greater angle than that on which it had been moving, the movement of the sand toward the front of the field would be slowed. The faster moving dunes toward the rear of the field should tend to overtake the slower lead dunes and the percentage of dune cover will increase. To analyze the strength of this relationship in the study area, the following null hypothesis will be tested:

There is no significant relationship between the percentage of dune cover in a field and the angle of the slope on which the field is moving.

This hypothesis is accepted. Apparently slope angle has virtually no effect on percentage of dune cover in this re-

Table 4. Pearson correlation coefficients for sand dune fields.

Hypothesis	Total* n=30	Silica n=20	Gypsum n=5	Oolite n=5
1. Elevation and Mean Grain Size	r = .2410 r^2 = .0581 s = .100	r = -.0348 r^2 = .0012 s = .442	r = .0307 r^2 = .0009 s = .480	r = -.8313 r^2 = .6911 s = .041
2. Mean Grain Size and Standard Deviation	r = -.5874 r^2 = .3450 s = .001	r = -.8087 r^2 = .6540 s = .001	r = -.9090 r^2 = .8263 s = .016	r = .8017 r^2 = .6427 s = .051
3. Area and Vegetation Cover	r = -.5838 r^2 = .3408 s = .001	r = -.5068 r^2 = .2568 s = .011	r = -..5983 r^2 = .3580 s = .143	r = -.4041 r^2 = .1633 s = .250
4. Dune Height and Area	r = .2152 r^2 = .0463 s = .127	r = .6570 r^2 = .4316 s = .001	r = .4059 r^2 = .1648 s = .249	r = .2771 r^2 = .0768 s = .326
5. Slope Orientation and Field Orientation	r = .5630 r^2 = .3170 s = .001	r = .1664 r^2 = .0277 s = .242	r = .9323 r^2 = .8692 s = .010	r = .9484 r^2 = .8995 s = .007
6. Dune Cover and Slope Angle	r = .0598 r^2 = .0036 s = .377	r = .1875 r^2 = .0352 s = .214	not computed	r = -.2500 r^2 = .0625 s = .343

* Hypothesis rejection or acceptance is based on this column. Less than or equal to .10= rejection. Greater than .10= acceptance.

search area. The majority of dunes in this study may have been derived from beach deposits, as mentioned previously, and probably have not moved far from their original sediment sources. Under these circumstances, slope angle is unrelated to the proximity of dunes to each other.

Hypothesis No. 7

Three sand lithologies occur in the study area: silica (quartz), gypsum, and oolite. Examination of the data suggests that a relationship between lithology and phi-mean grain size should exist. Oolite sands, possibly because of their accretionary origin, are generally larger in diameter than sands of silica or gypsum lithology. Gypsum, on the other hand, tends to weather into smaller grains than silica or oolite grains. To analyze the strength of this relationship in the study area, the following null hypothesis was tested:

There is no significant relationship between the phi-mean sand grain size in the study area and the lithology of the sand.

This hypothesis is rejected. There are statistically significant differences in grain size among the silica, gypsum, and oolite populations. The phi-mean size of silica group is 2.44, of the gypsum group is 2.16, and that of the oolite group is 1.81. These differences probably result from the differing processes responsible for the formation of each type of sand. Oolite sand grains, formed by accretionary processes, tend to be larger than either silica or gypsum sands, which are formed by degradational processes. Gypsum is lighter per unit volume than silica, permitting larger particles to be moved by a given wind velocity. In a comparable sample, gypsum sands may be larger in diameter than silica sands. (Note: Complete data and discussion of statistical techniques are available in four appendices in Dean, 1976. Data concerning each of 57 dune sampling sites are listed in Appendix I. Data concerning each of 31 sand dune fields are listed in Appendix II. Phi-moment statistical data for each of 169 sand samples are listed in Appendix III. Sieving data concerning each of 169 mechanically dry-sieved sand samples are listed in Appendix IV).

Mason and Folk (1958) pointed out in their study of depositional environment of sediments from a Texas barrier bar, that eolian sediments tend to be positively skewed because of the lack of a coarse tail and the presence of a fine tail of silt. Beach sediments tend to be negatively skewed because of the addition of a small tail of coarse grains. Friedman (1961), in a study of the relationship of grain-size distribution to depositional environment, plotted phi-skewness against phi-mean grain size. His eolian and beach sands consistently clustered.

In this study plots of phi-skewness against phi-mean grain size and against phi-kurtosis were made to determine if some of the sediments in the study area were eolian and others lacustrine in origin. Neither of these plots show any apparent clustering. This may indicate that there is actually no difference in the environment under which these sediments were deposited and supports the probability that these sediments are all remnants of beaches deposited on Lake Bonneville during the Pleistocene that have since been reworked by eolian processes.

CONCLUSIONS

Data collected in the study area were used to test possible origins for the dune material. Results of parametric testing indicate that, in the greater part of the study area, dunes may be of very local lacustrine origin and may not have moved far to attain their present locations. The dunes, therefore, appear to be Lake Bonneville sediments reworked by eolian processes into predominantly parabolic dunes.

Gypsum sands found between the Terrace and Newfoundland Mountains do not resemble active dunes, but may be dunes of an earlier dry cycle modified by a temporary rise in the lake level.

ACKNOWLEDGMENTS

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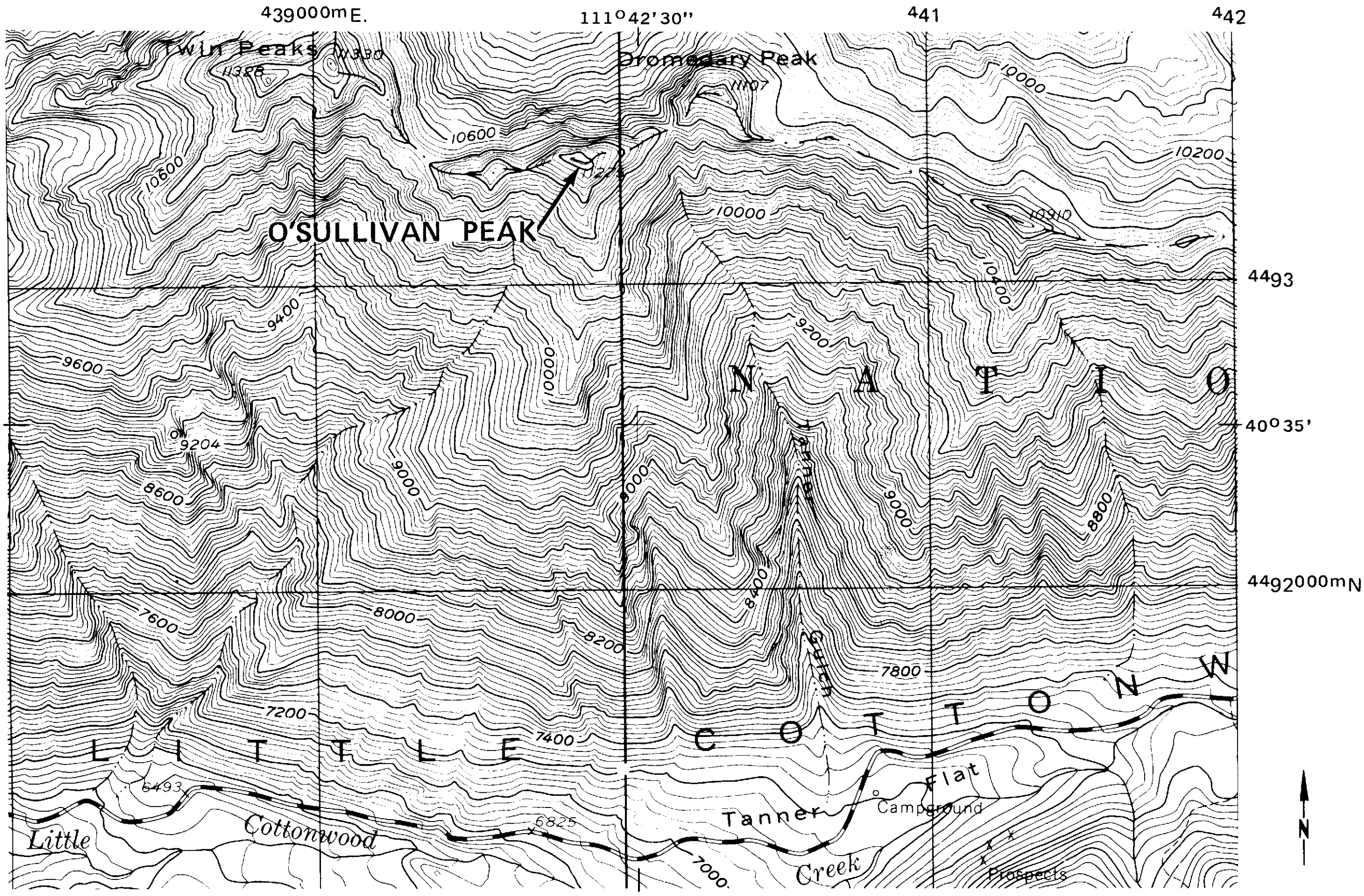

Base from U.S. Geological Survey topographic quadrangle: Dromedary Peak, Utah, 1955.

SCALE 1 : 24000

0 ½ 1 Mile

0 .5 1 Kilometer

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

PEAK NAMED FOR TIMOTHY O'SULLIVAN, PIONEER PHOTOGRAPHER, 1840 - 1882

Timothy O'Sullivan was born in Ireland; but when he was two years old, his family sailed for America where they settled in Staten Island, New York. As a boy, Tim was introduced to photography by Mathew Brady, well known photographer, who also lived on the Island. O'Sullivan spent a number of years serving his apprenticeship in Brady's New York photo gallery.

O'Sullivan covered the Civil War, 1861 - 1865, as one of Brady's war photographers. Since any picture taken by one of Brady's group became a "photo by Brady", many of the war's finest photographs, taken by O'Sullivan, have been mistakenly attributed to his employer.

In 1867 O'Sullivan signed on as official photographer for the Clarence King geological expedition which took him into the western Rocky Mountains and the Great Basin. During this survey O'Sullivan made many fine photographs of the Wasatch Mountains, canyons, and nearby desert country. He is credited with the first photographs of the Great Salt Lake. After his stint of service with King, O'Sullivan joined the Thomas Selfridge expedition which was to survey a possible canal route through the dense jungles of the Isthmus of Darien (Panama).

In 1871, he was back again in the West, this time with Lt. George Wheeler's geological survey. This expedition traversed parts of eastern Nevada and Arizona to prepare accurate maps of these territories.

O'Sullivan's equipment was a large 20x24-inch camera, which used the wet collodion plate system. This required coating the glass plates just prior to exposing them, then quickly developing the glass negatives under primitive conditions that today would be considered next-to-impossible.

Tim O'Sullivan returned to Staten Island in 1882. He died of tuberculosis at the age of 42. His body rests in an unmarked grave in a Staten Island cemetery.

Note: Mr. Whitehead, a photographer for the U.S. Forest Service, was instrumental in naming an 11,275 foot peak in the Wasatch Mountains, O'Sullivan Peak, in 1978. He obtained this information about O'Sullivan from James D. Horan's book, "Timothy O'Sullivan, America's Forgotten Photographer". The peak is 23 miles southeast of Salt Lake City, Utah, and lies between Big and Little Cottonwood Canyons.

COAL DRILLING, JOHNS VALLEY, GARFIELD COUNTY, UTAH

by Hellmut H. Doelling[1] and Fitzhugh D. Davis[2]

ABSTRACT

Four holes were drilled in Johns Valley, Garfield County, Utah, in late 1976 for the purpose of finding new coal resources. The holes were drilled by a lessee on State of Utah lands. An eighteen-foot coal bed (Smirl zone) was intercepted at the top of the Cretaceous Dakota Formation that strikes N. 23° E. and dips 20° northwest in SW 1/4 section 33, T. 33 S., R. 2 W. The Cretaceous rocks and the coal are truncated beneath an unconformity below the Tertiary sediments. The unconformity at the drill-site lies about 360 feet beneath the surface. In other parts of Johns Valley other drill holes show the unconformity to lie 200 to 600 feet beneath the surface. The axes of thick coal beds in the Alton field (Dakota coals) and Kaiparowits Plateau field (Straight Cliffs coals) converge on Johns Valley. U. S. Geological Survey drilling in SE 1/4 section 10, T. 35 S., R 2 W. has proven the presence of thick coals in the Straight Cliffs Formation in the Johns Valley area. Johns Valley and vicinity should provide fertile ground for expanding Utah's coal resource. However, the structural relations beneath the unconformity may be complex and will require further study.

INTRODUCTION

The presence of coal at depth in Johns Valley was reported by Eardley and Cohenour in January of 1963 in Utah Geological and Mineralogical Survey Report of Investigations 1. The discovery was made in U. S. Geological Survey wells drilled to study ground water conditions. The best show was in U. S. Geological Survey test hole No. 17, located in the southeast quarter of section 33, T. 33 S., R. 2 W. A U. S. Geological Survey letter file indicated the coal to be 20 feet thick. Oral communication with U. S. Geological Survey personnel indicated 30 feet of coal at a depth of 420 feet and 5 feet of coal at a depth of 480 feet. Other wells were drilled by the U. S. Geological Survey and test hole No. 11, located in the southwest quarter of section 29, T. 34 S., R. 2 W., intercepted several thin beds of coal 1-3 feet thick after reaching an unconformity at 354 feet. The cuttings were described and a report subsequently published by Carpenter and others (1964 and 1967). In the 1964 publication the notation for the coal in test hole No. 17 for the 420-450-foot interval reads:

> Coal, black, mostly lignite (?), but some subbituminous (?) which increases in amount with depth; contains interbeds of white, sandy silt to clay in intervals 440-450 feet; some lignite shows relic, organic-plant structure, some contains pyrite growths.

The drilled water wells were not specifically logged for coal and no core was available for quality determinations. In late 1976 the Utah Geological and Mineral Survey obtained an opportunity to receive more detailed information when coal drilling was carried out on state lands by a lessee.

Properties drilled are owned by the State of Utah, and at the time of the exploration work, leased to Utah Resources International Inc., a Utah corporation. Drilling costs were arranged by the corporation and geologic assistance was provided by the state in a cooperative information gathering project.

Location

Johns Valley is located north of Bryce Canyon National Park in south-central Utah. The drilling area is about 35 road miles east of the Garfield County seat of Panguitch and 90 road miles east of Cedar City, the largest town in southern Utah. Johns Valley lies 200 miles south of Salt Lake City (figures 1 and 2).

The locations of the four wells drilled for this project are listed with their elevations and total depths on table 1.

These wells and the water wells drilled by the U. S. Geological Survey during their 1962 study are plotted on the geologic sketch map (figure 3). A land ownership map is provided as figure 4.

GENERAL GEOLOGY

Figure 1. View looking easterly across Johns Valley toward the Escalante Mountains. Beneath 200 to 600 feet of cover under the valley floor are formations of Late Cretaceous age containing thick coal beds.

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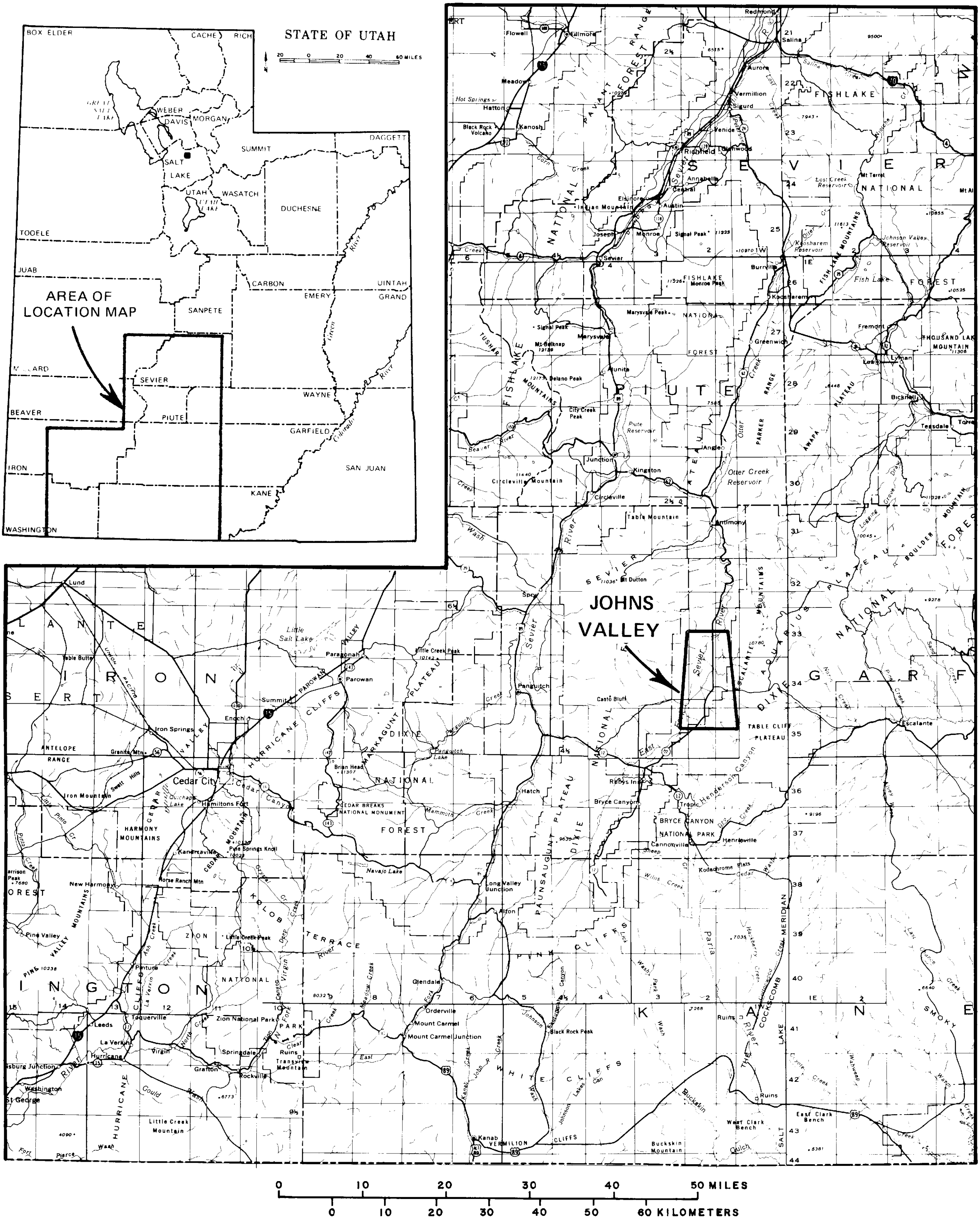


Figure 2. Index and location maps of Johns Valley.

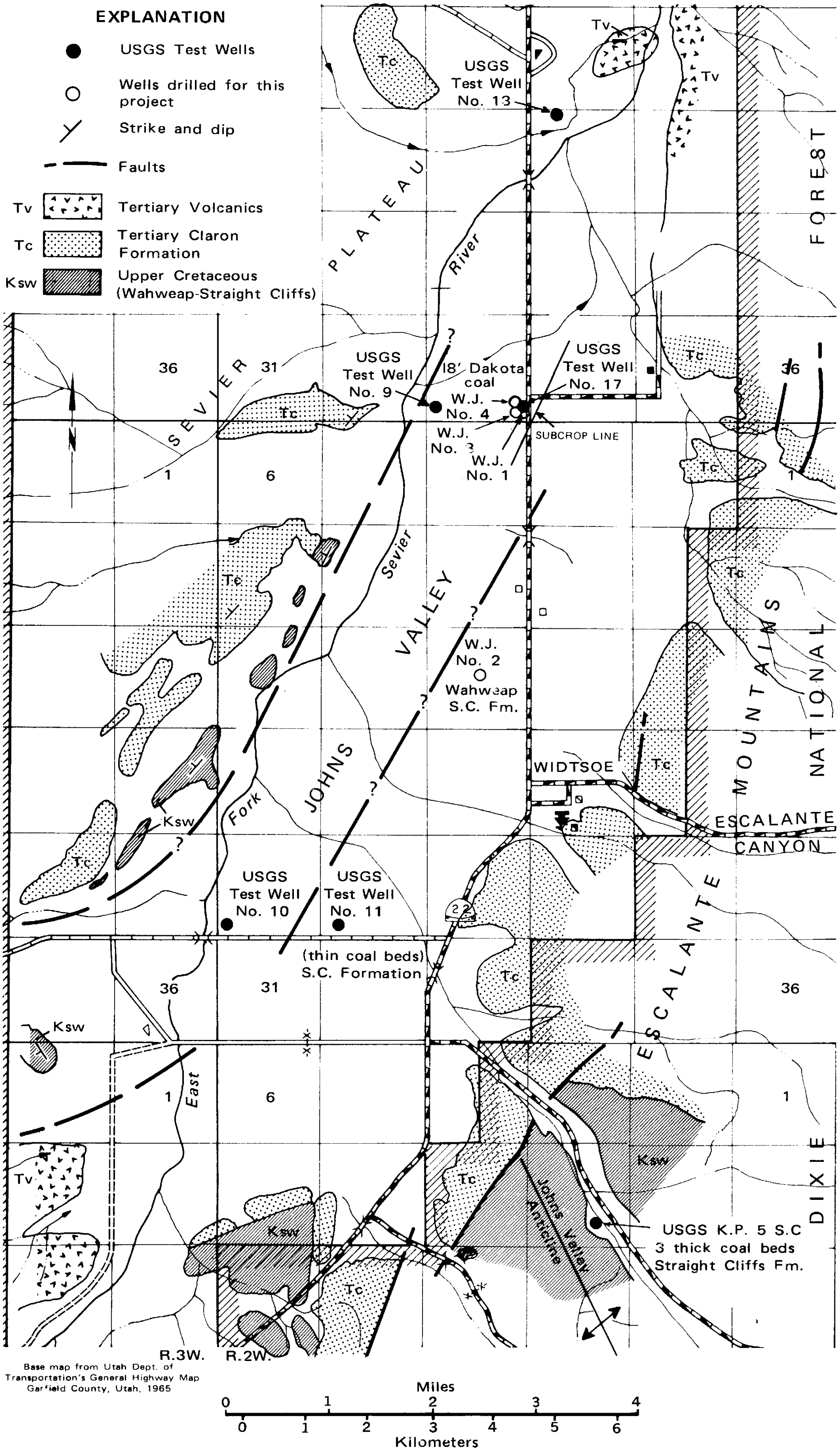


Figure 3. Geologic sketch map of Johns Valley drilling area.

Table 1. Well locations

	Feet Elevation	Coordinates	Feet Total Depth
Widtsoe Junction No. 1	7330	78′ N/S, 114′ W/E 33-33S-2W	633
No. 2	7425	2500′ S/N, 2550′ W/E 16-34S-2W	622
No. 3	7324	78′ N/S, 614′ W/E 33-33S-2W	632
No. 4	7316	849′ N/S, 622′ W/E 33-33S-2W	690

No detailed geologic map of Johns Valley is available. All published maps are at a small scale and do not portray the complexity of geology that exists. Published maps include the southwest quarter of the Utah State geologic map (1963), Carpenter and others, plate 1 (1967), and Doelling (1975). There is little agreement between the maps and none are completely correct.

Johns Valley is a high 3-mile wide valley trending roughly north-south for a length of 20 miles. It is bounded on the west by the Sevier Plateau and on the east by the Escalante Mountains. The valley is surfaced by alluvium and other surficial deposits, so that the bedrock is effectively covered. Drilling in the valley has encountered the same bedrock formations that crop out in the surrounding hills. The generalized geologic column is shown on Table 2.

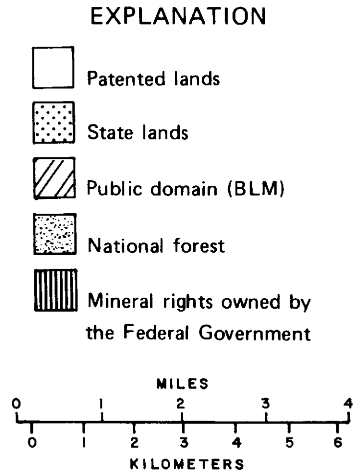
The lower part of the Tertiary Claron Formation rests unconformably upon the Upper Cretaceous (Wahweap-Straight Cliffs Formation undifferentiated). These are the principal exposed units in the surrounding hills (figure 3). In response to a regional dip most volcanic exposures are to the north, but remnants can be found elsewhere. Claron Formation outcrops dominate in the Sevier Plateau in the central part of the area and to the south. Claron Formation outcrops also dominate in the central part of the area in the Escalante Mountains, but Cretaceous units are exposed to the south.

STRUCTURE

Johns Valley is structurally controlled by north-northeast trending faults now mostly concealed by the surficial cover. The Paunsaugunt fault extends into the area from the south but cannot definitely be traced through the valley. Two important east-by-northeast trending faults (Ahlstrom Hollow faults) project into Johns Valley near its southwest end, southwest of the mapped area.

Rocks exposed west of Johns Valley, in the Sevier Plateau, dip moderately to the northwest; the strike varies from N. 20° to N. 35° E. The rocks in the Escalante Mountains to the east of the valley are warped, but have a gentle northward regional dip. In the southern Escalante Mountains the axis of the Johns Valley anticline trends to the northwest and is truncated by a fault at the southeast edge of Johns Valley (figure 3). The axis of the anticline is not reflected in the Tertiary units northwest of this fault in Johns Valley, but it may be traceable in the subsurface beneath the unconformity at the base of the Tertiary.

Drilling at Johns Valley has indicat-



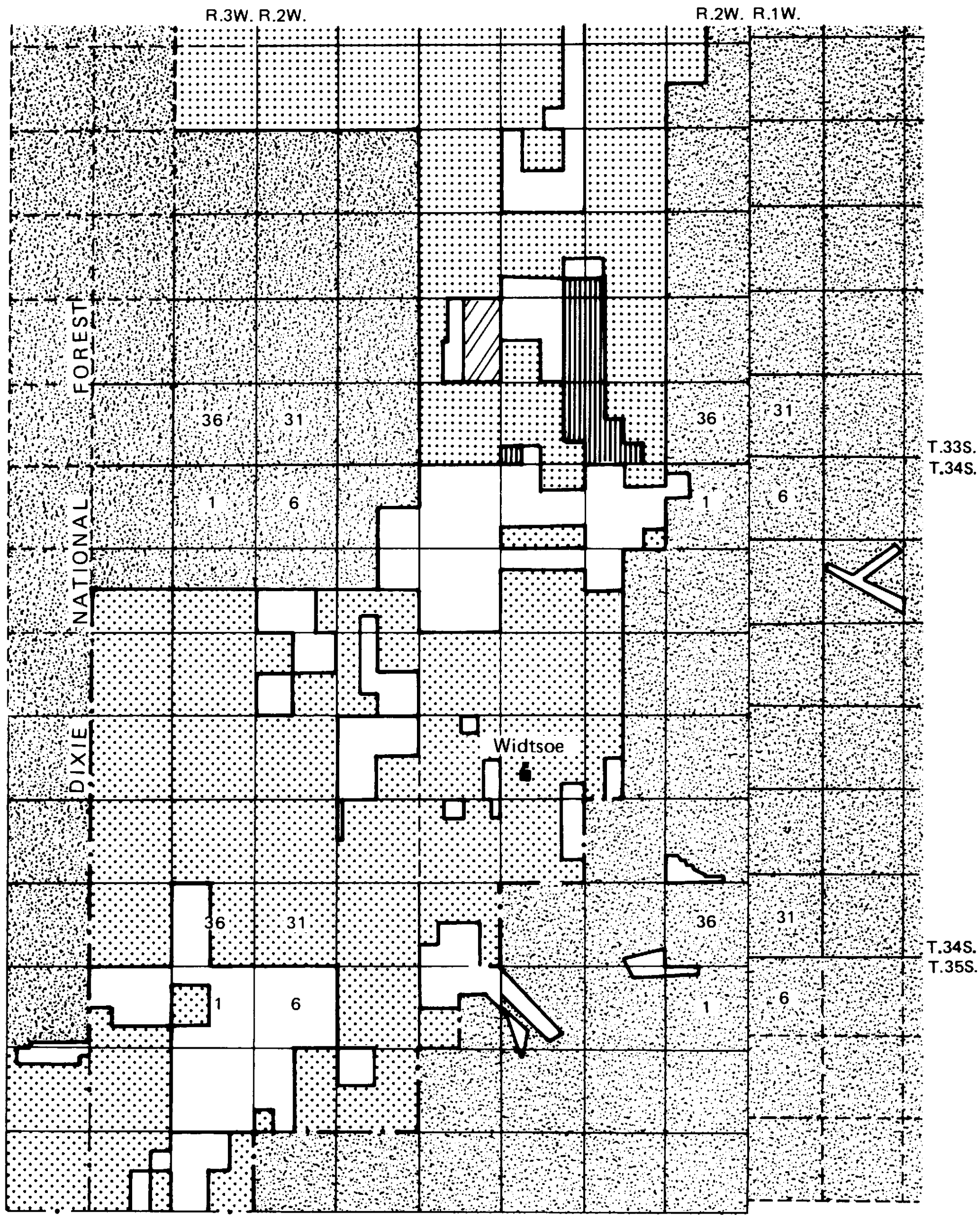


Figure 4. Johns Valley land and coal ownership map, 1974.

Table 2. Geologic column in the vicinity of Johns Valley

Age	Formation	Description
Quaternary	Alluvium	Orange to pale brown silt, clayey silt, sand, pebbles and cobbles, unconsolidated, surface to most of Johns Valley.
Tertiary	Sevier River Formation	Cobbles, pebbles, sand, silt and clay, poorly consolidated, older alluvial fans buried beneath the alluvium.
	Volcanics	Many varieties, especially latite, quartz latite, interbedded tuffs, breccias, volcanic sediments.
	Claron Formation	Pink and white limestone, calcareous shale, siltstone, sandstone and conglomerate, "Bryce Canyon or Wasatch Formation", up to 1600 feet thick.
	Angular unconformity	
Cretaceous	Wahweap-Straight Cliffs Formation undifferentiated	Mostly gray to yellowish gray, interbedded sandstone, siltstone, mudstone, claystone, conglomerate, carbonaceous shale and coal, 900 to 1800 feet thick.
	Tropic Shale	Dark gray, drab marine shale, with subordinate gray fine-grained sandstone, 650 to 1000 feet thick.
	Dakota Formation	Interbedded sandy shale, carbonaceous shale, shaly sandstone, siltstone, claystone, coal, 150 to 400 feet thick.

ed that the unconformity at the base of the Tertiary Claron is significant. Pre-Claron erosion has stripped off overlying sediments down to the Dakota Formation (table 2) and simultaneous folding has tilted the beds below to 20° from the horizontal. Information is still lacking to fully describe the structure beneath the unconformity. A cross-section drawn perpendicular to the valley axis and through section 33, T. 33 S., R. 2 W., is given as figure 5, but should be regarded only as hypothetical. The authors feel that Johns Valley beneath the unconformity is a faulted anticline in which all of the fault blocks but one are upthrown to the east. It is suspected that the one fault having the upthrown block to the west is a major fault, of considerable displacement, and that it bisects the valley. These faulted blocks suffered considerable erosion prior to Tertiary sedimentation, and some were subjected to collapse. The position of these faults and the strikes and dips of formations beneath the valley fill will determine the feasibility of mining coal in Johns Valley.

