Geology of the Ash Meadows Quadrangle Nevada-California

By CHARLES S. DENNY *and* HARALD DREWES

CONTRIBUTIONS TO GENERAL GEOLOGY

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The history of a desert basin and its bordering highlands

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By Charles S. Denny and Harald Drewes

ABSTRACT

The Ash Meadows quadrangle lies about 25 miles east of Death Valley and includes the southern part of the Amargosa Desert, a broad lowland adjacent to the Amargosa River. The southeastern spur of the Funeral Mountains projects a short distance into the quadrangle from the west, and the northern end of the Resting Spring Range lies in the southeast corner. The mountains rise 2,000–3,000 feet above the adjoining piedmonts that are largely coalescing alluvial fans. The Ash Meadows, located in the northeastern part of the quadrangle, contain several flowing springs such as Devils Hole, a large sink in Middle Cambrian limestone and dolomite.

Within the quadrangle, about 5,000 feet of Silurian to Mississippian limestone and dolomite forms the backbone of the Funeral Mountains and is overlain by 3,000–5,000 feet of fluvial and lacustrine deposits of Tertiary, perhaps Oligocene age. The spur is an eastward-dipping fault block bounded on the south by the Furnace Creek fault zone. The block itself is broken by two sets of normal faults.

Volcanic rocks, part of those that form much of the Greenwater Range to the southwest, form a small butte in the southwestern corner of the quadrangle.

On the east side of the Amargosa Valley lies Shadow Mountain, which forms the end of the Resting Spring Range, and a group of isolated hills near Devils Hole. Both highlands consist of about 5,000 feet of gently dipping Cambrian rocks, chiefly quartzite, limestone, and dolomite. The rocks of Shadow Mountain form an east-dipping fault block overlain at its north end by fanglomerate and finer grained beds of Tertiary age. The rocks of the hills near Devils Hole are broken by numerous steep faults of small displacement.

The rocks of the mountains and hills throughout the quadrangle are overlapped by alluvial-fan deposits of Quaternary age, largely undeformed beds of gravel, sand, and breccia. Away from the highlands, the fan deposits intertongue with playa and spring deposits, largely silt and lesser amounts of sand or clay. No fossils have been found in these arid-basin sediments, but Pleistocene fossils are known from similar deposits in the Amargosa Valley about 30 miles to the south. Surficial deposits of limited extent include dune sand, scree, and landslide breccia. Alluvium floors the lowlands along the Amargosa River and

its principal tributaries. Artifacts associated with the alluvium suggest that most of it is at least 2,000 years old. Some alluvium and some of the dune sand, however, are younger.

The piedmonts between mountain and lowland include four geomorphic units: desert pavement, pediment, and washes, the last divisible into washes floored with unweathered gravel and those where the stones on the surface have a coating of desert varnish. The size of a piedmont and the proportion of pavement, wash, or pediment on its surface depend upon the structural history of mountain and basin and the processes acting upon them. The configuration of the piedmont may represent an approach toward a steady state of balance or dynamic equilibrium between the rate at which detritus is brought to the piedmont from the adjacent highland and the rate at which it is removed by erosion.

Patterned ground, reminiscent of that found in cold climates, occurs throughout the quadrangle. The patterns are due to the orderly arrangement of such features as desiccation cracks, shrubs, terracettes, and linear or oval-shaped areas of large and small fragments of rock.

INTRODUCTION

The Ash Meadows quadrangle, in the southern part of the Amargosa Desert, is a broad area of sloping piedmonts bordered by small mountain ranges. The Amargosa River flows southward through the desert for more than 100 miles (fig. 1), roughly parallel to and about 25 miles east of Death Valley, until it reaches the point where it turns westward into Death Valley and there flows northwestward for about 40 miles until it loses itself on the saltpan near Badwater. The Ash Meadows are largely a wide expanse of swamp or meadow, but includes some areas of sand dunes and bare ground. The name connotes extensive areas of salt crust or white clay which give an ashen color to the landscape. Within the Meadows are several large flowing springs, one of which, Devils Hole, has been set aside as a part of Death Valley National Monument.

In 1956–58, Denny, with the able assistance of H. F. Barnett, Jack Rachlin, and J. P. D'Agostino, mapped the Quaternary deposits of the quadrangle and the older rocks in the northern end of the Resting Spring Range. He was especially concerned with the form and origin of the alluvial fans (Denny, 1964). Drewes, in 1958, mapped the Tertiary and Paleozoic rocks of the eastern spur of the Funeral Mountains and of the hills near Devils Hole. Previously he had completed a study of the Funeral Peak quadrangle which adjoins the Ash Meadows area on the southwest (Drewes, 1963). We are grateful for criticism of this report by several of our colleagues in the Geological Survey and also by Charles B. and Alice P. Hunt.

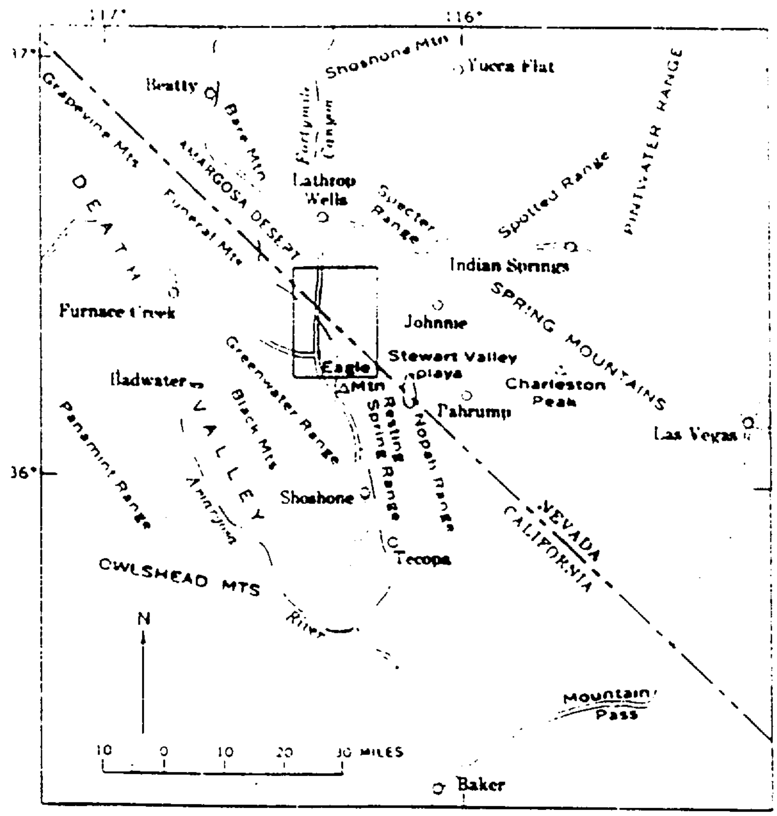

Figure 1.—Index map of parts of Nevada and California showing location of Ash Meadows quadrangle.

GEOGRAPHY

The Ash Meadows quadrangle (pl. 1) lies within the Amargosa Valley and includes Death Valley Junction, an abandoned mining settlement on the dismantled Tonopah and Tidewater Railroad. The junction is at the terminus of one of the principal access routes into Death Valley from the east (fig. 1). One of the two highways leading southward from Tonopah and Beatty, Nev., to Baker, Calif., transects the quadrangle; the other follows the length of Death Valley.

The quadrangle is largely a plains area; only about 10 percent is mountain or hill. Local relief on the plains is rarely more than 50 feet. The average gradient of the Amargosa River is about 14 feet per mile. Shadow Mountain, the higest peak (alt 5,071 ft), lies about 3,000 feet above Alkali Flat, the lowest point. The mountain fronts are both linear and embayed.

The highlands are bordered by sloping piedmonts, largely coalescing fans that range from 1 to 6 miles in length. There are only small areas of pediment cut on rocks of late Tertiary age and commonly veneered with gravel. The fans have slopes near their apices that range from about 300 to 800 feet per mile. Downfan, slope decreases to less than 100 feet per mile.

The surface of most fans is not smooth but is cut by washes that lie many feet below the surrounding gravel plain. Such dissection reaches depths of as much as 60 feet near the highlands. Near the toes, however, the surface approaches a plain, and the floors of the larger washes may actually lie slightly above their surroundings. The skin of most fans is a mosaic of areas of desert pavement and of wash.

The piedmonts lead down to broad lowlands such as the flood plains of the Amargosa River and of Carson Slough or the playa of Alkali Flat and of a second unnamed playa in the northeast corner of the quadrangle. Both of these playas are no longer enclosed but drain to the Amargosa River. Marshlands border the upper reaches of Carson Slough.

The surface of the Amargosa Desert exhibits patterns formed by surface features of many kinds: arrangements of salt efflorescences, of stones and finer material, or of miniature terraces; mosaics composed of braided channels and areas of desert pavement; and groups of shrubs.

The hills and mountains in the quadrangle have bare slopes of 3,000–5,000 feet per mile or roughly 30°–45°. Small deposits of scree are found in many places, but most of the mapped scree is on Shadow Mountain. Dark-gray quartzite forms the upper slopes of Shadow Mountain; its lower flanks are of similar but slightly paler colored rock. Viewed from the west, the contact between these rocks of differing color is horizontal, and the mountain's summit appears in the late afternoon light as if in shadow. A tongue-shaped landslide projects eastward from the base of the Funeral Mountains just south of Bat Mountain, and on the piedmont northeast of the mountain, landslide masses of Tertiary limestone form low white hills (Denny, 1961).

Sand dunes supporting a scattered growth of mesquite occur in the northern half of the quadrangle; the largest sand-covered areas are on the plains east of Carson Slough where the dunes reach heights of 50 feet. A small butte, capped by a spring deposit, rises about 150 feet above Fairbanks Spring near the head of Carson Slough; other, less conspicuous mesas of similar material lie south of Longstreet Spring. Still other small unmapped bodies of spring deposits occur in the Ash Meadows.

There are nearly 20 flowing springs in or near the Ash Meadows (Lyle, 1878; Ball, 1907; Stearns, Stearns, and Waring, 1937; Hunt and Robinson, 1960). Most of these springs, including several circular pools 20–40 feet in diameter and 5–20 feet deep, are in Cenozoic rocks. Two springs, Point of Rocks and Devils Hole, are in Paleozoic limestone and dolomite. Devils Hole is a rectangular opening about 50 feet deep that contains a pool about 10 feet wide by 65 feet long. Many of the springs contain the *Cyprinodont* fish whose presence in such isolated places led Hubbs and Miller (Miller, 1946, 1948; Hubbs and Miller, 1948) to postulate the existence of very extensive pluvial lakes and connecting drainageways over much of western United States during the Pleistocene.

The water table is near the surface in much of the Ash Meadows and at Death Valley Junction. Loeltz (1960) estimates that the annual discharge from the springs is about 18,000 acre feet of water annually. The limestones and dolomites of the northeast part of the quadrangle provide channelways to bring water into the area. Although similar rocks apparently form the treeless hills between Devils Hole and Johnnie (fig. 1), it is doubtful that these hills receive sufficient precipitation to produce such a discharge. The spring water probably has its ultimate source in precipitation on the northern part of the Spring Mountains about 20 miles to the east. Hunt and Robinson (written commun., 1962) suggest that the springs in the Ash Meadows have their source in the lowlands near Pahrump, which in turn derive their water from the Spring Mountains. The lowest part of these lowlands is a playa, known as Stewart Valley, which is about 300 feet higher than and about 10 miles southeast of Ash Meadows.

The only mining in the quadrangle is a small bentonite prospect north of Bat Mountain. The numerous clay pits in the Meadows and near Clay Camp have not been worked for many years, probably at least since the railroad was dismantled about 1940.

The climate is warm and dry. The average annual precipitation probably is between 3 and 4 inches per year in the lowland (Troxell and Hofmann, 1954; U.S. Weather Bureau, 1932) and slightly higher on the adjacent mountains. Snow seldom reaches the Amargosa Desert but mantles the neighboring mountains for short periods in winter. On the valley floor, the average maximum monthly temperature for July is more than 100°F; minimum winter temperatures are below freezing in December and January. The highest temperature recorded at Clay Camp near the center of the quadrangle was 118° F in July; the lowest was 3°F in December. A thermometer resting on a desert pavement southwest of Grapevine Springs, the bulb covered by a layer of fine sand about one grain thick, registered a high of 162° F during the period from May 1957 to February 1958.

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The region is virtually treeless, but desert shrubs are scattered over the surface of the fans. Mesquite grows on all sand dunes and along the Amargosa River west of California State Highway 127. A mesquite tree near Franklin Well is about 15 feet high, and some in the Ash Meadows reach heights of 10 feet.

STRATIGRAPHY

Rocks of Paleozoic and of Tertiary age make up the highlands; the lowlands are mantled by Quaternary deposits. Shadow Mountain and the hills near Devils Hole include about 5,000 feet of Cambrian strata, chiefly quartzite and massive limestone or dolomite. An equal thickness of Silurian to Mississippian limestone and dolomite forms the backbone of the northern part of the spur of the Funeral Mountains that lies within the quadrangle. Bat Mountain and the remainder of the spur comprise 3,000 to 5,000 feet of fluvial and lacustrine deposits of Tertiary age. Similar rocks are exposed in the hills at the north end of the Resting Spring Range. The volcanic rocks of the Greenwater Range project into the southwest corner of the quadrangle to form a small butte.

Arid-basin sediments of Quaternary age cover the lowlands. Gravel, breccia, sand, and silt form alluvial fans; silt and clay underlie playas. Quaternary deposits of limited extent include spring or swamp deposits, scree, sand dunes, landslide breccia, and alluvial deposits along washes.

PALEOZOIC ROCKS

The areal extent of the Palesozoic rocks in the highlands is small. These formations were not studied in detail, and their description is perforce brief. Dark-gray or banded medium-gray and dark-gray dolomite, limestone, and quartzite are the most abundant rocks. In this area, somber colors are typical of the Paleozoic rocks and brighter yellowish-brown or reddish-brown hues are characteristic of outcrops of the younger formations. The formation names assigned to the Paleozoic rocks on the east side of the quadrangle are based on similarity of the rocks to those described by Hazzard (1937) in the Nopah and Resting Spring Ranges. The rock units recognized in the Funeral Mountains on the west side are based on similarity to rocks described by McAllister (1952) in the northern Panamint Range and elsewhere in the Funeral Mountains (McAllister, written commun., 1961).

ROCKS OF THE RESTING SPRING RANGE

QUARTZITE OF SHADOW MOUNTAIN

Shadow Mountain[1] is composed of quartzite and minor amounts of micaceous shale and quartzite-pebble conglomerate. The total thickness of these rocks is probably several thousand feet. Beneath this massive quartzite and adjacent to the block of unidentified limestone and dolomite at the west base of the mountain are about 250 feet of interbedded quartzite and phyllitic shale and a few thin beds of light-brown dolomite. The quartzite under the lower slopes of the mountain is light gray to grayish orange pink; under the upper slopes which simulate the shadow, the quartzite is a more somber pale red to pale yellowish brown. On fresh surfaces the rocks are more varied in color, with light values of red, purple, brown, and green in the lower part of the section and dark values of brown and purple in the upper part. The individual strata are commonly 1–5 feet thick, and crossbedding, ripple marks, and scour features are characteristic. Most of the quartz grains are coarse to medium-coarse sand, but granule beds and pebble beds are present also. Micaceous silty beds are intercalated with some of the quartzite.

This sequence of quartzite is lithologically similar to the Stirling Quartzite as described by Hazzard (1937, p. 306–307). Noble and Wright (1954), however, believe that both the Wood Canyon Formation and the Stirling Quartzite are present in Shadow Mountain (Quartzite Peak). The thin-bedded rocks near the west base of the mouintain may be the top of the Johnnie Formation.

UNIDENTIFIED LIMESTONE AND DOLOMITE

A small fault block of interbedded limestone and dolomite lies at the west base of Shadow Mountain. The limestone is medium light gray to pale yellow brown, and the dolomite is light gray to medium dark gray. Chert is absent except for a few siliceous nodules and stringers. The bedding planes in these much-deformed rocks are inconspicuous or discontinuous, and breccia zones are abundant. The minimum thickness of rock exposed is perhaps 200 feet. These strata are possibly of Middle Cambrian or Upper Cambrian age because the older carbonate rocks are brown or very pale orange and because most younger carbonate rocks of Paleozoic age contain abundant chert.