Widtsoe Junction No. 1

The location of the Widtsoe Junction No. 1 hole was chosen to verify the presence of coal reported in Geological

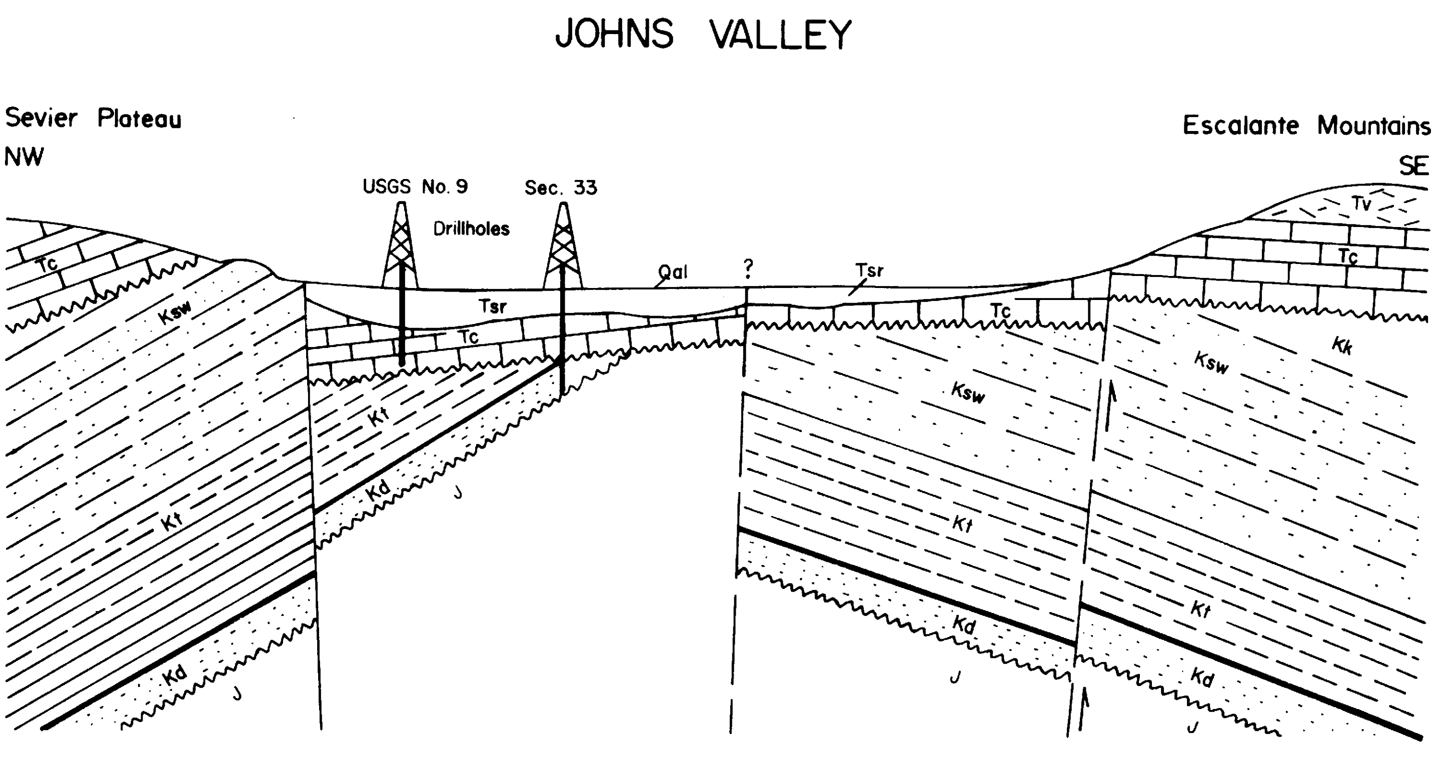


Figure 5. Hypothetical sketch of structure under Johns Valley. No scale intended; vertical component scale greatly exaggerated. Qal= aluvium, Tv= volcanics; Tsr= Sevier River Formation; Tc= Claron Formation; Kk= Kaiparowits Formation; Ksw= Straight Cliffs-Wahweap Formations; Kt= Tropic Shale; Kd= Dakota Formation; J= Jurassic.

Survey test hole No. 17. The new hole was positioned 120 feet southwest of No. 17. The log of Widtsoe Junction No. 1 is given and graphically illustrated as figure 6 and, in detail, in the Appendix. An interpretation of U. S. Geological Survey test well No. 17 is illustrated in figure 7.

In Widtsoe Junction No. 1, the alluvium was found to a depth of 19 to 20 feet. Under this, from 20 to about 200 feet, are older alluvial materials, tentatively assigned to the Sevier River Formation. This formation consists of coalescing alluvial fans and contains considerable amounts of volcanic material.

At a depth of 200 to 210 feet the color of sediments changes to pink from light brown. Gravel persists, but there are many intervals of very calcareous and clayey well-indurated siltstones with white or pink color to a depth of about 360 feet. The 200 to 360-foot interval in Widtsoe Junction No. 1 is tentatively assigned to the Claron Formation. U. S. Geological Survey geologists consider this first 360 feet to be entirely in alluvium and it would be difficult to prove otherwise. The U. S. Geological Survey recognized the Tertiary Claron Formation in U.S.G.S. test hole No. 9, 5000 feet to the west from a depth of 315 feet to the bottom of the hole at 550 feet. This interval contains no gravel and no volcanic material.

The Cretaceous Tropic Shale is intercepted 360 feet beneath the surface, indicating a major unconformity. At 402 feet a core was retrieved containing *Exogyra sp.,* a common fauna found at the base of the Tropic Shale and at the top of the Dakota Formation. At 430 feet a 15-foot bed of sandstone was encountered. Alternating black and white laminae in the sandstone indicated a dip of at least 12°.

At 443 feet, the drill found the top of an 18-foot coal bed. This coal, packaged and sent to Commercial Testing and Engineering Company in Denver, Colorado for testing, is mostly dull black with abundant plant imprints and marcasite films. The floor of the coal bed is a sandstone over 11 feet thick. Drilling was continued to a total depth of 633 feet. Most of the subcoal rock is light to dark-gray siltstone and shale. The hole ends in the Dakota Formation, which is more than 231 feet thick.

Widtsoe Junction No. 2

The location of Widtsoe Junction No. 2 was chosen about 2½ miles south of Widtsoe Junction No. 1 and half-way between it and U. S. Geological Survey test well No. 11. In No. 11 1- to 3-foot coal beds were discovered at depths of 354, 365, 388, and 394 feet and the hole was stopped at a depth of 480 feet. The thickness of sandstone recorded in the log of test well No. 11 indicates that either the Wahweap-Straight Cliffs or the Dakota Formation was found immediately beneath the unconformity at 223 feet.

In Widtsoe Junction No. 2 the unconformity was reached at 425 feet and the drill then penetrated 197 feet of Upper Cretaceous rock. The abundant sandstone beds are similar to the Wahweap-Straight Cliffs Formation outcrops nearby. Occasional terrestrial gastropods were intercepted, but no carbonaceous or coal beds were encountered. Coal is known to be present in the Straight Cliffs Formation of the area, but in a particular zone near the middle of the thick formation. Because the project was committed to shallow drilling it was decided to abandon the hole well above this zone. A graphic log of Widtsoe Junction No. 2 is given in figure 8.

Widtsoe Junction No. 3

The drilling of Widtsoe Junction Nos. 1 and 2 made it clear that the structure of the Upper Cretaceous rocks is complex and that more information could be gained by offsetting the next hole 500 feet to the west of Widtsoe Junction No. 1 on the assumption that

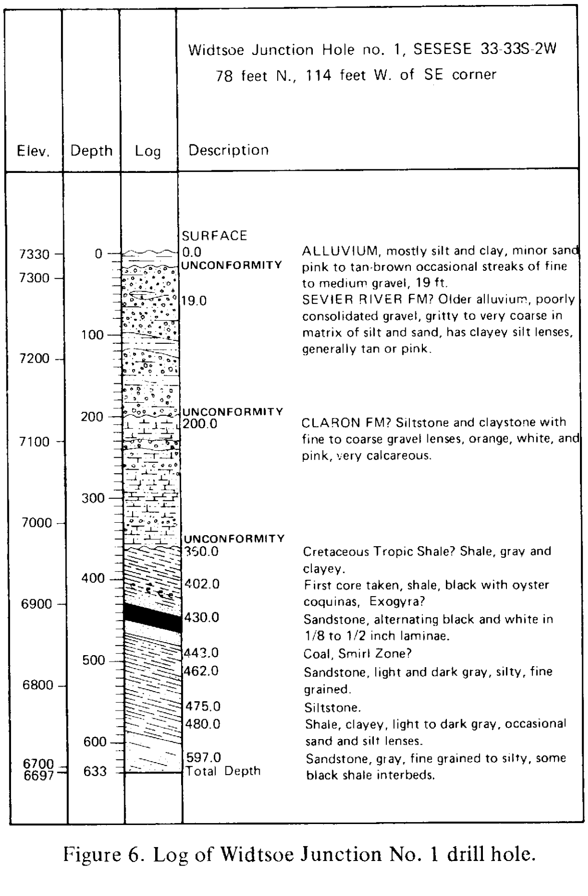


Figure 6. Log of Widtsoe Junction No. 1 drill hole.

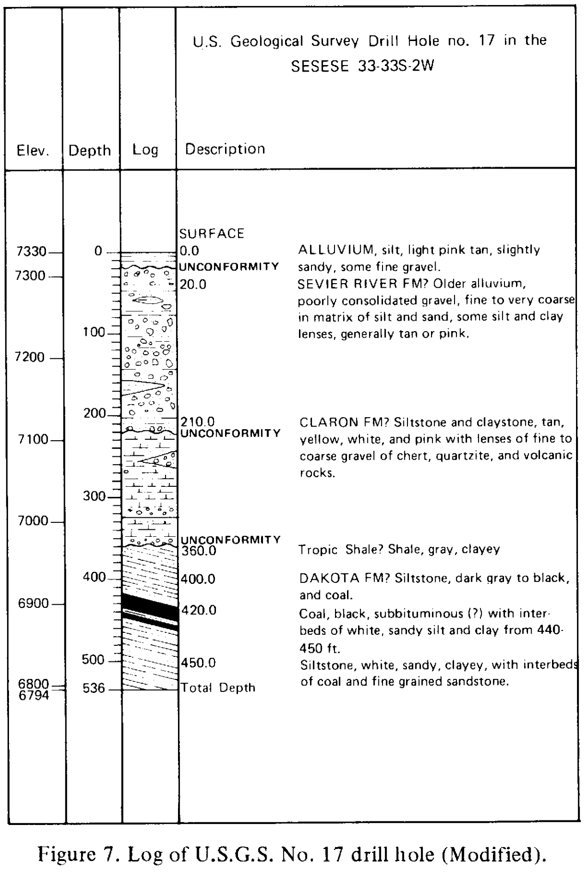


Figure 7. Log of U.S.G.S. No. 17 drill hole (Modified).

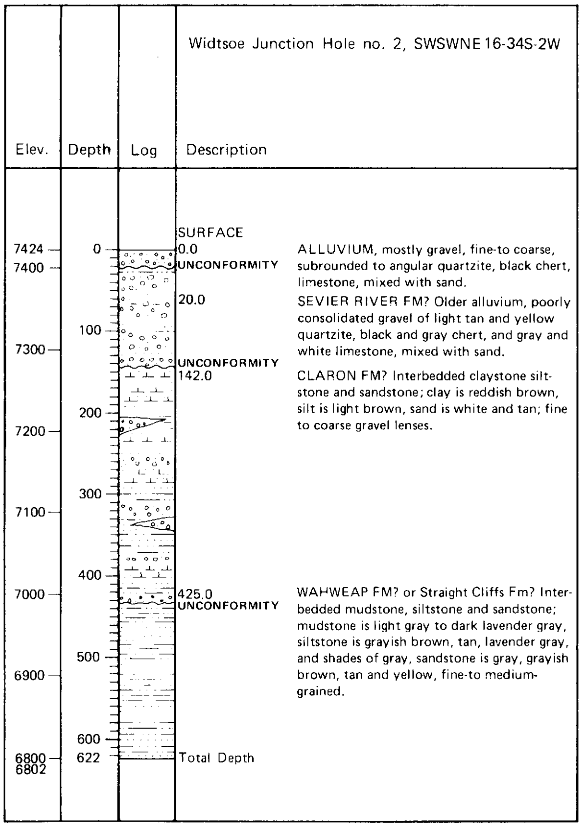


Figure 8. Log of Widtsoe Junction No. 2 drill hole

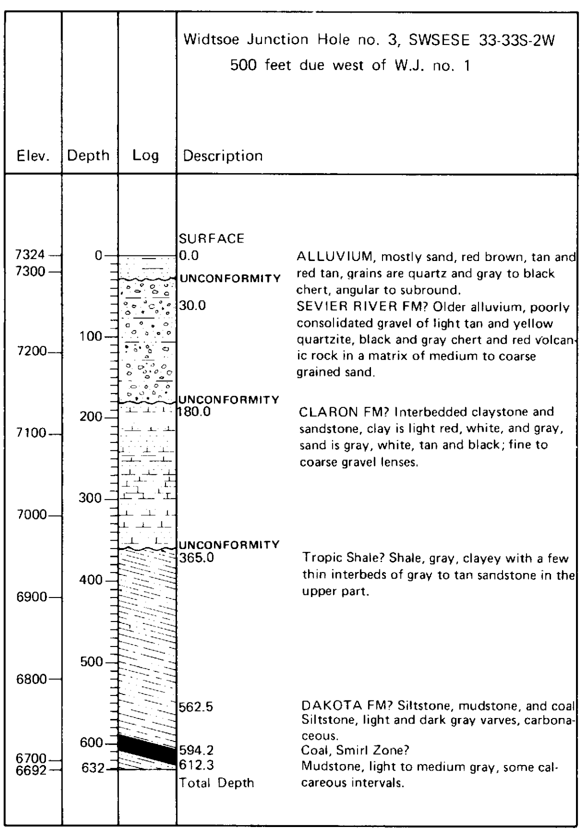


Figure 9. Log of Widtsoe Junction No. 3 drill hole.

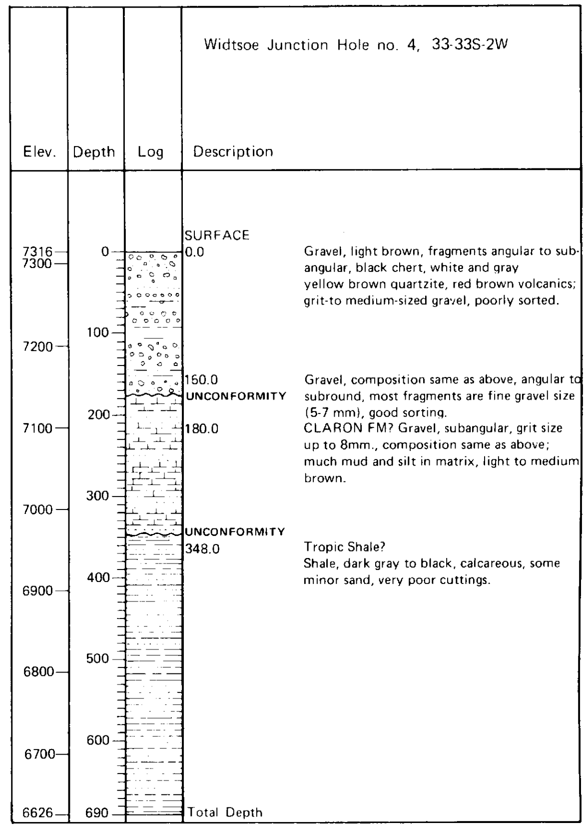


Figure 10. Log of Widtsoe Junction No. 4.

the dip of the 18 foot coal bed discovered in Widtsoe Junction No. 1 would be in that direction. In Widtsoe Junction No. 3 the Tropic shale was encountered at 365 feet and the top of the Dakota Formation at 562 feet. The 197 feet of Tropic Shale were a monotonous gray silty or clayey shale with a few fine-grained sands in the upper part (figure 9). The 18-foot coal bed was encountered in the Dakota Formation at a depth of 594 feet. Much of the core above the coal was lost and no confirming fossils were identified. Two feet of siltstone with light and dark laminae were located immediately above the coal. This same unit is present as an 11-foot fine-grained sandstone above the coal in Widtsoe Junction No. 1. From the base of the coal to the bottom of the hole at 632 feet the rock is a silty gray mudstone or shale. The coal bed drops 151 feet in elevation in the 500 foot distance between Widtsoe Junction No. 1 and Widtsoe Junction No. 3.

Widtsoe Junction No. 4

This hole is located about 770 feet north of Widtsoe Junction No. 3 and was drilled to complete a 3-point problem to determine the attitude of the coal bed. The entire hole was rotary drilled and no core collected. A generalized log is given as figure 10. It was electrically logged, as were holes Widtsoe Junction Nos. 1 and 3. The electric logs are compared in figures 11, 12 and 13. The drill intercepted the unconformity at about 345 feet and was bottomed at 690 feet. Most of the hole beneath the unconformity was drilled in the Tropic Shale and no coal was encountered to the total depth. Comparison of the electric logs, however, indicates that the drill was halted a few feet above the coal bed, now calculated to be present in this hole at a depth of 695 feet ± 5 feet.

Structure of section 33, T. 33 S., R. 2 W. beneath the unconformity

The resolution of the three-point problem using the elevations of the coal beds from holes Widtsoe Junction Nos. 1, 3, and 4 indicates that the coal bed strikes N. 23.5° E. and dips 20° northwesterly, similar to the strike and dips of rock outcrops along the eastern edge of the Sevier Plateau (figures 3 and 5). If the Claron Formation exists in any of the holes in section 33, including U.S. Geological Survey test well No. 9, then a fault must exist between section 33 and the rock outcrops to the west. The valley block would be down-dropped 500 to 1,000 feet. The attitude and nature of rocks in the Escalante Mountains to the east indicates another fault or faults to the east of section 33 (figures 3 and 5).

QUALITY OF THE COAL

The coal core from Widtsoe Junction No. 1 was divided into six samples for testing. The results are shown in table 3.

The lower 10 feet of the coal bed is low-sulfur coal. Large amounts of marcasite were noted in the core in the upper part of the bed. Much of this may be washable. The uppermost 3 feet are high in ash. If these 3 feet are sacrificed in mining the remaining coal will have the following characteristics:

Thickness	Btu/lb	Sulfur	Ash
15.3 ft.	9,658	1.40%	7.06%

The coal bed contains no splits or other observable impurities throughout the entire 18-foot interval.

RESERVES AND RESOURCES

The coal bed shows no signs of deterioration, splitting, or thinning between holes Widtsoe Junction No. 1 and Widtsoe Junction No. 3. A measured reserve is calculated on the basis of 1,000 foot centers. Most of this is located in the SE SE section 33, T. 33 S., R. 2 W. and takes into consideration that the coal will only extend 200 feet southeast of Widtsoe Junction No. 1 where the bed will be truncated at the unconformity. About 40 acres are considered for 1.2 million tons in place. The indicated reserve, with 1 ½ mile centers, would provide 25 million tons in place. Each square mile of 18-foot coal will provide 20 million tons of coal in place. Depth considerations will limit the mining width to about a mile and more drilling is necessary to determine the length of the mineable band.

The trend of thick Kaiparowits Plateau coal beds (Straight Cliffs Formation) is northwesterly and the trend of thick Alton field coal beds (Dakota Formation) is northeasterly and these trends converge in Johns Valley. The U. S. Geological Survey recently drilled a hole along Clay Creek (U. S. G. S., K. P. 5 SC, figure 2) and intercepted three thick coal beds, 12, 14, and 12 feet thick at depths of 508, 530, and 551 feet in the Straight Cliffs Formation. This U. S. G.S. hole is located in SE ¼ section 10, T. 35 S., R. 2 W. and on figure 3. The potential for thick beds under Johns Valley is excellent. Their mineability depends on whether they can be found in a reasonable structural situation.

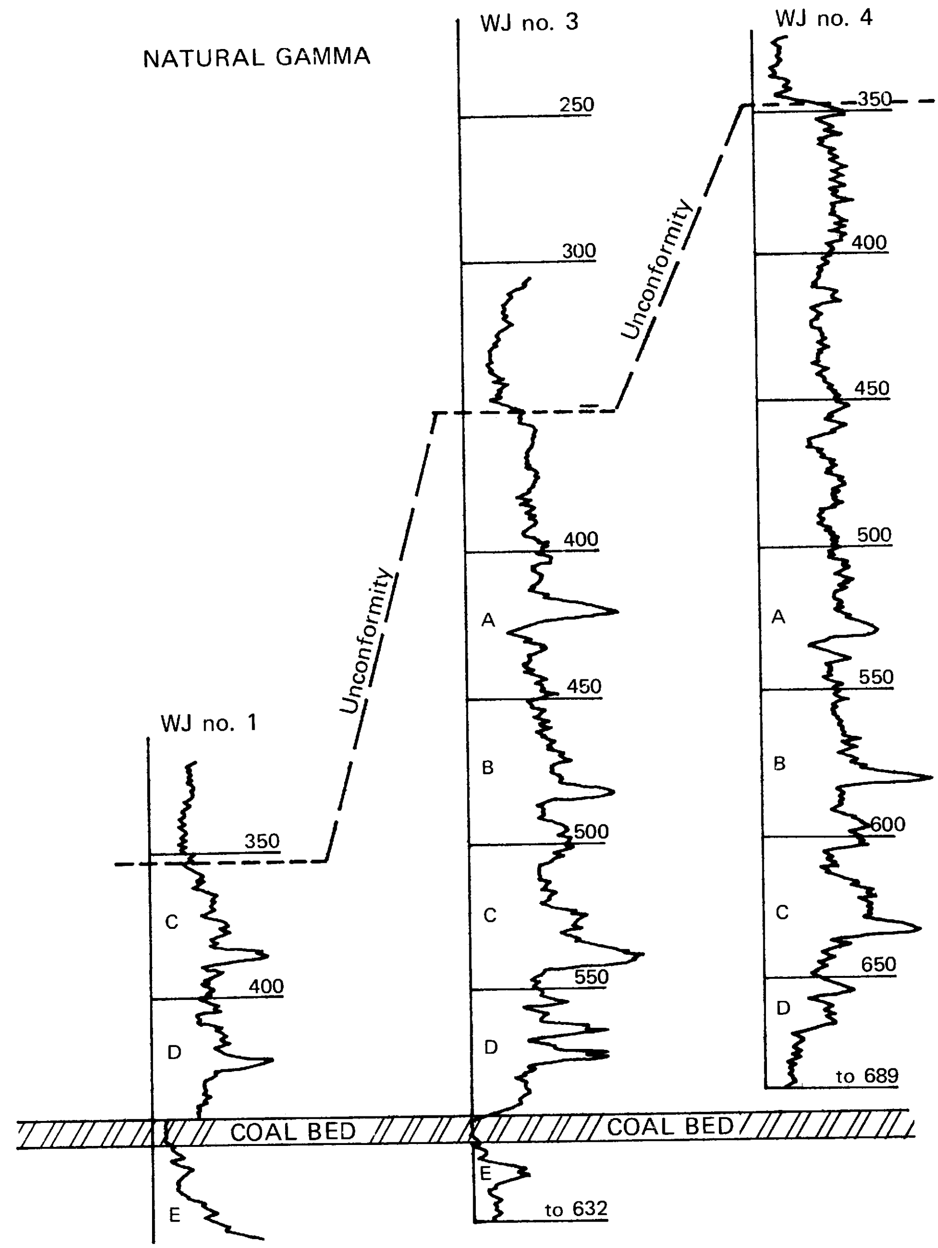


Figure 11. Comparison of natural gamma logs in holes Widtsoe Junction Nos. 1, 3 & 4.

Summary

The results of drilling and the accompanying research are summarized as follows:

1. Coal beds are found in Upper Cretaceous rocks in the Straight Cliffs and Dakota Formations.

2. Coal beds exceeding four feet in thickness are present; one discovered exceeds 18 feet.

3. The coal is subbituminous A in rank, some may be marginal high-volatile C bituminous in rank. The average Btu/lb. in the 18-foot bed is 9,500 as received.

4. The sulfur content varies from coal bed to coal bed and within the coal bed. Analyses range from 0.63 to 2.56 percent. The 18-foot bed in section 33 averages 1.5 percent. The lower 10 feet average 0.79 percent sulfur. Much marcasite is present as films in the upper part. Washing will probably yield a good result in sulfur reduction.

5. The ash content of the 18-foot bed is 8.6 percent. If the upper 3 feet are eliminated the content is 7 percent.

6. Tertiary and Quaternary sediments truncate Upper Cretaceous formations along an unconformity about 200 to 600 feet beneath the surface. Mining will probably be confined to underground methods. In section 33, where the 18-foot coal bed was drilled, the unconformity is 345 to 365 feet beneath the surface.

7. The rock formations beneath the unconformity are structurally deformed. The beds are moderately folded and faults are inferred. In section 33 the beds strike N. 23.5° E. and dip 20° northwesterly. Even though the strike and dip of beds in section 33 has been determined, this information should not be assumed for the remainder of Johns Valley without additional drilling or geophysical work. The attitude of beds may be steeper or more gentle than those in section 33. The displacements, number, trends, and positions of the inferred faults are concealed and can only be determined by geophysical work.

8. The measured and indicated reserve as determined by this drilling project is 1.2 and 25 million tons in-place, respectively. It is centered around the southeast part of section 33–an 18-foot coal bed contains about 20 million tons in-place per square mile. At a dip of 20° the coal bed will drop 1800 feet per mile; the safe mining width will be limited to a little over a mile perpendicular to strike. The length of the coal body remains undetermined.

9. The potential for finding thick coal beds in the Johns Valley and surrounding plateau area is excellent in both the Straight Cliffs and Dakota Formations. The trend of thick Kaiparowits Plateau field (Straight Cliffs Formation) coal beds is northwesterly and the trend of thick Alton field (Dakota Formation) coal beds is northeasterly. These trends converge in Johns Valley. The depth to the coal and the structural complexity will influence the mineability.

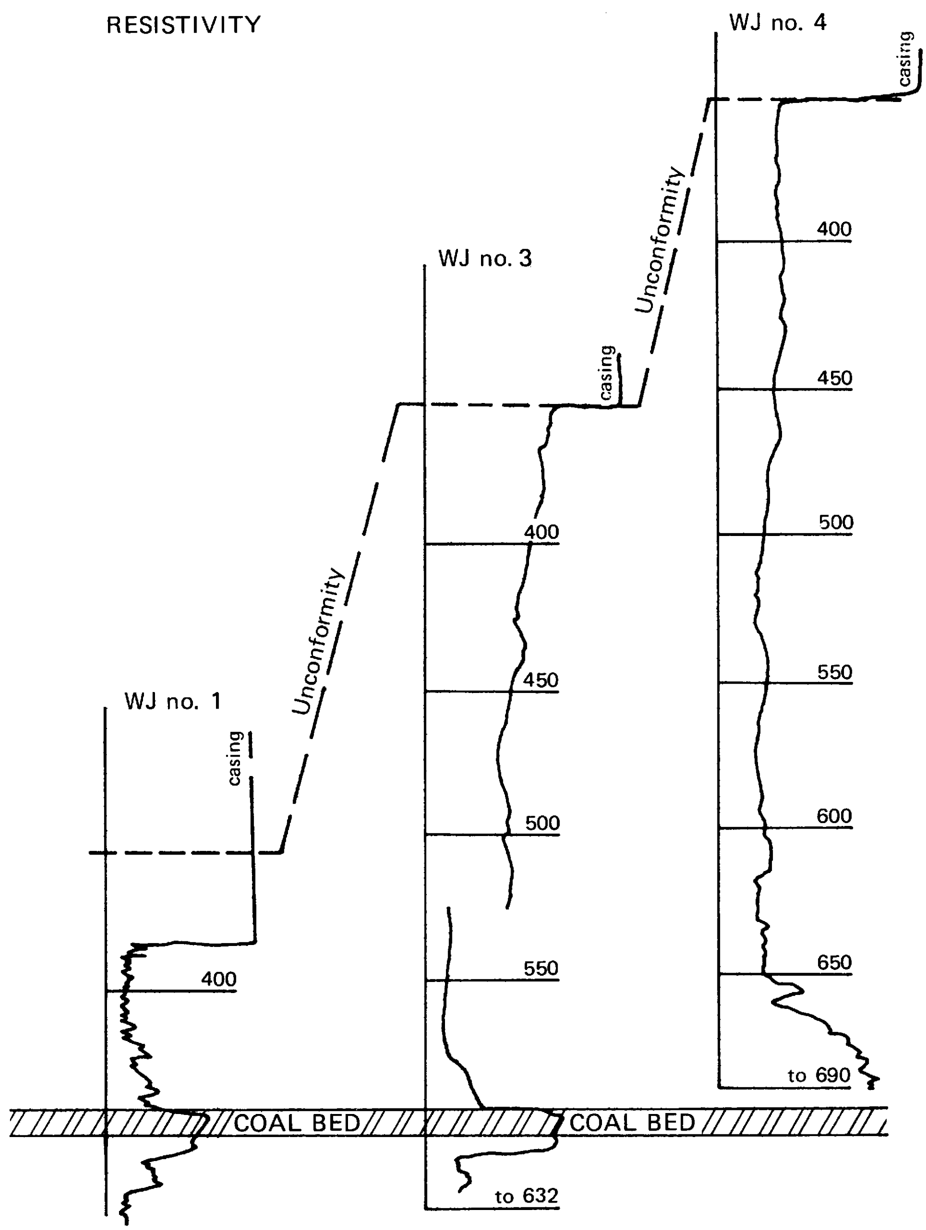


Figure 12. Comparison of resistivity logs in holes Widtsoe Junction Nos. 1, 3 & 4.