ROCKS OF THE DEVILS HOLE AREA

The hills near Devils Hole in the northeast part of the quadrangle are underlain by three sequences of Cambrian limestone and dolomite, which are separated by two thin but conspicuous clastic units contain-

[1] Called Quartzite Peak on other maps. See Hazzard (1937, fig. 2), Noble (1941, pl. 1), Noble and Wright (1954, pl. 7), Jennings (1958).

ing abundant fossils. The whole section is 2,000–3,000 feet thick. The upper clastic unit and overlying limestone and dolomite are part of the Nopah Formation. The middle sequence of carbonate rocks and the lower clastic unit together form the upper division of the Bonanza King Formation of Palmer and Hazzard (1956). The lower sequence of limestone and dolomite, part of the lower division of the Bonanza King Formation, crops out only in one small area at the edge of the quadrangle east of Devils Hole. The adjacent hills further to the east are composed of the rocks of the Devils Hole area and older beds of Cambrian age.

BONANZA KING FORMATION

Only about 100 feet of the lower division of the Bonanza King Formation is exposed in the quadrangle. Cliff-forming medium- to dark-gray limestone and dolomite form beds 1–3 feet thick. The clastic unit at the base of the upper division is 100–200 feet thick and consists of shale and siltstone intercalated with thin fossiliferous limestone beds; it forms a pale yellow-brown ledge between the gray cliffs of carbonate rock. The bulk of the upper division is banded light-gray and medium-gray limestone and dolomite in units 100–200 feet thick. About 60 percent of the rock is limestone and 40 percent dolomite. This proportion is reversed for correlative rocks in the Nopah Range (Hazzard, 1937, p. 277) east of Shoshone (fig. 1).

The trilobites in the lower clastic unit, identified by A. R. Palmer, U.S. Geological Survey, are a Middle Cambrian assemblage (USGS colln. 2456–CO) that includes *Alokistocare* sp. and "*Ehmania*" sp. The same lithology and fauna occur in Hazzard's (1937) unit 7A, the base of the Cornfield Springs Formation in the Nopah Range. Palmer and Hazzard (1956) revised this part of the section and dropped the name Cornfield Springs Formation. Although the name is no longer valid in the type area, the lithologic division found there is practical in the Nopah Range and at least as far north as the Devils Hole area. The uniform gray dolomite beneath the lower clastic unit in the latter area is correlative with the Bonanza King Formation of Hazzard (1937) and the lower division of the Bonanza King Formation of Palmer and Hazzard (1956). The banded limestone and dolomite is correlative with the Cornfield Spring Formation of Hazzard (1937) and the upper division of the Bonanza King Formation of Palmer and Hazzard (1956).

NOPAH FORMATION

In the northernmost of the hills near Devils Hole, about a mile southeast of Longstreet Spring, the Nopah Formation rests conformably on the Bonanza King Formation. The basal unit, the upper clastic beds mentioned above, is a yellowish-brown shaly limestone that is about 150 feet thick. It contains several highly fossiliferous bioclastic brown limestone units 4–8 feet thick. Other bioclastic limestone beds near the top of the shaly limestone unit and in the bottom of the overlying dolomite and limestone unit are sparsely fossiliferous. The top of the shaly unit also contains some nodular limestone. The dolomite and limestone above the basal unit are similar to the upper division of the Bonanza King Formation. The total thickness of the formation exposed is about 1,000 feet, the top half or more being absent.

The basal shaly limestone unit contains a trilobite assemblage that has been identified by A. R. Palmer as belonging to the Nopah Formation. The assemblage comes from two collections. The lower one (USGS colln. 2457–CO) from near the base of the formation contains:

Cernuolimbus cf. *C. semigranulosus* Palmer
Dunderbergia cf. *D. variagranula* Palmer
Homagnostus obesus (Belt)
Minupeltis cf. *M. conservator* Palmer
Pelagiella sp.
Prehousia sp.
Pseudagnostus cf. *P. communis* (Hall and Whitfield)
Chancelloria sp.

According to Palmer, this collection is characteristic of the Dunderberg Shale at Eureka, Nev.

The upper collection (USGS colln. 2458–CO), from near the top of the shaly limestone unit and 80 feet above the lower collection, contains:

Cheilocephalus sp.
Dellea? sp.
Elviniella sp.
Homagnostus sp.
Oligometopus breviceps (Walcott)
Pseudagnostus sp.
Pterocephalia cf. *P. sanctisabae* Roemer
Pseudosaratogia leptogranulata Palmer
Sigmocheilus sp.
Linnarssonella sp.

According to Palmer, these fossils are typical of the assemblage found just above the middle of the Dunderberg Shale in central Nevada.

ROCKS OF THE FUNERAL MOUNTAINS

HIDDEN VALLEY DOLOMITE

Near the north end of the southeast spur of the Funeral Mountains, about 500 feet of thick-bedded medium-gray dolomite including some darker and lighter beds underlies two small areas west and southeast of a knob at altitude 3,377 feet. The dolomite contains a little chert but no fossils and is assigned to the upper part of the Hidden Valley Dolomite because it lies beneath a sandstone-bearing and quartzite-bearing dolomite identified by J. F. McAllister (written commun., 1961) as the base of the Lost Burro Formation. The dark-gray Ely Springs Dolomite is not exposed.

LOST BURRO FORMATION

A light- and medium-gray dolomite that contains a little clastic limestone and is 2,000–3,000 feet thick is assigned to the Lost Burro Formation. It overlies the Hidden Valley Dolomite with apparent conformity. The basal 225 feet of the formation contains clastic rocks. The lowest 150 feet of the basal unit is gray dolomite that contains some brown dolomitic sandstone and sandy dolomite and underlies a bench. Above these rocks is 75 feet of medium-gray dolomite and some light-gray, blackish-brown-weathering quartzite in beds 1–3 feet thick. The basal clastic unit is identified as the Lippincott Member of the Lost Burro Formation by J. F. McAllister (written commun., 1961).

Dominantly light gray to yellowish gray, slightly cherty dolomite about 1,000 feet thick overlies the Lippincott Member of the Lost Burro Formation. About 250 feet above the clastic rocks there is a 50-foot-thick unit of dark-gray dolomite beds, and about 750 feet above the clastic rocks some dark-gray limestone containing horn corals, algae, and stromatoporoids is interbedded with the dolomite.

Medium-gray thick-bedded dolomite and limestone about 1,500 feet thick form a cliffy unit near the top of the formation. A particularly dark banded dolomite occurs at the base of the unit, and at the top of the unit there is some interbedded limestone. The uppermost 50 feet of the formation, as identified by McAllister, consists of medium-dark-gray platy limestone that contains silty partings, light-gray sandstone, and purplish-gray quartzite. Some limestone beds interbedded with or just above the quartzite are crinoidal and contain fragments of cephalopods and gastropods.

TIN MOUNTAIN LIMESTONE

A dark-gray cherty limestone, about 450 feet thick, that forms much of the crest of the southeasternmost spur of the Funeral Mountains is assigned to the Tin Mountain Limestone. It lies comformably on, and grades up from, the underlying silty limestone and interbedded quartzite. At the base of the formation some crinoidal limestone contains fragments of cephalopods and gastropods. A little pale-yellow-brown dolomite overlies the crinoidal limestone. The bulk of the formation contains silty partings, though fewer than in the underlying rock;

some of the silty partings are reddish brown. The amount of chert increases upward.

Corals, Bryozoa, and brachiopods are common throughout the formation and were collected in two places. Helen Duncan, U.S. Geological Survey, identified the corals and Bryozoa; Mackenzie Gordon, Jr., U.S. Geological Survey, identified the other forms. The first collection (USGS 20579-PC) was made near the southernmost tip of the southeastern spur of the Funeral Mountains a quarter of a mile S. 70° E. of a knob 2,997 feet in altitude in the Ryan quadrangle. This location is at or near the site mentioned by Noble (1934, p. 177) and Noble and Wright (1954, p. 155). The collection contains:

Rylstonia? sp. indet.
Cyathaxonia sp.
Cladochonus sp. indet.
Fenestella sp. indet.
Pelmatozoan debris
Productoid cf. *Levitusia* sp. indet.
Rhipidomella sp.
Punctospirifer sp.
Spirifer 2 spp.
Straparollus (*Euomphalus*) sp.

The second collection (USGS 20580-PC) is from a site in the Ash Meadows quadrangle at elevation 3,680 feet, half a mile S. 10° W. of a knob (alt 4,756 ft) and contains:

Enygmophyllum sp.
Amplexus? sp. indet.
Cyathaxonia sp.
Cladochonus sp.
Fenestella 3 spp. indet.
Penniretepora 2 spp. indet.
Diploporaria? sp.
Rhipidomella sp.
Leiorhynchus? sp.
Crurithyris sp.

According to Duncan and Gordon, these faunas are dated as Early Mississippian and are typical of the Tin Mountain Limestone.

PERDIDO(?) FORMATION

The southeast spur of the Funeral Mountains has two peaks about three-quarters of a mile apart; both are less than a quarter of a mile inside the adjoining Ryan quadrangle. The southern peak (alt 4,962 ft) is built of a very cherty limestone tentatively assigned to the Perdido Formation. The east slope of the peak within the Ash Meadows quadrangle is underlain by 400–500 feet of these cherty rocks, a medium-dark-gray silty limestone that weathers pale yellow brown. The base of the formation is taken as the lowest unit that contains abundant chert; the top is not present in the area. No fossils were collected, and the reliability of the chert as a formation indicator is questionable.

TERTIARY ROCKS

Rocks of Tertiary age are exposed on the east flank of the Funeral Mountains and at the north end of the Resting Spring Range. The total area of outcrop is only about 6 percent of the area of the quadrangle, roughly 15 square miles, but Tertiary rocks probably lie beneath a veneer of Quaternary deposits throughout much of the lowlands. The rocks are largely alluvial-fan and playa deposits but include some volcanic rocks. Sedimentary units grade laterally over short distances from shale to conglomerate or from limestone to fanglomerate. Such facies changes and an absence of index fossils make it impossible to correlate the Tertiary rocks from place to place. Description of these rocks is by their geographic area.

ROCKS OF THE FUNERAL MOUNTAINS

Tertiary sedimentary rocks underlie about 5 square miles of the southeast spur of the Funeral Mountains that lies within the Ash Meadows quadrangle. Seven major lithologic units include, from bottom upward: lower fanglomerate, lower shale, lower limestone, lower conglomerate, upper limestone and shale, upper fanglomerate, and upper conglomerate. A major unconformity separates the lower units from the upper ones, and minor unconformities that have only a slight angular discordance underlie the lower conglomerate and the upper fanglomerate. The composite maximum thickness of the units is about 5,000 feet. The strata rest unconformably on Paleozoic rocks, are tilted eastward about 30°, and are broken by normal faults of at least two ages. These Tertiary beds were mapped by Noble and Wright (in Jennings, 1958) as of Oligocene age, a part of their sequence of older Tertiary sedimentary rocks, including the Titus Canyon Formation (Stock and Bode, 1935). Similar rocks, also mapped by Noble and Wright (in Jennings, 1958), cro · out in the foothills to the west in the Ryan quadrangle and to the south in the Eagle Mountain quadrangle. At the north end of the spur in the Ash Meadows quadrangle, the three units at the base of the Tertiary sequence are the lower fanglomerate, the lower shale, and the lower limestone. In the Ryan quadrangle, about 2 miles to the west, a similar succession of rocks form a long, north-trending ridge (Jennings. 1958) and may be correlative with the rocks of the spur.

LOWER FANGLOMERATE

The thick fanglomerate near a knob (alt 3,377 ft) at the north end of the spur of the Funeral Mountains is the lowest stratigraphic unit of Tertiary age in the spur. It is as much as 600 feet thick near the knob, but thins southeastward and probably pinches out less than a mile from the knob. The fanglomerate is thick bedded to massive, grayish red to brownish gray. The boulders and cobbles within it are chiefly gray dolomite, pale-yellow-orange dolomite, purplish coarse-grained quartzite, and limestone. A few shale particles are also present. The association of these lithologies suggests a source in the Stirling Quartzite and the Noonday Dolomite, neither of which are now exposed nearby. The fragments of gray dolomite may have come from rocks of Middle Cambrian to Devonian age, for most older rocks contain only brown dolomite, and few younger rocks contain any dolomite. The lower fanglomerate is similar to but not correlative with the upper fanglomerate, which caps the south end of the spur.

LOWER SHALE

A section of reddish shale and associated rocks underlies the north-sloping valley east of the 3,777-foot knob and is present in small fault blocks south and southwest of the knob. The section is largely white to light-red shale and siltstone, plus small amounts of sandstone, fine-grained conglomerate, limestone, tuffaceous rocks, bentonite, and one bed of indurated rhyolite tuff. The rocks are poorly exposed. The bedding planes are commonly a few inches apart, except for the tuffaceous rocks which are thick bedded. The layer of indurated tuff is 10–40 feet thick and weathers into blocks. Unweathered tuff is light brownish black to grayish pink; its weathered surface is brownish black. More than 90 percent of the tuff consists largely of glass shards, brown cryptocrystalline material, and alteration material. Imbedded in the tuff are fragmental crystals of sanidine, quartz, plagioclase (albite or sodic oligoclase), biotite, titaniferous magnetite, and a few rock fragments. Sanidine forms large subhedral fragments, and some of the fragments contain fresh plagioclase. Most plagioclase is partly altered to sericite and has lost the fresh appearance of sanidine. Some biotite is oxidized or replaced by sericite. The shard structure of the groundmass has not been stretched (not welded), but the glass of the shards has crystallized to a radial, fibrous material. Similar devitrified material is scattered in the groundmass. The lower shale unit can be separated from the upper limestone and shale unit because the older unit contains bentonite and tuff.

LOWER LIMESTONE

More than 50 feet of yellowish-gray fine-grained limestone overlies the lower shale north and west of the 3,377-foot knob. It is thick bedded and forms prominent cliffs and knobs. The limestone con-

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tains some fossils that resemble algae and plant stems. North of the knob, the limestone grades laterally into a conglomerate whose cobbles, pebbles, and matrix are a similar limestone. The unit is probably correlative with the thick limestone on the ridge to the west of the quadrangle and is distinguishable from the upper limestone only by its stratigraphic position.

LOWER CONGLOMERATE

A conspicuously red pebble conglomerate and sandstone, more than 1,500 feet thick, lies unconformably on the lower shale unit. The basal unconformity truncates the lower limestone unit, more than 100 feet of the underlying shale, and the indurated tuff. Most of the conglomerate is uniformly red, but in the area of outcrop west of the large landslide masses, a tongue of yellowish-brown conglomerate lies between red beds. The lower conglomerate contains well-rounded pebbles and scattered cobbles of reddish-gray felsite, quartzite, and some granitic rocks. Beds range from ¼ to 3 feet thick. The unit is distinguishable from the upper conglomerate only by its stratigraphic position.

UPPER LIMESTONE AND SHALE

A varicolored shale and overlying yellowish-gray limestone have a combined thickness of 150–200 feet and unconformably overlie the lower conglomerate (fig. 2*A*). The basal unconformity is large, for the unit truncates a postlower conglomerate horst and graben. The shale is thin bedded and dominantly red, locally green or olive gray. Intercalated with the shale are a few beds of siltstone, sandstone, limestone, tuffaceous rocks, and gypsum. Outcrops of the shale are badly slumped. The thickness is generally about 75 feet, but in a few places may be much thicker.

Above the shale is about 60 feet of thick-bedded cliff-forming limestone that thickens northward to perhaps 200 feet. Algal markings are abundant, and, in a few places, silicified plant stems as large as ½ by 3 inches are common, but diagnostic fossils are absent. Toward the north the limestone interfingers with the overlying fanglomerate: toward the south it is overlain by about 50 feet of tuffaceous siltstone and limestone.

UPPER FANGLOMERATE

A poorly bedded boulder fanglomerate lies with slight angular discordance on the upper limestone and shale. As much as 1,500 feet of fanglomerate forms the southernmost ridge of the spur, but thins northward to less than 100 feet and interfingers with the overlying conglomerate. The basal unconformity truncates the thin tuffaceous beds capping the underlying unit to the south and truncates a jumble

A

B

FIGURE 2.—Paleozoic and Tertiary rocks of the [illegible] Mountains and alluvial-fan deposits near Resting Spring Range. *A*, Unconformity [illegible] between the Perdido(?) Formation of Mississippian age (dark beds in left foreground) and the upper limestone and shale unit of Oligocene(?) age (light-colored beds [illegible] foreground); the limestone at the top of this unit is overlain by the [illegible] cliffs in right background. View looking north from southeast of [illegible] Mountains near eastern edge of Ryan quadrangle. *B*, Bouldery fanglomerate [illegible] probably mudflow [illegible] deposit is faintly stratified. Scale is [illegible] NE¼SE¼ sec. 26, T. 25 N., R. 6 E.

of large blocks of the underlying limestone to the north. However, south of the landslide to the south of Bat Mountain, the fanglomerate appears to interfinger with the underlying limestone. The fanglomerate consists of subangular cobbles, boulders, and subordinate pebbles set in a limy and sandy matrix. The fragments are chiefly purplish quartzite, gray dolomite, and very pale orange dolomite: limestone and shale are also present. This assemblage of fragments suggests a source in lower Paleozoic rocks, particularly the Cambrian sequence.

UPPER CONGLOMERATE

A few hundred feet of moderate-red pebble conglomerate and sandstone overlie and intertongue with the upper fanglomerate along the east base of the mountains. The pebbles are well rounded and consist of quartzite, volcanic rocks, and granitic rocks, much like those in the lower conglomerate.

AGE AND CORRELATION

The Tertiary rocks of the Funeral Mountains are perhaps as old as the Oligocene Epoch. These largely clastic rocks resemble the Titus Canyon Formation of Stock and Bode (1935) which occupies similar structural troughs to the northwest along the eastern edge of the Funeral Mountains and their northern extension, the Grapevine Mountains (fig. 1). Correlation between the Titus Canyon Formation, which is well dated as early Oligocene, seems probable but is not as yet demonstrable. If the boulders in the upper and lower fanglomerates of the spur are, in fact, from the lower Paleozoic rocks of the region, these fanglomerates are probably older than the Miocene or Pliocene Furnace Creek Formation, for the source area of lower Paleozoic rocks was to the west of the Ash Meadows quadrangle in an area now buried beneath the Furnace Creek Formation and younger beds.

ORIGIN AND ENVIRONMENT

The Tertiary rocks of the spur of the Funeral Mountains within the Ash Meadows quadrangle were deposited in a basin occupied by a fluctuating or intermittent lake. Alluvial fans bordered the mountains that formed the western side of the basin, and volcanoes that ejected pyroclastic material of rhyolitic composition lay to the northeast. The fanglomerates were derived from highlands whose base was not more than 3–4 miles distant and probably was close by. Within the quadrangle, the lower fanglomerate thins southward, but in the Ryan quadrangle about 2 miles to the west it is tremendously thickened. The upper fanglomerate thins rapidly to the northeast, and north of the landslides intertongues with conglomerate. Both fanglomerates are largely poorly sorted, coarse-grained detritus from sedimentary rocks of Cambrian age and possibly also from other Paleozoic rocks. In the main body of the Funeral Mountains to the west, Cambrian rocks are largely buried beneath younger Paleozoic sediments. The fanglomerates, therefore, were probably derived from highlands southwest of the Furnace Creek fault zone and perhaps in the position of the modern Greenwater Range and the Black Mountains to the southwest. Part of the source area of older Paleozoic rocks is now buried beneath the volcanic and sedimentary rocks of Tertiary and Quaternary ages, but in much of the source area rocks of Precambrian age are exposed and the rocks of Paleozoic age have been removed (Drewes 1963).

The two bodies of red conglomerate are probably stream deposits. The sorting, rounding, and small size of the fragments suggest a distant source, at least distant with respect to the provenance of the fanglomerate. The pebbles of felsitic, granitic, and sedimentary rocks are an assortment that may have come from the mountains north of Lathrop Wells (fig. 1). The limestone and shale units were deposited in and along the edge of a fluctuating lake or playa. The trace of gypsum suggests at least a brief period during which the lake had no outlet. Explosive eruptions of rhyolitic volcanoes northeast of the quadrangle spread tuff and ash throughout the area.

ROCKS OF THE RESTING SPRING RANGE

A sequence of Tertiary rocks having a total thickness of several thousand feet crops out at the north end of the range. About 2 miles north of Shadow Mountain a reddish-brown fanglomerate rests unconformably on Cambrian rocks and forms low hills. Overlying the fanglomerate is a thick section of rocks that are chiefly sandstone and claystone. These finer grained clastics are in turn capped by another fanglomerate that makes up the hills east of Grapevine Springs. No fossils have been found in the Tertiary rocks north of Shadow Mountain. The younger fanglomerate is perhaps early Pleistocene. The older fanglomerate and the overlying fine-grained beds are similar lithologically to some of the Tertiary rocks on Bat Mountain.

FANGLOMERATE

Low hills along the state line south of the Old Traction Road are composed of reddish, firmly cemented boulder fanglomerate which contains cobbles and boulders of quartzite and of Paleozoic carbonate rocks as much as several feet in maximum diameter. The basal 30–50 feet of the unit is a breccia of quartzite blocks in a gray but locally reddish matrix. The fragments are commonly 2–3 feet in diameter; a few are as large as 6 feet. The breccia grades upward into faintly bedded or massive reddish fanglomerate. Toward the top, the largest fragments are of pebble size and the beds of fanglomerate are separated by lenses of brown pebbly sandstone. The fanglomerate is about 800 feet thick and rests with angular unconformity on quartzite that is strongly brecciated. The top of the unit is placed at the top of the uppermost bed of fanglomerate.

The fanglomerate was deposited as gravel on an alluvial fan. The basal breccia is probably scree derived from an adjacent steep face or cliff composed of quartzite. Weathering broke the upper few feet of the quartzite into blocks, and those near the surface accumulated as talus. The others still remain more or less in place on top of less-weathered quartzite. Perhaps some of the breccia slid downslope, such movement contributing to the shattering of the blocks.

The highland source was Shadow Mountain, and the areas of carbonate rocks were probably more extensive than at present. If the reddish color of the fanglomerate matrix is inherited from that of the weathered source rocks, it suggests an episode of weathering unlike any during the later Quaternary. Throughout the Death Valley region, Quaternary alluvial deposits composed of fragments of Paleozoic carbonate rocks have not weathered to red colors.

The fanglomerate is nonfossiliferous, but it is without doubt of Tertiary age. Lithologically it is indistinguishable from the Oligocene(?) fanglomerate of the Funeral Mountains about 10 miles distant.

SANDSTONE AND CLAYSTONE

The lowlands north and northwest of the Resting Spring Range are underlain by a thick sequence of fine clastic rocks largely concealed beneath younger formations. Moderate-brown to very light gray, locally yellow or green, sandstone and claystone predominate, but subordinate amounts of conglomerate, siltstone, tuff, and limestone are present also. The rocks are loose to moderately cemented and are well bedded, the individual layers ranging from paper-thin to several feet thick. The sandstone is locally pebbly and shows crossbedding and ripple marks. Claystone and siltstone are gray, and the individual beds are commonly not more than an inch thick. In a few places the claystone is gypsiferous. Scattered conglomerate beds contain pebbles of quartzite, limestone, dolomite, and tuff; one such bed contains many cigar-shaped pebbles that are fractured. Layers of white tuff containing pumice fragments are common. One or two beds of pale-yellow-orange, very fine grained limestone occur in the lower part of the formation not far from the state line.

In the north-central part of the quadrangle, clastic rocks, mapped as part of the sandstone and claystone unit, apparently lie unconformably beneath the surrounding Quaternary sediments. Near Clay

Camp, both flat-lying and inclined layers of sandstone, siltstone, conglomerate, and fanglomerate are poorly exposed. The coarser grained beds contain pebbles of quartzite, limestone, dolomite, conglomerate, and volcanic rocks.

In the hills east of where the Old Traction Road crosses the State line, the sandstone and claystone unit rests conformably on and is interbedded with the uppermost pebble beds of the underlying fanglomerate. On the north flank of these hills the unit is overlain by and interbedded with the fanglomerate near Grapevine Springs. The total thickness of the unit may be as much as 2,000 feet.

The sandstone and claystone unit includes both fluvial and lacustrine deposits. The mapping outlines a depositional basin at least 12 miles long in a northwest direction. The bordering highlands were either low or far removed in comparison with those of the preceding or the following epochs of fanglomerate deposition. Limestone and evaporites are scarce; apparently during much of the time the depositional basin did not include a playa. Now and then there were showers of ash.

No fossils have been found in the sandstone and claystone unit. These rocks closely resemble some of the rocks of Oligocene(?) age in the southeast spur of the Funeral Mountains, such as the upper limestone and shale unit.

ORIGIN AND ENVIRONMENT

The Tertiary rocks at the north end of the Resting Spring Range were deposited both as alluvial fans and as lake sediments. The depositional basin was occupied by a playa only for short periods. The present-day configuration of mountain and basin has existed almost unchanged since these rocks began to be deposited. While the sandstone and claystone unit was being laid down, the north end of the Shadow Mountain block was lower and less extensive in relation to the surrounding basin than it was during the time of accumulation of the fanglomerate near Grapevine Springs. A more profound departure from the present is suggested by the presence of deformed fanglomerate in the central lowlands near Clay Camp.

ROCKS OF HILL SOUTHWEST OF DEATH VALLEY JUNCTION

FURNACE CREEK FORMATION

The isolated butte in the southwest corner of the quadrangle includes a few beds of tuff and siltstone assigned to the Furnace Creek Formation of Miocene and Pliocene age (Drewes, 1963). Fine-grained tuff and siltstone form thin beds, and coarse-grained material makes thick beds that contain pumice fragments as much as 1 inch in diameter.

TERTIARY AND QUATERNARY ROCKS

FANGLOMERATE NEAR GRAPEVINE SPRINGS

Boulder-covered hills extending from Grapevine Springs southeastward to the Old Traction Road are underlain by brown thickbedded or massive fanglomerate. Although poorly exposed, the unit apparently includes many hundreds of feet of fanglomerate and intercalated thin beds of pumice and of tuffaceous sandstone. The pebbles and boulders are chiefly subangular fragments of quartzite and Paleozoic carbonate rocks in about equal proportions. The fanglomerate near Grapevine Springs is well indurated, but less so than the older underlying reddish fanglomerate, a few boulders of which are found in the younger fanglomerate unit. Similar fanglomerate, included with that near Grapevine Springs, occurs in a small downfaulted basin just south of Shadow Mountain, in a small area west of the mountain, and in the hills south of Last Chance Spring near the Ash Meadows Rancho. At the north end of the Resting Spring Range the fanglomerate may be as much as 1,000 feet thick. Although over much of the area the rocks appear to be undeformed, the hills east of Grapevine Springs are a cuesta of southward-dipping fanglomerate overlying finer clastic rocks.

On the south slope of Shadow Mountain a narrow downfaulted wedge of brown fanglomerate extends for about half a mile into the quadrangle from the east, and small caps of fanglomerate cover two bedrock spurs a short distance to the west. At least 100 feet of southward-dipping boulder fanglomerate rests unconformably on the quartzite of Shadow Mountain. The fanglomerate includes abundant subangular fragments of quartzite and micaceous shale and also a few fragments of Paleozoic carbonate rocks and of a reddish fanglomerate that resembles the older fanglomerate unit north of the mountain. The fanglomerate is moderately well indurated, is massive or well bedded, and contains conspicuous lenses of white pumice.

In a small area west of Shadow Mountain, a well-bedded pebble fanglomerate rests conformably on finer grained, tuffaceous rocks. In the hills south of Last Chance Spring, at least 500 feet of gray fanglomerate and intercalated tuffaceous sandstone rests with apparent conformity on finer grained beds. This pebbly to bouldery fanglomerate forms clearly defined beds and contains fragments of quartzite and Paleozoic carbonate rocks.

In some places the fanglomerate near Grapevine Springs is clearly unconformable on the underlying rocks; elsewhere its stratification appears to be parallel with that of the underlying sandstone and claystone unit. Near the state line the fanglomerate is not deformed.

The fanglomerate was derived from the Resting Spring Range, and the source may have been about the same size as Shadow Mountain although perhaps not in the same place. The width of outcrop of the fanglomerate at the northwest end of the range is about equal to the distance that bouldery gravel is carried at the present time from the apex of the fan northwest of Shadow Mountain. The fanglomerate accumulated at a time of frequent showers of pumice and ash. The abundance of fragments of reddish fanglomerate in the beds near Grapevine Springs and their scarcity in the Quaternary alluvial fan deposits suggest that the area of outcrop of the older fanglomerate unit north of Shadow Mountain was more extensive during the accumulation of the fanglomerate near Grapevine Springs than at present. The undeformed part of the fanglomerate, which is largely in California west of the Old Traction Road, may be part of a fan that sloped northwestward from Shadow Mountain and had its apex in the NW¼ NE¼ sec. 24, T. 25 N., R. 6 E. If the fanglomerate in Nevada, including the hills near Grapevine Springs and those south of Last Chance Spring, is part of the same fan, it was a little larger than the modern fan northwest of Shadow Mountain.

The few small remnants of the fanglomerate near Grapevine Springs south of Shadow Mountain suggest that an extensive fanglomerate unit once covered that area also.

The fanglomerate near Grapevine Springs is nonfossiliferous. It is perhaps of early Pleistocene age but may belong to the close of the Pliocene Epoch. Because a considerable part of it has been removed by erosion or has been downfaulted and buried beneath later Quaternary deposits, the unit is probably older than the late Pleistocene.

ROCKS OF HILL SOUTHWEST OF DEATH VALLEY JUNCTION

FUNERAL FORMATION

A butte in the southwest corner of the quadrangle is an eastern outlier of the volcanic rocks that form much of the Greenwater Range to the west (Drewes, 1963). About 40 feet of dark vesicular basalt, assigned to the Funeral Formation of Pliocene and Pleistocene(?) age, rests conformably on tuff of the Furnace Creek Formation. Boulders of the basalt mantle the slopes of the butte.

QUATERNARY ROCKS

Most of the Ash Meadows quadrangle is underlain by unconsolidated or, at most, weakly indurated rocks of Quaternary age, largely alluvial-fan and playa deposits accumulated in a desert basin. Surficial deposits of limited extent include dune sand, scree, spring deposits, and landslide breccia. Over broad areas the rocks are not

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exposed in section; only in a few places have they been dissected to depths of as much as 50 feet. The Quaternary rocks are virtually undeformed and unfossiliferous. Artifacts are found on or in the sand dunes, in alluvium along the Amargosa River, and on low terraces along the river and one or two of the larger washes.

The total thickness of the Quaternary rocks is unknown. The drillers' log of a water well at Death Valley Junction lists 25 feet of coarse gravel, in part cemented, resting on about 120 feet of clay that includes two thin, water-bearing gravel beds (Pacific Coast Borax Co., written commun., 1957). A second well nearby is said to have been drilled to a depth of 800 feet, the lower 700 feet entirely in clay (Ben Barlow, oral commun., 1956). Several drillers' logs (Office of State Engineer, Carson City, Nev.) of water wells in the Amargosa Desert near the T and T Ranch, a few miles northwest of the quadrangle, report "gravel and clay" to depths of as much as 700 feet. Whether these wells penetrate Tertiary rocks is unknown.

ARID-BASIN SEDIMENTS

Virtually undeformed strata of Quaternary age, including alluvial-fan, spring, and playa deposits, floor the Amargosa Desert. White clay and silt in the Ash Meadows, for example, intertongue to the east with gravel and sand, part of an alluvial apron that surrounds the hills near Devils Hole. The gravelly alluvium rests unconformably on the Paleozoic rocks of the Devils Hole area, although the hills themselves doubtless owe their existence to faulting. Spring deposits rest on and are intercalated in the clastic sediments.