Table 3. As Received Analyses

	Interval	Thickness	Btu/lb.	Sulfur	Ash content
Sample 1	443.3-446.3	3.0ft.	8440	2.09%	16.29%
Sample 2	446.3-448.3	2.0	9764	2.56	6.26
Sample 3	448.3-451.8	3.5	9704	2.45	7.02
Sample 4	451.8-455.1	3.3	9672	0.88	7.64
Sample 5	455.1-458.5	3.4	9421	0.63	9.45
Sample 6	458.5-461.6	3.1	9787	0.87	4.39
Weighted averages, 6 Samples		18.3	9459	1.51	8.57
Weighted averages samples 2-6					
Moist, mineral free Btu/lb. = 10,247	= Subbituminous A coal				

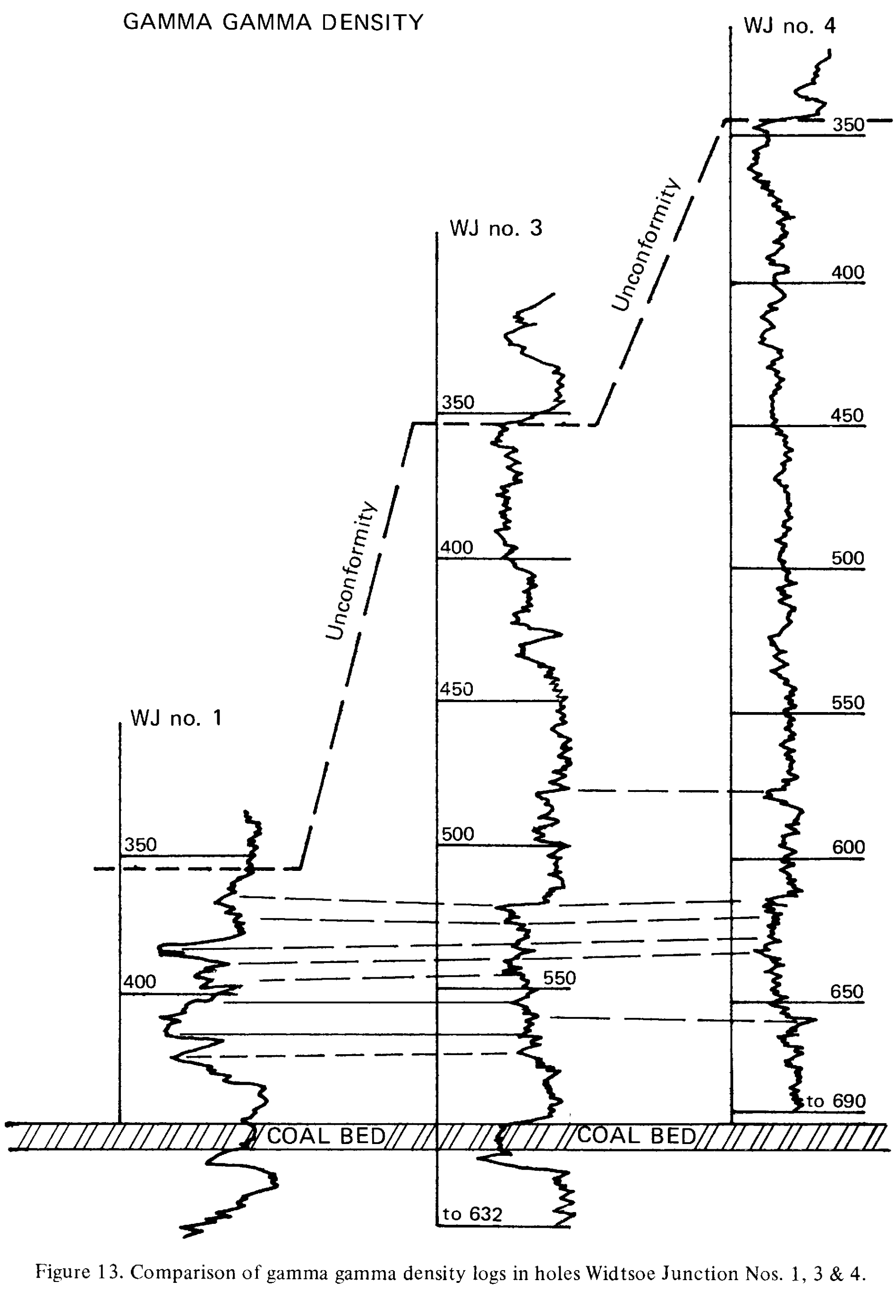


Figure 13. Comparison of gamma gamma density logs in holes Widtsoe Junction Nos. 1, 3 & 4.

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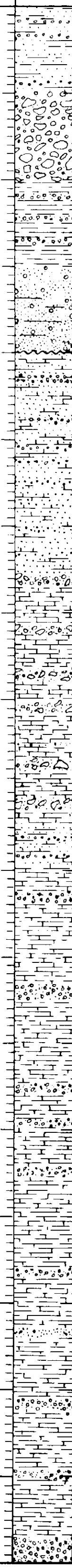
APPENDIX

Project: Widtsoe Junction Coal Drilling, Drill Hole No. 1
Location: SESESE 33-33S-2W, Garfield County, 78 feet north, 114 feet west of the southeast corner of section 33. Driller: Unzicker & Wells
Elevation: 7330 feet Total Depth: 633 feet
Begun: October 4, 1976 Completed: November 5, 1976

Elev.	Depth	Log	Description
7330	0	SURFACE	ALLUVIUM Clay, silt, and minor sand, pink to tan-brown, occasional zones of fine to medium gravel.
7320	10	10.0	Silt, orange-brown, occasional streaks of fine pebble gravel.
7310	20	UNCONFORMITY 19.0	SEVIER RIVER FM.? Gravel, gritty to medium, subround to subangular, quartzite, black chert pebbles, interstitial silt and sand, interbedded lenses of silt, loosely consolidated.
7300	30	30.0	Gravel, as at 19.0, some coarse, increase in sand and silt.
7290	40	40.0	Gravel, grit to very coarse, interstitial silt and sand, some silt lenses, silt is clayey.
7280	50		
7270	60	60.0	Gravel, grit to medium, interbedded with silt lenses, much coarse sand.
		68.0	Gravel dominates, some coarse.
7260	70		
		73.0	Siltstone with lenses of gravel, grit to medium, sandy.
7250	80		
		85.0	Gravel, very fine to coarse, cobbly, only occasional silt or sand lenses, jumpy drilling.
7240	90		
7230	100	100.0	Gravel, grit to fine, tan and pink, interstitial silt and clay, occasional silt and sand interbeds, silt and clay increase to 125.0.
7220	110		
7210	120		
		125.0	Gravel, grit to cobbles, occasional silt or sandy silt lenses.
7200	130		
7190	140		
		147.0	Silt, clay, and sand with interspersed fine gravel.
7180	150		

(continued)



Elev.	Depth	Log	Description
7170	160		
7160	170	170.0	Gravel, coarse, some silt and clay, difficult drilling.
7150	180	180.0	Siltstone and claystone, fine to medium gravel at intervals, some coarse, slow drilling.
7140	190	190.0	Gravel and coarse sand, some silt, smooth and fast drilling.
7130	200	UNCONFORMITY	CLARON FM.? Siltstone and claystone, clay tan to red and sticky, some fine to medium gravel, quick drilling.
7120	210		
		217.0	Drilling slows down.
7110	220		
		223.0	Siltstone, very little claystone, occasional gravel, slow drilling.
7100	230	231.0	Gravel, fine to coarse, some cobbles, interbedded with calcareous siltstone, clay, very slow drilling.
		233.0	Siltstone and claystone, pink and white, calcareous and hard, occasional coarse gravel zones (241 & 249).
7090	240		
7080	250		
		255.0	Siltstone, brown, sandy, some fine gravel, fast drilling.
		259.0	Siltstone and claystone, orange-brown, occasional lenses of fine to medium gravel, hard slow drilling.
7070	260		
7060	270		
7050	280		
7040	290		
7030	300	301.0	Claystone and siltstone, calcareous, tan to red-brown, occasional fine gravel or coarse sand, some volcanic pebbles. Hard drilling.
7020	310		
		313.0	Sandstone with a few pebbles, smooth quick drilling.
		314.0	Claystone and siltstone, like 301.0, alternatingly hard and soft drilling.
7010	320		
7000	330		
		337.0	Gravel with interstitial silt and clay, difficult drilling.

(continued)

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(continued)

Elev.	Depth
6990	340
6980	350
6970	360
6960	370
6950	380
6940	390
6930	400
6920	410
6910	420
6900	430
6890	440
6880	450
6870	460
6860	470
6850	480
6840	490
6830	500
6820	510

Log	Description
345.0	Gravel, light tan to brown, grit to medium, with lenses of clay and silt, calcareous.
357.0	Siltstone and claystone, tan-brown, contains grit, calcareous.
UNCONFORMITY 361.0	CRETACEOUS, DAKOTA FM.? Shale, gray, clayey.
387.0	Siltstone, gray, moderate drilling speed.
389.0	Shale, gray, clayey, slow drilling.
CORING BEGINS 402.0	Sandstone, medium gray, fine-grained, highly fractured with contorted thin laminae of silt-shale, black.
403.0	Shale, black, carbonaceous, sandy, clayey, fossiliferous (oysters, *Gryphaea? Exogyra?*, best at 403.7)
404.5	Core lost but some sludge recovered, sandstone, black, with black shale interbeds, fine-grained, calcareous clayey, about 4 feet of sludge recovered.
422.0	Shale, dark gray to black, silty, some fine sand, carbonaceous.
424.0	Siltstone, medium gray, sandy, shaly, with thin calcareous stringers.
425.4	Siltstone, medium gray, sandy, massive, calcareous, some finely disseminated pyrite.
427.9	Sandstone, laminated light-gray and black, very fine-grained and silty, laminae paper thin to 1/2 inch thick, calcareous, very silty 3 inches from base, laminae dip 12°, good marker.
443.1	Bone coal
443.3	Coal, black, lustrous, marcasite films on bedding, very uniform, 18.7 feet.
462.0	Sandstone, light and medium gray, fine-grained, some coaly streaks, some contorted bedding, calcareous, looks like beach sand.
473.3	Siltstone, finely laminated light to medium gray, sandy, calcareous.
475.1	Sandstone, light gray, very fine-grained, silty, calcareous.
475.6	Siltstone, medium-gray, sandy, marcasite on some bedding planes, some loss of core.
482.0	Shale, light to medium gray, clayey.
483.0	Coal, lignitic.
483.3	Siltstone, light to medium gray, some carbonized wood dragments, argillaceous.
486.3	Shale, medium to dark gray, coaly.
492.0	Shale, light gray, silty, argillaceous.
493.4	Siltstone, light gray, shaly.
494.4	Shale, medium gray, minor silt.
495.8	Sandstone, gray-yellow-brown, silty, limonite on small cracks, calcareous.
496.2	Siltstone, light gray, clayey.
497.4	Sandstone, laminated light to medium gray.
499.0	Siltstone, medium gray, sandy.
499.5	Shale, black, coaly, thinly laminated, marcasite films.
501.5	Siltstone, light gray
CHURN DRILLING 502.0	Shale, gray, silty, alternating with dark gray, carbonaceous.

(continued)

Elev.	Depth
6810	520
6800	530
6790	540
6780	550
6770	560
6760	570
6750	580
6740	590
6730	600
6720	610
6710	620
6700	630

Log	Description
527.0	Siltstone, light to medium gray, interbedded with shale, medium to dark gray, sparse marcasite blebs.
529.5	Shale, black, carbonaceous, marcasite along bedding occasional thin stringers of coal and woody plant debris.
531.0	Shale, medium gray, marcasite pods, some coalified debris.
532.3	Siltstone, medium gray, sandy, marcasite blebs.
532.8	Shale, dark gray to black, carbonaceous
533.1	Sandstone, light gray, fine-grained, massive, soft, friable.
537.0	Shale, medium to dark gray, some siltstone and sandstone interbedded.
562.0	Shale, light to medium gray, silty
564.2	Siltstone, light gray, with some interbedded very fine grained sandstone.
572.0	Shale, light greenish gray, some interbedded siltstone.
573.0	Shale, dark gray, carbonaceous
576.0	Shale, greenish gray, massive
592.0	Shale, grayish green, silty, some plant fragments.
597.2	Sandstone, light gray, very fine-grained, massive, calcareous.
602.0	Sandstone, dark gray, silty, shaley
609.0	Sandstone, light gray, very fine-grained, interbedded with shale, dark gray to black, carbonaceous.
612.0	Sandstone, light to medium gray, very fine-grained, interbedded with shale, black, and thin coal seams (1/16"), freely disseminated pyrite.
622.0	Sandstone, light gray, calcareous, some interbedded black shale.
626.0	Sandstone, light gray, silty, interbedded with light green and light to medium gray shale.
633.0	Total depth

GEOLOGY OF THE CRYSTAL GEYSER AND ENVIRONMENTAL IMPLICATIONS OF ITS EFFLUENT, GRAND COUNTY, UTAH

by James L. Baer[1] *and J. Keith Rigby*[1]

ABSTRACT

A geologic study was done in conjunction with an environmental impact investigation of the Crystal Geyser, 6.5 kilometers (4 miles) southeast of the community of Green River, Utah. Periodic eruptions of salt-laden waters from the geyser flow into the Green River and provide a source of salts into the Colorado River drainage system. Eruptions average 120 cubic meters (0.1 acre feet) of CO_2 charged water with abundant Na, Ca, K. and Mg salts.

The mineral laden waters form tufa deposits along a nearly 2 kilometer (1.3 miles) exposure that is situated along and controlled by the Little Grand Wash Fault. Three distinctive levels of tufa deposits indicate that the mineral-laden springs have been active along the fault for several hundred thousand years.

Several methods considered to control the salt laden effluent were rejected as either impractical or too expensive.

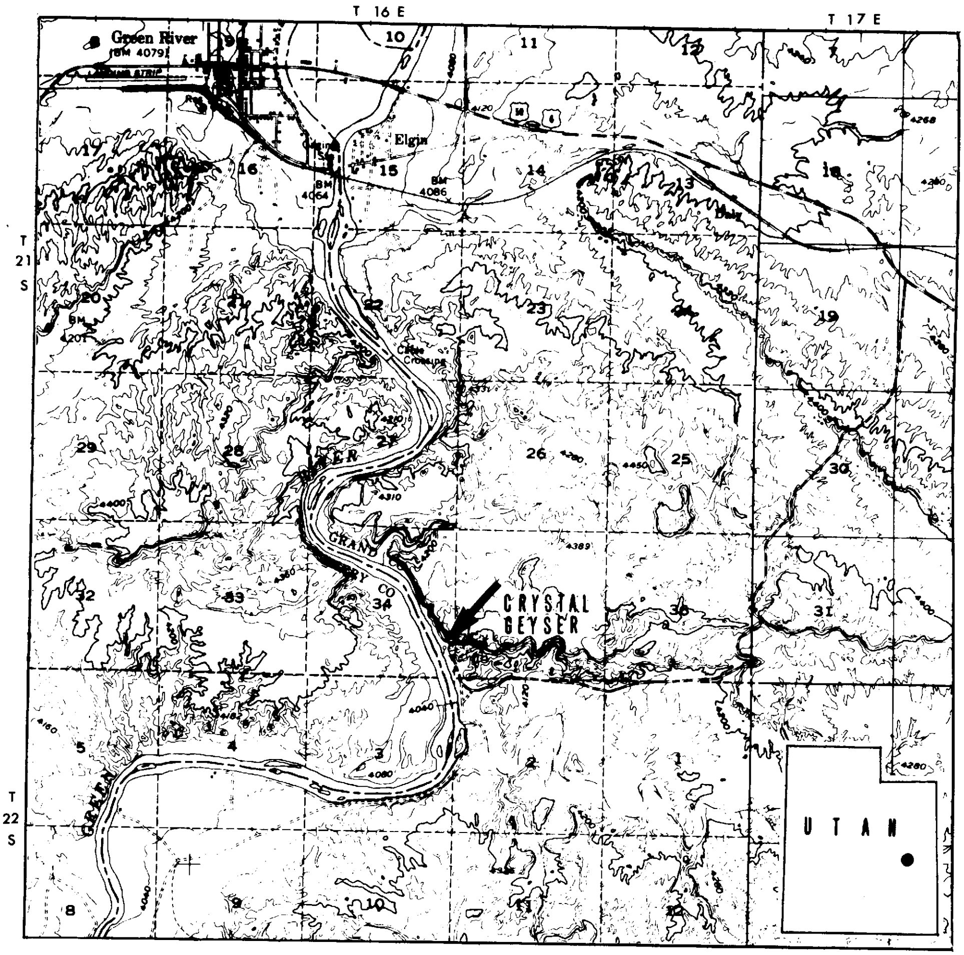

Figure 1. Index map.

INTRODUCTION

A geologic study of the Crystal Geyser area was made, in conjunction with an environmental impact investigation conducted by a team of geologists, engineers, economists, and biologists from Brigham Young University, to ascertain significant geologic factors controlling the periodic eruptions of Crystal Geyser and to determine a feasible means of preventing the salt-laden spill waters from flowing into the Colorado River.

Crystal Geyser is located in the southeastern corner of Section 34, T. 21 S., R. 16 E. and is approximately 6.4 kilometers (4 miles) southeast of the community of Green River (figure 1). The geyser and its related springs are located on the east bank of the Green River. The area is presently accessible by a graded dirt road which leads south for approximately 8.9 kilometers (5.5 miles) from U.S. Highway 50 and 6 from approximately 7.5 kilometers (4.5 miles) east of Green River. Crystal Geyser now erupts periodically through a 16 inch casing from the No. 1-X well drilled as a petroleum test to a total depth of 801 meters (2,627 feet) by Glen Ruby and associates between November 1935 and July 1936. The casing probably reaches to a depth of less than 31 meters (100 feet), but the casing record is not available.

GENERAL GEOLOGY

The study area lies within the Colorado Plateau physiographic province. The prominent eastern flank of the San Rafael Swell is approximately 20.8 kilometers (13 miles) due west and the southern edge of the Book Cliffs is 12.8 kilometers (8 miles) due north of the study area. Exposed bedrock is Jurassic and early Cretaceous, with the Entrada Formation, Curtis Formation, Summerville Formation, Morrison Formation, Dakota Sandstone, and Mancos Shale represented either in part or in entirety (figure 2). These rocks are generally dipping gently to the north.

The Crystal Geyser is situated alongside the Green River and in the fault zone of the Little Grand Wash Fault. Travertine spring deposits are found along the fault trace in the general vicinity of Crystal Geyser. These deposits are from the escaping salt-laden waters and appear to have been forming from at least the Pleistocene to the present time.

OCCURRENCES AND CONTROLS OF SPRING DEPOSITS

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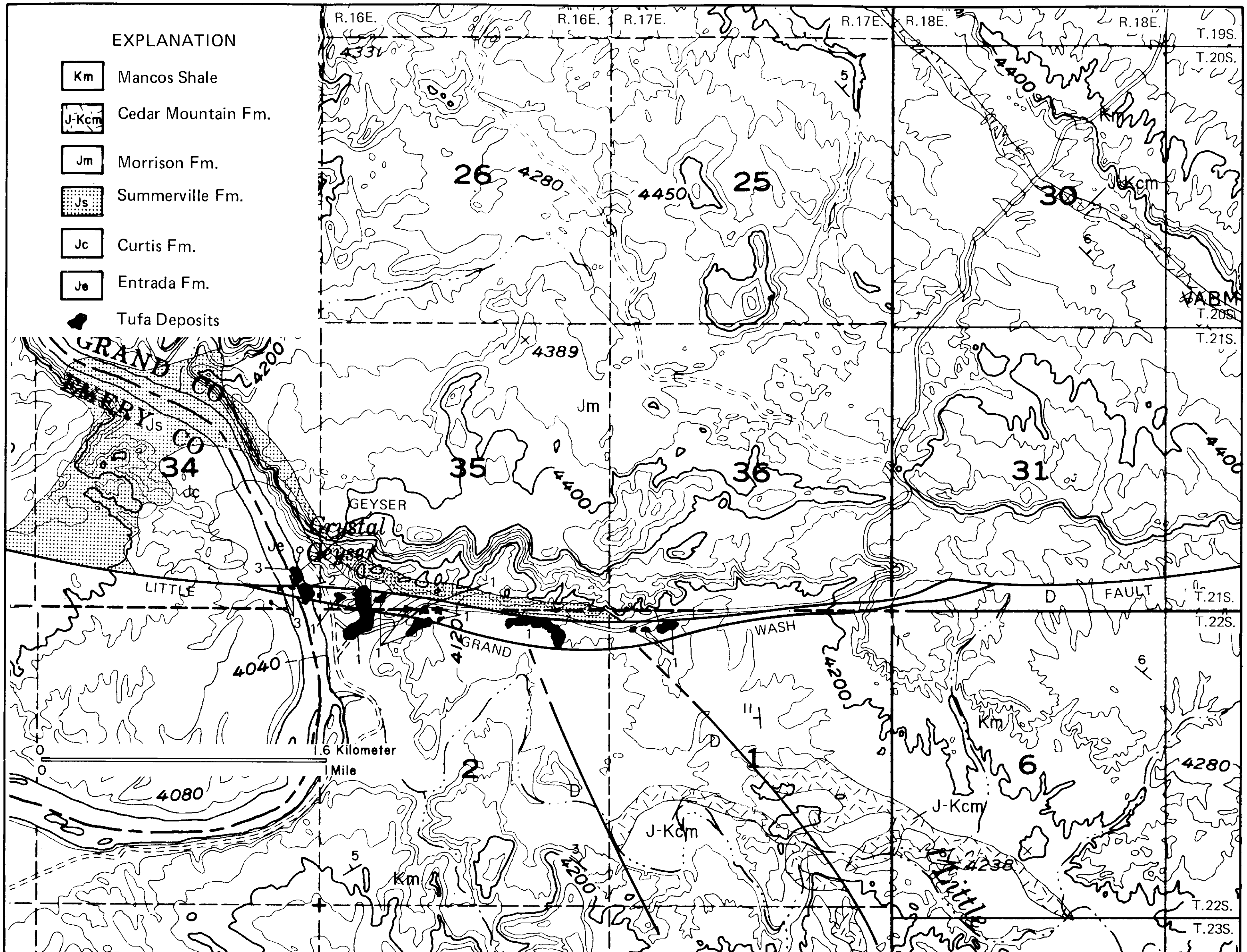

Figure 2. Geologic map of Crystal Geyser, showing deposits and their relationship to Little Grand Wash Fault near Crystal Geyser, modified slightly from McKnight (1940).

A series of tufa occurrences stretches eastward approximately 2.4 kilometers (1.5 miles) from the Green River and the geyser site along the base of the hills generally north to the access road (figures 2, 3). Three general ages of tufa development are recognizable and they cover collectively an area of approximately one square kilometer. The youngest tufas (Level 3) are currently being deposited by the geyser and presently active springs, at an elevation of approximately 1262 meters (4085 feet). Older tufas, at a slightly higher elevation than the geyser, (Level 2) are adjacent to the currently active area on the south. They are most prominent in the general vicinity of the turn-around point on the access road. Considerably older tufas (Level 1) are located at higher elevations, approximately 1297 meters (4200 feet), and occur mainly east of the geyser in a linear belt across the southern part of Section 35. These three levels are differentiated on figure 2.

Figure 3. Aerial view of Crystal Geyser looking west. 1 - oldest tufa (Level 1). Ma - Mancos Shale, Cm - Cedar Mountain Formation, E - Entrada Formation, C - Curtis Sandstone, S - Summerville Formation, Mo - Morrison Formation. 2 - tufa apron (Level 2), 3 - tufa surrounding the Glen Ruby Well 1-X (Level 3).

The tufas occur along a major east-west fault, named the Little Grand Wash Fault by McKnight (1940) (figure 2). He mentions that in the general vicinity of the geyser area the Little Grand Wash Fault splits into two faults separated by approximately 124 meters (400 feet) along most of their trend. Toward the east and west these two faults merge; beyond these points no tufa deposits are found. Obviously the tufa deposits owe their origin to springs issuing along the faults which serve as channel-ways through the underlying shaly impervious Mesozoic rocks.

The youngest (level 3) tufas are in the general vicinity of the geyser (figure 2) and are being actively built by four eruptive centers. The geyser is the principal outlet but mineral-laden waters also issue from three springs, one approximately 21 meters (70 feet) to the east and one approximately 9 meters (30 feet) to the north of the well site along the margins of the tufa field, and one approximately 60 meters (200 feet) to the west in the bed of the Green River. During observed eruptions water comes from all four centers although only minor activity was observed in the Green River spring.

The modern actively-building (level 3) tufa is generally iron-stained and shows fine delicate terracettes. Included with the actively-building tufa are recently abandoned older tufas that have formed small cones approximately 90 meters (300 feet) to the east, between a minor fault and the well. Approximately 9 meters (30 feet) to the south of the well are small steep cones 6 to 9.3 meters (20 to 30 feet) in diameter and 1 to 1.3 meters (3 to 4 feet) high that also mark position of former spring activity, immediately predating the current sites (figure 3). These tufas are included with the younger active tufas to make up Level 3 deposits.

Older Level 2 tufas, deposited at a slightly higher elevation, have lost much of their delicate structure, but still show some porosity and thin laminate foreset characteristics. Typical of Level 2 tufas is the rounded hill near the access road turn-around and the cone along the river bank near the end of the road, to the west. Tufas of this general age extend to the southeast, along both the east and west sides of the access road, for approximately 91.4 meters (300 feet). Both the active Level 3 and intermediate Level 2 tufas are deposited in a valley carved by the Green River at essentially its present elevation and, hence, are not of significantly different ages.

The third group of tufa occurrences, Level 1, is considerably older and forms the most extensive deposits of spring-produced rocks in the area at elevations up to 37 meters (120 feet) above Level 3 tufas. Cones and broad aprons and scattered outliers of Level 1 tufa and travertine extend eastward for approximately 1.6 kilometers (1 mile) from the crest of the hill that is one-quarter mile east of the well site. The most extensive tufa deposit is the massive travertine vein, apron and cones built up approximately 366 meters (1200 feet) due east of the well site along the Little Grand Wash Fault. The broad apron extends southward for at least 305 meters (1000 feet) and terminates approximately 30.5 meters (100 feet) above the present river level. The high tufa cones are up to 61 meters (200 feet) above the present river level.

A second broad apron of Level 1 tufa is located approximately 0.8 kilometers (one-half mile) southeast of the active geyser area, and extends at least

305 meters (1000 feet) south from the general line of tufa cone development along the fault zone into an area capped by terrace gravels. These oldest Level 1 tufas are interbedded with river terrace gravels 46 to 61 meters (150 to 200 feet) above the present elevation of the Green River. These Level 1 tufas are the most extensive spring deposits of the area and indicate that springs have issued naturally along the controlling fault for an estimated several hundred thousand years (figure 4).

GEOLOGY OF THE WELL

Following the discovery of gas and petroleum seeps in the vicinity, the Glen Ruby No. 1-X well was drilled on the crest of a small faulted anticlinal structure in a search for oil.

The only records available for the 2627 foot well from which the Crystal Geyser is at present erupting are driller's records which leave considerable information wanting (McKnight, 1940). The well was spudded into the Level 3 tufa cone and drilled approximately 21.5 meters (70 feet) through tufa (well below the present river level), at which level the well apparently crossed to the north side of the controlling Little Grand Wash Fault (figure 5). After crossing the fault, the well penetrated the upthrown Entrada Formation, which is a series of inter-bedded red to gray shale, siltstone, and sandstone beds for approximately 149 meters (490 feet); the Carmel Formation, a series of brown to red sandstones with thin interbedded gray to brown shale, with a total thickness of 62 meters (205 feet); the Navajo Sandstone, 117 meters (383 feet) of mainly gray to brown sandstone with thin gypsum beds near the top; the Wingate-Kayenta Formations, approximately 162 meters (532 feet) of brown to red brown shale and sandstone; the Chinle Formation, a series of interbedded red to red brown shale and sandstone, with some yellow shale, that has a total thickness of approximately 91 meters (297 feet), and 218 meters (715 feet) of brown shale with thin green shale interbeds assigned to the Moenkopi Formation. The lower portion of the Moenkopi sequence is a red brown shale and is slightly sandy. The well bottomed after drilling 1.5 meters (5 feet) into a light gray cherty limestone, thought to be the eroded top of the Permian Kaibab Limestone.

SOURCE OF THE WATER AND DISSOLVED SALTS

The well appears to offer a local relief point for carbon dioxide-charged water trapped in the Navajo Sandstone, which is approximately 215 meters (700 feet) beneath the surface at the well site. Navajo Sandstone also produces carbon dioxide-saturated water at Woodside Geyser, in section 9, T. 18 S., R. 14 E., 41 kilometers (25 miles) northwest of Crystal Geyser, and commercial carbon dioxide in Farnham Dome, east of Wellington (Mahoney and Kunkel, 1963) in section 6 T. 15 S., R. 11 E., 83 kilometers (52 miles) to the northeast of Crystal Geyser.

The water probably originates as meteoric water that percolates into the exposed Navajo Sandstone along the east side of the San Rafael Swell (figure 6). The Navajo Sandstone is a clean, porous quartz sandstone which occurs between impervious Triassic and Jurassic rocks and, hence, is an ideal aquifer. This formation has an eastward sloping gradient from the San Rafael Swell to a low point in the broad north-plunging regional syncline at about the position of the geyser.

Here the Little Grand Wash Fault effectively seals off ground water from the south, and also forms the structural control for trapping the dissolved carbon dioxide. In addition the fault provides an accessway for the dissolved salts and gases to reach the surface (figure 5). The small spring north of the geyser and the spring area east of the geyser site are probably connected with the fault along the east and north side of the active tufa cones.

Approximately 2730 metric tons (3,000 tons) of Na, Ca, K, and Mg salts are contributed to the Green River annually by this spring system (table 1). These salts include carbonates, bicarbonates, sulfates, and chlorides. The ultimate source of the salts is unknown. A possible source is the dissolving of rock fragments and minerals within the Navajo Sandstone and adjacent formations by slightly acidic groundwaters percolating through them. Carbon dioxide gas would be an expected by-product at this reaction. This dissolved carbon dioxide eventually builds enough pressure to cause the eruptions.

NATURE OF ERUPTIONS AND THEIR POSSIBLE CONTROL

At the time of observation, Crystal Geyser erupted at irregular intervals of from 4 to 6 hours (table 2). Each eruption was characteristically predicted or preceeded by a slow rise of the water level in the conduit. The water effervesces as it rises. As the pressure of dissolved gases, mainly CO_2, is released, the gas expands and the water eventually begins to spill from the conduit and the eruption then quickly builds into a geyser (figure 7) that reaches heights of 21 to 27 meters (70 to 90 feet).

Eruptions average 7 minutes (tables 2 and 3) in duration and during that time emit nearly 123 cubic meters (0.1 acre-feet) of mineral-laden water (tables 1,2, 3). Approximately 50 percent of the water from the main outlet reaches the river. The remainder soaks into the porous tufa cone and percolates back

Figure 4. Three tufa levels, 3 - youngest tufas next to well, 2 - intermediate age tufas, 1 - oldest and highest tufa.

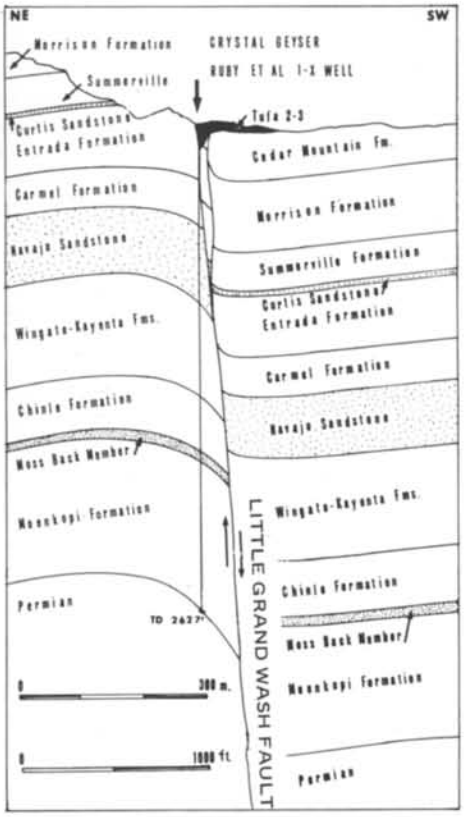

Figure 5. Cross-section interpretation of Glen Ruby No. 1-X well.

through the cone to partly recharge the system. When geyser waters were pumped away the eruptions became less frequent and of lower volume. However, when the geyser waters were trapped by a small dike arrangement and allowed to percolate back directly into the cone, the eruptions were more frequent and of higher volume than the normal undistrubed eruptions.

The principal reason for the present study was to ascertain a feasible means of preventing the mineral-laden runoff from reaching the Green River reservoir. Several possible means were proposed. The first was to build a dike around the main outlet to impound the water and channel it to an evaporating pond to the southeast. This suggestion would utilize the available terrain and is the least expensive. However, the impounded water would probably cause the geyser to erupt more frequently. The available natural storage area is of insufficient capacity to handle the accumulated runoff. Furthermore, the natural storage area is in lowlands along Little Grand Wash and would be subject to periodic flashfloods that could both destroy the reservoir and flush the concentrated salts into the river.

A second possibility, a modification

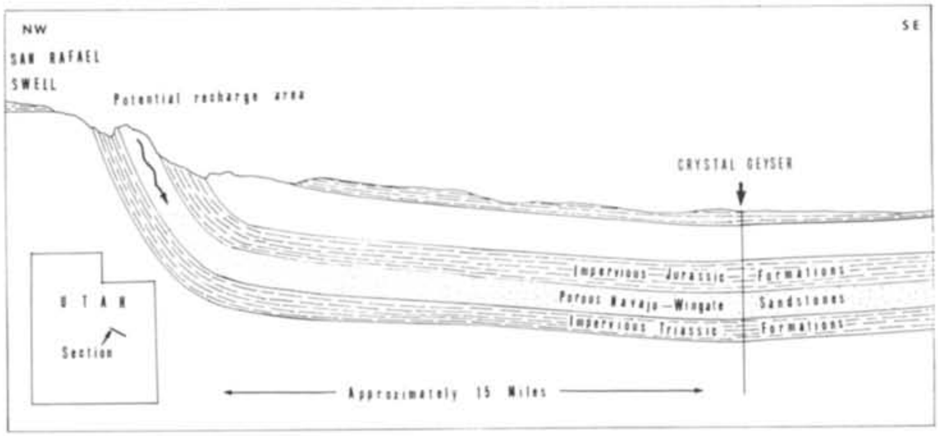

Figure 6. Generalized cross-section depicting expected source and route of waters emitting from Crystal Geyser..

of the first plan, was to pump the impounded water to a larger slightly elevated pond area above the probable path of flashfloods. This suggestion avoids the disadvantages of the first, but would be much more expensive.

A third suggestion, to drill a relief well near the Ruby No. 1-X well, from which the water could be inexpensively retained in evaporation ponds, was rejected because the area of collection of the CO_2 and water is so diffuse that such a well would probably be ineffectual.

A fourth suggestion, that the Crystal Geyser source be sealed by a grout curtain, is impractical because the gas-charged waters would eventually find a new outlet along the Little Grand Wash Fault, as they obviously have at several times and places in the past.

CONCLUSIONS

The Crystal Geyser is a naturally occurring CO_2-charged spring that is a point source of salts entering first the Green River, then the Colorado River. The geyser has been spilling out along the Little Grand Wash Fault for at least several hundred thousand years. This spring has had its discharge localized, but not totally constrained, by the drilling of a petroleum exploration well.

Approximately 2730 metric tons (3,000 tons) of Na, Ca, K, and Mg salts are contributed to the Colorado River drainage system annually by the spring system. This study indicates that the total amount of the salts entering the Colorado River drainage could be reduced, but it would be expensive, and the Crystal Geyser complex is only one minor source of salts into the Colorado River System. Control is probably not worth the expenditure.

ACKNOWLEDGMENTS

We express our thanks to Drs. James Barton and Dean Fuhriman for allowing us the use of data they acquired in the environmental impact study..

Figure 7. Crystal Geyser in eruption phase.

Table 1. Quality of the Water from the Main Geyser*

Electrical conductivity	15, 130 x 10' micromhos/cm @ 25°C
pH	6.9 (Laboratory)
% Sodium	72 (Dry salts)
Sodium adsorption ratio	30
Residual Carbonates	207 milligrams per liter
CATIONS	
Calcium (Ca)	991 milligrams per liter
Magnesium (Mg)	232 milligrams per liter
Sodium (Na)	4070 milligrams per liter
Potassium (K)	363 milligrams per liter
ANIONS	
Carbonate (CO_3)	none
Bicarbonate (BCO_3)	4620 milligrams per liter
Chloride (Cl)	3990 milligrams per liter
Sulfate (SO_4	2300 milligrams per liter
Total alkalinity	3790 milligrams per liter $CaCO_3$
Brown suspended material	iron
Freezing point of filtered sample	0° C

Table adapted from Barton and Fuhriman, 1973
* Sample taken 3 November, 1972

Table 2. Some Characteristics of the Flow from the Geyser under natural conditions*

Date	Time Eruption Began	Length of Eruption (Minutes)	Time Between Eruptions	Volume of Water Discharged During Eruption	
				Cubic Meters	Acre feet
13 June 1968	07:15		4 hrs 00 min		
13 June 1968	11:15	6.8	4 hrs 15 min	127.0	0.103
13 June 1968	15.30	7.3	4 hrs 15 min	118.4	0.096
13 June 1968	20:00	7.0	4 hrs 15 min	124.6	0.101
19 July 1972	02.48	6.9	4 hrs 15 min	118.4	0.096
19 July 1972	08:25	7.7	4 hrs 15 min	106.1	0.086
19 July 1972	13:24	6.1	4 hrs 15 min	109.8	0.089
19 July 1972	18:27	7.2	4 hrs 15 min	119.6	0.097
19 July 1972	23:41	6.9	4 hrs 15 min	118.4	0.096
20 July 1972	05:10 est.	---	4 hrs 15 min	----	----
20 July 1972	10:40	7.5	4 hrs 15 min	115.9	0.094

*Modified from Barton and Fuhriman, 1973

Table 3. Summary of Crystal Geyser Eruptions*

Height of eruption	40 to 50 feet
Duration of eruption	7 minutes
Time interval between eruptions	4 to 6 hours
Water always saturated with gas	Principally carbon dioxide
Water temperature	15.5° to 17.8°C (60° to 64° F)
Volume discharge of an eruption	123.3 cubic meters (0.1 acre-feet)
Total dissolved salts in the water	11,000 to 14,000 mg/1
Approximate salt contribution per eruption	1.36 to 1.81 metric tons (1.5 to 2.0 tons)
Approximate salt load per year	2720 metric tons (3,000 tons)

*Modified from Barton and Fuhriman, 1973

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LAND SURFACE INSTABILITY ON THE WASATCH PLATEAU CENTRAL UTAH

by Andrew E. Godfrey[1]

ABSTRACT

A field reconnaissance survey of surface instability on the Wasatch Plateau of central Utah was made to aid land management planning on portions of the Manti-LaSal and Fishlake National Forests, where landslips are a major hazard. The study area was divided into six physiographic subsections, each presenting unique land management problems. Then, using the parameters of lithology (stratigraphic formations), slope, climate, and aspect, each subsection was divided into landslip-hazard classes. These ranged from 1, having a high probability of landslips, to 4, having a very low probability. The effect of grazing, road and dam building, and tectonic activity is also considered. Using air photography, maps, and air and field reconnaissance, maps of the subsections and instability zones were produced for forest managers.

This study found that slopes underlain by the North Horn Formation are very unstable and that northerly-facing slopes are generally more unstable than southerly facing slopes. All the currently active landslips in the Rolling Basinlands Subsection are found on north-facing slopes.

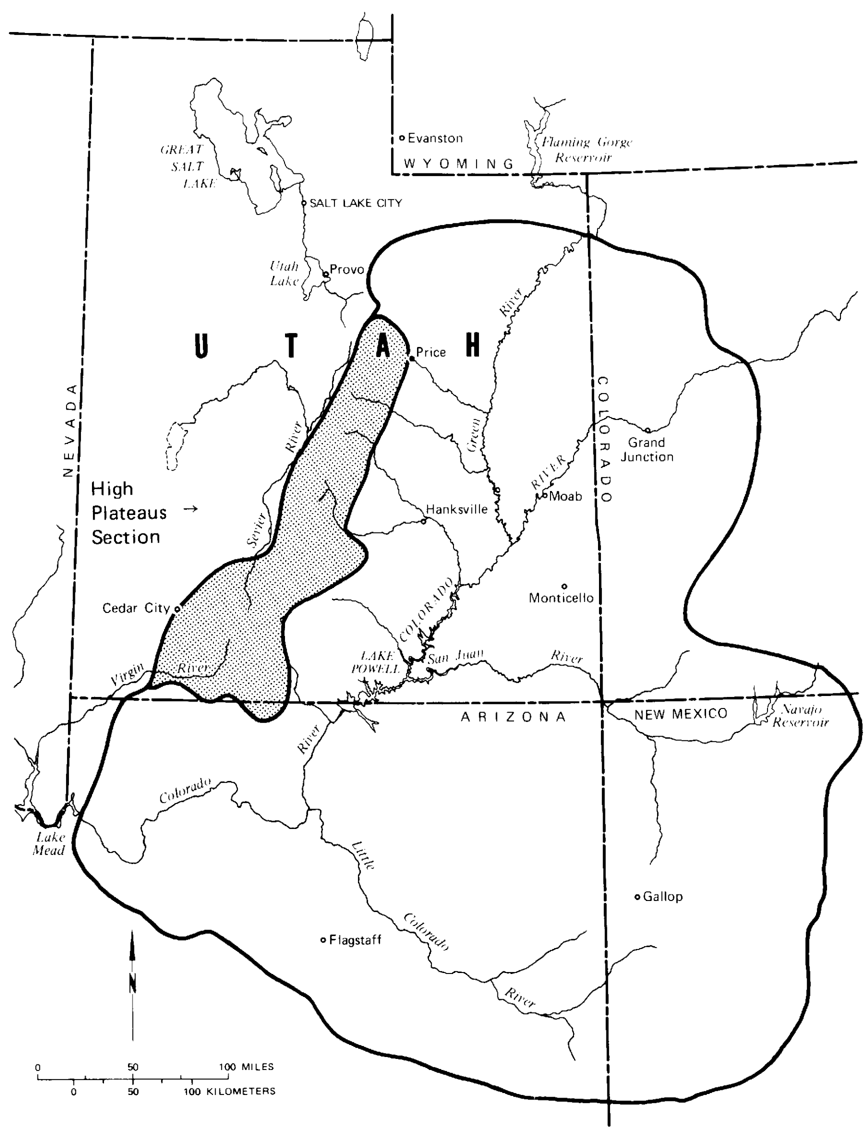
INTRODUCTION

Surface instability is a limiting factor in resource and land use management on the Wasatch Plateau portion of the Manti-LaSal and Fishlake National Forests. This report is a reconnaissance survey of mass land movement hazards on the Wasatch Plateau portion of the Manti-LaSal and Fishlake National Forests. Maps, aerial photographs and aerial reconnaissance were utilized to delineate subsections, areas of similar physiography which would appear to present similar land stability features. These subsections were mapped and further examined to locate areas where landslips have occurred; such areas were field checked to determine if the landslips are active, and to establish the criteria controlling present day land movement.

Description of the Study Area

The Wasatch Plateau, located in central Utah, is roughly bounded by US Highway 6 and 50 on the north, Interstate 70 on the south, the towns of Salina, Manti, Ephraim, and Mount Pleasant on the west, and the towns of Emery, Castle Dale, Huntington, and Price on the east (figure 1). This study covers approximately 1,200 square miles and was mapped on a reconnaissance scale during the summer of 1971.

The Wasatch Plateau lies within the High Plateaus Section of the Colorado Plateau physiographic province of the United States as described by Hunt



Outline Map of Colorado Plateau Province and High Plateaus Section.

[1] U.S. Forest Service
Vernal, Utah 84078

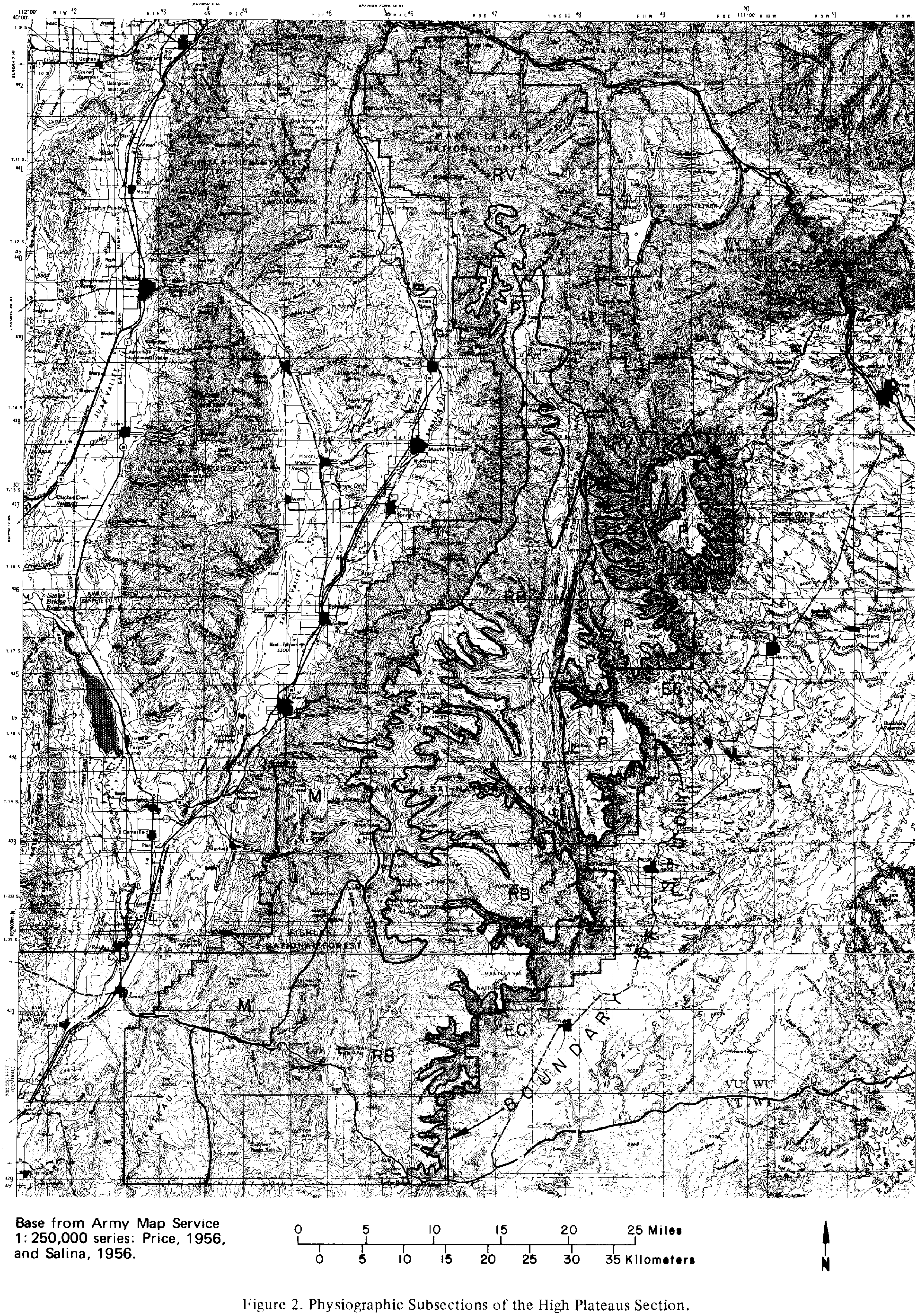


Figure 2. Physiographic Subsections of the High Plateaus Section.

(1974) (figure 1), or the Basin and Range-Colorado Plateau Transition Province of Stokes (1977). Within the Wasatch Plateau, areas of similar landscape, topography, and climate, i. e., physiographic units, were delineated to form six logical subsections (figure 2) using the process described in Godfrey (1977). The area within each subsection has a basically uniform appearance which suggests similar land management problems. These subsections are:

1. Lakes Subsection (L)
2. High Plateaus Subsection (P)
3. Ridge and Valley Subsection (RV)
4. Eastern Clifflands Subsection (EC)
5. Monocline Subsection (M)
6. Rolling Basinlands Subsection (RB)

Geologic Formations

Because the lithologies and statigraphic positions of the geologic formations are primary factors involved in the development of the land stability characteristics of the study area, a brief description of the formations present in the study area is given here. Figure 3 shows the stratigraphic position of the formations underlying the study area and illustrates schematically the typical slopes formed by each formation. In the descriptions of the formations that follow, (from older to younger) the thicknesses and portions of the lithologic descriptions are from Speiker and Billings (1940, p. 1177) for the Cretaceous Mancos Shale to the Tertiary Flagstaff Limestone, and from Speiker (1949 p. 33-35), for the Colton and Green River formations.

Cretaceous

Masuk Member of the Mancos Shale ---4000 feet

Uniform, massive gray marine shales of which only the upper part is exposed along the eastern boundary of the Manti-LaSal Forest. Because of its rapid runoff characteristics, this formation tends to be rather barren and thus susceptible to severe sheet and gully erosion. Although not particularly susceptible to mass instability, this formation is slippery when wet and does provide lubrication for the movement of blocks of over-lying sandstone.

Star Point Sandstone—450 feet

Massive cliff-forming, buff sandstone, medium to fine-grained. Unlike the over-lying Castlegate Sandstone this formation contains some interbedded shales which produce steplike topgraphy. This formation is quite stable; however, the more rapid erosion of the under-lying Masuk Shale removes support by undercutting, which leads to block falls. The blocks so produced then move down the shale-colluvial slopes as planar block glides.

Black Hawk Formation—1500 feet

Medium-to-fine-grained, buff and gray sandstone, gray shale, coal; major coal producing formation in the area. Although not as unstable as is the North Horn Formation, the Black Hawk underlies several areas of active movement. It produces abundant colluvial material which can be unstable.

Castlegate Sandstone—3000 feet

Massive, cliff-forming, gray sandstone, coarse-grained to conglomeratic. In addition to producing massive cliffs, this formation is subject to severe jointing, which produces large boulders. Although the Castlegate is stable, undercutting of the Black Hawk Formation beneath it removes support from the jointed cliffs. This results in block falls and subsequent sliding of the large blocks down the shale and colluvial slopes.

Price River Formation--600 feet

Red to gray sandstone and conglomerate with varying amounts of shale. The appearance of this formation varies with geographical location. To the northwest, it is a coarse, conglomeratic unit with minor amounts of shale. This material appears to be stable. To the southeast, the size of the conglomerate decreases and shale interbeds appear. As a result, the topography changes from vertical cliffs to staircase forms, and the stability decreases as the proportion of shale increases.

North Horn Formation--2000 feet

Buff, gray, red sandstone, gray to variegated shale, conglomeratic, some limestone. This is probably the most important formation in the study area because it is exposed over large areas and is extremely unstable. The shales which comprise a major component of this formation become highly plastic when wetted and are capable of extensive mass movement. Since the sandstones and limestones of this formation are not well indurated, they cannot act as stabilizing agents.

Tertiary

Flagstaff Limestone--300 to 500 feet

Gray, tan, white limestone with minor amounts of shale and sandstone. This formation is, in general, stable. However, where the slopes are oversteepened or where support has been removed from the base of a dip slope, the shale partings can form glide surfaces for movement of the limestone blocks.

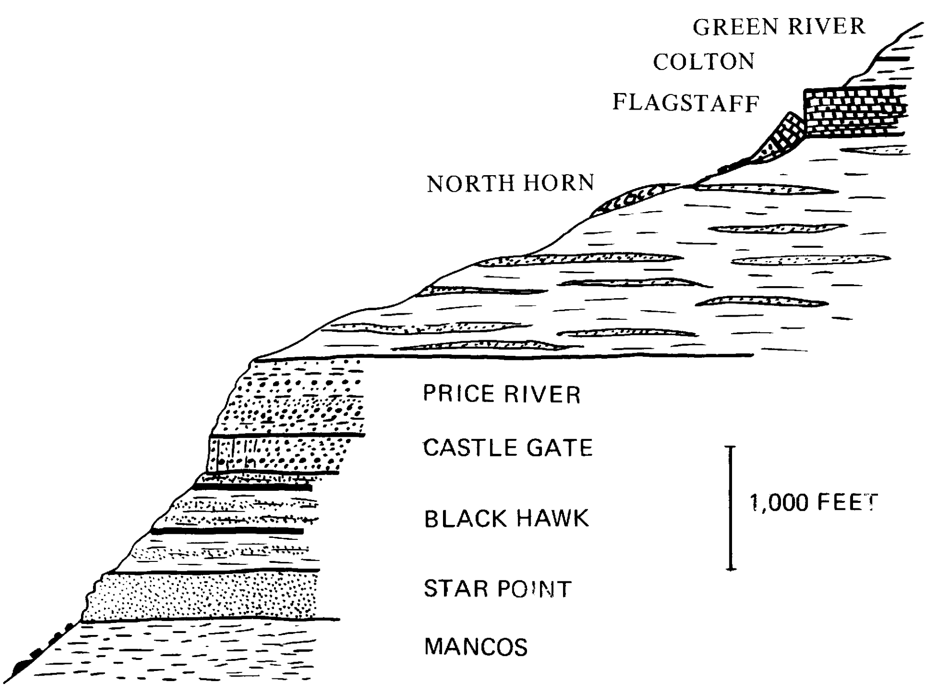


Figure 3. General Stratigraphic Section of the Formations Present in the Study Area


Figure 4a. General view of Lakes Subsection.


Figure 4b. General view of High Plateaus Subsection.


Figure 4c. Typical view of Ridge and Valley Subsection.


Figure 4d. General view of Eastern Clifflands Subsection.


Figure 4e. General view of Monocline Subsection.


Figure 4f. View of the Rolling Basinlands Subsection.

Colton Formation--0-500 feet

Varicolored to gray shale, buff to brown sandstone, some local limestone; exposed along the western border of the study area and along the lower part of Salina Creek. This formation is similar in lithology to the North Horn Formation and is thus potentially unstable if wetted. However, its major exposures are in the more arid portions of the study area so that it poses no substantial problem.

Green River Formation--200 to 800 feet

Gray to light blue shale and white to tan limestone, minor amounts of sandstone and conglomerate. Because the lithology and geography of exposure are similar to those of the Colton Formation, it poses the same problems of potential instability.

Quaternary Deposits

These deposits are quite varied because they reflect different parent materials. Their thicknesses vary, although each is generally less than 100 feet. Because of the mechanisms of their deposition and their positions on the landscape, these deposits fall into four basic categories, each with different stability characteristics:

1. Alluvium - These are the most stable deposits because water-washing has removed the fine material, leaving behind sand and coarser material. Except for deposits on the pediments on the eastern edge of the Manti-LaSal National Forest, these deposits are located in valley bottoms.

2. Moraines - The major deposits are located in the northern end of Joes Valley graben and in Manti and Six Mile Canyons. Although generally stable, these deposits may have North Horn shale cores and could show local instability.

3. Colluvium - Ubiquitous in the study area, colluvial deposits vary greatly in their landslide potential, depending on the steepness of the slopes on which they rest.

4. Landslide deposits. Because the slides have a shear plane at their bases, they can be reactivated at any time and are the most unstable deposits on the Wasatch Plateau.

DESCRIPTIONS OF THE SUBSECTIONS

The Lakes Subsection

The area is one of gently-rolling hills and valleys and is underlain by glacial till. It is basically stable under current conditions (figure 4-a). This subsection lies in the northern extension of the Joes Valley graben, and extends from Scad Valley divide on the south to Lower Gooseberry Reservoir on the north. To the east and west it is bordered by, but does not include, the long steep slopes that rise to the Ridge and Valley and Rolling Basinland Subsections. Speiker and Billings (1940, p. 1183) describe the region as follows:

> ...The surfaces are hummocky and irregular, and are dotted with hundreds of small depressions, most of which are occupied by ponds and marshes except in very dry seasons. Postglacial erosion has hardly begun to modify these features....

The elevation of this subsection is about 9000 feet and precipitation averages about 30 inches annually (Jeppson and others 1968). Most of this area is underlain by the North Horn Formation, with the exception of some areas along the eastern border which are underlain by Castlegate Sandstone and the Price River Formation. The North Horn Formation here is mantled by glacial till which, because of its hummocky appearance, can be confused with fossil landslide topography.

This subsection is relatively stable because the underlying topography consists of gently rolling rather than steeply-sloped hills. The numerous natural ponds and lakes, in contrast to sag ponds, rest on stable material and lie in or near the bottoms of valleys rather than being perched on shoulders; thus, they can be, and have been, successfully enlarged for use as reservoirs.

Despite the general stability of this area, there are some small earth flows and numerous seeps resulting from high ground-water levels and from drainage disrupted by glaciation.

The High Plateaus Subsection

Because of the flat-lying nature of the topography and the geology, this subsection is mostly stable but has unstable areas where the cirque headwalls along Skyline Drive have been over-steepened by glaciation (figure 4-b).

Except for some outliers along Trail and South Horn Mountains this subsection (figures 2) is located in the center of the study area and almost exclusively in the Manti-LaSal National Forest. Altitudes here are generally above 10,000 feet, making it the wettest and coldest portion of the study area. Precipitation, much of it in the form of snow, is usually greater than 30 inches annually (Jeppson and others, 1968). The long winters with their large diurnal fluctuations in temperature make frost wedging an important geomorphic process.

Most of this area is flat lying and is underlain primarily by Flagstaff Limestone; however, faulting has exposed the North Horn Formation in isolated patches. Generally, this subsection is stable.

A combination of past and present geomorphic and tectonic processes has formed narrow north-south trending bands of instability on both sides of the Skyline Drive (figure 2). Initially, slopes in these bands were over steepened either by glacial headcutting (figure 4-b) or by faulting. The slopes remain wet throughout most of the year because of the large drainage area above them and the large snow packs that accumulate on them each winter. Within these areas, instability is in the form of small-scale debris flows and blockslides.

The border between the High Plateaus and the adjacent Rolling Basinlands is also unstable. Here, undercutting of the North Horn Formation beneath the nearly vertical cliffs of Flagstaff Limestone has led to blocksliding and, in some areas, to large scale complex landslide blocks and debris-flows. Some large fossil landslips are located in this border region. The occurrence of large slides along the border of this subsection is the result primarily of the difference in climate in the two subsections, although plasticity of the shales may also be involved.

The Ridge and Valley Subsection

This area, located in the northern end of the study area (figure 2), is characterized by long, steep slopes with narrow summit areas and V-shaped valleys (figure 4-c). Topography here does not reflect geology. The subsection has fairly sharp boundaries with the High Plateaus and Lakes Subsections to the south and has gradational boundaries with the Monocline Subsection near Milburn and with the Eastern Clifflands Subsection around the Star Point area. Elevations here range from 6,000 to 9,000 feet. The topography is rounded. Precipitation averages 20 to 25 inches annually (Jeppson and others, 1968).

Structurally, this area is quite complex due to numerous faults and to its location at the junction of the Soldier

Monocline which dips to the north and the Wasatch Monocline which dips to the west. The entire area has been dissected in a dendritic drainage pattern; there are small flood plains along parts of the stream valleys.

The Castlegate Sandstone is not a cliff-former here as it is in other parts of the Wasatch Plateau. The Castlegate and Black Hawk Formations are both fairly sandy; the sand helps to increase drainage and to inhibit slipping of the plastic clays. To the east the Price River Formation as well as the underlying Castlegate and Black Hawk Formations are composed of pebble-sized material set in a clay matrix. To the northwest, around the area of Smith's Reservoir and westward, the Castlegate is composed of cobbles set in a sandy matrix and forms cliffs and slopes that are subject to severe gullying and fluvial erosion, but are not subject to landslides.

The North Horn Formation and Flagstaff Limestone behave as they do to the south. The Green River Formation is the most unstable and contains the only active slide in this section.

In the area of Little Clear Creek, north of Indianola, a jumble of Cretaceous and Jurassic sedimentary rocks appears to be similar in texture and stability to the Black Hawk and Castlegate Formations. Also in this area are Tertiary extrusive igneous rocks that appear to be rapidly weathering to form clays.

The Eastern Clifflands Subsection

The steep topography and the alternation of sandstone and shale formations make this subsection extremely prone to block sliding, especially when the toes of slopes are cut away (figure 4-d). This subsection includes the 2,000 foot cliffs facing Castle Valley and Ferron, Straight and Huntington Canyons that extend westward into the Plateau. Massive sandstone formations (Star Point and Castlegate) overlie shale formations (Masuk and Black Hawk). Erosion of the less resistant shale undercuts the sandstone layers, resulting in movement of the sandstone blocks by planar block glides. This type of movement is distinct from the earth flowage found in the adjacent Rolling Basinlands Subsection.

Monocline Subsection

This subsection is a westward sloping upland surface that has been cut by steep sided canyons. It is underlain by the North Horn and Flagstaff Formations that dip to the west. The broad interfluves are relatively stable while the steep canyon slopes are unstable (figure 4-e).

This subsection is located along the western border of the Manti-LaSal and Fishlake National Forests and extends from the southern end of the study area to Milburn (figure 2). Its eastern boundary is gradational with the High Plateaus Subsection. Elevations range from 10,000 feet near the top of the plateau to about 6,000 feet in Sanpete Valley. In general, the average annual rainfall increases with elevation, from about 15 inches in the valley to 30 inches near the crest of the plateau (Jeppson and others, 1968).

There are two quite different types and ages of topography in the Monocline Subsection. The older surface, represented by the uplands, is without great local relief and follows bedding except where it is interrupted by stoss slopes. Streams and glaciers have cut into the older surface of the Monocline and developed steep canyons between remnants of the older surface. The two types of topography present two types of instability problems in the area.

Unlike the other physiographic subsections of the Wasatch Plateau, where the formations are nearly flat lying, here the bedding dips as much as 20 degrees to the west. The Flagstaff Limestone and North Horn Formation each covers about half the area; the Colton and Green River Formations are exposed near the southern end. There are local deposits of glacial till in the stream valleys.

On the flat interfluves, slopes are fairly stable, especially where underlain by the Flagstaff Formation. However, most of the beds within the Flagstaff have shaly partings which can act as slip planes, enabling an entire bed to glide downhill where slope cutting takes place.