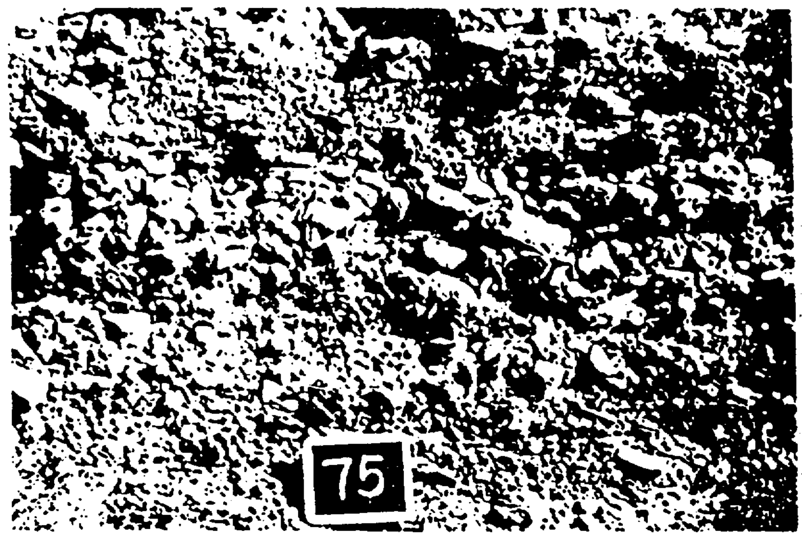
FAN DEPOSITS

The fan deposits include gravel, breccia, sand, silt, and a little clay and are divided into those containing many fragments of quartzite, limestone, and dolomite and those that include abundant pieces of volcanic rock. The fragments are angular and subangular. Boulders are most abundant near the mountain front. The pebbly gravel is commonly crossbedded and is interlayered with coarse, pebbly sand. The bouldery gravel is poorly sorted and irregularly stratified, and forms massive beds several feet thick. Along the strike, the fan deposits may change from bouldery gravel to sand within distances of only a few feet. The lenses of breccia, probably mudflow debris that makes up only a small part of the deposit, are unsorted mixtures of all sizes and shapes; they range from 1 to about 10 feet thick. Where exposed, the fan deposits are cemented by caliche, but over much of the quadrangle the deposits are dissected to depths of not more than 3 feet, and only near the mountain front are there continuous exposures as much as 10 feet high. In general, large highlands are bordered by more extensive fan deposits than are small hills, but the spatial relations of mountain and basin or the occurrence of Recent deformation may upset this generalization.

Much of the surface of the fan deposits is desert pavement. These smooth, gently sloping pavements are composed of closely packed angular fragments of rock whose exposed surfaces are either coated with varnish or etched by solution, depending upon their lithologic composition. Fragments of quartzite, of sandstone, and of volcanic rocks have a coating of desert varnish; basalt and andesite have darker coatings than quartz-rich rocks. Carbonate rocks on a pavement are etched and grooved by solution. The rest of the surface of the fan deposits consists of braided channels and gravel bars whose constituents are also slightly weathered.

Quartzite is the dominant constituent of the coarse fan deposits west of the Resting Spring Range, but quartzite conglomerate and micaceous shale are also present. The deposits include a few lenses of breccia or mudflow debris, chaotic assemblages of slabs of quartzite in a pale-gray silty matrix (figs. 2*B* and 3*A*). In the reentrant north of Shadow Mountain, Quaternary gravel rests unconformably on the older rocks. At the north end of the area underlain by the unidentified limestone and dolomite unit, slightly deformed bouldery gravel, mapped as of Quaternary age, lies against brecciated and discolored carbonate rocks, the contact being either a fault plane or a buried fault scarp. The gravel is well indurated and may belong to the fanglomerate near Grapevine Springs, which crops out about three-quarters of a mile to the southwest. Alluvial deposits southwest of Ash Meadows Rancho are at the mouth of a large wash that drains a large area to the east of the quadrangle.

The alluvial-fan deposits surrounding the eastern prong of the Funeral Mountains are similar to those adjacent to Shadow Mountain (fig. 3*B*). The gravel, however, contains a variety of rock types including limestone, dolomite, quartzite, fanglomerate, sandstone, and tuff. Fan deposits rest unconformably on the Paleozoic rocks of the hills near Devils Hole. The small bedrock hill east of Longstreet Spring, for example, is surrounded by a narrow apron of gravel that, within about 500 feet of the base of the hill, intertongues with white clay. Further from the hill, the deposits are largely fine grained and contain only a few lenses of limestone and dolomite pebbles. The extent of the gravel apron around the hills near Devils Hole is, of course, related to their size. Measurements, discussed in another publication (Denny, 1964), show that the area of the individual gravel fan around these hills is about equal to the size of its source area. Gravel



A

B

FIGURE [illegible].—[illegible] fan and playa deposits of Quaternary age. *A*, Pebble and cobble gravel with [illegible] faint stratification caused by varying proportions of pebbles and [illegible] NW¼NW¼ sec. 23, T. 25 N., R. 6 E. *B*, Faintly stratified pebble and [illegible] gully southeast of Bat Mountain; desert pavement [illegible] NE¼ [illegible] 7, T. 25 N., R. 5 E.

and sand form the plains south and west of Death Valley Junction and are composed largely of volcanic debris from the Greenwater Range which lies to the southwest outside of the quadrangle.

Pebble gravel and sand, the fragments dominantly of volcanic rock, mantle a considerable part of the plains between Amargosa River and Carson Slough. The gravel is coarser grained to the north outside the quadrangle and is the southern end of a broad alluvial plain that rises gradually northward into the hills north of Lathrop Wells (fig. 1). The deposit is crossbedded, and the pebbles in most outcrops are less than 2 inches in diameter. The sandy layers are weakly indurated. Throughout much of the uplands the deposit is only a few feet thick; the maximum observed thickness is about 25 feet in the bluffs overlooking Carson Slough (NE¼ sec. 19, T. 17 S., R. 50 E.) where the gravel contains a few boulders of vesicular basalt.

Estimates of the size of the material on the fans in the Ash Meadows quadrangle were made as part of a general study of fans in the Death Valley region (Denny, 1964). These estimates are an attempt to characterize the gravel on the surface of a fan and to compare the material from fan to fan. The numerical estimates are based on samples selected by means of a grid laid on the surface of the ground (Wolman, 1954). No size estimates were made of the fan debris exposed in cross section, nor were any bulk samples analyzed. The estimates of size of material were made at selected points along a traverse from apex to toe. Values obtained from four such traverses on three fans are shown in the semilogarithmic graph of figure 4.

Two traverses are on the piedmont northwest of Shadow Mountain, on the fan that heads in the reentrant northwest of the peak and that has its apex in the NE¼NE¼NW¼ sec. 18, T. 25 N., R. 7 E. The size estimates of one traverse are based on samples of unweathered gravel mapped as Recent alluvium, although some of the deposits sampled are so small that on plate 1 they are included in the surrounding alluvial-fan deposits. Samples from the second traverse on Shadow Mountain are of gravel on the surface of the alluvial-fan deposits (outside of areas of desert pavement) where the fragments are slightly weathered, having a coating of desert varnish. Thus the values from the first traverse characterize unweathered alluvium that is in transit downfan at present, and those from the second characterize material that has not been moved since it was coated. The fact that the weathered gravel is slightly coarser grained than the unweathered alluvium suggests that transportation and deposition of gravel was more active in the past than at present.

The third traverse is on the surface of Recent alluvium in a wash on a fan in the Devils Hole area, and the fourth is on Recent alluvium on a fan south of Bat Mountain on the west side of the quadrangle.

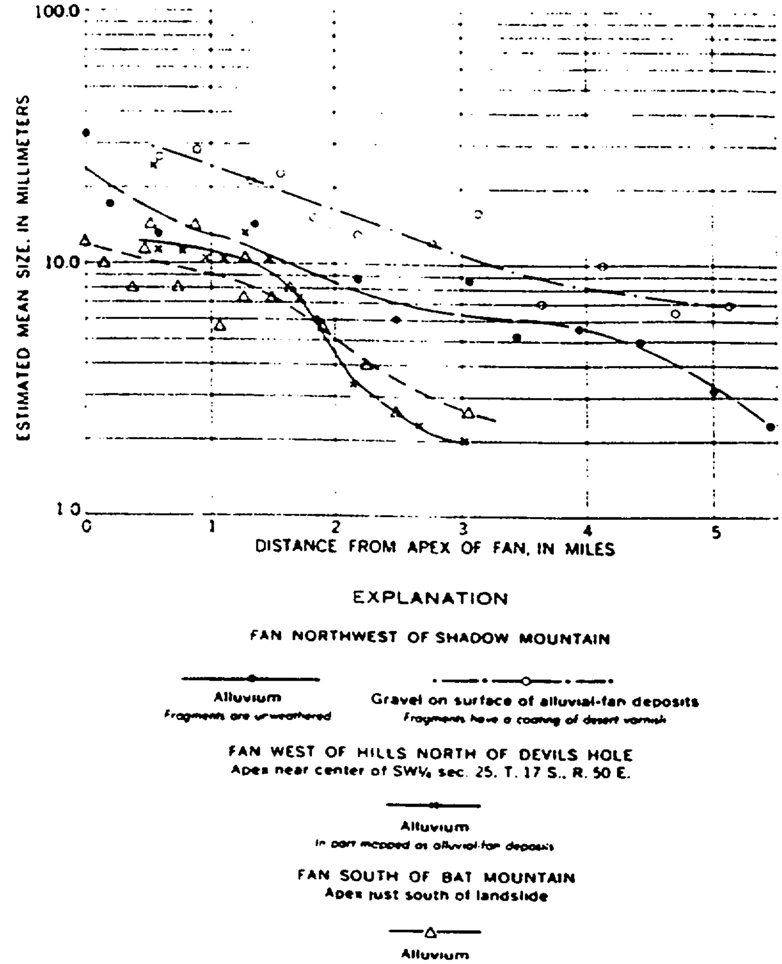


FIGURE 4.—Estimated mean size of samples of material on surface of alluvial fans in Ash Meadows quadrangle. Semilogarithmic scatter diagram showing the relation between the estimated mean size of samples from selected sites and the distance of these sites from apex of fan.

Inspection of figure 4 shows that the rate of decrease in size of material downfan varies from fan to fan. The two highlands on the east side of the Amargosa Valley are both composed of massive sedimentary rocks, and both furnish coarse detritus to the apices of their fans. At distances of more than 1–2 miles downfan, however, the size estimates on the smaller fan decline more rapidly than on the larger one. The small hills do not furnish sufficient water in flood to move the debris very far.

To generalize, the fan deposits adjacent to highlands of massive sedimentary rocks of Paleozoic age are coarse and bouldery. The fan debris gradually decreases in size away from the highland for perhaps two-thirds or three-quarters of the distance to the toe of the fan, where size rapidly decreases. Most of the fan debris at the foot of the Funeral Mountains is slightly finer grained than debris at the base of the other hills because the Funeral Mountains include a slightly greater amount of fine-grained or thin-bedded rocks than the other highlands.

The alluvial-fan deposits in the northwestern and southwestern parts of the area are dominantly of volcanic rock and have relatively distant sources. Within the quadrangle the material is chiefly pebble gravel and sand, although many boulders are present in the deposits west of Death Valley Junction, especially in the area north of the bed of the dismantled Death Valley Railroad. This pebbly gravel contains many boulders of vesicular basalt, and the matrix is tuffaceous.

The spatial relations of mountain and basin are as important as bedrock lithology in alluvial-fan formation. The alluvial deposits of the small fans that spread southward from the Funeral Mountains near the quadrangle boundary have about the same range in size at the mountain front as at the toe of the fan. The material travels southward to the toe and is then carried eastward in the large washes of a fan that heads in the Greenwater Range to the west. The toe of the coalescing fans that surround the southern part of the Funeral Mountains is also the lateral margin on the much larger fan from the Greenwater Range. Eastward from the west edge of the quadrangle, the toe of the Funeral fans lies progressively further from the mountain front and the debris near the toe decreases in size.

PLAYA DEPOSITS

Sand, silt, and clay underlie the lowlands in much of the Nevada part of the quadrangle. The strata are white or pale shades of gray and brown, are loose to weakly cemented, and contain a few lenses of fine pebble gravel. These fine-grained sediments, locally including tuffaceous materials and evaporites, probably accumulated in part near the distal end of an alluvial fan and in part on a playa. Fan gravel is gradational into playa deposits. The contact between them is placed where more than half of the material is sand, silt, and clay.

The playa deposits are well exposed. Numerous excavations—the clay pits—have been dug in the Ash Meadows and in the Amargosa Desert near Clay Camp. Natural exposures occur along the wash east of Rogers Spring, near Fairbanks Spring, along the west side of Carson Slough from 2 to 3 miles north-northeast of Clay Camp, and near Franklin Well. In the northeast corner of the quadrangle (S½ sec.

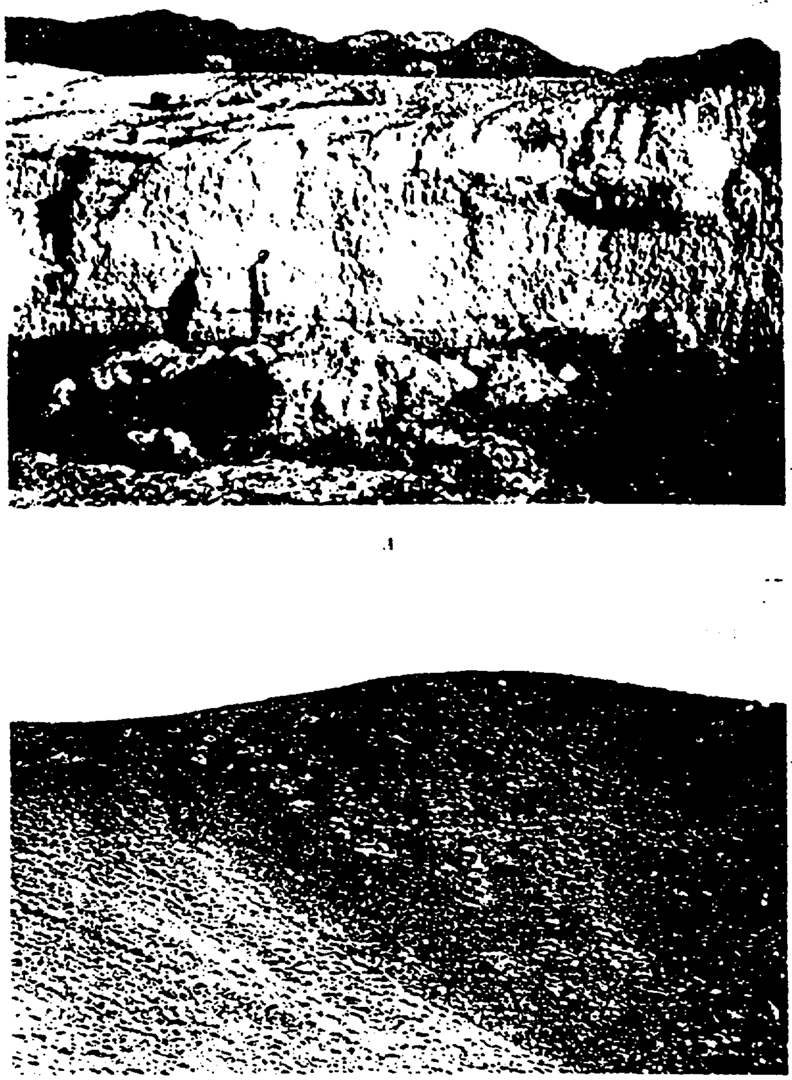
7, T. 17 S., R. 51 E.), white silty clay underlies the remnant of a playa, now isolated by dissection on all sides except to the south, and a larger playa lies about 2 miles to the east beyond the quadrangle boundary. The following section describes the Quaternary deposits exposed in the bluffs about 1 mile east of Rogers Spring.

Section of Quaternary deposits exposed in bluff on south bank of wash about 1 mile east of Rogers Spring (SW¼ SE¼ sec. 11, T. 17 S., R. 50 E.)

	Approximate thickness (feet)
1. Spring deposits(?), pale-yellow (5Y 8/3 to 7/3), hard, massive, and very fine grained. Numerous tubular openings ranging from 1/16 to ¼ in. in diameter. Surface of outcrop is rough and pitted	3
2. Sand, pale-yellow (2.5Y 8/4), medium- to fine-grained, loose, friable	2½
3. Gravel, gray, pebbly, crossbedded, friable, loose; contains some lenses of sand and fragments of clay. Pebbles are angular and slightly rounded; rock types include quartzite, chert, sandstone, limestone, and dolomite. Near top of unit, gravel is sandy and is interbedded with sand resembling that which overlies it	4
4. Clay, white, massive; hard when dry; blocky structure; contains nodular masses of evaporites(?). Includes thin beds of fine-grained sand that are most abundant near base of unit. At east end of section, unit 4 is only 3 feet thick because base of overlying gravel (unit 3) cuts down across the clay	5
5. Sand and gravel, loose, friable, thin-bedded. Sand, medium to very coarse grained; many grains well rounded; contains a few pebbles. Stratification locally wavy and broken. Gravel composed of angular and slightly rounded pebbles ranging from granule size to 1 inch in diameter; most are less than a half an inch in diameter. Pebbles are of quartzite, chert, and dark-gray carbonate rock. Unit contains a few mudballs and small white nodular masses of evaporites(?). Upper contact sharp, wavy	2
6. Clay, pale-yellow, pale-olive, and white (5Y 6/4 — 7/4 — 7/6), sandy; contains numerous small white nodules of evaporites(?). Structure blocky and massive. Upper contact sharp, wavy; local relief of 10 inches	3½
Total thickness exposed	20

Units 4 and 6 are believed to be playa sediments separated by fine-grained alluvial-fan debris; the position of the toe of the fan fluctuated from time to time. The stream that deposited the gravel of unit 3 apparently eroded the top of the underlying playa clay.