Glaciation of Twelve Mile and Six Mile Canyons accounts for their oversteepened slopes and the relatively flat floors mantled with till and slump debris. The till deposits are fairly stable except near the edge of steep fronts and in stream gullies. In contrast, the steep canyon sides are generally unstable. Abundant moisture, high slope angles, dip slopes, and the lithologic characteristics of the North Horn Formation all contribute to this instability.

Rolling Basinlands Subsection

Because this subsection is located on the sides of hills and is underlain by extensive areas of the North Horn Formation and by older landslides, it has the greatest slumping potential in the study area. The currently active slides in Bulger, Seely, and Ferron Canyons indicate that human activity is not necessary to cause mass movement (figure 4-f).

This subsection extends from, and is best developed at, the southern end of the Wasatch Plateau, where along Interstate Highway 70 it occupies the entire width of the Fishlake Forest. To the north it is bounded on the west by the High Plateaus Subsection and on the east by the Eastern Clifflands Subsection. Still further north, in the area of Joes Valley, the subsection is a graben bounded both to the east and west by plateau surfaces. In the drainages of Ferron and Muddy Creeks, this subsection forms the gently rolling shoulders between the canyons of the Eastern Clifflands and the flat surfaces of the High Plateaus. Elevations range from 6,000 feet to slightly above 9,000 feet. In general, the precipitation is between 20 to 30 inches annually (Jeppson and others, 1968).

The rolling nature of this subsection is a direct consequence of the underlying, easily eroded North Horn Formation shales and the presence of numerous fossil landslides, most of which are composed of North Horn material.

It is the most unstable subsection in the study area. Several areas such as the White Slides, Slide Lake, and the Clay Banks are presently active or have been active recently. Much of the land is subject to severe gullying. These areas are underlain by either the North Horn Formation or by fossil landslides composed of North Horn material. The gullying poses the immediate problem of excessive sedimentation in downstream reaches, and makes possible the reactivation of fossil landslides by undercutting the toes of these slides.

Minor, fairly stable portions of this subsection are underlain by the Flagstaff Limestone and Price River Formations.

The numerous fossil slides on the south-facing slopes and the active slides on the north-facing slopes suggest that many of the landforms in this subsection are near the instability threshold. The wetter microclimate on the north-facing slopes may explain the location of the active slides, and any removal of vegetation or ponding of water might lead to further instability. In addition, cutting of the toes of fossil slides by numerous gullies takes on added signifiance.

CAUSES OF SOME OF THE LANDSLIPS ON THE WASATCH PLATEAU

Natural landslips are found in Seeley Canyon, west of Joes Valley, and in Bulger Canyon, just north of Joes Valley, both in the Rolling Basinlands Subsection. Near their mouths, both can-

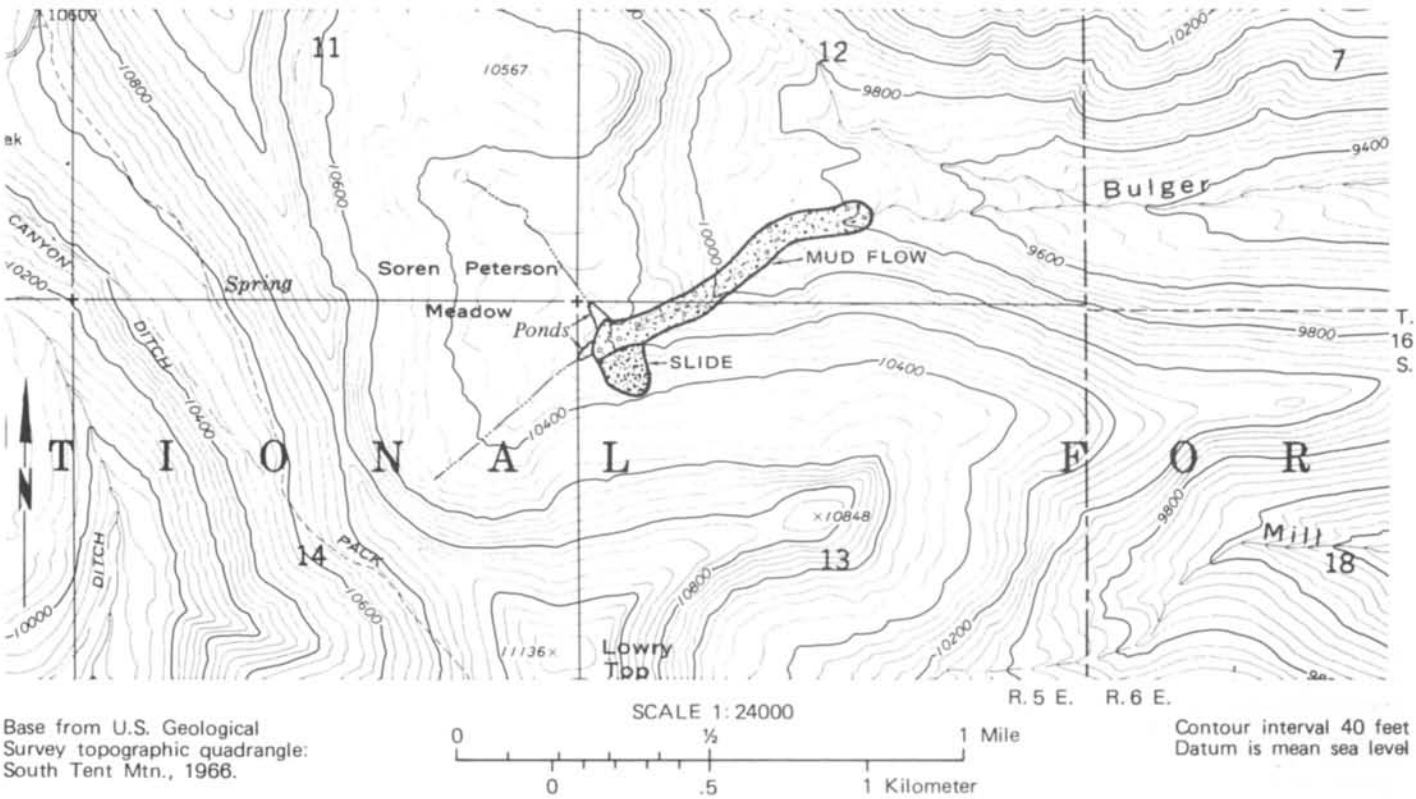


Figure 5. Map of the Bulger Canyon Slide and Mudflow

yons are underlain by the Black Hawk, Castlegate, and Price River Formations and appear to be stable at this time. However, removal of the vegetative cover could lead to gullying of the Price River Formation and thence to slumping.

Throughout most of their length, however, these canyons are cut into the North Horn Formation. As a result of the sinking of the graben which forms Joes Valley, the stream gradients and side slopes of both canyons have been over-steepened, leading to varying degrees of instability. The south-facing slopes are covered with aspen and are hummocky, indicating that they are sites of fossil landslides. These slides comprise several thousand cubic yards of material. Soil and vegetative disturbances, such as clear-cut logging, which could lead to increased run off (Bailey, 1971, p. 216-22), could result in gullying and ravelling of the slopes. An increased load on the heads of these slopes or undercutting of their toes could reactivate the landslides. In Bulger Canyon, slides have produced benches just above the stream gullies that appear stable at present, but the slides could be reactivated by the mechanisms listed above.

The north-facing slopes are generally straight and covered with mature stands of spruce and fir, giving an appearance of stability. However, the slide in Bulger Canyon (figures 5, 6) is in an area that appeared on aerial photos, taken before the landslide occurred, to be stable. Undercutting of the toe of the north-facing slope by rapid stream downcutting, and water saturation of the bedrock and overlying colluvial material led to slumping of the slope. In contrast, the area in which the Seely Canyon slide occurred appears to be one of repeated slide activity in the past, as evidenced by older (1957) aerial photos. Here, the sliding has been caused by the down-cutting of Seely Creek, plus the removal of material by an unnamed tributary.

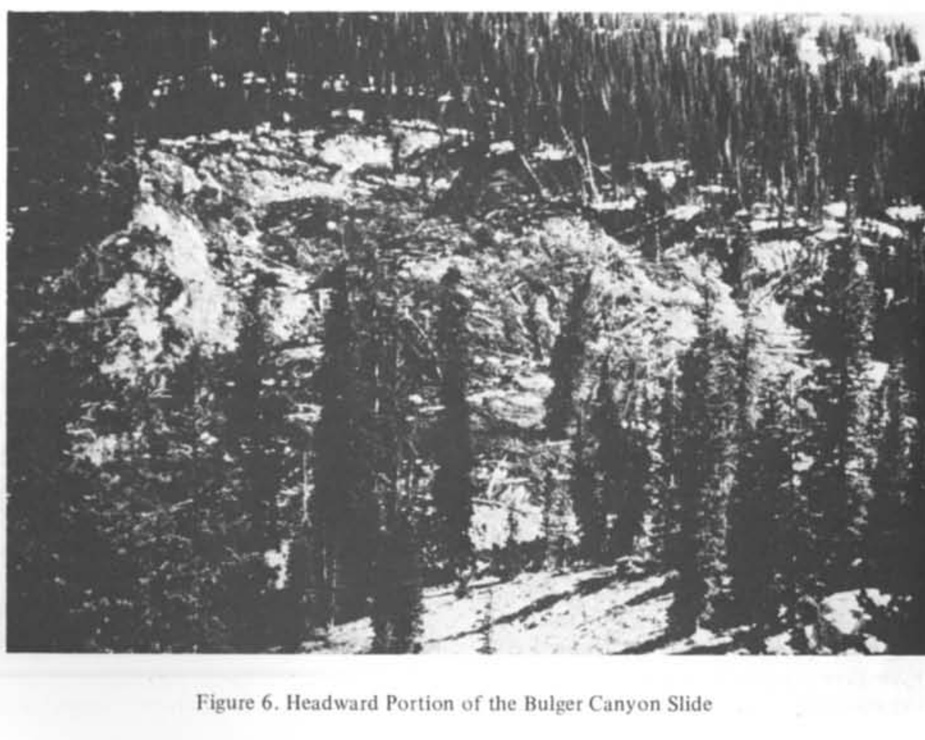


Figure 6. Headward Portion of the Bulger Canyon Slide

Several factors have combined to produce the slumping in these canyons: First, these canyons are at altitudes between 7,000 and 9,000 feet, where the average annual precipitation is greater than 20 inches and a considerable snow pack is available to release moisture into the soil. The soils of the north-facing slopes receive little sunlight to dry them out.

Second, throughout most of their length they are underlain by the North Horn Formation with an interbedded sequence of betonitic (?) shales and sandstones. The sandstone beds provide aquifers for water to enter the shale beds.

Third, because of the geologically recent tectonic uplift of the entire Wasatch Plateau and the down-dropping of the Joes Valley graben, the streams have cut steep-sided canyons and presently are undercutting the slopes.

Fourth, the area immediately to the west is seismically active, so that there are periodic shock waves to trigger slumping.

In these slides slumping begins at the base of the slope creating a slump block 10 to 30 feet wide and about 100 yards long. The downward movement of the block removes support from the slope above and subjects that portion of the slope to tension stresses. In the Seely Creek slide, tension cracks were observed all the way up the slope from the area of active sliding to the base of the cliff. These tension cracks may remain open for years and provide additional avenues for water to infiltrate and to lubricate the sole of the slide. Once slumping starts it tends to proceed intermittently over a period of years.

The slumping of these slopes also provides thousands of cubic yards of material to be carried by streams into Joes Valley Reservoir. The sudden influx of this material into the channel can cause mudflows. The mudflow in Bulger Canyon (figure 5) was 3/4 mile long on July 2, 1971 and was still active days later. The absence of vegetation on the slump and the flowing of water primarily through rather than over the mudflow, results in a maximum of sediment being transported by the stream.

A second cause of landslip activity is the formation of lakes and ponds in the sag areas behind back rotational slump blocks. Several of these sag ponds have been enlarged for use as reservoirs such as Grassy Flat Reservoir and at Slide Lake above Swasey Creek. The filling of Slide Lake has led to renewed movement of older landslide material. The ponds not only add weight to the head of the slide, but also provide water to increase the pore pressure of the groundwater within the slide.

A third cause of landslips is undercutting. In the border region between the Rolling Basinlands and High Plateaus. Subsections, Flagstaff Limestone cliffs are continually being undermined by the more rapid erosion of the underlying North Horn Formation. Ground water entering through the joints in the Flagstaff Limestone contributes to block falls, block slides, debris flows, and rotational slumping.

STABILITY CLASSIFICATION

This study is primarily concerned with delineating areas susceptible to landslips and, in a very rough way, with indicating the possible size of the expected slumps. Since the possible causes of landslips include a variety of historic, geologic, and meteorologic factors, prediction of their timing and magnitude will be problematic at best.

With this in mind, the following classification scheme was devised. Four classes of stability ranging from highly unstable (Zone I) to stable (Zone 4) are distinguished on the basis of presence or absence of fossil slides, bedrock formation and dip of beds, angle and height of slopê, aspect, and climate (amount of precipitation).

Table I shows the basic classification scheme and the interpretation of the probable stability hazard of each zone. The table also indicates, for each zone, the conditions, natural and man-made, that could cause landslips to occur. This does not imply that when such conditions exist, landslips will inevitably occur; it only means that the conditions listed are the minimum which could trigger slope failure.

Table I. Stability Zones

Zone 1: Unstable

Areas that are actively sliding or moving today, plus other areas in the physiographic subsection that have the same bedrock formation, climate, slope, and aspect. These are the most unstable areas and may begin to move without the impetus of human activity. For example, based on the presence of several active landslips on the steep north-facing slopes of canyons leading west from Joes Valley, every steep north-facing slope having a similar rock type and amount of precipitation in the Rolling Basinlands Subsection was classified Zone I (unstable of its own accord)

Zone 2: Relatively Unstable

Areas of dormant or fossil landslides. Areas underlain by the same geologic formations as areas of Zone 1, but with either gentler slope, more southerly aspect or a drier climate; or areas with deep gullies in which streams are cutting away the toes of slopes that may lead to landslides. Human activity could increase the probability of landslips in this zone.

Zone 3: Relatively Stable

Areas of fluvially-dissected slopes underlain by the more stable formations of the region; however, where there are local areas of high slope angles and local gullying, small slumps and local sloughing might occur. These areas are relatively stable, but excessive human activity could produce slope failure.

Zone 4:

Flat-lying areas underlain by stable formations. No stability problems are anticipated in these areas.

Table 2 shows the criteria that are used to delineate the four stability

Table 2. Criteria for delineating stability zones

Zone	Defining Features	Type of movement or interpretive character
	LAKES SUBSECTION	
1	Not present	-----
2	Slopes over 40%; about 30 inches annual precipitation; North Horn and Price River Formations present, all aspects.	Debris flows
3	Slopes under 40%; mostly less than 20%; North Horn and Price River Formations and morainal and outwash material; all aspects.	Mostly small scale debris flow some small block slide.
4	Valley bottoms, generally less than 10% slope	Since material is in valley bottom there is little instability except small scale stream bank sloughing

(continued)

Table 2 (continued)

Zone	Defining Features	Type of movement or interpretive character
	HIGH-PLATEAUS SUBSECTION	
1	Short slopes over 40%; precipitation over 30 inches and may reach 40 inches; Flagstaff limestone, east and west facing slopes.	Generally small scale debris flows occurring on short slopes oversteepened by faulting or glacial scour, also some small block slides
2	Slopes of 20 to 40% that flatten near base; precipitation 20 to 30 inches; underlain by North Horn Formation; all aspects.	Mudflows mainly; however, blocks of overlying Flagstaff Limestone may ride on top of the North Horn.
3	Slopes under 6% underlain by North Horn Formation.	Mudflows
	Slopes under 20%, mostly above 6% underlain by Flagstaff Limestone.	Debris flows
	Precipitation 30 to 40 inches; slopes have all aspects.	Some debris falls from cliffs of Flagstaff Limestone
4	Slopes generally less than 6%, underlain by Flagstaff Limestone	Low probability of landslips
	RIDGE AND VALLEY SUBSECTION	
1	Slopes over 40% underlain by North Horn, Black Hawk, and Green River Formations; north and northeast aspect; Precipitation 20 to 25 inches.	Mudflows and debris flows; landslips are generally small scale.
2	Slopes mostly over 40% underlain by the Black Hawk, Price River, Castle Gate, North Horn, Flagstaff and Green River Formations. Slopes have all aspects. Precipitation 20 to 25 inches.	Mostly small scale debris flows and mudflows, but some debris slides.
3	Slopes mostly under 20% underlain by the Black Hawk, Price River, Castle Gate, North Horn, Flagstaff, and small areas of Green River Formations. Slopes have all aspects. Precipitation is 20 to 25 inches.	These slopes are generally stable but extensive cutting could produce landslips.
4	Gentle slopes mainly under 6% that form the narrow ridge crests and stream valleys underlain mainly by Black Hawk, North Horn, and Flagstaff Formations. Slopes have all aspects. Precipitation is 20 to 25 inches.	Low probability of landslips. Some streambank sloughing.
	EASTERN CLIFFLANDS SUBSECTION	
1	Not present	-----
2	Slopes mostly over 40%, some vertical, underlain by the Mancos, Star Point, Black Hawk, and Castlegate Formations. Precipitation generally less than 20 inches. Aspect is mostly to the east, but some north and south facing slopes are present.	Block falls and planar block glides.
3	Not present	-----
4	Small mesa caps with slopes under 6% underlain by Castle Gate Sandstone; precipitation under 20 inches.	Low probability of landslips

(continued)

zones in each of the six physiographic subsections.

In describing the type of movement the classification scheme of Shroder (1971, p. 2) is used. The precipitation data are from Jeppson and others (1968) Hydrologic Atlas of Utah.

The criteria used in this study to define the stability zones are consistant with the conclusions of Shroder. Shroder (1971, figure 5, table 7) found that north facing slopes are more unstable than slopes with other aspects; most of the active landslips in the present study are found on north facing slopes. Shroder, (1971, p. 14) also found that many landslips in the High Plateaus section of the Colorado Plateau are associated with the North Horn Formation, which also agrees with the findings of this study.

Figure 7 shows an example of one of the maps produced using the criteria listed in Tables 1 and 2. Similar 7 1/2 and 15 minute quadrangles were made for the whole study area and then reduced to a 1/2 inch to the mile planimetric base for use by the Forest Service. Since it is impossible to reproduce here all the maps that are necessary to cover the entire project area, a selected one only is shown as an illustration. A full set is available at the Forest Supervisor's office, Manti-LaSal National Forest, Price, Utah.

SUMMARY AND CONCLUSIONS

To delineate mass land movement hazards in the Wasatch Plateau of central Utah, the area was divided into physiographic subsections, each having a basically uniform topographic expression suggesting similar land management problems. Each subsection was examined for evidence of and locations of areas of instability, and for the criteria controlling the instability. Based on these data, which include presence of active or fossil landslides, lithologic character of the underlying bedrock, amount of precipitation, and steepness and aspect of slopes, four stability zones are defined and mapped. Zone one, most unstable, is present in all but one of the subsections; areas of greatest hazard are shown to have slopes greater than 40%; to be north facing; to be underlain by the North Horn Formation, and to have annual rainfall of greater than 30 inches.

ACKNOWLEDGMENTS

The Intermountain Region, U. S. Forest Service, financed the field work while Devon Nelson, John Strang, and Jim Butler, of the Forest Service, gave encouragement and assisted in the

Table 2 (*continued*)

Zone	Distinguishing Features	Type of movement or interpretive character
	MONOCLINE SUBSECTION	
1	Steep canyon side slopes ranging up to 60%, but may be flat on benches that are underlain by the North Horn Formation. They have both north and south aspect.	Large scale complex landslide blocks and mudflows.
	West facing dip slopes underlain by the Flagstaff Limestone. Slopes commonly over 50%; precipitation ranges from 16 to 30 inches.	Block falls and debris flows.
2	West facing dip slopes of 20 to 40% underlain by the North Horn Formation; 12 to 30 inches of precipitation.	Complex landslide blocks and mudflows.
	East facing scarp slopes and west facing slopes of over 20% where the slope is greater than the dip. Precipitation over 16 inches.	Block falls and debris flows
3	West facing dip slopes on the Flagstaff Limestone that slope 6 to 10%. Precipitation 16 to 30 inches.	Planer block glides
	West facing slopes of 30% where slope is greater than the dip. Underlain by Flagstaff Limestone.	Debris flow
	Morainal deposits in the valley bottoms, mostly under 10% slope and dip slopes of the Colton and Greenriver Formation where precipitation is less than 16 inches.	Debris flows and mudflows.
4	Alluvial deposits in lower portion of canyons; slopes under 6%; precipitation under 16 inches.	Some stream bank sloughing possible.
	ROLLING BASINLANDS SUBSECTION	
1	North facing gullied slopes of 10 to 60% underlain by the North Horn Formation; steep slopes of over 60% facing all directions underlain by the Flagstaff Limestone; in both cases precipitation is 20 to 30 inches.	Large scale complex landslide blocks and mudflows; rockfalls and rockslides.
2	South and east facing gullied slopes of 10 to 60% underlain by the North Horn Formation; steep, 60% + slopes that are east or west facing underlain by the Castle Gate and Price River Formations; precipitation is 20 to 30 inches.	Complex landslide blocks and mudflows; rockfalls and block slides.
3	Moraines and outwash derived from the North Horn Formation in Valley bottoms. Slopes mostly under 10% but some short steep slopes; slopes between 10 to 20% underlain by the Price River and Flagstaff Formations.	Small scale debris flows
4	Alluvial valley bottoms with slopes under 6%; gentle slopes mostly under 6% underlain by the Price River Formation.	Some stream bank sloughing; low probability of landslips.

preparation of the initial report. Elaine Moore, of Vanderbilt University, assisted by drafting the illustrations.

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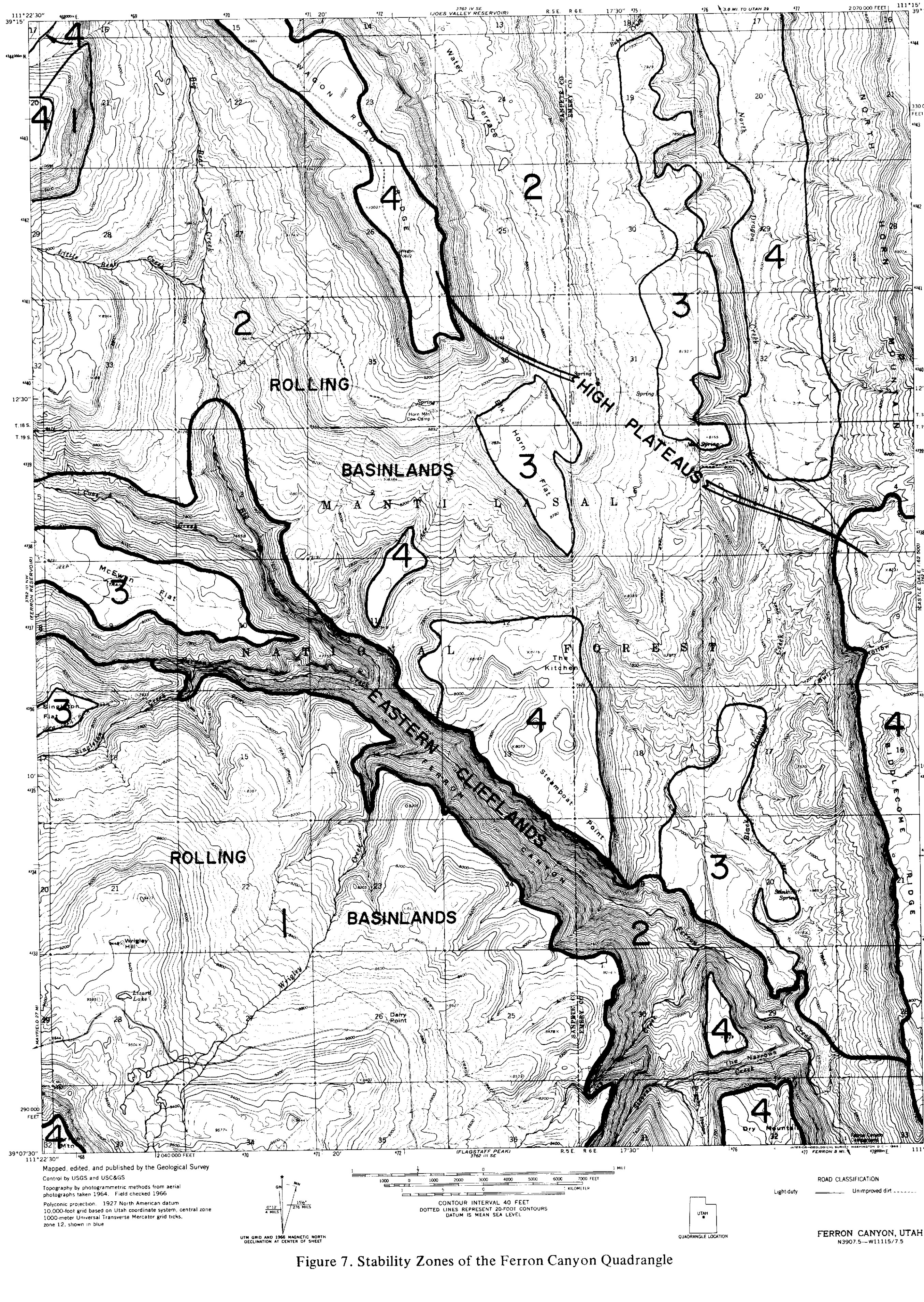

Figure 7. Stability Zones of the Ferron Canyon Quadrangle

Cottonwood Lake in the Wasatch Mountains. Photo by Timothy O'Sullivan.

STRATIGRAPHY AND ATTENUATION FAULTING IN THE NORTHERN HOUSE RANGE, UTAH

by Thomas C. Chidsey, Jr. [1]

ABSTRACT

The northern House Range of western Utah consists of a sequence of Lower to Upper Cambrian carbonates, shales and quartzites. Measured stratigraphic sections provide detailed descriptions of lithology, sedimentary structures, thicknesses and topographic expression of non-faulted formations present in the study area.

Three episodes of structural activity in the area created: (1) Cretaceous Sevier Orogenic southeasterly trending high-angle normal faults, north-south trending high-angle reverse faults, and attenuation faults; (2) Oligocene (?) dikes, diatremes, minor faults and fractures; and (3) Miocene to Recent Basin and Range block faults and gravity glide faults.

Attenuation faults, on several scales, cause thinning of both incompetent and competent formations. Lateral as well as vertical removal of beds occurs over very short distances throughout the area. Attenuation faults are found between high-angle normal faults (tear faults), as younger units slid over older units.

INTRODUCTION

In several parts of the Basin and Range Province certain older faults have been characterized as "younger on older thrusts" or attenuation faults. In 1974, Brigham Young University Field Camp geologic mapping outlined an area in the House Range where sections of the normal Cambrian stratigraphic succession were cut out by attenuation faulting (Hintze, L. F., oral commun., 1977). Reconnaissance in the area also showed several other types of Sevier and younger structures present. Formations ranging from Lower to Upper Cambrian age and various unconsolidated Quaternary deposits are found within the area.

The primary objectives of this paper are to (1) describe in detail the stratigraphy with measured sections of formations and (2) describe the occurrence, nature, and briefly consider the origin of the attenuation faults as well as the other structures in the area.

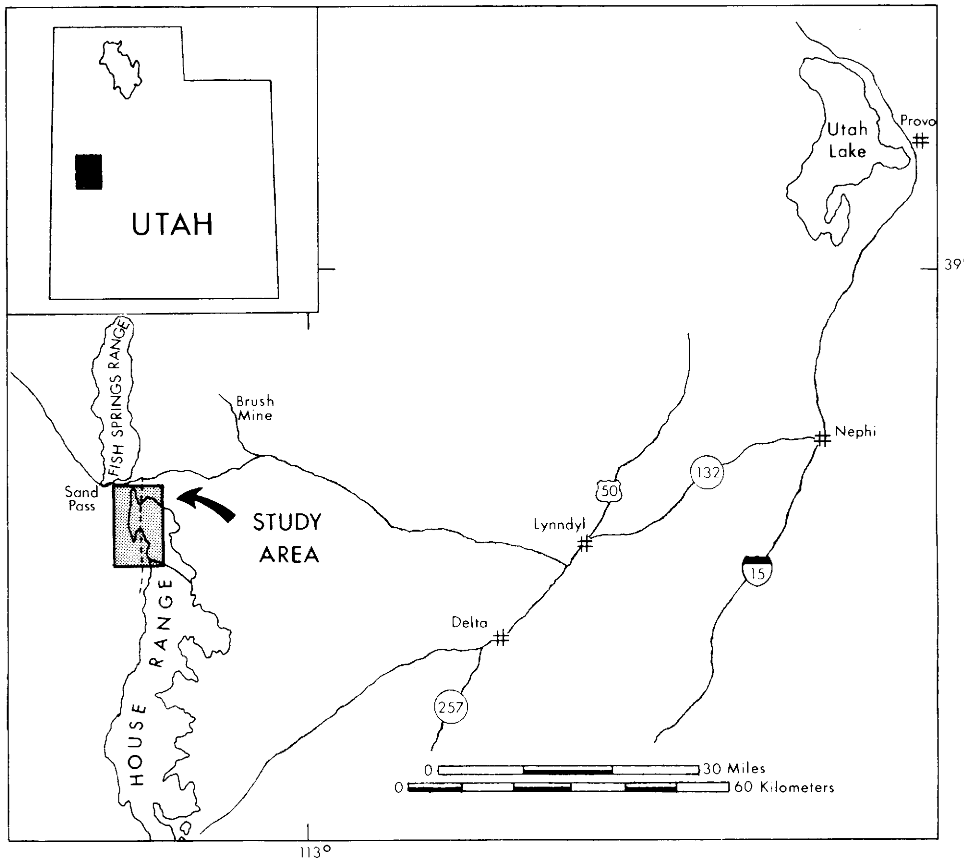

Figure 1. Index Map

Location

The study area is located on the north end of the House Range about 70 kilometers northwest of Delta, Utah (figure 1). Dirt roads provide access to within five kilometers of any part of the area.

Previous Work

The only previous work in the study area has been done by the Brigham Young University Geology Field Camp conducted by Dr. L. F. Hintze in 1974. The first descriptions of the House Range were made by Gilbert (1875). Davis (1905) investigated block faulting in the House Range, and Walcott (1908) first described the Cambrian stratigraphy. Subsequent stratigraphic work has recently been summarized by Hintze and Robison (1975).

Low angle faults of the eastern Great Basin were studied and mechanisms for their displacement were described by Hose and Danes (1973). Attenuation faults in the Fish Springs Range and House Range were briefly described by Hintze (1976).

Physiography

The northern House Range is a typical Basin and Range upthrown fault block and rises 1,358 meters above the western valley floor. The mapped area reaches a maximum altitude of 2,408 meters above sea level in the southern portion.