In some of the clay pits, pale-olive clay occurs as irregular masses and lenses in white fine sand to silty clay that is commonly massive and weakly to firmly cemented (figs. 5A and 7). The olive clay apparently was the material mined; blocks of the enclosing white indurated material were dumped nearby. The olive clay may have filled irregular openings in the enclosing white material, or the interfinger-



A

B

FIGURE 5.—Playa deposits in the lowlands and scree on Shadow Mountain. A, White massive nodular silty clay with an irregular bed of [illegible] near base; materials similar to those shown in figure 7. B, Dark-colored bands of varnished boulder scree on rounded north slope of summit [illegible].

ing may have been subsequent to the deposition of both materials, perhaps related to repeated wetting and drying of the surface of a playa.

SPRING DEPOSITS

Firmly cemented clastic material, largely sand and silt, occurs near the flowing springs. In places the material is porous and finely crystalline. The deposits are pale gray or pale brown and include many casts and molds of plant stems. Broad areas of wet, turfy meadow constitute a considerable part of the Ash Meadows. On the bottom of small pools the stems of reeds or sedges are now being buried by clay or silt, presumably material blown into the pool. The draining and drying of such a pool may cause the sediment to become indurated; leaving molds of the stems when the organic matter has disappeared. Gradual dissection by Carson Slough is an adequate explanation for these relic spring deposits; it is unnecessary to postulate any change in the total discharge of all the springs in the Meadows. Spring deposits mantle low ridges and extend down to the floor of the intervening washes. Similar deposits cap buttes as much as 100 feet high or are intercalated in the finer clastic sediments. Only some of the larger and more conspicuous spring deposits are shown as a separate unit on plate 1.

Just west of Devils Hole a sheet of spring deposits, not shown on plate 1, measures roughly 500 by 1,500 feet and mantles ridges and shallow gullies. The edge of the sheet is lobate, and the fingers point

FIGURE 6.—Indurated caprock (spring deposit(?) overlying a fine pebble gravel) resting with local angular discordance on clay, silt, and sand.

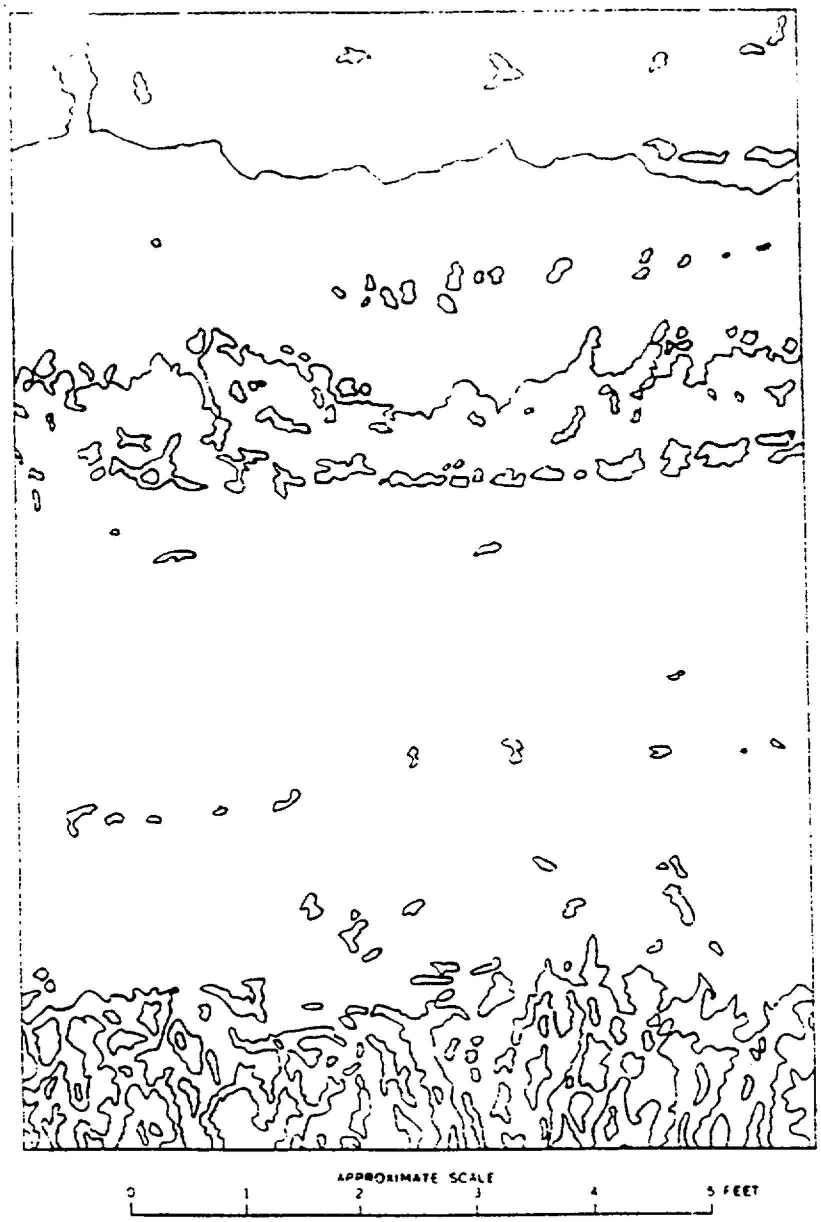


FIGURE 7.—Cross section of playa deposits. Olive clay (dark areas) and enclosing white clay that is massive and slightly indurated. Exposure is in prospect pit about 2 miles northwest of Devil Hole (center sec. 26, T. 17 S., R. 50 E.).

downwash. The deposits are at least 2 feet thick, thinning to a few inches near their borders; on ridges they overlie a desert pavement. An east-trending narrow band of slightly more massive deposits suggests seepage along a fissure. The sheet is draped over the landscape and is perhaps the relic of a wet meadow which surrounded a flowing spring.

The prominent butte northeast of Fairbanks Spring has a hard massive cap of spring deposits that is nearly 20 feet thick. Conformably below the caprock is nearly a hundred feet of brown and light-brown sandy silt and clay containing nodular masses of evaporites(?). The great thickness of the caprock suggests that it was deposited around a spring and is not merely a weathered crust, though no sign of such an opening was found. The Quaternary rocks near Fairbanks Springs are undeformed, and the caprock is isolated and exposed because of dissection by Carson Slough.

Three small mesas south of Longstreet Spring have indurated caprocks and are mapped as spring deposits (pl. 1). The caprock is largely a massive pale-brown, very fine grained sandstone 2–3 feet thick; locally the material is coarse grained and faintly stratified. Below the cap of the eastern mesa is about 2 feet of fine pebble gravel that thins westward and rests on clay, silt, and sand. The contact locally shows a slight angular discordance (fig. 6). No gravel occurs beneath the caprock of the two mesas just to the west. The tops of the mesas slope westward, parallel to that of the apron of alluvial-fan deposits to the south. The caps of the mesas are remnants of westward-sloping sheets of alluvial-fan debris. The eastern mesa lies at about the western limit of gravel on the ancient fan; further westward, perhaps near the toe of the ancient fan, the material was largely sand. The location of these caprocks near present-day springs suggests that the alluvial apron west of the hills was once the site of a swampy meadow which is now drained.

ORIGIN AND ENVIRONMENT

The alluvial fan, playa, and spring deposits accumulated in an arid basin whose bordering highlands were almost the same as they are today. The small clay-covered flat in the northeast corner of the area may be a remnant of the ancestral playa. Alluvial fans spread out from the highlands to an extensive playa that, in the Pleistocene, occupied much of the Nevada segment of the quadrangle. Springs in the Ash Meadows probably supplied water to the playa and the Meadows were areas of swamp, much as they are today. The ancestral playa apparently extended southward into California probably as far as Eagle Mountain (fig. 1). Dissection of the playa probably began in the late Pleistocene, and in the Nevada part of the quadrangle reached to depths of at least 100 feet. Washes from volcanic mountains to the north (fig. 1) spread a layer of gravel on top of the playa deposits in the northern part of the area. Erosion has now removed or redistributed part of this cover.

Alkali Flat, at the southern edge of the quadrangle, is almost undissected. In late Recent time the Amargosa River was dammed west of Eagle Mountain, and a small playa—Alkali Flat—was built in the river valley just north of the mountain. The construction of the Flat coincides with the dissection of the much more extensive "ancestral" playa mentioned above. The building of the Flat may be due to the rise of Eagle Mountain or perhaps to the growth of the adjacent fans at a time of increased flood flow from the neighboring highlands.

AGE AND CORRELATION

The arid-basin sediments probably include deposits of both Pleistocene and Recent ages. No fossils have been found. Similar materials in the Amargosa Valley to the south include "dissected playa or lake beds * * * [which] between Shoshone and Tecopa contain elephant remains that, according to Curry (personal comm.), who collected them, are Pleistocene" (Noble, 1941, p. 957–958). Along the Amargosa River west of Franklin Well the alluvium that overlies the playa and the fan deposits has been dated archeologically by Alice Hunt (1960, p. 65) as about 2,000 years old. Most of the arid-basin sediments are probably of Pleistocene age.

LANDSLIDE BRECCIA

Tongue-shaped masses of landslide breccia, including some brecciated sheets of limestone or megabreccia (Longwell, 1951), lie on the piedmont east of the Funeral Mountains. Northeast of Bat Mountain several masses of breccia form conspicuous low hills on the piedmont east of the mountains. South of Bat Mountain a mass of breccia is largely within the range, and just east of the peak is another small slide. Detailed maps of the several slides are published elsewhere (Denny, 1961).

The landslide breccia is either a disordered mass of fanglomerate and limestone blocks or large plates of limestone resting on breccia, on gravel, or directly on Oligocene(?) rocks stratigraphically above those included in in the plates (pl. 1, section *A–A′*). The southern slide filled a narrow gully near the mountain front and spread out over the apex of the adjacent fan. The single or forked tongues of breccia northeast of Bat Mountain are separate landslides that moved down gullies on the piedmont which has since been lowered 30 to 40 feet by erosion.

All the landslides came from the steep eastward-dipping beds of fanglomerate and limestone (upper fanglomerate unit and upper limestone and shale unit, pl. 1) that have shale and other thin-bedded rocks beneath them. Uplift of Bat Mountain along high-angle faults set the stage for the erosion of cliffs on its northern and western sides. Material from these cliffs descended into gullies and moved out onto the piedmont. The individual tongues are discrete slides that moved down the piedmont in shallow gullies carved partly in bedrock and partly in gravel. Sliding occurred more than once, but the precise age of any one of the slides is unknown. Subsequent erosion has left the slides standing above their surroundings.

SCREE

Much of the quartzite of Shadow Mountain lies beneath a discontinuous mantle of scree, but only the larger masses of this bouldery deposit are shown on the map (pl. 1). A scree of basalt boulders mantles the slopes of the small butte in the southwest corner of the quadrangle. Unmapped bodies of scree lie on the slopes of the Funeral Mountains and of the hills near Devils Hole.

The typical scree on Shadow Mountain is composed of cobbles and boulders of quartzite, and the stones on the surface have a dark coating of desert varnish. Scree occurs on all sides of the peak, chiefly as tongue-shaped masses in the heads of gullies. Only near the summit does scree mantle ridge crests (fig. 5*B*). Between the tongues of boulder scree are bands of pebble scree whose stones are not varnished and are imbedded in a sandy matrix. In the upper foot of the boulder scree most of the fragments are varnished on all sides and there is no matrix between them. From a depth of 1–1½ feet the stones are not varnished but are coated with sand. In the few pits excavated to greater depths, the material consisted of pebbles of quartzite imbedded in a fine sandy matrix.

The estimated mean size of the fragments on the surface of three bodies of scree on Shadow Mountain is given below; the estimates were determined by the method noted on page L25.

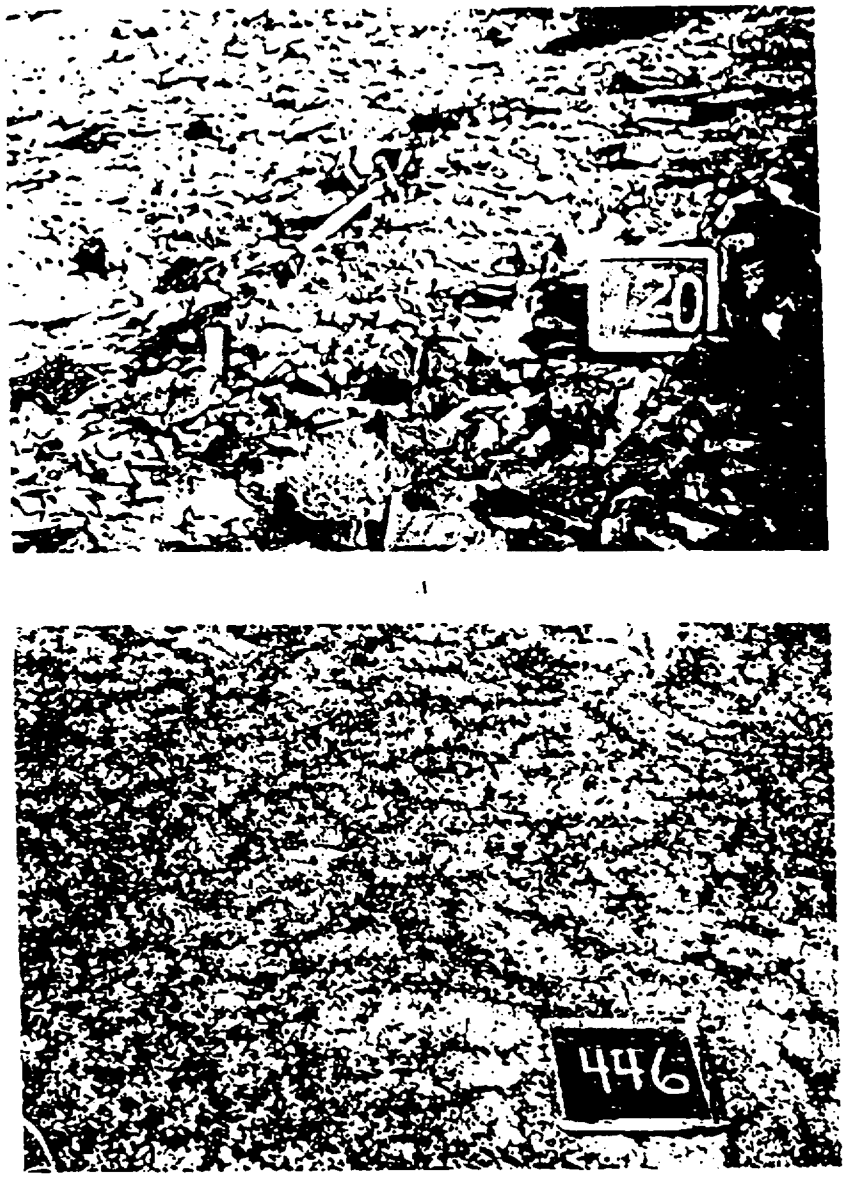
Kind of surface	*Slope* (°)	*Estimated mean size* (mm)
Varnished fragments and no fines	29	80
Do	31	175
Unvarnished fragments and a little fine sand	29	10

The rounded crests of the high ridges on Shadow Mountain are draped with dark bands of scree. Stripes of varnished boulders are separated by areas of fine scree with abundant shrubs. On gentle slopes near the summit, masses of fine scree have moved within the last few years. Unweathered fragments of quartzite are piled up behind bushes to a height of several inches, or form a tongue that has moved down over varnished boulder scree (fig. 84). Tongue-shaped masses of scree in a gully are dissected along their lower edges by a wash that heads in the same gully or in a neighboring one. Scree forms low ridges that trend downslope and are surfaced with either varnished boulders or pebbly sand in which scattered shrubs grow. Fine pebbly scree floors gullies cut in coarse boulder scree, or rests on top of and is completely surrounded by boulder scree.

The scree on the butte southwest of Dealth Valley Junction forms an almost continuous mantle of boulders that conceals the underlying tuff. These basalt boulders have a black coating of desert varnish. The surface of the deposit has the form of low ridges and shallow gullies trending downslope. Mantles of varnished boulders, largely talus, are, of course, characteristic of many areas of basaltic rocks in the western United States.