Several spectacular canyons are cut into the massive limestones and quartzites. Streams flowing west into White Valley have formed a bajada, with a playa lake in the valley center which is dry most of the year. Lake Bonneville terraces, bars and spits, first described by Gilbert in 1872, are beautifully displayed along the range front.

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The region is arid with sparse vegetation in the valley bottom, composed of sagebrush, greasewood, and scattered grasses. Juniper, scrub oak and pinyon pines are found at higher elevations.

Methods of Investigation

Geologic mapping (plate 1, in pocket in back of book) was completed with the use of enlarged aerial photographs on a scale of 1:14,000. Stratigraphic sections were measured for both description of formations and attenuation fault analysis, using a Jacob's staff and Brunton compass.

STRATIGRAPHY

General Statement

The northern House Range contains an exposed stratigraphic sequence of Lower Cambrian to Lower Upper Cambrian strata approximately 2,300 meters thick consisting of quartzites, limestones, shales and dolomite (figure 2). Quaternary deposits include Lake Bonneville terraces and bars, colluvium, alluvium, and fans.

Mapped units are distinct, easily identified, and follow the terminology of the Middle Cambrian used by Hintze and Robison (1975). The completeness of the formations varies, however, due to attenuation and high-angle faulting. Sections were measured where disturbance was minimal within the study area; sections of the Lamb Dolomite and Trippe Limestone were measured outside the mapped area because those within the area are badly faulted and fractured.

See Appendix for measured sections. The locations of these sections are shown on figure 3.

Cambrian System

Prospect Mountain Quartzite

The Prospect Mountain Quartzite is the oldest formation (Lower Cambrian, Hague, 1883) in the study area and is 670 meters thick. Its light brown beds form ridges and cliffs throughout the western area. Several faults displace the formation and small outliers can be found in the alluvium or near Lake Bonneville terraces. Cross-bedded, fine-grained, unfossiliferous, the formation is typical of the Prospect Mountain Quartzite described by Hintze and Robison (1975).

Pioche Formation

The Pioche Formation consists of two members, a lower member of Lower Cambrian and the Tatow Member of Middle Cambrian age. Outcrops are extensive throughout much of the study area and form a slope above the Prospect Mountain Quartzite.

The lower member is a thin- to thick-bedded, gray green, slightly cross-bedded quartzite interbedded with thin, micaceous and argillaceous green shale. The base of this slope forming unit is marked by an *Olenellus* Zone.

The Tatow Member consists of thin- to thick-bedded, fine and medium-grained calcareous sandstone interbedded with gray arenaceous limestone and lenses of gray green, micaceous and arenaceous shale. Clay nodules and stringers were common in the limestone but no fossils were found in the study area.

Howell Limestone

The Howell Limestone, is found throughout much of the study area and is divided into two members, the Millard Member and the unnamed upper member.

The Millard Member is 63 meters thick and forms a thick-bedded vertical cliff at the base of the Howell Limestone. Units are medium blue gray, fine to medium-grained and in some places contain thin lenses and nodules of clay. Meringue surface weathering produces a mottled appearance with patches of orange and brown.

The unnamed upper member of the Howell Limestone forms a series of light gray to medium gray cliffs each about 5 meters high separated by rubbly slopes 2 meters across. These fine-grained limestones commonly contain "bluebird structures", white blebs of calcite described by Merriam (1964, p. 37). No fossils have been found in the study area.

Chisholm Formation

In the study area the Chisholm Formation appears as a dark, slope-forming band above the Howell Limestone. It has three characteristic units. The lowest unit, 16 meters thick, consists of dark greenish gray thin-bedded limestone and shales. The middle unit, 45 meters thick, has distinct pisolites and oncolites with thin-bedded dark gray-limestones forming ledges and interbedded shales forming slopes. *Glossopleura* are common in the upper part of this middle unit as well as bluebird bodies. Fifteen meters of olive gray, thin-bedded shale and limestone with some oncolites make up the slope forming upper unit.

Dome Limestone

In the study area the Dome Lime-

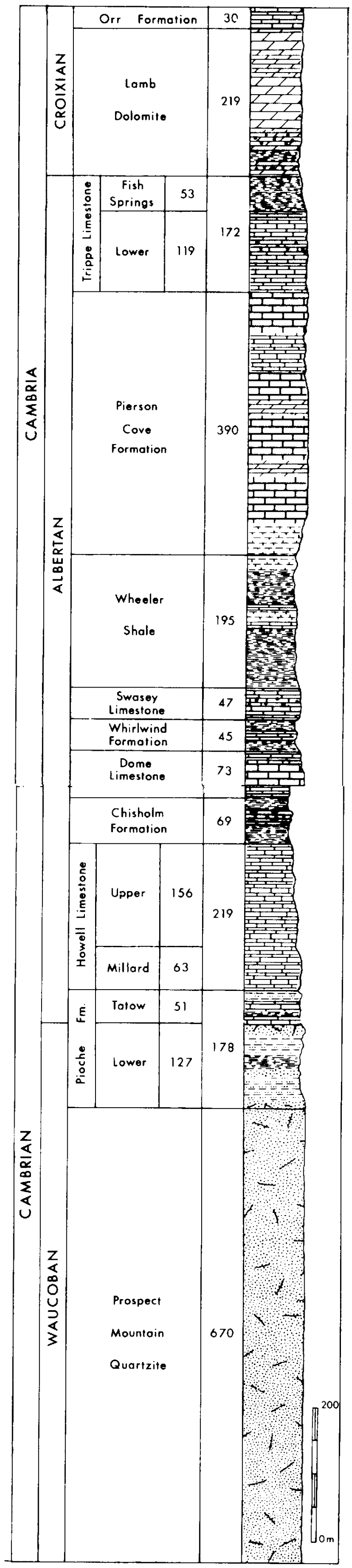

Figure 2. Generalized Stratigraphic Section

stone consists of three major units. Boundstone and dark gray, thin-bedded limestone beds are found at the base. The middle unit is a very homogeneous, massive, light gray limestone cliff with some silica blebs present. The uppermost unit is a slope and ledge forming light gray limestone with almost 25 percent calcite stringers and a rough meringue-weathered surface. Slopes are formed where somewhat argillaceous units occur.

Whirlwind Formation

The Whirlwind Formation is found throughout the southern portion of the area and is approximately 45 meters thick and forms a pronounced slope.

The Whirlwind is divided into three main units. The lower and upper units consist of medium gray, fine-grained, thin-bedded, argillaceous limestones interbedded with tan and greenish-gray calcareous shales. The middle unit consists of an arenaceous limestone ledge, 3 to 4 meters thick. This dull gray, thin-bedded unit is almost a trilobite coquina in which *Ehmania* predominates and *Ehmaniella* was noted.

Swasey Limestone

The Swasey Limestone consists of a lower thin-bedded, shaly limestone having a gradational contact with the underlying Whirlwind Formation. The remaining units are predominantly dark gray, fine-to medium-grained limestone that generally form a cliff. Bedding ranges from thin to thick, exhibiting some mottling and banding. Oolites and pisolites occur throughout most of the beds.

Wheeler Shale

The Wheeler Shale, famous for its trilobite specimens, forms a large steep slope the lower boundary of which is the most striking contact in the area.

The formation consists of fine-grained, dull black, calcareous, platy and fissile shale that contains numerous trilobite fossils. Thin-bedded argillaceous and arenaceous limestones are interlayered with the shale and form steep flaggy slopes. Both limestones and shales have been stained or weathered to various shades of yellow, red and brown by iron oxide leaching.

Pierson Cove Formation

The Pierson Cove Formation forms a striking vertical cliff above the Wheeler Shale and is easily traced on aerial photographs by its dark tone.

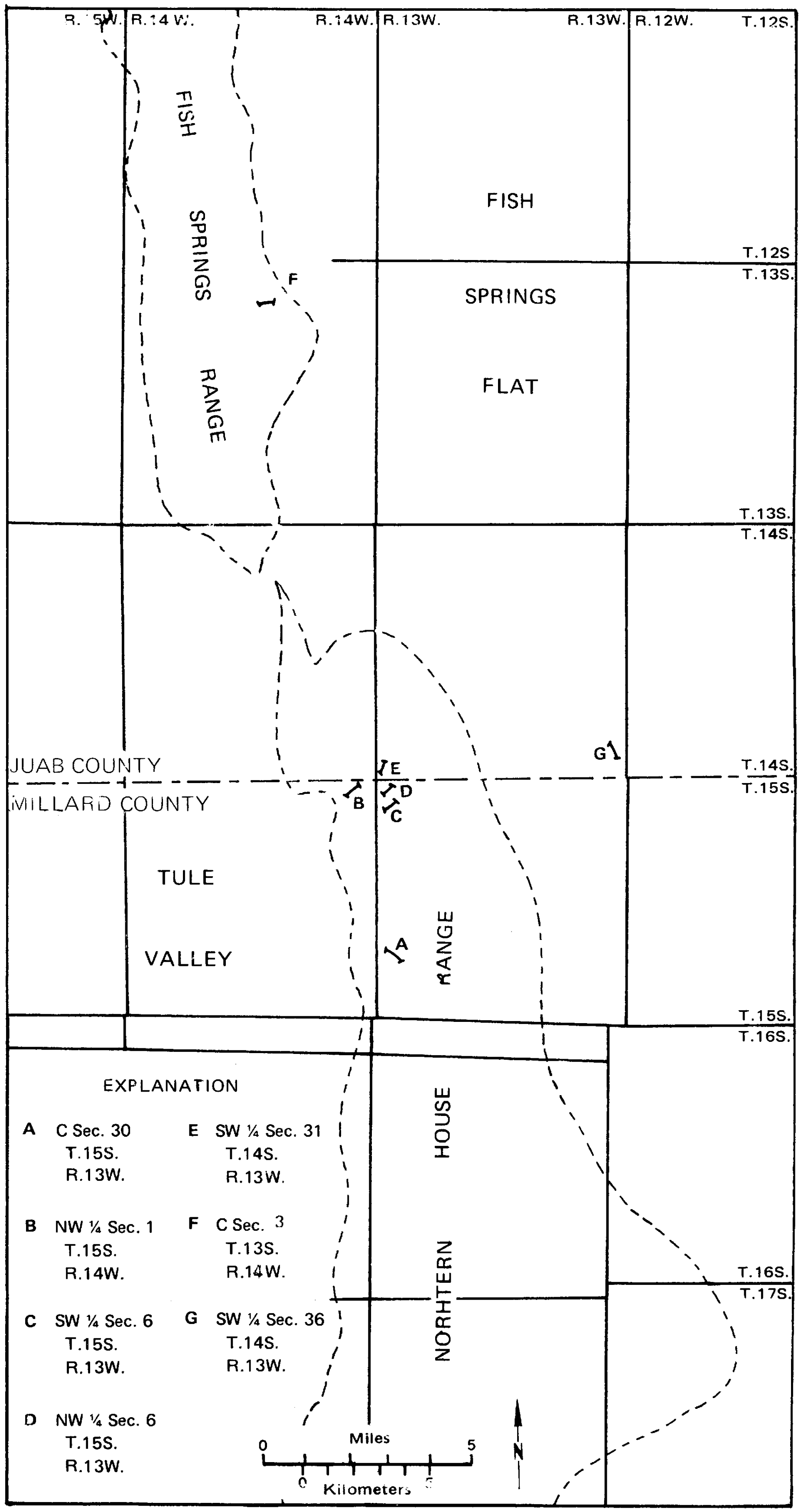

Figure 3. Locations of Stratigraphic Sections A through G

In the study area the Pierson Cove Formation can be divided into four distinct units. The lowest unit consists of red iron oxide-stained fissile shale and thin-bedded limestone, looking very much like the Wheeler Shale but with more limestone. The second unit of the Pierson Cove is a dark gray to medium gray limestone, with some dolomite, that forms the thick vertical cliff. The thin-bedded, finely crystalline limestone contains some flattened and irregular chert nodules and occasionally white calcite rods. The third unit is a ledge- and slope-forming, medium gray limestone about one-fourth the thickness of the vertical cliff. The fourth unit, dark to medium gray limestone, forms a massive bedded. vertical cliff at the top of the formation.

Trippe Limestone

The Trippe Limestone is divided into two members, the lower member and the Fish Springs Member. Fossils place its age in the uppermost Middle Cambrian (Hintze and Robison, 1975).

The lower member of the Trippe Limestone consists of a series of dark gray, mottled, limy mudstones and pale orange, laminated, dolomitic boundstones. The coarse-grained, limy mudstones, which contain some pisolites, form ledges and small vertical cliffs and the boundstones form small ledgy slopes. The boundary with the upper Fish Springs Member is drawn where these ledges are in contact with covered slope. Exposed only in the gullies, the Fish Springs Member is composed of olive-green shale interbedded with thin-bedded, medium gray limestone containing flat-pebble, interformational conglomerate in the lower section, and dark gray, thin-bedded limestone, silty or mottled, in the upper section.

Lamb Dolomite

Nolan (1930) proposed the name Lamb Dolomite for exposures in the Gold Hill mining district and Bick (1966) assigned it Late Cambrian age. This rather uniformly thick formation crops out only in the northeastern part of the study area, where it has been severely faulted and fractured.

The Lamb Dolomite consists of alternating light and dark gray dolomite beds of medium thickness, thinning upward in the section. The lowest unit is distinguished by abundant pisolites, some of which demonstrate dolomitic recrystallization. Grain sizes range from fine to medium, and beds form cliffs with dolomite talus covering the Fish Springs Member of the Trippe Limestone below.

Orr Formation (Big Horse Member)

The Orr Formation was originally proposed by Walcott (1908) and later subdivided into members. Only a few small outcrops are present, located in the northeast part of the study area. They consist of light medium gray limestones containing some small fossiliferous units. The color and character of the exposures is so similar to the underlying Lamb Dolomite that dilute hydrochloric acid is needed to differentiate the two.

Quaternary System

A variety of Quarternary deposits are found within the study area. Those mapped are discussed below.

Lake Bonneville Deposits

Extensive Lake Bonneville bar deposits composed of diatomaceous earth are found in the northern part of the area especially near Tatow Knob. Beach gravels are also common in the same area. Lake terraces composed of silts, well rounded cobbles and occassionally caliche conglomerate, can be seen on the west side of the range and to the south near Tatow Knob.

Alluvium

Thick deposits of alluvium fill the graben valleys and dry stream beds. Deposits consist of well rounded, unconsolidated stream and sheet wash gravel, sand, silt, and mud. In the northwest area, chunks of Lake Bonneville caliche conglomerate have also been incorporated into the alluvium.

Colluvium

Deposits of alluvium and colluvium were mapped separately because of the broken, angular nature of the colluvial material and its close proximity to outcrops. Sorting is poor due to lack of transport, and talus debris is a common constituent.

Alluvial Fans

Streams carrying material to the north and especially to the west deposit classic Basin and Range alluvial fans. Fans, particularly on the west, are several kilometers across and coalesce into bajadas in White Valley.

INTRUSIONS

A north-south trending series of small latite dikes was mapped in the northwest portion of the study area (figure 5, tectonic map). These dikes are commonly brecciated and have been altered by hydrothermal solution activity. Colors vary from light gray to very light gray on fresh surfaces and from light olive gray to brownish orange where weathered. Intrusions produce a skarn zone in surrounding shales and limestones. Quartzite xenoliths are common as well as somewhat resorbed pieces of the intrusion itself indicating two pulses of magmatic injection. Small slickensides observed toward the center of the dikes suggest post-intrusive fault movement. Nearly every dike is located on or close to a high-angle fault.

The age of the intrusions is probably Oligocene. An attempt was made to obtain sphene for fission-track dating, but there was none present due to alteration or lack of any to begin with. The petrography, however, is very similar to the quartz latites on the west side of the Keg Mountains described by Shawe (1972) and assigned an age of 30.8 m.y. by Lindsey and others (1975).

STRUCTURAL GEOLOGY

General Statement

The structural history of the study area can be divided into three main periods of activity. Those structures reflecting tectonic forces of the Cretaceous Sevier Orogeny include southeasterly trending high-angle normal, high-angle reverse, and attenuation or low angle faults (Hintze, 1976). Structures resulting from a possible Oligocene (?) intrusion include numerous fractures, minor high-angle normal faults, and diatremes. Finally, structures involving Miocene to Recent crustal extension (Stewart, 1971) include glide faults (Armstrong, 1972) and Basin and Range block faulting.

Sevier Orogenic Structures

East-West High-Angle Normal Faults

The mapped area is divided along its south border from the rest of the House Range by a major southeasterly trending high-angle normal fault with more than 600 meters of vertical stratigraphic separation, juxtaposing Prospect Mountain Quartzite against Swasey Limestone (Plate 1, geologic map and figure 5. tectonic map). This fault separates the

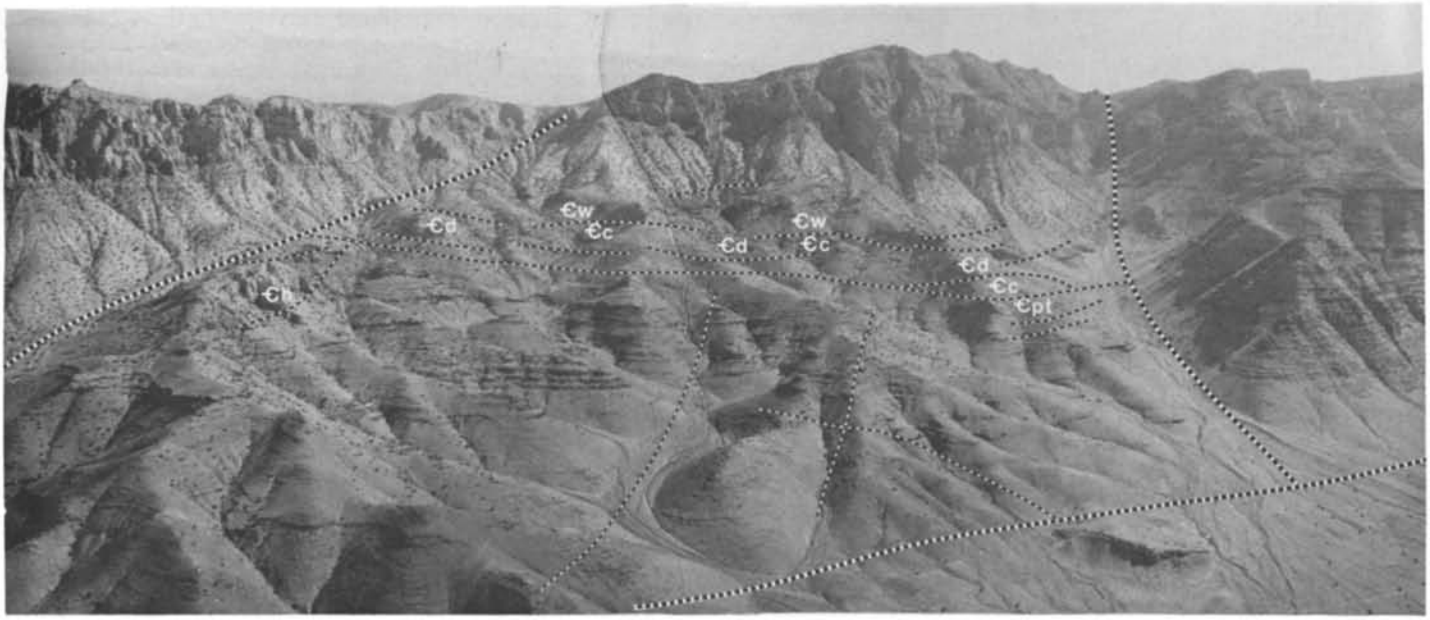

Figure 4. Oblique view of west front of range, showing several formations cut out by attenuation faults. For explanation of symbols see Plate 1.

more complex geology of the study area from the simpler area south of the fault.

Most other east-west high-angle normal faults in the study area show vertical stratigraphic separations ranging from less than 15 meters to 600 meters with the majority less than 60 meters (Figure 5, tectonic map). All trend slightly toward the southeast, and some zones of hydrothermal alteration occur along their fault lines, spreading into surrounding country rock (see N.E. 1/4 Section 12 on tectonic map, figure 5).

The high-angle normal faults appear to be the oldest of the faults in the area. Thye are cut by high-angle reverse faults and Basin and Range normal faults. No strike-slip component along these faults could be determined from the field exposures within the study area, but relationships in other areas suggest these may be tear faults.

Attenuation Faulting

Attenuation faults are common in the southeast portion of the mapped area (geologic map, plate 1 and tectonic map, figure 5). Both massive and thin bedded formations have been affected.

One of the most striking aspects of attenuation faults is that they can cut out entire formations or significant stratigraphic sequences laterally over very short distances. Figure 4 shows an oblique aerial view of the attenuation faulting in the southern mapped area. The view is to the east. The north-south striking units in the photograph consist of Prospect Mountain Quartzite through the Pierson Cove Formation in the normal stratigraphic sequence. In this area the section is disturbed by not one, but a succession of overlying attenuation faults. Seven sections were measured, beginning left of the large canyon on the right side of the photograph and continuing north of the photograph (figure 6), to demonstrate quantitatively the stratigraphic thinning due to attenuation (see table 1). Though the area is also complicated by normal faulting, the effects of attenuation are unmistakable.

In attenuated section 1 (table 1), the Tatow Member of the Pioche Formation has been thinned in both its lower and upper units by 8 meters (see table 1 and figure 2 for normal measured sections). Even more significant is that the Chisholm Formation rests on the Tatow Member of the Pioche Formation. The entire Howell Formation (both Millard and upper members) of over 120 meters in thickness is missing. This formation of medium- to thick-bedded limestone can hardly be considered incompetent.The Chisholm Formation itself has been attenuated by 11 meters and is highly brecciated. Above the Chisholm, the Dome Limestone has also been attenuated by a total of 7 meters in its lower and upper members. The Whirlwind Formation appears fairly complete; above it attenuation faulting has thinned the Swasey Limestone by 8 meters and removed some of the Wheeler Shale.

Five-hundred meters to the north (figure 4), the Pioche Formation is missing due to normal faulting, but some of the Howell Limestone is present (though it is brecciated rubble and also cut by a normal fault). The Chisholm Formation is continuous across the entire photo (figure 4) even though it has been attenuated between 10 to 20 meters. However, the Chisholm Formation is in contact with the Whirlwind Formation in several places (See plate 1, geologic map). Thus, the very massive, competent Dome Limestone is completely missing, then completely present, in and out over very short distances (200 to 700 meters). The Whirlwind Formation is fairly complete across the photograph (figure 4), and the Swasey Limestone and Wheeler Shale vary in amounts of 30 to 50 meters of attenuation. In the left part of figure 4, the Howell Limestone is present, though it is attenuated.

In the N.E. 1/4 of Section 12 (see figure 6, table 1, and figure 5, tectonic map), the Tatow Member of the Pioche Formation, the Howell Limestone (both Millard and upper members) and the Whirlwind Formation are present, though attenuated. The Chisholm Formation and the Dome Limestone, a combined thickness of over 140 meters, have been totally removed. The Swasey Limestone and the Wheeler Shale sections are nearly complete.

To the northeast, in the N. 1/2 of Section 7 and all of Section 6, the Dome Limestone and the Wheeler Shale are significantly attenuated. In Sections 1 and 36 parts of upper Howell Limestone, Whirlwind Formation and Swasey Limestone are largely attenuated. Finally, in the northwest portion of the mapped area (see S. 1/2 Section 23), the Chisholm Formation has been somewhat attenuated.

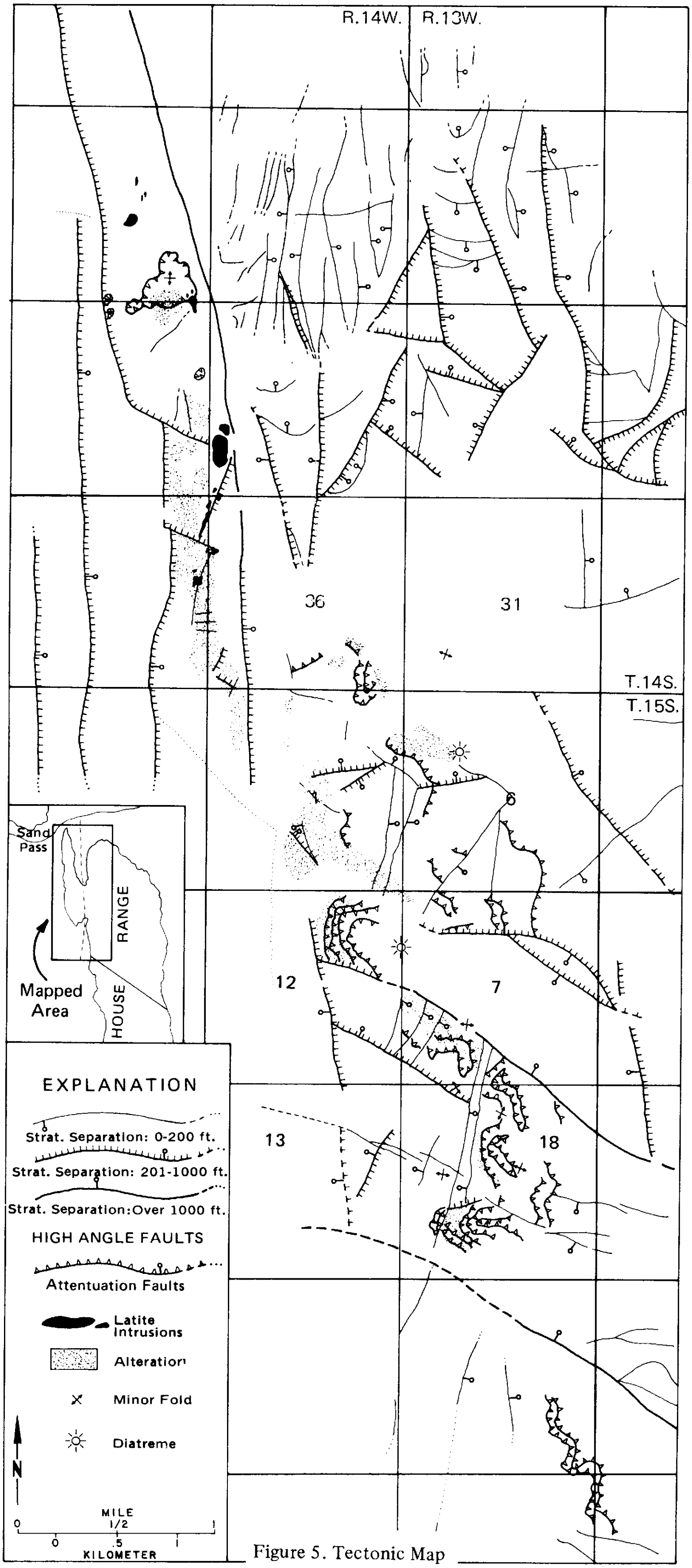

Figure 5. Tectonic Map

Small asymmetrical folds were commonly found in every attenuated area (figure 4). These minor folds are possibly drag folds. There are not enough of these structures present to make a statistical analysis.

Extreme brecciation may make bedding planes unrecognizable. Typically, entire units may consist of a mass of brecciated limestone, filled with calcite veins and easily crumbled when hammered.

A small scale attenuation fault was found in the upper Dome Limestone near attenuated section 4 (figure 7). This cross-sectional view shows, on the left of the photo, a breccia zone with an associated attenuation fault to the right. It is easy to see the units are attenuated out by the fault which then moves along a bedding plane.

On yet a smaller scale, a hand-size rock specimen, found on a rubble covered slope (probably Howell Limestone) near attenuated section 3, displays a brecciated zone followed by attenuation of small laminae (figure 8). In thin section (figure 9) the strained crystals indicate the compressional character of the forces involved.

In the southern part of the area (plate 1 and figure 5) a major southeasterly trending high-angle normal fault terminates attenuation faulting (except in the Howell Limestone farther south across some minor high-angle reverse faults of less than 100 meters displacement, the Howell Limestone is complete).

In other parts of the study area attenuation faults are found terminated or offset by southeasterly trending high-angle normal faults related to the Sevier Orogeny (see Section 12 and 13 on the tectonic map. figure 5) by northerly trending high-angle reverse faults. The attenuation faults are also cut by the Oligocene (?) quartz latite dikes.

Quite commonly, attenuated units are altered by younger silicification and ankeritic dolomitization which may make recognition of the unit difficult. The location of this alteration is shown on figure 5

In summary, attenuation faulting in the northern House Range generally has the following characteristics:

1. It has removed significant stratigraphic sequences or even one or more entire formations.

2. It may occur in either incompetent or competent rocks.

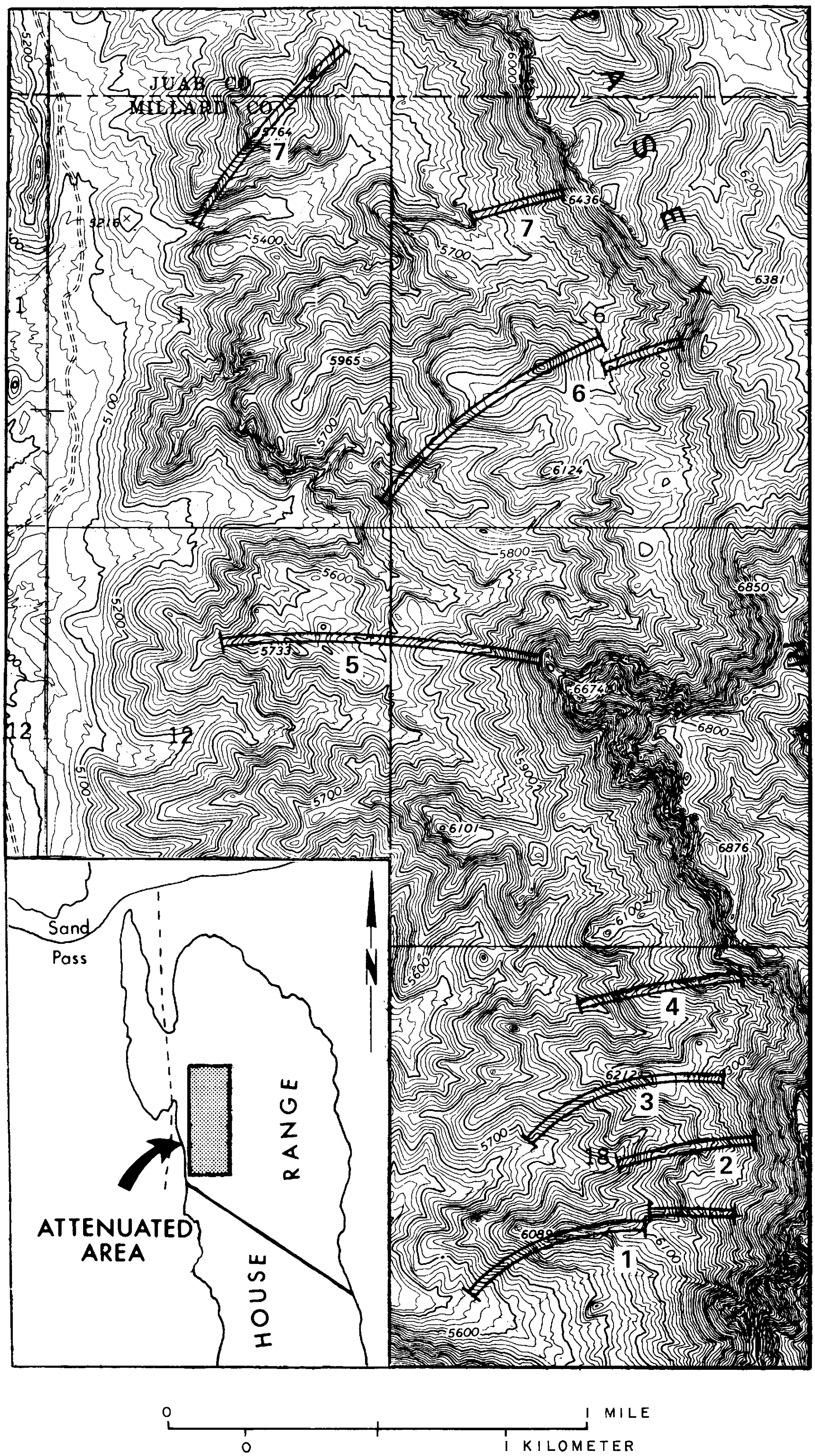

Figure 6. Locations of 7 measured attenuated sections

3. Attenuated formations may vary in thickness laterally over very short distances.

4. A vertical succession of partially or totally attenuated formations commonly occurs.

5. Small asymmetrical folds result from attenuation fault movement.

6. Rock units may be highly brecciated.

7. Attenuation faults occur on several orders of magnitude.

8. Attenuation faults are terminated by both Sevier high-angle normal and reverse faults

9. Attenuation faults are cut by Oligocene intrusions.

High-Angle Reverse Faults

High-angle reverse faults are especially common in the northwest portion of the mapped area. Stratigraphic separation ranges from 15 meters to over 600 meters. The reverse fault with the greatest stratigraphic separation occurs in E. 1/2 Sec. 26 and W. 1/2 Sec. 25 on the geologic map (Plate 1). Here, lowermost Middle Cambrian has been faulted against uppermost Middle Cambrian. Numerous other parallel north-south trending high-angle reverse faults along the western part of the mapped area cut the Prospect Mountain Quartzite and Pioche Formation. Similar faulting exists on the northern end of the Fish Springs Range (Oliveira, 1975).

These high-angle reverse faults cut both attenuation faults (see S. 1/2 Sec. 23 on geologic map) and the southeast trending high-angle normal faults, indicating they are younger and represent the last phase of the Sevier Orogeny.

Oligocene (?) Structures

Fractures and Minor High-Angle Faults

Numerous brecciated fractures, minor high-angle reverse. and normal faults occur in the Pierson Cove Formation, Trippe Limestone and Lamb Dolomite of the northeast mapped area. The breccia makes it extremely difficult to determine relative fault movement especially in the Lamb Dolomite. Large calcite veins of probable hydrothermal origin are also common. (Chidsey, BYU

Table 1. Measured sections in attenuated area.

Formation	Attenuated Section 1	2	3	4	5	6	7	Normal Section
Wheeler	126.0	164.4	157.5	O–N.F	183.6	150.6	195.0	198.2
Swasey	38.7	33.0	31.5	34.5	42.0	24.0	21.0	47.3
Whirlwind	31.5	36.6	27.9	40.5	33.0	36.0	27.0	45.7
Dome	66.0	O–A.F	36.0	34.5	O–A.F	58.5	72.0	82.3
Chisholm	58.5	49.5	40.5	36.0	O–A.F	66.0	69.0	54.9
Upper Howell	O–A.F	O–N.F	O–N.F	O–N.F	17.4	70.5	155.0	167.4
Millard Member of Howell	O–A.F	O–N.F	O–N.F	O–N.F	10.0	O–N.F	O–N.F	64.0
Tatow Member of Pioche	43.5	O–N.F	O–N.F	O–N.F	30.6	O–N.F	O–N.F	51.2

Note: Thickness measured in meters. O–N.F. = zero thickness due to normal faulting. O–A.F. = zero thickness due to attenuation faulting.

in press 1977).

The linear and occasionally radiating patterns of these faults and fractures and the presence of several diatremes reflect the possibility that a buried intrusion pushed upward and shattered the rocks (Chidsey, in press).

Structures of Miocene to Recent Age

Glide Faults

Glide faults, normal faults formed by the influence of gravity, occur only in the S W 1/4 of Section 24 and can easily be viewed from the road. Several slices of Lamb Dolomite have been displaced 10 to 30 meters toward the south along slightly concave fault planes.

The concave geometry and occurrence in a parallel series is an ideal example of inverse imbrication, the result of crustal extension and gravity (Armstrong, 1972). Although the exact age cannot be determined, it is assumed to be Late Tertiary because the entire Basin and Range was undergoing crustal extension at that time.

Basin and Range Block Faulting

North-south trending high–angle normal faults are common in the northeast section of the mapped area. Their stratigraphic separations range from 15 to 80 meters, and comprise about 15 percent of all the faults in the area (see figure 4 and plate 1). They are typically high-angle and cut across all earlier features. A major north-south range front block fault, the House Range Fault, is buried in the alluvium on the western side of the study area, separating the horst of the House Range from the graben of White Valley. These extensional structures are typical of the Basin and Range features described by Stewart (1971). Block faulting began in Miocene time and has continued up through the present as indicated by recent fault scarps on the eastern side of the Fish Springs Range (Lee Piekarski, oral communication, 1976).

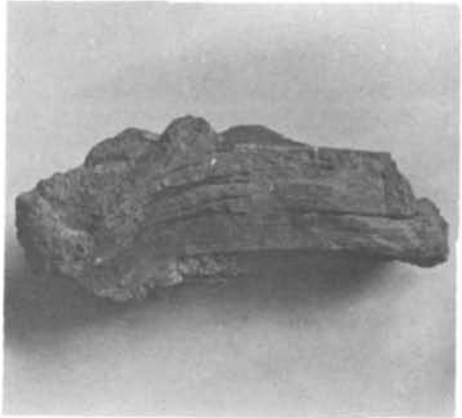

Figure 8. Small scale attenuation fault in hand specimen (20 cm long).

Figure 7. Attenuation fault showing brecciation and truncation of beds (arrow) in Dome Limestone.

Origin and age of Attenuation Faults

An attenuation fault (Hintze, 1976) is defined as a low-angle fault where younger rocks have been displaced on older rocks and a thinning of the normal stratigraphic succession has taken place, often cutting out entire formations or significant portions. These structures are found regionally throughout much of Nevada and western Utah (Hose and Danes, 1973; Hintze, 1976); however, terminology for their description varies. The northern House Range displays excellent examples of attenuation faults on several scales.

Three interpretations concerning origin of these attenuation faults have been summarized by Armstrong (1972). They are gravity gliding due to crustal extension during the Sevier Orogeny (Hose and Blake, 1969); regional decol-

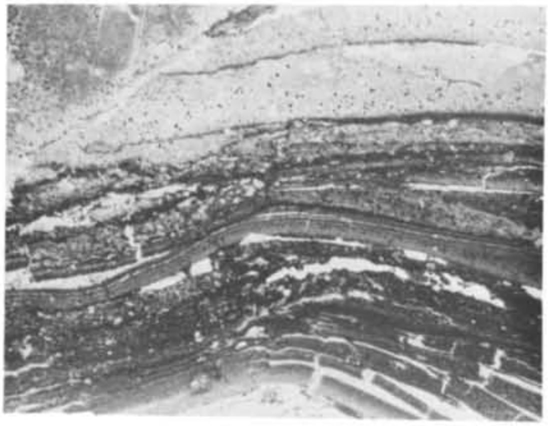

Figure 9. Thin section of specimen in figure 8 showing attenuation fault (5x).

lement and underthrusting older than or equivalent to the Sevier thrust belt (Misch, 1960); and gravity gliding due to crustal extension during the Tertiary (Armstrong, 1972).

Attenuation implies extension, with resultant thinning. Hose and Danes (1973) point out that where attenuation occurs regionally, there is a lack of internal compressional features. In the study area major compressional folds are totally lacking and apparently undeformed strata have a generally uniform easterly dip between 7 and 10 degrees, part of which may be a result of Basin and Range block fault tilting. Minor asymmetrical folds and extreme brecciation within units are the result of slight wrinkling of the moving blocks.

Armstrong (1972) proposed that attenuation faults tend to follow incompetent strata, but in the northern House Range competent strata (Howell and Dome Limestone formations) are found to be just as susceptible to attenuation faulting as incompetent strata, and these thick formations are commonly cut out. Studies by Drewes (1958 and 1967) in the Snake and Schell Creek ranges show that massive units of even greater thicknesses have been similarly attenuated.

The large southeasterly trending high-angle normal faults (or tear faults) related to the Sevier Orogeny tend to terminate or offset the attenuation faults, implying that attenuation faults develop as secondary structures in crustal blocks, moving independently of other blocks between tear faults. Pulling apart of deeply buried rocks may have caused attenuation of the near-surface rocks to various degrees. Thus, attenuation faults in the northern House Range fit the regional concept of crustal extension. (Hose & Danes 1973).

Stratigraphic age brackets to define the structural history are lacking in the study area. During the Late Mesozoic, the area was uplifted into the Sevier Arch; accompanying erosion removed all rocks younger than Cambrian (Harris, 1959). However to the west, in the Confusion Range, rocks ranging from Cambrian through Triassic in age have similarly been attenuated (Hose, 1977).

Tertiary (Oligocene) (?) intrusives cut across the attenuation faults in the north portion of the study area. This would appear to support Hintze's (1976), suggestion that regionally, attenuation faulting is Late Cretaceous (Sevier Orogenic) in age.

SUMMARY OF GEOLOGIC HISTORY AND CONCLUSIONS

During Early Cambrian time, sedimentation in the study area was representative of environmental conditions throughout the Paleozoic Cordilleran miogeosyncline. The Prospect Mountain Quartzite was part of a terrigenous sand sheet with a source to the east and northeast (Palmer, 1971). At the end of Early Cambrian time, shales and fauna indicate that a major eastward marine transgression occurred (Palmer, 1971). The thick sequence of Middle Cambrian limestones and shales found in the area represent very shallow-shelf marine shoals (Kepper, 1972). Several detrital embayments in the study area are indicated by the Whirlwind and Wheeler shales (Robison, 1964). By Late Cambrian time, seas had completely transgressed eastward over the area, including it as part of the broad shoal-bank envisioned for Utah at that time by Hintze (1973). Formations in nearby ranges include Ordovician through Lower Triassic sediments, in addition to the Cambrian formations found in the northern House Range. This indicates that the same sequence existed at one time in the northern House Range. Intense erosion of these deposits began in the Late Mesozoic as the area was uplifted along the western edge of the Sevier Arch (Harris, 1959). The area was further uplifted during the Late Cretaceous period as part of the Sevier Orogenic belt in eastern Nevada and western Utah (Armstrong, 1968), causing the following structures to be developed: (1) high-angle reverse faults; (2) east-west high-angle normal faults (probably tear faults); and (3) attenuation faults.

The attenuated faults are low angle faults which displace younger over older rocks and cause the removal of significant stratigraphic sequences. These faults, which are terminated or offset by Sevier high angle normal faults (possibly tear faults) and by high angle reverse faults, appear to have developed as secondary structures in blocks of crust between the tear faults.

Intrusion by quartz latite dikes occurred probably during the Oligocene. Possible emplacement of a magma at shallow depth generated the minor faults and diatremes. Subsequent hydrothermal solutions altered sediments in the area along some of the east-west high-angle normal faults and the attenuation faults.

The topography of the area seen today is the result of Basin and Range block-faulting with some glide faults that began in Miocene time and have continued to the present. Quaternary valley fill and alluvial fan deposits were modified during the Pleistocene Epoch by Lake Bonneville. Stream erosion and mass wasting are the dominant processes occurring today.

ACKNOWLEDGMENTS

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NOTE: A paper by Dr. L.F. Hintze, "Sevier orogenic attenuation faulting in the Fish Springs and House Ranges, western Utah" was published in Brigham Young University Geology Studies, vol. 25, part 1, p. 11-25, while this paper was in press.

MEASURED SECTIONS

Cambrian Systems, Northern House Range, Millard and Juab Counties, Utah

by Thomas C. Chidsey, Jr.

PIOCHE FORMATION, Tatow Member (Section A on figure 3)

Unit	Description	Thickness (Meters)
11	Sandstone, pale yellowish brown, weathers pale orange, medium bedded, fine-grained, micaceous, flaggy, forms a ledgy slope.	5.8
10	Dolomitic limestone, medium gray, weathers dark gray, thick bedded, fine-grained, forms a cliff.	4.0
9	Sandstone, grayish orange, weathers moderate yellowish orange, medium bedded, medium to coarse-grained, scolithus tubes, forms a ledgy slope.	7.0
8	Limestone, dark gray, weathers grayish blue to reddish brown, thin bedded arenaceous, oncolitic in lower 5 feet, striped, forms a ledgy slope.	4.6
7	Sandstone, medium gray, weathers dark yellowish orange, thin bedded, fine to medium-grained, micaceous, forms a step-like slope.	6.4
6	Limestone, dark gray, weathers light gray, medium bedded, medium-grained, oncolitic, forms a cliff.	2.1
5	Limestone, medium bluish gray, weathers brownish dark gray, thin bedded, fine-grained, arenaceous, striped, forms a ledgy slope.	3.0
4	Limestone mottled with dolomite, medium gray, weathers dark gray, massive bedding, medium-grained, oncolitic, forms a cliff.	8.2
3	Quartzite, yellow gray, weathers dusky yellow, massive irregular bedding, medium-grained, scolithus tubes, flaggy, forms a cliff.	1.5
2	Dolomitic limestone, gray blue, weathers to brown gray, thin bedded, micritic, forms a ledgy slope.	1.5
1	Dolomite, medium bluish gray, weathers medium brown, thick bedded, fine-grained, forms a cliff	7.0
	Total Thickness	51.1

PIOCHE FORMATION Lower Member (A on figure 3)

Unit	Description	Thickness (Meters)
21	Siltstone, gray green, weathering pale olive, thin to thickly laminated, micaceous, shaly parting, forms a slope.	4.9
20	Quartzite, siltstone interbedded, gray green, weathers dusky green, thin bedded, fine-grained, forms a ledgy slope.	8.2
19	Siltstone, pale olive, weathers gray olive, thin bedded, micaceous, paper parting, flaggy, forms a slope.	3.4
18	Sandstone, pale blue, weathers gray blue, thin to thick bedded, fine-grained, micaceous, cross-bedded, scolithus tubes, forms a ledgy slope.	10.7
17	Covered slope	2.1
16	Quartzite, interbedded shaly siltstones, pale purple, weathers grayish red, thin bedded, fine-grained, micaceous, some cross-beds, forms a ledgy slope.	11.3
15	Quartzite, light olive gray, weathers grayish red, thin bedded, coarse-grained, flaggy, interbedded with some brown silty shale, forms a ledgy slope.	6.1
14.	Sandstone, light olive gray, weathers grayish olive, thin bedded, fine-grained, micaceous, flaggy, forms a slope.	11.0
13.	Shale, pale olive, weathers dark olive, thinly laminated very fine-grained, fissile, forms a slope.	5.5
12.	Shale interbedded with quartzite, yellowish green and yellowish brown respectively, weathers the same, thin bedded, fine-grained, micaceous, forms a ledgy slope.	8.8
11	Quartzite, very dusky red, weathers moderate brown, thin bedded, cross-bedded, fine to medium-grained, forms a vertical ledge seen as a thin black line on aerial photos.	2.1
10	Shale, grayish green, weathers the same, thin bedded, fine-grained, micaceous, flaggy, forms a slope.	3.0
9	Siltstone, moderate yellow brown, weathers dark yellow brown, medium bedded, medium-grained, micaceous, scolithus tubes, forms a step-like slope.	4.3
8	Sandstone dark yellow brown, weathers gray brown, thin bedded, fine-grained, micaceous, scolithus tubes, *Olenellus,* forms a ledgy slope.	3.3
7	Quartzite, blackish red, weathers dusky red, thin bedded fine to coarse-grained, forms a cliff.	7.6
6	Quartzite, grayish orange to pinkish gray, weathers dark yellowish brown, medium bedded, forms a cliff.	4.3
5	Sandstone, yellowish gray, weathers grayish orange pink, thin bedded, fine to medium-grained, micaceous, forms a slope.	8.8
4	Quartzite, grayish yellow green, weathers light brown, thin to medium bedded, cross-bedded, coarse-grained, micaceous, forms a cliff.	4.6
3	Siltstone, dusky yellow, weathers moderate brown gray, medium bedded, medium-grained, forms a slope.	6.7
2	Quartzite, light gray, weathers moderate yellow brown, medium bedded, cross-bedded, coarse-grained, forms a ledge.	1.5
1	Siltstone, dusky-yellow, weathers moderate brown, medium bedded, cross-bedded in some small quartzite beds, medium-grained, forms a slope.	10.7
	Total Thickness	129.0

HOWELL LIMESTONE (A on figure 3)

Unit	Description	Thickness (Meters)
13	Limestone, medium gray, weathers dark olive gray, medium bedding, fine-grained, forms a ledgy slope.	10.1
12	Limestone, dark gray, weathers medium gray, thick bedded, medium-grained, bluebird bodies, forms a vertical cliff.	6.1
11	Covered slope	4.0
10	Limestone, dark gray, weathers medium gray, medium to thick bedding, medium-grained, forms a ledge-slope series.	5.5
9	Covered slope	6.1
8	Limestone, medium gray, weathers medium light gray, thin to medium bedded, fine-grained, surface pitted, mottled, forms a step-like slope.	7.6
7	Limestone, dark gray, weathered light gray, medium-grained, mottled bluebird bodies, forms a massive vertical cliff.	10.7
6	Limestone, grayish black, weathers light medium gray, thick bedded, medium-grained, meringue surface, mottled, bluebird bodies, forms a series of 3 meter cliffs.	12.2
5	Limestone, grayish black,weathers light gray, medium to thick bedding, fine-grained, mottled, bluebird bodies, forms a ledge-slope series.	6.1
4	Same as unit 6.	19.8
3	Same as unit 5.	33.5

Unit	Description	Meters
2	Limestone, medium dark gray, weathers dark gray, thick to massive bedding, medium to coarse-grained, bluebird bodies, blocky splitting, forms a near vertical cliff.	15.9
1	Limestone, dark gray, weathers medium dark gray, medium to thick bedded, medium-grained, bluebird bodies, forms a smooth ledgy slope.	29.9
	Total Thickness	167.4

HOWELL LIMESTONE, Millard Member (A on figure 3)

Unit	Description	Meters
3	Limestone, medium light gray, weathers light gray, thick bedding, micritic, forms a vertical cliff.	38.1
2	Limestone, medium gray, weathers medium light gray, medium bedded, micritic, forms ledges	10.7
1	Limestone, dark gray, weathers gray black, massive bedding, micritic, forms a vertical cliff.	15.2
	Total Thickness	64.0

CHISHOLM FORMATION (B on figure 3)

Unit	Description	Meters
3	Shale, interbedded limestone, olive gray, weathers grayish orange, thin bedded, fine to medium-grained, oncolitic, forms a slope.	22.7
2	Limestone, black, weathers dark gray, thin to medium bedded, fine-grained, mottled, bluebird bodies, oncolitic, forms a ledgy slope.	19.2
1	Covered slope	12.8
	Total Thickness	54.9

DOME LIMESTONE (B on figure 3)

Unit	Description	Meters
3	Limestone, medium gray, weathers light olive gray, medium bedded, fine-grained, meringue surface, forms a ledge-slope series.	18.3
2	Limestone, 2 feet of boundstone at base, medium gray, weathers medium light gray, massive bedding, medium-grained, silica blebs, forms a vertical cliff.	42.7
1	Limestone, dark gray, weathers light dark gray, thin to medium bedded, cross-bedded, fine-grained, arenaceous, meringue surface, forms a ledge slope.	21.3
	Total Thickness	82.3

WHIRLWIND FORMATION (C,D on figure 3)

Unit	Description	Meters
3	Shale, calcareous, dark gray, weathers olive gray, thin bedded, fine-grained, interbedded argillaceous limestones, dark gray, forms a slope.	17.7
2	Limestone, arenaceous, dark gray, weathers medium dark gray, thin bedded, coquina containing *Ehmania* and *Ehmaniella,* forms a small cliff.	2.1
1	Shale and limestone, interbedded, calcareous and arenaceous, dark gray, weathers light tan, thin bedded, flaggy, trilobite hash , *Ehmaniella* , forms a slope.	25.9
	Total Thickness	45.7

SWASEY LIMESTONE (C, D on figure 3)

Unit	Description	Meters
3	Limestone, light medium gray, weathers light gray, thin to medium bedded, coarse-grained, oolitic, contains calcite veins, forms an irregular cliff.	7.6
2	Limestone, medium gray, weathers light gray, massive, medium-grained, oolitic, meringue surface forms a vertical cliff.	12.2
1	Limestone medium dark gray, weathers medium gray, thin bedded, mottled, fine crystalline meringue surface, forms a ledgy slope.	27.4
	Total Thickness	47.3

WHEELER SHALE (C and D on figure 3)

Unit	Description	Meters
8	Shale interbedded limestone, grayish red, weathers light red, laminated to thin bedded, fine-grained, calcareous, silty, forms a ledgy slope.	7.6
7	Shale, moderate yellowish brown, weathers yellowish gray to orange, laminated, papery splitting, calcareous, forms a ledgy slope.	73.2
6	Shale, interbedded limestone, yellow brown, weathers dark yellowish orange, laminated to thin bedded, fine-grained, arenaceous, *Elrathia,* forms a slope with a few ledges.	19.2
5	Shale, interbedded limestone, medium dark gray, weathers moderate reddish brown, laminated to very thin bedded, fine-grained, forms a rounded cliff.	25.0
4	Shale, moderate yellowish brown, weathers yellowish gray, thin laminated to thin bedded, fine-grained, calcareous, *Agnostid* trilobites, forms a ledgy slope.	43.6
3	Shale, interbedded limestone, medium dark gray, weathers yellowish orange, thin laminated to thin bedding, paper to flaggy splitting, calcareous, some chert, forms a rounded cliff.	5.2
2	Shale, light olive gray, weathers moderate olive brown, laminated to thin bedded, fine-grained, calcareous, forms a slope.	16.8
1	Covered slope	7.6
	Total Thickness	198.2

PIERSON COVE FORMATION (E on figure 3)

Unit	Description	Meters
4	Limestone, dark gray, weathers medium dark gray, massive bedded, coarse-grained, bluebird bodies, mottled, forms a vertical cliff.	61.0
3	Limestone, grayish black, weathers dark gray, thin to medium bedding, medium-grained, chert nodules, forms 10 foot ledges and 20 foot wide slopes.	62.5
2	Limestone, grayish black, weathers medium dark gray, thin to medium bedding, fine to medium-grained, some dolomitic beds, forms a massive vertical cliff with talus slope at the base.	220.1
1	Limestone, dark gray, weathered moderate red, thin bedded, fine-grained, shaly, calcareous, ledgy slope.	48.8
	Total Thickness	392.4

TRIPPE LIMESTONE Fish Springs Member (F on figure 3)

Unit	Description	Meters
2	Shale, olive green, weathers light olive green, very thin bedded, fine-grained, trilobite *Eldoradia* common, few outcrops, forms a slope.	42.7
1	Shale, light gray, weathers yellow orange, laminated, fine-grained, forms a slope.	9.1
	Total Thickness	51.8

TRIPPE LIMESTONE, Lower Member (F on figure 3)

Unit	Description	Meters
5	Limestone, medium dark gray, weathers pale orange, massive beds, medium to fine-grained, blocky splitting forms a vertical cliff.	51.8
4	Covered slope	41.1
3	Limestone, medium dark gray, weathers very pale orange, massive beds, blocky splitting, forms a cliff.	35.1
2	Boundstone, medium dark gray, weathers very light gray, medium bedded, fine-grained, forms a vertical cliff.	15.2
1	Boundstone, medium dark gray, weathers very pale orange, medium bedded, medium to fine-grained, forms a massive vertical cliff.	9.1
	Total Thickness	152.4

LAMB DOLOMITE (G on figure 3)

Unit	Description	Meters
12	Dolostone, dark gray, medium bedded, coarse-grained, forms a ledge.	9.1
11	Dolostone, light gray, weathers light dusky gray, medium-grained, forms a slope of light soil	36.6
10	Dolostone, dark gray, medium bedded, medium-grained, blocky meringue surface, forms a ledge.	6.1
9	Dolostone, light tan, medium bedded, medium-grained blocky, forms a ledge.	4.6
8	Dolostone, dark gray, medium bedded, coarse-grained, blocky, meringue surface, forms a ledge.	6.1
7	Dolostone, light gray, medium to thin bedded, coarse-grained blocky, forms a ledge.	22.9
6	Dolostone, medium gray, weathers dark gray, medium to thin bedded, medium-grained, blocky, forms a ledgy slope	15.2
5	Dolostone, light dusky gray, weathers light dusky brown, medium bedded, coarse-grained, meringue surface, forms a ledge.	15.2
4	Dolostone, medium gray, weathers light gray, medium bedded, fine-grained, forms a ledgy slope.	68.0
3	Dolostone, dark gray, medium bedded, contains pisolites, forms a ledge.	2.1
2	Shale, medium tan olive, weathers tan to medium gray, medium bedded, forms a slope.	1.5
1	Dolostone, dark gray medium bedded, abundant pisolites, forms a cliff.	4.6
	Total Thickness	192.0

Mt. Agassiz, in the Uinta Mountains Photo by Timothy O'Sullivan.

EARTHQUAKE EPICENTERS IN UTAH
JULY 1 - DECEMBER 31, 1977

Reported by:
University of Utah Seismograph Stations
Department of Geology and Geophysics
University of Utah, Salt Lake City, Utah 84112

EARTHQUAKES

Beginning with this issue of Utah Geology, earthquake epicenters in the Utah region are reported by the University of Utah Seismograph Stations in a computerized listing (table 1), together with a corresponding epicenter map (figure 1) to meet increasing technical needs for Utah earthquake data.

For each located earthquake, the new format specifies: the origin time (in Coordinated Universal Time, UTC*), epicentral coordinates (in degrees), focal depth (km), estimated Richter magnitude (M_L**),geographic location, and azimuth to the epicenter (specified in degrees, clockwise from north) from a nearest "key" reference point (some of which are shown on the epicenter map (figure 1). It should be noted that earthquakes located with inadequate depth control are routinely restricted to a depth of 7 km, the average focal depth for well-located earthquakes in the Utah region.

Earthquakes plotted in figure 1 extend as far north as 42.5° N latitude, corresponding to the northern boundary of a standard study area used by the University of Utah Seismograph Stations. This added coverage usefully allows an overview of seismicity in the Utah-Idaho border area, historically one of Utah's most seismically active regions.

The detection and location of earthquakes on a state-wide basis is now systematically complete for earthquakes having a magnitude above approximately 2.0. Only shocks of magnitude 1.5 or greater are summarized in the epicenter list, but all 353 earthquakes located during the sample period, including shocks of smaller magnitude, are plotted in the epicenter map. A greater density of stations in north-central Utah, compared to other parts of the state, accounts for the recording and location of a greater number of small-magnitude earthquakes in that area. During the year 1977, a relative increase in the number of small-magnitude events in south-central and southern Utah is explained principally by the expansion of the University of Utah seismic network in these areas. Known blasts have been excluded from the epicenter list, but a few included events may in fact be artificial. Readers requiring additional technical data for the earthquake locations in figure 1 are referred to the University of Utah Seismograph Stations.

The largest earthquake during the report period occurred on September 30, 1977 (UTC) with a Richter magnitude of 4.4 and the epicenter located about 33 km north of Duchesne and 6 km south of Moon Lake. The earthquake was felt widely spread in the small towns and cities in the Uintah Basin in Duchesne and Uintah counties, Utah, and in western Colorado as far north as Petty Mountain (5 km east of Moon Lake), as far west as Fruitland, as far south as Duchesne, and as far east as Craig, Colorado. No serious damage was reported. The main shock was followed by several hundred aftershocks Carver and others, 1978), the largest of which was a magnitude 4.0 earthquake on October 11, 1977 (UTC), with an epicenter located apparently within about 3 km of the main shock. This earthquake was felt almost as widely spread as the main shock, although not by as many people because it occurred about two hours after midnight (local MDT) when most persons were asleep.

During the report period, one other earthquake was large enough to be felt--a magnitude 2.6 shock on November 28, 1977 (UTC) located 12 km northeast of Huntsville (see Table 1).

ACKNOWLEDGEMENTS

Operation of the University of Utah seismic network is supported by the U.S. Geological Survey, the National Science Foundation, and State of Utah funding to the University of Utah. Partial support for compilation of these earthquake data was provided by the Utah Geological and Mineral Survey.

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* UTC = Greenwich Mean Time (GMT). April 24 - October 30, 1977: UTC = Mountain Daylight Time (MDT) + 6 hrs. October 30, 1977 - April 30, 1978: UTC = Mountain Standard Time (MST) + 7 hrs.

** The Richter magnitude (M_L) is the magnitude related, directly or indirectly to seismic amplitudes on Wood Anderson seismographs.