In the hills of the Devil's Hole area, the largely bare-rock surface of the hills is separated from the adjacent piedmont by a narrow band of many closely spaced gullies that are walled by coarse and fine scree. Such patterns of gullies and intervening spurs are characteristic of the transition from hills to piedmont and are perhaps an expression of a dynamic equilibrium between the rate at which scree is produced by weathering on the bare mountain slope and the rate at which scree is eroded and the material carried down onto the piedmont. The gradual wearing back of the bedrock slope above the band of gullies causes them to deepen and thereby isolate masses of scree downslope from further sedimentation. In this way, the amount of scree separated from its source gradually increases. These abandoned deposits of scree are eroded and the material transported down onto the piedmont. If we assume that the rate of the supply of detritus to form scree is constant, in time the rate at which the scree is removed will equal the rate at which material is supplied to it. Thereafter, this system of erosion and deposition will remain in balance until upset by some change in process or in geometric relation of mountain slope to piedmont.

The scree in the Ash Meadows quadrangle is detritus from an adjacent bedrock slope or from older scree. Much of it has accumulated as individual blocks at the base of a cliff to form talus. The localization of some scree in gullies suggests a casual relation to running water. Such scree—boulder colluvium is perhaps a more appropriate term—may accumulate to a considerable thickness before a high flow of water moves the debris down the gully and out onto the adjacent fan. Scree on divides is derived by weathering from adjacent bedrock or older scree.



A

B

FIGURE 8.—Scree on Shadow Mountain and patterned salt crust. *A*, Tongue-shaped mass of unvarnished fragments (light colored), outlined by hammer, ruler, and slate, that rests on older varnished scree; shrub in foreground; summit cone of Shadow Mountain, altitude 5,000 feet. *B*, Polygonal arrangement of pebbles on salt-encrusted surface of playa deposits; the slate is about 10 inches long; locality is south of Ash Meadows Road just east of Carson Slough (NE¼SW¼ sec. 8, T. 25 N., R. 6 E.).

The varnished coatings on the exposed fragments of most deposits of scree suggest that they are old, but how old is a moot question. Present-day frost action is doubtless responsible for the fine scree on the summit of Shadow Mountain, and perhaps the coarse scree dates from a time of more effective frost action in the past, either in the late Pleistocene or about 2,000 years ago during a moist-climate episode when there was a shallow lake on the floor of Death Valley (C. B. Hunt, written comm., 1960).

The occurrence of varnished or solution-faceted pieces of rock in the upper few feet of scree suggests that the stones were weathered prior to burial. Accumulation may have been piece by piece over a long interval of time. A weathered boulder moves down off a bedrock face from time to time, and gradually scree accumulates at the base of the steep slope. Given sufficient time, such a slow process could form a thick deposit.

The occurrence of coarse and fine scree reflects in part at least the presence, under the adjacent slope, of both thin-bedded or well-jointed rocks and thick-bedded or massive rocks. A bouldery surface, however, may be only superficial. Exposures show that the coarse material at the surface becomes finer grained at depth, and a similar relationship can be inferred from the occurrence of fine scree completely surrounded by boulder scree. The presence of both coarse and fine scree in the same gully suggests that both large and small fragments weather out of the bedrock upslope. The sorting may reflect differences in runoff intensity from storm to storm.

GRAVEL ALONG AMARGOSA RIVER

A low gravel terrace occurs along the Amargosa River from about State Route 126 southward to Ash Meadows Road. In some places the surface of the terrace is a desert pavement. A gray pebble gravel contains abundant fragments of volcanic rocks and a subordinate number of quartzite, chert, limestone, dolomite, and sandstone fragments. The pebbles commonly range from $\frac{1}{4}$ to 1 inch in diameter. The deposit is crossbedded and includes layers of coarse- to medium-grained sand and sandy silt. Locally it is overlain by 2–3 feet of fine, crossbedded sand. The terrace is perhaps as much as 6 feet above the dry river bed and 2–4 feet above the toe of the fans from the Funeral Mountains.

Pebbles in the gravel come both from the mountains north of Lathrop Wells and from the Funeral Mountains. The pebbles of volcanic rock were reworked presumably from the gravel that mantles the uplands near Clay Camp. The pebbles of sedimentary rock came either directly from the Funeral Mountains or were reworked out of the adjacent fan deposits. The gravel extends only a short distance upriver from the highway crossing and probably did not come down the river from the northwest. The sand that overlies the gravel contains a few pieces of charcoal and chipped flakes of rock. This sand is probably part of the Recent alluvium that west of Franklin Well is overlain by archeological material believed by Alice Hunt (1960) to be about 2,000 years old.

DUNE SAND

Sand dunes are on the alluvial plains or near the toes of fans and are composed of coarse- to medium-grained sand. The largest areas of dunes are on the east bank of Carson Slough and the adjacent plains. A few small dunes occur on the uplands north of Clay Camp. Many dunes are underlain by playa deposits, and most of them are not far removed from springs or swamps. The dunes have irregular shapes: most are 5–10 feet high, but some are as much as 30 feet high. Some of them are slightly elongate in plan. The dunes are bare, except for scattered mesquite, and change shape from time to time. None of the dunes, however, appear to be moving across the plains. In a few places near dunes the surface of the playa deposits has been slightly eroded by wind-driven sand.

Archeological remains on the surface of the dunes belong to the Death Valley III and Death Valley IV stages (A. P. Hunt, 1960, p. 65, 168–171), which span the last 2,000 years. The dune sand is apparently derived from alluvium. Perhaps the sand north of Clay Camp came from the adjacent alluvial-fan deposits. Gravel fans with extensive areas of pavement are devoid of dunes, probably because the surface of the gravel is not a good source of sand.

The largest area of dune sand, west of Crystal Pool, has a straight and abrupt east face that lines up with that of smaller dunes to the north. The arm of alluvium east of these dunes suggest that their linear front is an erosional feature. It is tempting, neverthess, to speculate that this alinement reflects a structure in the underlying rocks.

During times of high wind, sand can be seen moving across the surface of the Amargosa Desert. There is no evidence in the quadrangle that the dunes were ever more extensive or more actively moving than they are at present. Whether the presence of mesquite is a contributor to dune formation or merely a result thereof is not clear. All the dunes support mesquite, but extensive areas of mesquite are on plains where dunes are virtually absent.

ALLUVIUM

Material that ranges in texture from boulders to silt floors narrow washes and broad flood plains. The amount of clay in the alluvium appears to be small but was not determined by mechanical analysis. The lithology of the deposit reflects that of the adjacent rocks. The coarse fragments are mostly unweathered and lack a coating of desert varnish. Along the Amargosa River and Carson Slough, the alluvium is largely sand or silt. Large areas along Carson Slough have a salt crust. Near Ash Meadows Road the crust disappeared during heavy rains in the spring of 1958, but the white coloration returned within a week or two after the rains had ceased. On the fans, the alluvium is chiefly sand and gravel. The delineation of alluvium on the fans (pl. 1) is a generalized portrayal of what is actually a mosaic of small bodies of unweathered alluvium and of weathered fan deposits, the latter including areas of wash floored with varnished fragments and areas of desert pavement.

The alluvium on the fans is confined in narrow channels of which a few head in the mountains, but most head in an area of desert pavement. Many of the elongate bodies of alluvium do not extend as far as the toes of the fans. Near the toes, however, other small elongate bodies of alluvium are separated by small areas of desert pavement. This distribution of alluvium suggests that some of the deposits come from catchment basins on the adjacent steep mountain slopes and others from smooth areas of desert pavement where runoff is rapid.

The recent alluvium on the fans is finer grained than the varnished gravel on adjacent alluvial-fan deposits (fig. 4). The weathered gravel is more extensive than the alluvium, and the floods that moved the latter were probably not as extensive as those that moved the older gravel.

The thickness of the alluvium is unknown. Few exposures reach depths of more than 10 feet. No fossils have been found.

In her study of the archeology of Death Valley, Alice Hunt (1960, p. 65) mentions briefly sites along the Amargosa River in the Ash Meadows quadrangle:

> * * * Late Death Valley II (Amargosa) sites are numerous along and near the Amargosa River, which is now dry most of the year, in the valley next east of Death Valley. Some crudely shaped tools, a washed fireplace, and numerous flakes were found in the alluvial bank of the river to depths 3 feet below the surface. Diagnostic tools were not found in the alluvium but the artifacts almost certainly are from the numerous Late Death Valley II sites along the edge of the river floodplain. Sites with pottery and arrowheads are few along the river and are largely restricted to the existing springs.

The Late Death Valley II occupation is believed by Alice Hunt to have ended at about the beginning of the Christian era, and to have been contemporaneous with a Recent pluvial lake which covered the floor of Death Valley to a depth of about 30 feet (C. B. Hunt, written commun., 1960). In Death Valley, occupation sites of this same stage are found around springs that are now dry but presumably were flowing at the time of occupation. It is likely, therefore, that much of the alluvium along the Amargosa River is at least 2,000 years old.

STRUCTURE

FUNERAL MOUNTAINS

Within the Ash Meadows quadrangle, the southeastern spur of the Funeral Mountains is an eastward-dipping fault block, bounded on the northwest by a fault that we have named the Bat Mountain fault. Smaller faults within the block strike either parallel to it or terminate against it at a low angle. At least two periods of deformation occurred.

The Funeral Mountains (fig. 1) are bounded on the southwest by the Furance Creek fault zone, one of the master faults of the region. The zone follows the southwest base of the Grapevine Mountains and the Funeral Mountains to the Amargosa Valley, where it turns southward to extend perhaps as far as the point where the Amargosa River crosses the Shoshone-Baker highway (Noble and Wright, 1954, pl. 7; Jennings, 1958). The fault zone is concealed in the Ash Meadows quadrangle, but probably lies close to the southern end of the spur, where the northeasterly strike of the Tertiary rocks changes abruptly to the east.

The Bat Mountain fault northwest of the spur extends southwest into the Ryan quadrangle and is inferred to terminate in the Furnace Creek fault zone. Both faults are largely concealed beneath the Quaternary deposits. The rocks of the spur are uplifted several thousand feet relative to those to the west, and the displacement increases toward the Furnace Creek fault zone.

Within the spur, which is bounded on the west by the Furnace Creek fault zone and the Bat Mountain fault, the older of the two sets of small normal faults strikes northward and joins the Bat Mountain fault obliquely. On the northeast slope of Bat Mountain a horst of Paleozoic limestone and dolomite is separated from the adjacent Tertiary rocks by high-angle faults (section *B–B′*, pl. 1). The upper limestone and shale unit lies unconformably on the beveled top of the underlying horst and graben structure.

The younger set of normal faults trends northeast in the southern part of the spur and swings north and northwest in the northern part. Many of the faults dip about 65° west, or about normal to the bedding in the upper fanglomerate unit. The western blocks generally dropped relative to those to the east. Toward the south, some of the younger faults become a zone of faults and the throw increases, but even here is not more than a few hundred feet. Near the northwest side of the spur the younger faults join some of the older set. Here the movement apparently took place along both sets at the same time. The throw of the fault immediately east of the knob at altitude 3,377 feet decreases southward from about 400 feet at a point three-quarters of a mile from the Bat Mountain fault to about 50 feet 1½ miles from it.

The oldest movement on the faults at the southeastern spur of the Funeral Mountains is inferred to be Oligocene. The area southwest of the Furnace Creek fault zone was raised at least twice to supply the debris for the two bodies of fanglomerate at Bat Mountain. Probably during this same time movement took place along subsidiary faults in the older rocks of the spur. By Miocene or Pliocene time the Funeral Mountains were raised relative to the area southwest of the Furnace Creek fault zone, and the lacustrine and volcanic rocks of the Furnace Creek Formation were deposited west of Death Valley Junction. The rocks of the spur were broken again by many faults during this interval. The abrupt west face of the spur, largely outside of the Ash Meadows quadrangle, suggests that the youngest movement on the Bat Mountain fault is no older than the Quaternary Period. No movement has taken place along the small faults mantled by landslide breccia since the breccia was deposited, perhaps in late Pleistocene time.

DEVILS HOLE AREA

The unnamed range, largely outside the northeast edge of the Ash Meadows quadrangle but extending into it at a point about 2 miles northeast of Point of Rocks Springs, is in general a gently northeast dipping block that contains one or two thrust faults of undetermined size. Along the westernmost of these faults, gently dipping Middle and Upper Cambrian rocks moved over steeply dipping Lower and Middle Cambrian rocks. The rocks of the Devils Hole area appear to be extensions of the upper plate.

Alluvial deposits overlap the Paleozoic rocks of the hills near Devils Hole in the northeast part of the quadrangle, and the faults along which the hills are believed to have been elevated relative to the adjacent plains are nowhere exposed. The rocks of the hills are broken by numerous north- to northwest-trending steep faults, which have displacements rarely exceeding 200 feet. In the hill north of Devils Hole, the eastern fault blocks are dropped with respect to the western ones. Three sinkholes, of which Devils Hole is the largest, lie on or close to small faults; very likely their solution was structurally controlled. The rocks in the hill north of Point of Rocks Springs are gently arched and are also broken by north- to northeast-trending steep faults. The blocks along the crest of the anticline are upthrown.

The rocks in the spur along the eastern edge of the area are broken in a less systematic manner along northwest-trending steep faults.

On the gently sloping surface of the playa deposits about a mile southwest of Devils Hole, small areas of gravel are shown bordering the trace of an inferred fault. Areas of gravel abut against playa deposits along a north-trending line. The distribution of gravel and playa deposits suggests differential erosion along some sort of structural break. The trace of the doubtful fault lines up with two springs about a mile to the north.

RESTING SPRING RANGE

Shadow Mountain is a block of east-dipping Paleozoic rocks (section E–E', pl. 1) that has risen relative to its surroundings. The border faults are nowhere exposed, for on all sides fanglomerates of Cenozoic age rest unconformably on the older rocks. West of the peak a small mass of disordered blocks of limestone and dolomite has apparently been dropped down relative to the main body of the mountain along a northeast-trending fault. The range diminishes in altitude northward, presumably because the amount of displacement along its concealed border faults also decreases. At the north end of the range, the surface of the block passes beneath the older of the fanglomerates that is displaced a few hundred feet by movement along high-angle faults that strike northward and die out in the overlying finer grained beds.

The Paleozoic rocks of the range are apparently displaced along other north-trending faults that were not mapped. South of Shadow Mountain, a small southward-dipping wedge of fanglomerate has been dropped relative to the Paleozoic rocks along an east-trending high-angle fault.

South of Grapevine Springs, the nearly straight western limit of the younger fanglomerate suggests faulting, but exposures on the south side of the broad wash near the state line (sec. 11, T. 25 N., R. 6 E.) show the fanglomerate near Grapevine Springs resting unconformably on the sandstone and clay unit. At the north end of the range the Tertiary rocks form a broad anticline whose axis lies close to the broad wash entering the quadrangle from the east.

GEOMORPHOLOGY

ALLUVIAL FANS

Alluvial fans are accumulations of detritus at a place where a debris-carrying wash from a highland becomes free to migrate from side to side. The fan-building wash has a smooth profile and passes without a break in slope from highland out onto fan. The point at which the wash leaves its confined channel and moves from side to side varies from fan to fan. On some it is at the mountain front, on others half-way down to the toe of the fan. Deposition will take place where the channel is unconfined, if the gradient at that place is less than that upstream, and the wash will thus acquire a smooth profile from head-waters to toe of fan.

The mountains and hills of the Ash Meadows quadrangle are surrounded by coalescing alluvial fans that have a complex surface—a mosaic of desert pavements and of washes. On the geologic map (pl. 1) the areas where the surface of the alluvial-fan deposits is desert pavement are shown by pattern. The rest of the surface of the alluvial-fan deposits consists of abandoned washes that have not carried water for some time. The surface form and origin of two fans in the quadrangle and others nearby are discussed in detail elsewhere (Denny, 1964).

WASHES

The modern washes, the Recent alluvium of plate 1, differ from the abandoned washes in topographic form and in the nature of the material at the surface. Braided channels and gravel bars constitute the modern washes. Desert shrubs are absent, and the stones on the surface are mostly unweathered. The channels and bars of the abandoned washes support a growth of desert shrubs and are floored with stones that have a coating of desert varnish. The surface material is coarser grained, and the microrelief between channel and bar is greater than in the modern washes.

As has just been stated, the distinction between modern and abandoned washes is based in part on the presence or absence of desert varnish. Such black coatings are found on quartzite, sandstone, and volcanic rocks; the volcanic rocks commonly have darker coatings than the other rock types. These thin coatings are removed from a stone when it is moved by running water. Thus, if we knew when a stone had been coated with varnish, or perhaps how long a time is required for a stone to acquire such a coating, we would have a minimum age for the last movement of the stone. This age would be the minimum length of time since the last flood came down the wash in which the stone lies.

Observations that have a bearing on the age of desert varnish were made along the Old Traction Road (pl. 1), which crosses the fans west of Shadow Mountain. Stones overturned during the building of the road about 1905 have not acquired a coating of varnish since that time. At a locality in the Mohave Desert, however, varnish has formed on rhyolite fragments during a 25-year period (Engel and Sharp, 1958). The Hunts (A. P. Hunt, 1960; C. B. Hunt, 1954, 1961) present impressive archeological and geological evidence that much desert varnish has considerable antiquity. They believe that in Death Valley most varnish was formed not later than about the beginning of the Christian era. The weight of the evidence certainly indicates that many deposits whose surface stones are varnished are much more than 2,000 years old.

DESERT PAVEMENT

Pavements are segments of fans that have received no additions of detritus for a long time and serve as an armor that protects the underlying material from removal by water or by wind. The areas of desert pavement on the fans are smooth, gently sloping surfaces composed of closely packed angular fragments of rock that range in size from pebbles to large boulders. Most of the stones are varnished, except those of carbonate rock that are etched by solution. The exposed surface of a boulder of carbonate rock is eroded, and material is deposited beneath it. As a result, many such fragments on a pavement have smooth and etched upper surfaces and a buried surface that is rounded or irregular depending on the original shape of the fragment (Bryan, 1929, p. 194). Pavements rest on and in a silt that is several inches thick.

The silt beneath the stone armor is firm in place but very friable in hand specimen and has conspicuous circular cavities that give it a vesicular structure. Origin of the silt is unknown; apparently it is formed by both chemical and mechanical weathering of gravel and sand similar to that which underlies it.

Pavements are broken by miniature terraces with risers less than an inch high and lengths ranging from a foot to more than 10 feet. After a prolonged rain, when the silt is saturated with water, the silt at the edge of a pavement next to a gully tends to flow down into it. This movement places the silt that is further away from the gully under tension. Some of the risers of the miniature terraces are believed to be tension cracks produced by the downslope movement of a 1–2-inch layer of silt on which the armor of stones rode. Movements of this sort on an abandoned segment of a fan carry material from high points and fill low spots. Debris is also transported by surface wash and by wind action. These processes combine to transform the channels and bars of a desert wash into a smooth pavement.

Pavements are born dissected. Although at first glance, a smooth desert pavement may appear to be an end point in the evolution of the surface form of a fan, all pavements are dissected irrespective of their location or history. All the larger areas of pavement are cut by narrow washes that head in them. These gullies have probably been in existence at all times and do not record a specific climatic or tectonic episode of accelerated erosion.

PIRACY

On the piedmont at the north end of the Resting Spring Range a spectacular piracy has taken place. A wash floored with alluvium heads in the quartzite hills along the State line and lies along the contact between Quaternary and Paleozoic rocks. The wash turns southwestward into a narrow gully (SW¼NW¼NE¼ sec. 24, T. 25 N., R. 6 E.) and passes through a large area of desert pavement to emerge on another broad wash. At one time, however, the wash did not turn southwest but followed a northwesterly course, roughly parallel to the State line. The point of diversion is where the present wash leaves the alluvium and turns southwestward to pass through a small inlier of fanglomerate. Between the inlier and the hills of fanglomerate a few hundred feet to the northeast, alluvial-fan deposits form a 2-foot bank on the north side of the alluvium. The exposed fragments on top of the bank have a coating of desert varnish. The diversion is a recent event. A large flood from the quartzite hills might discharge both into the gully and over the low bank to the northwest. Southwest of the point of diversion, the floors of narrow washes that head in the pavement are slightly below that of the broad wash. This wash apparently cut back its south bank in the vicinity of the fanglomerate inlier and intersected the head of a gully in the pavement.

Piracies have taken place repeatedly on the larger fans in the Death Valley region and are responsible for the development of many large areas of desert pavement. Piracy may occur wherever washes from a mountain have steep gradients and a coarse bedload compared with washes that head on the adjacent piedmont. Such piedmonts consist of areas of gravel deposits, derived usually from highlands of resistant rock and separated by gullies or small valleys carved by local washes either in gravel or in bedrock less resistant than that of the highlands. The erosion of the gullies is due in part to piracy of the sort just described. Great local relief is characteristic of such piedmonts, which have been clearly described and illustrated from the Henry Mountains region, Utah, by Hunt (in Hunt, Averitt, and Miller, 1953, p. 191), whose analysis was based in part on an earlier study by Rich (1935, p. 1002–1003). An example from the Shenandoah Valley, Virginia, is described by Hack (1960, p. 91–94). In the Ash Meadows quadrangle, the topography of the inner part of many piedmonts close to the mountain front is one of narrow ridges and deep ravines. North and northwest of the Resting Spring Range, for example, the outcrops of the sandstone and claystone unit are largely on the lower sides of deep gulches where these weakly consolidated rocks adjoin hills of firmly cemented fanglomerate.

An example of possible future piracy is at the north end of the Resting Spring Range, where a broad wash, floored with alluvium, parallels the State line and emerges onto the piedmont at a point about 1 mile south of Grapevine Springs. This wash has a much larger drainage area than a small one just south of it that, west of the hills, is carved in the sandstone and claystone unit. At the west front of the hills, the surface of the broad wash lies 25–30 feet above the floor of the small wash to the south and is separated from it by a narrow ridge of gravel. If the broad wash were to widen its bed by cutting back its south bank a few hundred feet, it would breach the gravel ridge and flow down into the small wash. The broad wash would then deposit its load in the more gently sloping channel of the small wash, perhaps burying it completely.

RECENT HISTORY

That the fans were at one time flooded more extensively than they are at present is shown by the greater areal extent of abandoned washes compared with that of modern washes. Many of the modern washes, the Recent alluvium of plate 1, do not reach the toe but end on the fan. The piedmont northwest of Shadow Mountain, for example, is a complex grouping of pavement, abandoned wash, modern wash, and pediment. The proportions of these four geomorphic units and their equivalents on the geologic map (pl. 1) are tabulated below. The area of deposition on the fan at present—the modern washes—is about 15 percent of the total area of the piedmont.

Geomorphic unit	*Geologic unit (pl. 1)*	*Estimated proportion of total area of piedmont (percent)*
Pavement	Alluvial-fan deposits	35
Abandoned washes	Alluvial-fan deposits	40
Modern washes	Alluvium	15
Pediment	Sandstone and claystone unit and playa deposits.	10

On the north side of Shadow Mountain, a narrow wash floored with alluvium runs westward from the mountain front for about half a mile (SW¼SW¼ sec. 7, T. 25 N., R. 7 E.). The wash fingers out on the edge of an oval-shaped area of fan deposits that is almost completely surrounded by desert pavement (largely in N½ sec. 25, T. 25 N., R. 6 E.). The surface of the pavement lies many feet above the oval except on its southwest side where the fan deposits of the oval overlap the desert pavement. The stones on the surface of the gravel that floors the oval are varnished and are slightly coarser grained than those on the surface of the alluvium in the narrow wash to the east. Present-day floods from the mountain drop their load before reaching the oval. The now-varnished gravel in the oval was deposited by floods that were more extensive and carried slightly coarser material than those of recent years. Thus, for some time, perhaps for the last several thousand years, most of the coarse detritus from the mountain has been deposited within about a mile of its front.

On the central part of the fan northwest of Shadow Mountain, ribbons of alluvium head in areas of desert pavement. Runoff on a pavement is more rapid than on the surface of a wash (C. B. Hunt, written commun., 1960) and probably facilitates the erosion of gullies in the weathered gravel beneath the pavement. This alluvium is finer grained than that near the mountain front or on the surface of the adjacent alluvial-fan deposits (fig. 4). The slope of the fan decreases in its central part, perhaps because of this decrease in size of its debris.

ORIGIN

The larger fans in the quadrangle and elsewhere in the Death Valley region have a complex surface of pavements and washes. Denny (1964) has suggested that these fans approximate or are approaching a condition of dynamic equilibrium wherein their surface form is so adjusted that the rate at which detritus is supplied to them from the adjacent mountains equals the rate at which material is removed from them by erosion. Let us assume, for example, that material is supplied by Shadow Mountain to the fan north of it at a constant rate and is deposited near the apex. Elsewhere on the piedmont, large areas of pavement and small areas of pediment are being eroded, and material is being carried off the fan to the flood plain of Carson Slough. Piracies take place, such as the one of Recent date described earlier. The locus of deposition shifts downfan, and additional segments of the fan are abandoned. Thus the area of the fan's surface that is being eroded, that is, the amount of material being removed, will increase until it equals the amount supplied. The processes of deposition and erosion will thereafter be in a steady state of balance and will remain so as long as the topographic position of mountain and basin and the geologic processes remain the same (Nikiforoff, 1942). The total volume of detrital material on the fan will not change, the volume of fine material reaching the adjacent flood plain being balanced by the amount of coarse detritus supplied by the highland.

If position of mountain and basin and the geologic processes change in the future as they have in the past, a change will occur in the rates of deposition, weathering, and erosion. The equilibrium between erosion and deposition will be shifted, and changes in the form and size of the piedmont will result. In the Death Valley region, the variations in piedmonts from range to range suggest that they tend to adjust rapidly to changes in the equilibrium of which they are a part.

Pavements, as already mentioned, are born dissected. The transformation of an abandoned wash into a smooth pavement involves the movement of debris down into the gullies that dissect the pavement where the material remains until carried down the gully and on down the fan. If the gullies ramify and grow deeper, they may approach a condition where the rate at which material is removed from the area of pavement by way of the gully balances the rate at which material is supplied to the gully from the adjacent pavement. Thus, a pavement, once formed, may persist for some time. Pavements occur in diverse locations, in one place partly buried by younger alluvium, elsewhere on a ridge 50 feet above the neighboring wash. It would be a remarkable coincidence if all pavements began to form at the same time; rather, the ubiquitous occurrence of dissected pavements suggests that they formed at various times in the past and have persisted to the present.

The processes of weathering, erosion, and deposition operate concurrently on the fans. It is only the intensity of these processes that varies from one segment of the fan to another. Pavements and associated gullies, as already noted, are the places where weathering and erosion dominate over deposition. They are segments of fans that have received no additions of detritus for a long time. The locations of these segments of fans change with time because of piracy. The formation of a complex mosaic of pavement and wash is conditioned by the local geology and is not primarily dependent on changes in the intensity of weathering, erosion, and deposition caused by changes in climate. Such changes doubtless have occurred, but it cannot be demonstrated that they have radically altered the history of any fan in the quadrangle.

To demonstrate that any of the alluvial fans in the quadrangle are in a steady state of balance or dynamic equilibrium requires actual measurements of the rates of erosion and deposition. None are available. Measurements of the size of many fans in the Death Valley region, however, indicate that, for this region, the area of a fan is roughly equal to one-third to one-half of its source area. This relation holds true for fans composed of different rock types and with diverse geologic histories, suggesting that perhaps these fans are approaching a condition of dynamic equilibrium. If so, the fans will not grow much larger in the future, but will maintain more or less their present size. The location of pavement, wash, or pediment will change from time to time, but the proportion of these three geomorphic units will remain about the same. The configuration of these fans may depend primarily upon some functional relation between the bedrock and the processes acting upon it, rather than upon their stage of development in an evolutionary sequence. The existing highlands have remained nearly unchanged for a long time, perhaps since the mid-Pleistocene. No fault scarps cut the arid-basin sediments.

The outcrop pattern (pl. 1) of the alluvial-fan and playa deposits is the result of the dissection of the ancestral playa (p. L32), whose surface was at least 100 feet above the bed of Carson Slough or the Amargosa River. The pattern depends ultimately on the local geology, which sets limits to mountain and piedmont and thereby determines the size of the adjacent fans. For example, alluvial-fan deposits cover the entire piedmont that extends westward from Shadow Mountain to Alkali Flat. To the north, however, playa deposits crop out in a narrow belt between the toe of the alluvial apron of Shadow Mountain and the alluvium along Carson Slough. The fact that these playa deposits intertongue with alluvial-fan deposits shows that the limit to which gravel was carried from the northwest slope of Shadow Mountain to the ancestral playa was the same as it is today. The gradual lowering of the piedmont west of Shadow Mountain during the dissection of the ancestral playa has not altered the limits of gravel transport on the piedmont.

This restricted belt, east of Carson Slough and south of Ash Meadows Road, consists of narrow finger-shaped areas of playa deposits, desert pavement, and alluvium (pl. 1). Similar belts of pavement fingers occur near the toes of many of the fans, such as those north and east of the Funeral Mountains. The belt west of the Resting Spring Range does not extend south to the quadrangle boundary, but is coextensive with the playa deposits. Perhaps where a wash has banks of sand and silt (playa deposits) the channel tends to maintain its position because it can easily move the fine material on its bed. On the other hand, where the wash is flowing entirely in gravel, as on the piedmont east of Alkali Flat, the occasional flows are more effective in eroding the banks of a wash than in moving the material on its bed. The wash tends to cut laterally and forms a wide, gravel-covered plain.

PEDIMENTS

Between fans are small areas of pediment. On the piedmont surrounding the Resting Spring Range the pediments are underlain by the sandstone and claystone unit. These weakly consolidated but deformed rocks are exposed in shallow gullies and are overlain unconformably by a few feet of alluvial-fan deposits. The unconformity at the base of these deposits is an erosion surface that bevels the deformed rocks. The unconformity is a pediment mantled by a younger gravel, which has since been dissected. These areas of pediment are places where erosion has dominated over deposition to the extent that rocks of early Pleistocene or older age are exposed beneath only a few feet of gravel.

PATTERNED GROUND

The Amargosa Desert exhibits patterns due to the orderly arrangement of various features such as desert shrubs, desiccation cracks, salt crusts, small terraces, or large and small fragments of rock. On many abandoned washes and on some pavements, desert shrubs are spaced uniformly, and the resulting design may be noticeable on aerial photographs. The surface forms portrayed by the stripes of boulder scree on Shadow Mountain or the terracettes that run across many pavements simulate ground patterns found in arctic or alpine regions.

Patterned ground in the Ash Meadows quadrangle is most conspicuous on alluvium or playa deposits, or on alluvial fan deposits where they veneer playa deposits. The optimum development of patterns in such areas is perhaps due to the presence of fine-grained silty material and a high content of soluble salts (carbonates and sulfates?). As with the patterns found in cold climates, those in arid regions can be grouped into more or less equidimensional forms on gently sloping land and elongate structures on steeper slopes.

Sorted polygons (Washburn, 1956) several feet in diameter occur in a few places on the surface of the playa deposits (fig. 9). Small stones, commonly less that 1 inch in diameter, fill shallow cracks or troughs a few inches deep. The adjacent material is a clayey silt. The pattern resembles others found in Death Valley (Hunt and Wash-

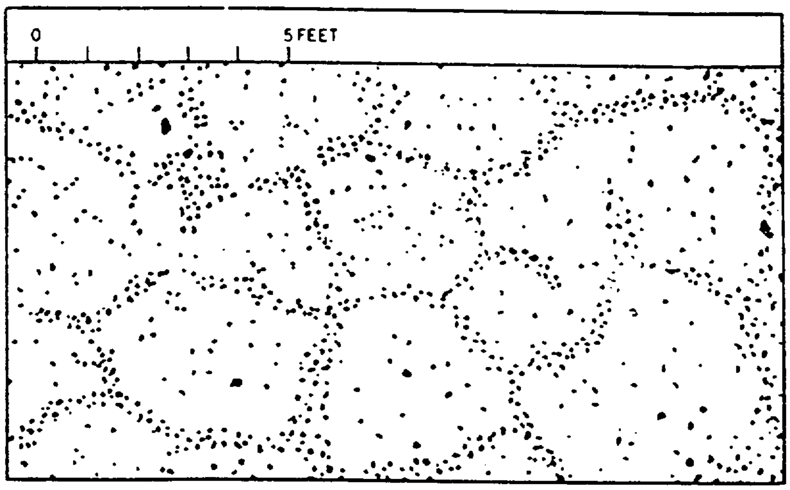


FIGURE 9.—Sorted polygons on surface of playa deposits north of Ash Meadows Rancho. Stones fill shallow cracks and are scattered over intervening fine material. Surface of playa deposits is almost level, and is probably flooded during rains; nearby ground is swampy. Sketched from high-angle oblique photograph, scale not uniform. Locality is a few hundred feet northeast of southwest corner sec. 13, T. 18 S., R. 50 E.

burn, 1960, fig. 185.1A) and presumably is caused by desiccation. These polygons were not excavated. Many of the centers appear to have a very slightly domed surface; the troughs widen at the top.