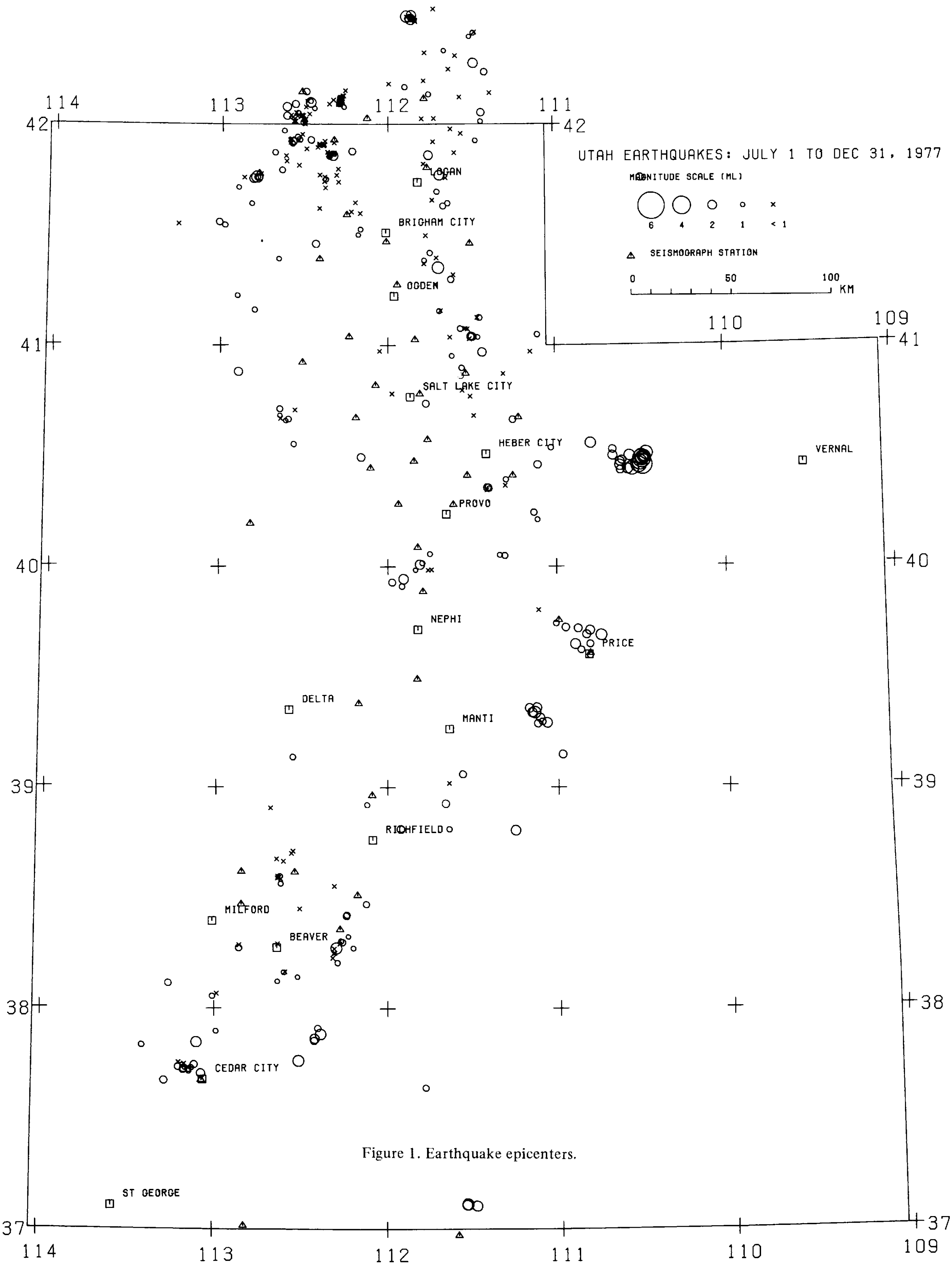

Figure 1. Earthquake epicenters.

UTAH EARTHQUAKES : JULY - DEC, 1977

YR	DATE	TIME	LAT-N	LONG-W	DEPTH	MAG	GEOGRAPHIC LOCATION	AZ
77	0701	1948	40.36	111.41	5KM	1.7	16.7KM (10.4MI) S OF HEBER,UT	179
77	0702	0312	41.04	111.49	7KM	1.8	15.3KM (9.5MI) E OF MORGAN,UT	90
77	0704	1610	41.77	111.69	17KM	2.2	12.3KM (7.6MI) E OF LOGAN,UT	73
77	0706	2218	41.04	111.50	7KM	1.6	14.4KM (9.0MI) E OF MORGAN,UT	91
77	0709	0207	37.88	112.38	7KM	2.4	8.1KM (5.0MI) NE OF PANGUITCH,UT	33
77	0709	0217	37.86	112.42	7KM	2.1	4.9KM (3.1MI) N OF PANGUITCH,UT	19
77	0709	0310	37.85	113.10	7KM	2.3	18.5KM (11.5MI) N OF CEDAR CITY,UT	351
77	0713	1926	41.75	110.47	7KM	1.7	68.4KM (42.5MI) NE OF EVANSTON,WY	37
77	0716	1240	39.30	111.09	7KM	1.5	11.8KM (7.3MI) NW OF CASTLE DALE,UT[1]	325
77	0718	0344	37.85	112.42	7KM	1.6	3.6KM (2.2MI) N OF PANGUITCH,UT	13
77	0721	0240	40.46	111.11	6KM	1.7	24.0KM (14.9MI) SE OF KAMAS,UT	146
77	0721	2116	40.01	111.81	1KM	2.1	7.7KM (4.8MI) SW OF PAYSON,UT	246
77	0726	0515	39.29	111.12	7KM	1.7	12.6KM (7.9MI) NW OF CASTLE DALE,UT[1]	314
77	0728	0432	40.66	111.25	7KM	1.5	3.1KM (1.9MI) N OF KAMAS,UT	18
77	0807	0926	39.95	111.91	2KM	2.2	11.2KM (7.0MI) W OF SANTAQUIN,UT	254
77	0808	1141	41.46	112.43	4KM	1.6	35.3KM (21.9MI) W OF BRIGHAM CITY,UT	261
77	0810	1546	40.49	112.16	11KM	1.7	12.6KM (7.8MI) E OF TOOELE,UT	110
77	0812	0417	37.11	111.49	7KM	2.3	74.3KM (46.1MI) S OF ESCALANTE,UT	172
77	0813	1245	39.65	110.89	7KM	2.2	9.6KM (6.0MI) NW OF PRICE,UT[1]	303
77	0819	0539	42.47	111.86	7KM	2.3	33.4KM (20.7MI) SW OF SODA SPRINGS,ID	219
77	0819	0547	42.49	111.86	7KM	2.1	31.5KM (19.6MI) SW OF SODA SPRINGS,ID	221
77	0819	0602	42.49	111.89	7KM	2.6	33.6KM (20.9MI) SW OF SODA SPRINGS,ID	223
77	0821	0454	38.93	111.66	7KM	1.7	16.9KM (10.5MI) E OF SALINA,UT	101
77	0827	0241	42.09	112.56	7KM	1.6	18.9KM (11.7MI) NE OF SNOWVILLE,UT	45
77	0831	2052	40.88	112.89	7KM	1.9	47.6KM (29.6MI) NW OF GRANTSVILLE,UT[1]	311
77	0904	0809	41.88	112.22	7KM	1.5	18.6KM (11.6MI) N OF TREMONTON,UT	348
77	0907	2111	39.34	111.14	7KM	2.6	17.9KM (11.1MI) NW OF CASTLE DALE,UT[1]	324
77	0908	0109	41.04	111.50	7KM	1.8	14.8KM (9.2MI) E OF MORGAN,UT	89
77	0910	1606	41.76	112.79	7KM	2.6	23.8KM (14.8MI) S OF SNOWVILLE,UT	195
77	0910	1946	41.76	112.81	7KM	2.0	25.0KM (15.5MI) S OF SNOWVILLE,UT	198
77	0911	0405	41.10	109.20	7KM	2.0	45.3KM (28.1MI) E OF MANILA,UT	75
77	0915	0340	42.04	112.61	7KM	1.7	11.8KM (7.3MI) NE OF SNOWVILLE,UT	50
77	0921	1257	39.93	111.97	7KM	1.6	12.2KM (7.6MI) E OF EUREKA,UT	101
77	0921	2057	37.12	111.54	7KM	2.5	72.8KM (45.3MI) S OF ESCALANTE,UT	176
77	0927	2136	37.11	111.55	7KM	2.2	73.2KM (45.5MI) S OF ESCALANTE,UT	176
77	0928	1352	41.86	112.33	6KM	2.1	20.9KM (13.0MI) NW OF TREMONTON,UT	320
77	0930	1019	40.46	110.48	7KM	4.4	33.2KM (20.6MI) N OF DUCHESNE,UT[2]	347
77	0930	1027	40.56	110.79	7KM	2.4	41.3KM (25.6MI) E OF KAMAS,UT	102
77	0930	1027	40.53	110.66	7KM	1.7	45.9KM (28.5MI) NW OF DUCHESNE,UT	331
77	0930	1044	40.43	110.62	7KM	1.7	35.0KM (21.7MI) NW OF DUCHESNE,UT	328
77	0930	1048	40.44	110.57	7KM	2.2	33.6KM (20.9MI) NW OF DUCHESNE,UT	334
77	0930	1120	40.46	110.62	7KM	2.4	37.1KM (23.1MI) NW OF DUCHESNE,UT	330
77	0930	1156	40.44	110.55	7KM	3.0	32.9KM (20.5MI) N OF DUCHESNE,UT	338
77	0930	1256	40.46	110.51	7KM	3.6	33.5KM (20.8MI) N OF DUCHESNE,UT	344
77	0930	1829	40.50	110.66	7KM	2.0	43.2KM (26.9MI) NW OF DUCHESNE,UT	329
77	1002	0145	40.51	110.46	7KM	2.9	38.5KM (23.9MI) N OF DUCHESNE,UT	352
77	1002	0715	40.49	110.49	5KM	3.3	37.1KM (23.0MI) N OF DUCHESNE,UT	348
77	1004	1913	40.49	110.47	7KM	2.9	36.7KM (22.8MI) N OF DUCHESNE,UT	350
77	1006	0938	40.48	110.49	6KM	2.9	35.8KM (22.3MI) N OF DUCHESNE,UT	348
77	1006	1048	42.10	112.47	1KM	2.2	20.7KM (12.8MI) SW OF MALAD CITY,ID	240
77	1010	0804	39.29	111.06	7KM	2.2	10.2KM (6.3MI) NW OF CASTLE DALE,UT[1]	335
77	1011	0756	40.48	110.49	6KM	4.0	36.0KM (22.4MI) N OF DUCHESNE,UT[3]	348
77	1011	1344	40.49	110.47	6KM	2.4	37.0KM (23.0MI) N OF DUCHESNE,UT	350
77	1011	1716	40.49	110.49	7KM	2.9	36.4KM (22.6MI) N OF DUCHESNE,UT	348
77	1015	0229	40.47	110.62	7KM	2.0	38.8KM (24.1MI) NW OF DUCHESNE,UT	331

UTAH EARTHQUAKES : JULY - DEC, 1977

YR	DATE	TIME	LAT-N	LONG-W	DEPTH	MAG	GEOGRAPHIC LOCATION	AZ
77	1016	1915	40.47	110.50	7KM	3.4	34.5KM (21.4MI) N OF DUCHESNE,UT	345
77	1017	1133	39.32	111.10	7KM	1.9	14.2KM (8.8MI) NW OF CASTLE DALE,UT[1]	326
77	1019	0316	40.50	110.56	7KM	2.4	39.5KM (24.6MI) N OF DUCHESNE,UT	340
77	1019	0634	41.92	112.57	7KM	1.7	13.2KM (8.2MI) SE OF SNOWVILLE,UT	113
77	1019	0942	40.48	110.61	7KM	1.9	39.0KM (24.2MI) NW OF DUCHESNE,UT	333
77	1020	1319	39.15	110.97	7KM	1.8	7.5KM (4.7MI) SE OF CASTLE DALE,UT	153
77	1021	0128	41.86	111.76	8KM	2.0	7.9KM (4.9MI) SE OF RICHMOND,UT	146
77	1021	1208	39.34	111.15	7KM	2.1	18.8KM (11.7MI) NW OF CASTLE DALE,UT	320
77	1021	1323	42.08	112.61	1KM	1.9	15.2KM (9.4MI) NE OF SNOWVILLE,UT	36
77	1027	1430	38.42	112.24	6KM	1.5	20.2KM (12.6MI) N OF JUNCTION,UT	355
77	1028	2013	40.74	111.77	2KM	1.5	6.6KM (4.1MI) E OF SALT LAKE CITY,UT	100
77	1031	1933	39.71	110.81	7KM	2.0	12.4KM (7.7MI) N OF PRICE,UT[1]	355
77	1031	1958	39.69	110.74	0KM	2.5	11.2KM (7.0MI) NE OF PRICE,UT[1]	28
77	1101	0255	39.72	110.88	7KM	1.8	14.9KM (9.2MI) NW OF PRICE,UT[1]	333
77	1103	0141	39.36	111.12	7KM	2.1	19.4KM (12.0MI) NW OF CASTLE DALE,UT	330
77	1103	0152	39.36	111.17	7KM	2.0	21.4KM (13.3MI) NW OF CASTLE DALE,UT	321
77	1104	0845	39.06	111.56	7KM	1.6	23.3KM (14.5MI) S OF MANTI,UT	164
77	1105	0508	39.65	110.81	7KM	1.6	5.5KM (3.4MI) N OF PRICE,UT[1]	349
77	1106	1428	39.72	110.95	7KM	1.7	18.9KM (11.7MI) NW OF PRICE,UT	317
77	1106	1709	40.97	111.43	7KM	1.9	6.8KM (4.2MI) NW OF COALVILLE,UT	329
77	1109	1915	39.62	110.86	7KM	1.6	5.7KM (3.6MI) NW OF PRICE,UT[1]	296
77	1111	0605	39.69	110.83	7KM	1.8	10.5KM (6.6MI) N OF PRICE,UT[1]	346
77	1117	0215	41.76	112.78	4KM	1.5	23.6KM (14.6MI) S OF SNOWVILLE,UT	192
77	1117	0722	37.75	113.11	3KM	1.6	8.2KM (5.1MI) NW OF CEDAR CITY,UT	331
77	1123	2057	37.68	113.28	7KM	1.6	19.1KM (11.9MI) W OF CEDAR CITY,UT	268
77	1124	0000	38.28	112.30	7KM	2.5	7.8KM (4.8MI) NW OF JUNCTION,UT	301
77	1128	0223	41.35	111.70	7KM	2.6	11.8KM (7.4MI) NE OF HUNTSVILLE,UT[4]	29
77	1129	2131	36.73	110.94	7KM	2.9	129.2KM (80.3MI) SE OF ESCALANTE,UT	153
77	1203	1714	38.81	111.92	7KM	1.7	14.8KM (9.2MI) E OF RICHFIELD,UT	70
77	1205	0544	37.73	113.17	2KM	1.7	10.5KM (6.5MI) NW OF CEDAR CITY,UT	299
77	1206	1903	37.71	113.07	1KM	1.9	2.8KM (1.7MI) N OF CEDAR CITY,UT	352
77	1211	0715	38.61	111.25	7KM	2.2	49.1KM (30.5MI) SW OF CASTLE DALE,UT	205
77	1227	1808	42.28	111.48	7KM	2.1	38.0KM (23.6MI) N OF GARDEN CITY,UT	349
77	1227	1928	37.77	112.51	7KM	2.5	9.3KM (5.8MI) SW OF PANGUITCH,UT	228
77	1231	0408	42.06	111.44	7KM	1.7	13.0KM (8.1MI) N OF GARDEN CITY,UT	343

Number of events 90

ADDENDA AND ERRATA

In the listings of the probable rockbursts in the coal-mining areas of Carbon and Emery counties, Utah, in the previous issues of Utah Geology, a footnote stating "No data available-Price Station (PCU) inoperative" should be added to the following:

Issue of Utah Geology Yr.	Vol.	No.	Page	Dates (UTC)- no PCU data available
1975	2	2	136	August 16 and 27, 1974. September 12 to 14, inclusive, 1974
1976	3	1	69	January 7 to 10, inclusive, 1975. January 20 and 22, 1975. March 11 to 13, inclusive, 1975. May 22, 1975, June 3, 1975
1976	3	2	124	August 11, 1975 December 5, 1975
1977	4	2	129	October 16 to November 16, inclusive 1976. December 4 and 5, 1976.
1977	5	1	84	January 31, 1977. February 18 and 19, 1977. May 21 to 28, inclusive, 1977. June 12 and 13, 1977.

Also, in Table 2 of Utah Geology, 1976, vol. 3, no. 1, page 69, the number of probable rockbursts should be changed to read as follows for April 1975:

Date	No. of probable rockbursts
April 9, 1975	1
April 10, 1975	0
April 13, 1975	1
April 14, 1975	2
April 22, 1975	2
Total for April, 1975	28

[1] Possible mine or quarry blast.

[2] Felt in Petty Mountain (5 km east of Moon Lake), Mountain Home, Talmage, Boneta, Altonah, Altamont, Bluebell, Tabiona, Fruitland, Duchesne, Bridgeland, Neola, Tridell, Roosevelt, Gusher, Lapoint, and Vernal, Utah; and in Fruita, Grand Junction, Clifton, Palisade, and Craig, Colorado.

[3] Felt in Mountain Home, Altamont, Bluebell, Tabiona, Hanna, Duchesne, Neola, Tridell, Roosevelt, Gusher, Vernal, and Manila, Utah; and in Fruita, Colorado.

[4] Felt in Huntsville, Eden, Pine View Dam, Ogden, North and South Ogden, Roy, Layton, Devils Slide, Ogden Canyon, and Weber Canyon.

Appropriations No. 01-61-03 Archives Approval No. 7800091

UTAH GEOLOGICAL AND MINERAL SURVEY

606 Black Hawk Way
Salt Lake City, Utah 84108

THE UTAH GEOLOGICAL AND MINERAL SURVEY is a Division of the Utah Department of Natural Resources and operates under the guidance of a Governing Board appointed by the Governor from industry and the public-at-large. The Survey is instructed by law to collect and distribute reliable information concerning the mineral resources, topography, and geology of the state, to investigate areas of geologic and topographic hazards that could affect the citizens of Utah, and to support the development of natural resources within the state. The *Utah Code Annotated, 1953 Replacement Volume 5, Chapter 36, 53-36-1 through 12,* describes the Survey and its functions.

The Survey publishes bulletins, maps, a quarterly newsletter, and a biannual journal that describe the geology of the state. Write for the latest list of publications available.

The Survey also sells the colored geologic map of Utah (Army Map Service base, 1:250,000, in four quarters), a project of the College of Mines and Mineral Industries of the University of Utah from 1961 through 1964. It acts as sales agent for publications of the Utah Geological Association and its predecessor organizations, the Utah Geological Society, the Intermountain Association of Geologists, and the Intermountain Association of Petroleum Geologists.

THE SAMPLE LIBRARY is maintained to preserve well cuttings, drill cores, stratigraphic sections, and other geological samples. Files of lithologic, electrical, and mechanical logs of oil and gas wells drilled in the state are also maintained. The library's collections have been obtained by voluntary donation and are open to public use, free of charge.

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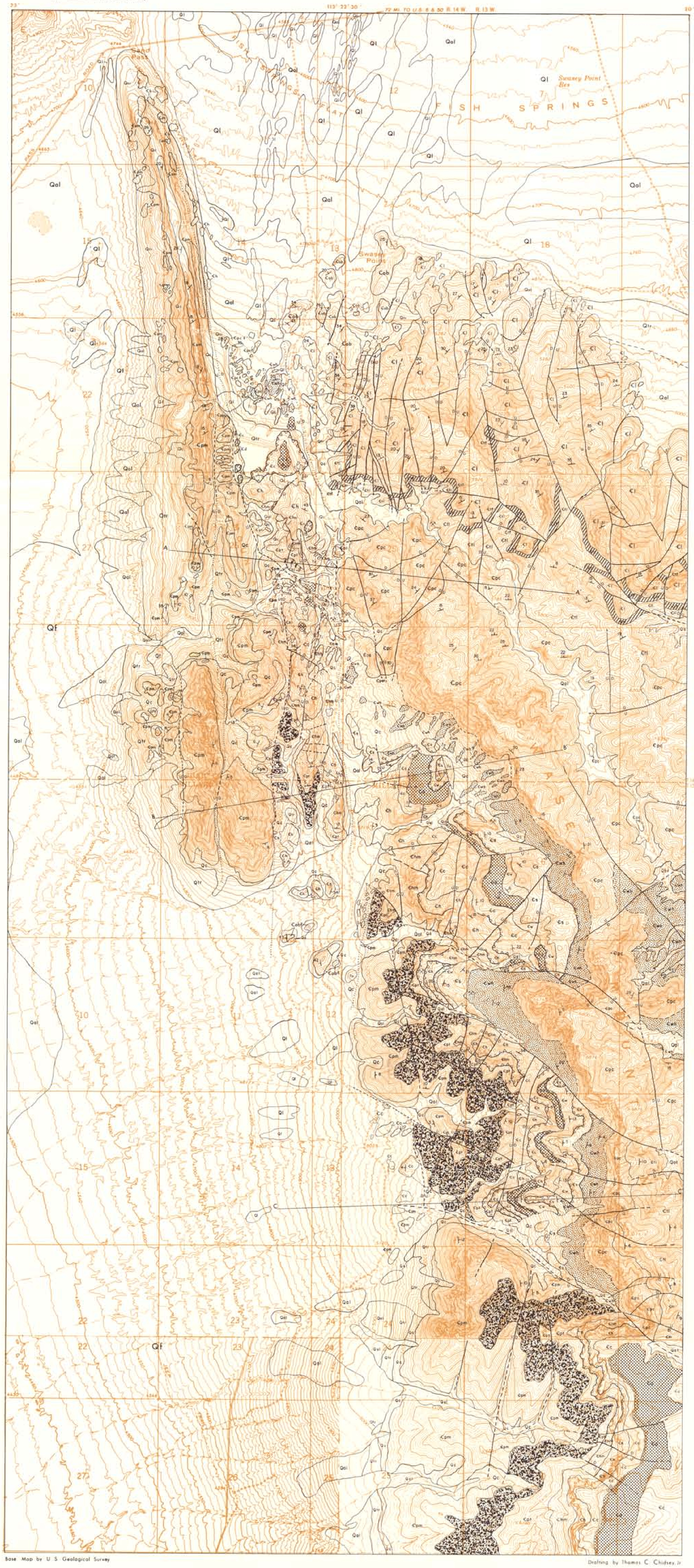
STATE OF UTAH
Department of Natural Resources
Utah Geological and Mineral Survey

PLATE 1
UTAH GEOLOGY, Vol. 5, No. 2
Thomas C. Chidsey, Jr., Geology of
Northern House Range, Western Utah



Base Map by U.S. Geological Survey

Drafting by Thomas C. Chidsey, Jr.

LEGEND

CENOZOIC — QUATERNARY

- Qal — Alluvium
- Qc — Alluvium & Colluvium
- Qf — Alluvial Fan
- Qtr — Lake Terrace
- Ql — Lake Deposit

CENOZOIC — TERTIARY

- Ta — Alteration
- Ti — Latite Intrusion

PALEOZOIC — CAMBRIAN — CROIXIAN

- Єob — Orr Formation
- Єl — Lamb Dolomite

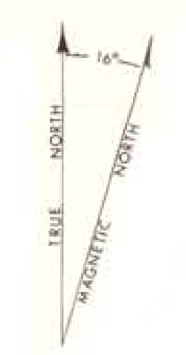
PALEOZOIC — CAMBRIAN — ALBERTAN

- Єtf — Trippe Limestone, Fish Springs Member
- Єtl — Trippe Limestone, Lower Member
- Єpc — Pierson Cove Formation
- Єwh — Wheeler Shale
- Єs — Swasey Limestone
- Єw — Whirlwind Formation
- Єd — Dome Limestone
- Єc — Chisholm Formation
- Єh — Howell Limestone
- Єhm — Howell Limestone, Millard Member
- Єpt — Pioche Formation, Tatow Member

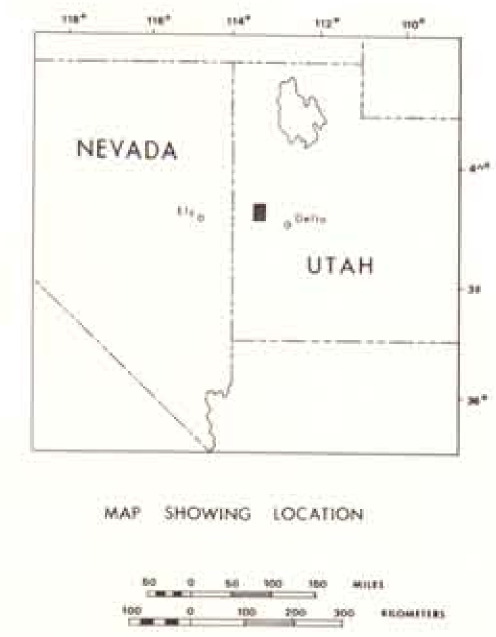
PALEOZOIC — CAMBRIAN — WAUCOBAN

- Єpl — Pioche Formation, Lower Member
- Єpm — Prospect Mountain Quartzite

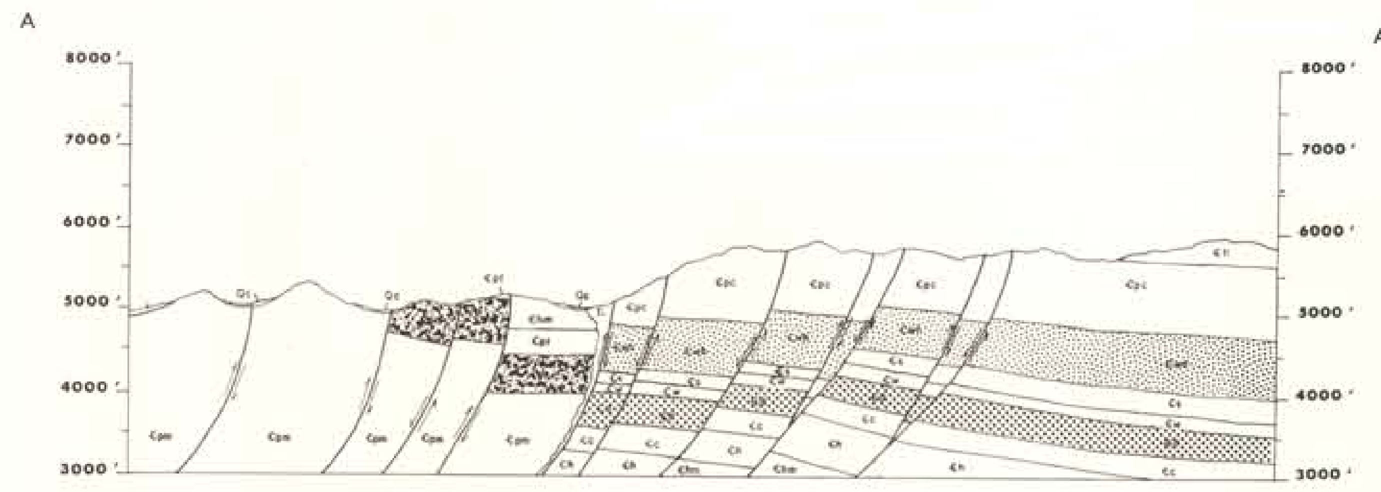
SYMBOLS

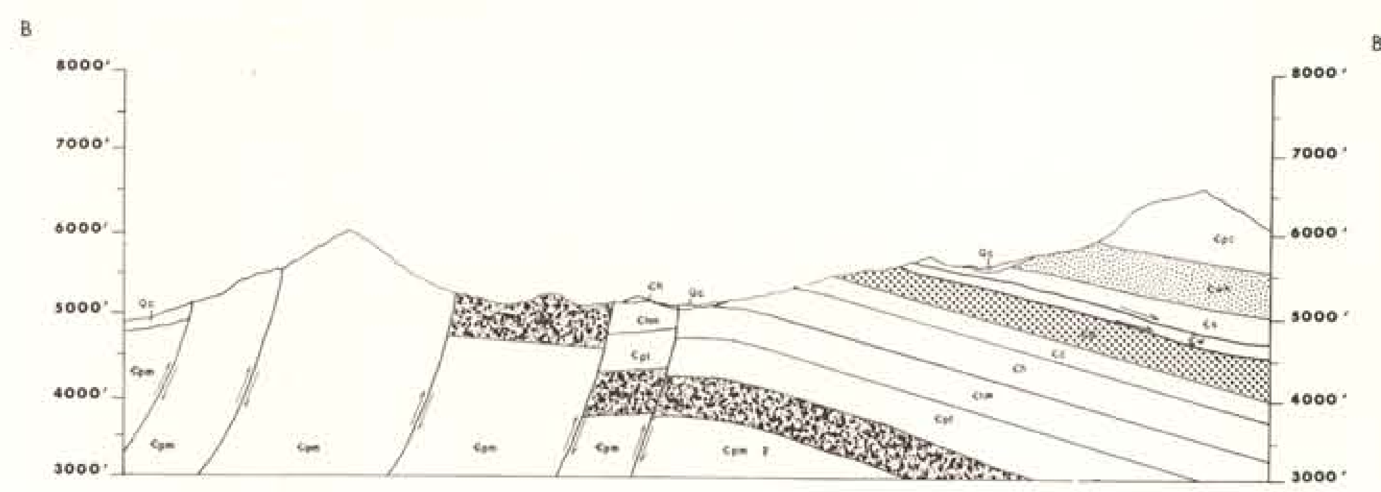


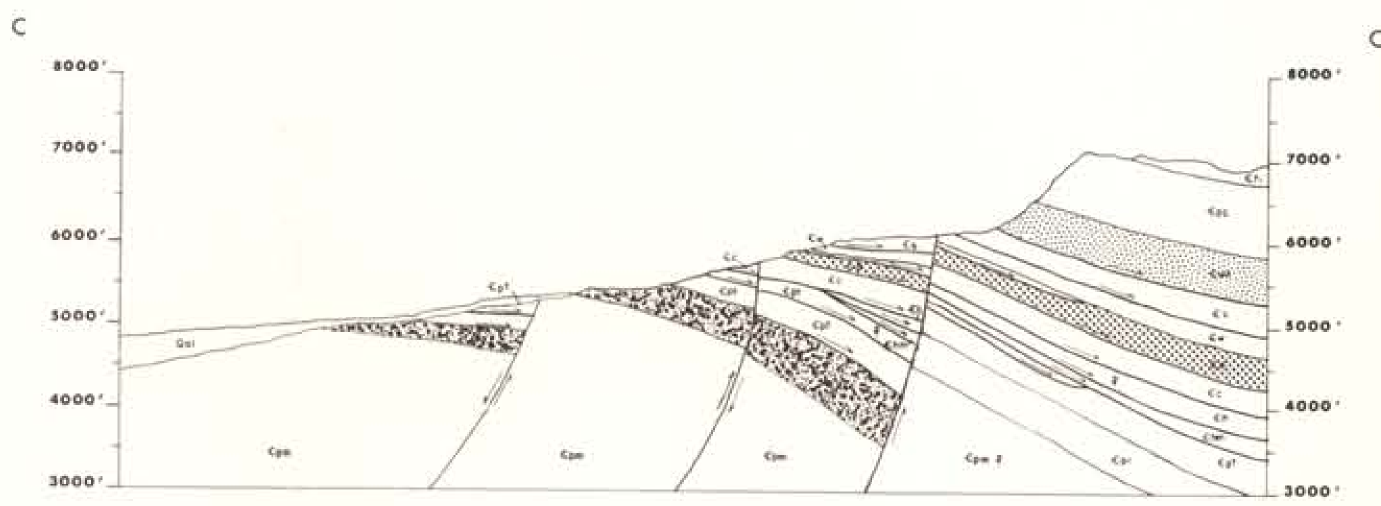
APPROXIMATE MEAN DECLINATION, 1976



MAP SHOWING LOCATION







Appropriations No. 01-61-03
Archives Approval No. 7800091

GEOLOGY OF THE NORTHERN HOUSE RANGE, WESTERN UTAH

by
THOMAS C. CHIDSEY, JR.

1/2 0 1 MILE
1/2 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET 40 FEET IN SOUTHERN AREA
DATUM IS MEAN SEA LEVEL

1977