Areas of salt-encrusted alluvium also show ground patterns. A pebble-covered surface of alluvium may be interrupted by areas of salt crust to give a patterned surface, and these areas of salt crust may themselves show a network of small stones (fig. 8*B*). In some places where an armor of stones rests on silty deposits, a spotted pattern is visible that is reminiscent of stone circles. Large fragments, ½–3 inches a common size, form circular or oval bands surrounding areas 2–3 feet in diameter where the fragments are smaller. White salt crusts appear between the stones of the circles, whose centers are very shallow basins less than an inch deep.

Small terraces are a common feature in the Amargosa Desert and indicate that sliding or slumping has taken place. Such lobate forms are most common where the underlying materials are fine grained. At a point about 2½ miles west of Ash Meadows Rancho (NE. cor. sec. 28, T. 18 S., R. 50 E.), terraces occur on a south-facing, 6° slope underlain by silty material. The individual terraces contour the slope and can be traced for distances of 5 to 30 feet. The risers are from a few inches to nearly a foot high and are faced with pebbles. The treads are of loose puffy silt containing a few small pebbles. Jeep tracks made in 1957 across other areas of puffy ground nearby were partially obliterated a year later.

Somewhat larger and more lobate terraces lie on the south-facing 10° slope of a ridge near Clay Camp (NW. cor. NE¼NW¼ sec. 1, T. 18 S., R. 49 E.). A pebble gravel composed of quartzite, sandstone, limestone, dolomite, conglomerate, and porphyry forms a pavement that mantles the hill. Near the base of the ridge a white salt crust caps prominent lobate terraces (figs. 10 and 11*A*). The risers, from a few inches to 1½ feet high, are faced with pebbles and cobbles. A few shrubs grow on the lower slopes of the ridge.

The material exposed in a trench dug through one of the terraces is illustrated in figure 12, and the accompanying photograph (fig. 11*B*) shows the right-hand terrace of the cross section prior to excavation. The treads have a firm but friable crust on which rest a few pebbles; the risers are of loose sand mantled by pebbles and cobbles, some of which lie on the face in an unstable position. Bedrock is within about 1 foot of the surface. The treads are underlain by loose sandy material that contains particles of white caliche. The risers are partially weathered bedrock, a mixture of sand, silt, and rock fragments.

We believe that the downslope movement recorded by these terraces was largely caused by the addition of water to the underlying material, perhaps partly by the formation of salts in the ground. The water

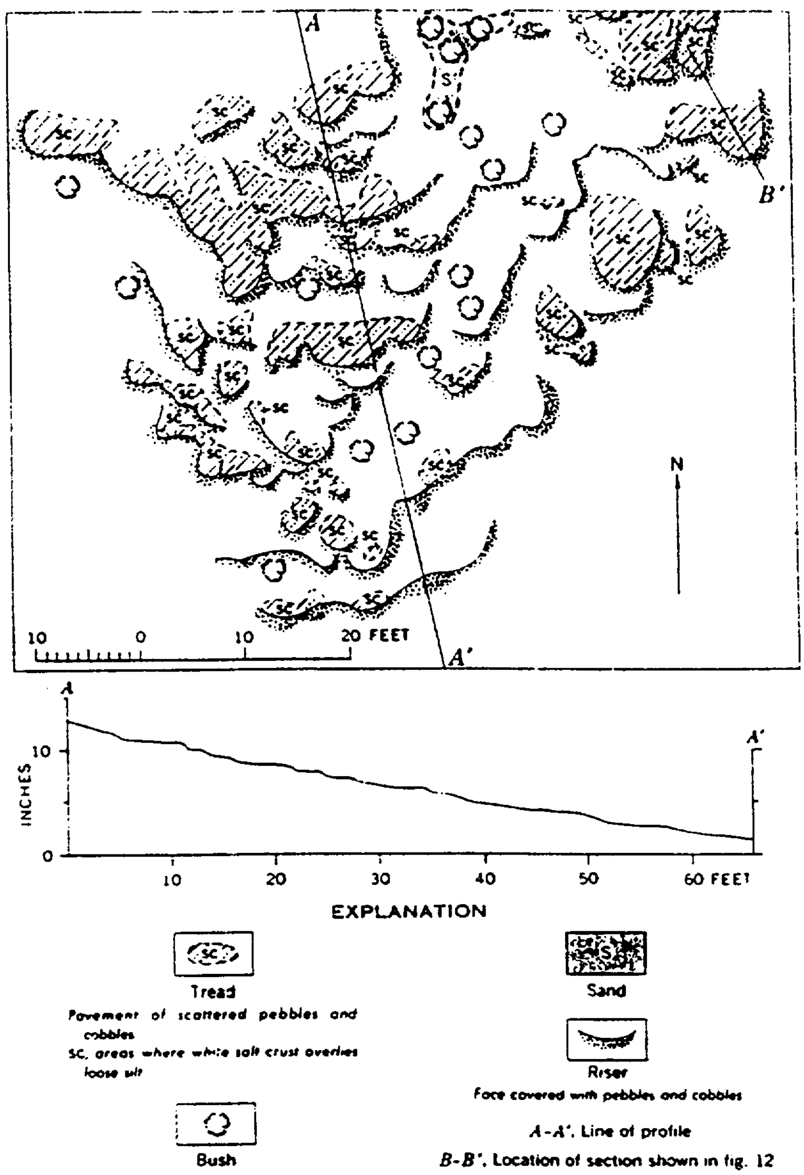
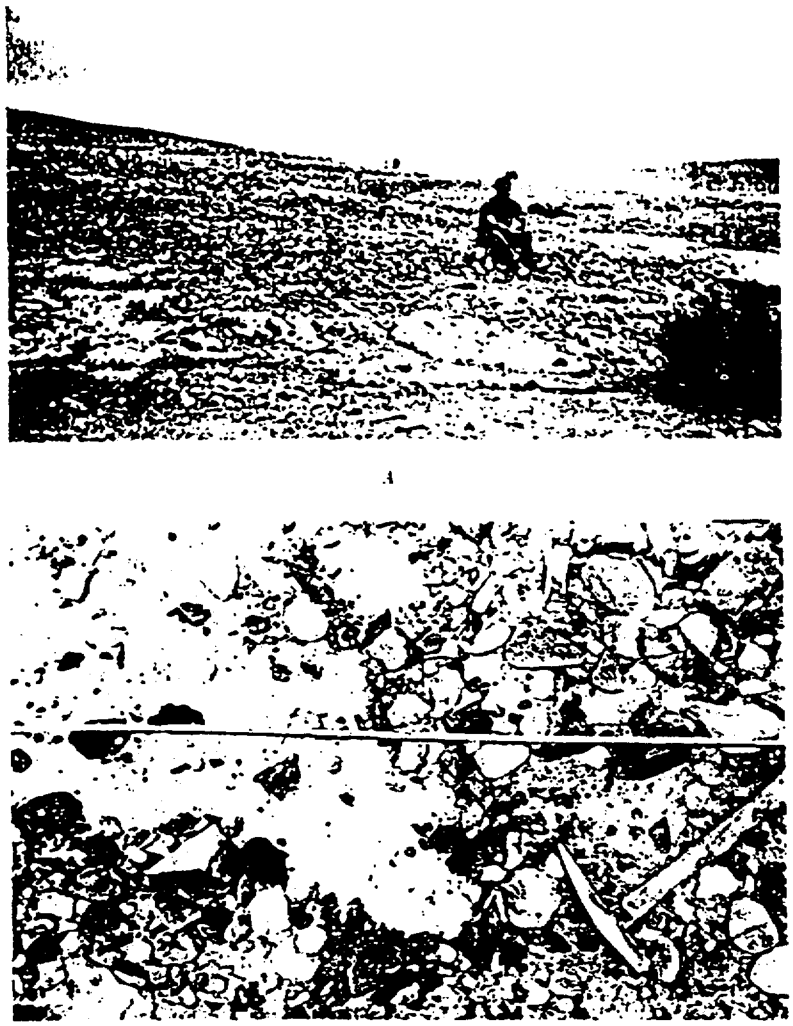


FIGURE 10.—Sketch map and profile of small terraces near Clay Camp. Material exposed in trench (section B–B') is shown in figure 12. Datum assumed.



A

B

FIGURE 11.—Small terraces near Clay Camp. A, Small terraces with curving risers faced with pebbles and cobbles; treads commonly have covering of scattered pebbles and cobbles interspersed with white areas of salt crust; terrace is on south-facing side of ridge about half a mile northwest of Clay Camp. (For map and profile, see fig. 10.) B, Tongue-shaped terrace with pebble-faced riser and white salt-encrusted tread; cross section through this terrace is shown in figure 12

may have come from occasional rains or from a rise in the ground-water table because of reduced evaporation and transpiration. Such a rise has been observed in Death Valley at times of cloudy weather in winter (C. B. Hunt, written commun., 1960).

Whether the terraces are forming today or are largely relics from a moister climatic episode is debatable. Hunt and Washburn (1960) hold that similar terraces in Death Valley are the result of past movements when the climate was more favorable than it is today. They observed rows of pegs across terraces in Death Valley and could find no evidence of movement during a 4-year period.

We believe that some of the terracettes in the Amargosa Valley are forming at present. The relation of terracettes to vegetation suggests present-day movement. On the east side of the hills north of Point of Rocks Springs are many small lobate terraces near the inner

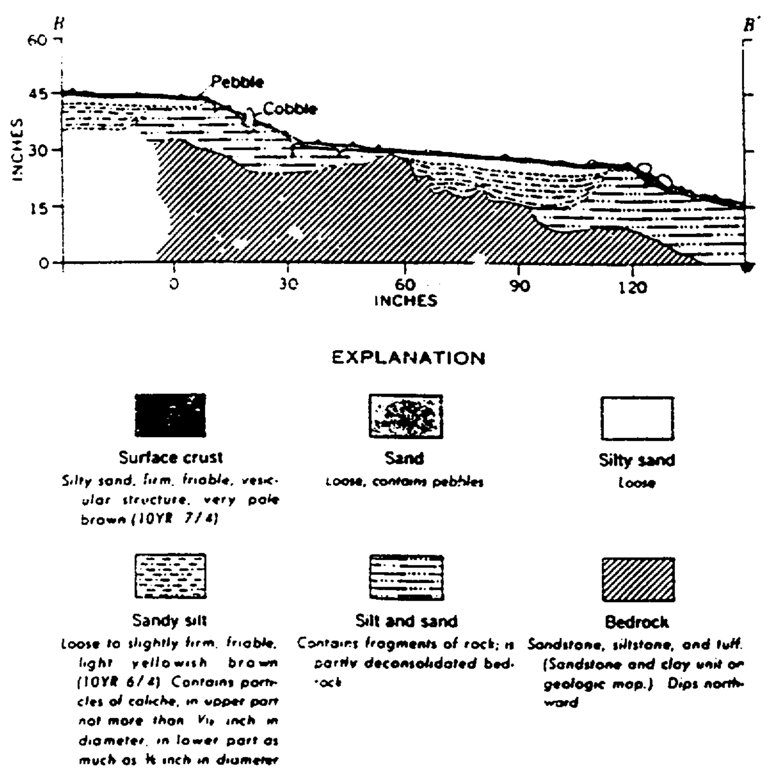


FIGURE 12.—Section through small terraces near Clay Camp. For map of terraces and location of section, see figure 10.

edge of the piedmont next to the mountain front. Some of the lobes appear to have moved around the base of adjacent shrubs. Some of the stones associated with the lobes lean against the stem of a shrub as if they had slid or rolled up against the stem. The uneroded or otherwise unmodified form of some terraces made of loose material suggest that no cloudburst has occurred since such terraces were formed. Stones on the risers of some terraces are loosely packed; a slight touch will send them rolling downslope. It is unlikely that a stone would have maintained such an unstable position for a long time. These stones probably have been pushed into their present attitude by movement of the terrace front within the last few years.

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Late Cenozoic rates of erosion in the western Española basin, New Mexico: Evidence from geologic dating of erosion surfaces

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ABSTRACT

Erosion surfaces in the Española basin formed before 350 ka and between 350 and 240, 240 and 130, and 130 and 80 ka, probably in response to climatic change and regional uplift. The surfaces are cut on Miocene, Pliocene, and Pleistocene deposits and range from about 200 m to 15 m above the present Rio Chama/Rio Grande system. Periods when the surfaces formed were dated using varnish-cation ratios from exposed clasts, the mass of soil carbonate, and amino-acid ratios in Pleistocene gastropods from underlying deposits. Thorium/uranium ages from soil carbonate were used to calibrate a local curve for varnish-cation ratios. The range in age determined for a given surface, although derived from different dating techniques, implies that parts of the surface were sites of erosion or aggradation after the surface formed.

From 1.1 Ma to present, denudation rates averaged 10 cm/1,000 yr from weakly lithified sandstone, less than 7 cm/1,000 yr from indurated tuff and boulder gravel, and about 4 cm/1,000 yr from tuff and basalt. Erosion surfaces were preserved as upland benches and terraces by stream incision during periods of pluvial climate and regional uplift, but our data do not permit clear separation of the two causes.

INTRODUCTION

Erosion surfaces in the Española basin, New Mexico, that cut across late Cenozoic bedrock and surficial deposits provide strong evidence for climatic change and regional uplift. Prominent Quaternary surfaces are preserved along the western margin of the basin at elevations 180–15 m above the Rio Grande and its tributaries. This paper reports geologic data for major surfaces of Quaternary age west of the Rio Grande and Rio Chama. We correlate these surfaces and estimate their ages from a curve of varnish-cation ratios (Harrington and Whitney, 1987), which has been calibrated with $^{230}Th/^{234}U$ ages of soil carbonate. These ages are supplemented by those calculated from amounts of soil carbonate, amino-acid ratios from gastropods, the distribution of Quaternary tephra, and radiocarbon dates. Our data suggest that late Cenozoic incision rates in the Española basin are similar to those reported from several nearby areas in the semiarid western United States.

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This study demonstrates that varnish-cation ratios (Dorn, 1983; Harrington and Whitney, 1987), when used with other dating methods, are useful for correlating and dating surfaces in arid and semiarid areas. Ages calculated from varnish-cation ratios also can provide indications about when specific areas on surfaces became stable. Local erosion and aggradation occur frequently on geomorphic surfaces, and it is often difficult to recognize evidence for such reworking. Under optimal conditions, the lowest varnish-cation ratio from an erosion surface provides a close minimum age for cutting of the surface (Harrington and Whitney, 1987). Groups of higher ratios indicate subsequent periods when other areas of the surface became stable. Varnish-cation ratios can thus be integrated with soil morphology, soil-carbonate accumulation, and isotopic ages to infer episodes or areas of reworking on erosion surfaces.

Erosion surfaces are cut across Miocene, Pliocene, and Pleistocene deposits that fill the Española basin, one in a series of structural troughs that comprise the Rio Grande rift in northern New Mexico. The rift was internally drained until the Rio Grande formed an integrated drainage system between 4.5 and 3.0 Ma. Upper Pliocene and Pleistocene deposits record alternating periods of erosion and aggradation in the basin, punctuated by eruption of the upper Pleistocene Bandelier Tuff. Quaternary surfaces consist mainly of (1) paleochannels preserved by coarse gravel and calcrete, (2) pediments that truncate late Tertiary and Quaternary deposits, (3) alluvial fans, and (4) terraces near present channels. The surfaces variously record periods of lateral cutting (Bull, 1979), episodic dissection of the basin fill, aggradation, and local warping associated with faults (Kelley, 1979; Harrington and Aldrich, 1984). Surface ages and elevations provide evidence for the history of river incision during the Quaternary. Inset relations of surfaces enable us to measure denudation rates (average rate of surface lowering, expressed in cm/1,000 yr) during several periods of the Pleistocene. By comparing denudation rates in areas of different lithology, we can also assess the significance of rock resistance for erosion rates integrated over hundreds of thousands of years.

Episodic aggradation and incision are correlated with climate change during the past 500 ka in New Mexico (Gile and others, 1981; Machette, 1985). Aggradation along the Rio Grande has occurred during transitions from periods of higher effective moisture (pluvial) to more arid conditions (interpluvial), such as the transition from the latest Pleistocene to Holocene. For example, the width of the Rio Grande meander belt near Española has narrowed substantially since about 15 ka, as alluvial fans prograded over Pleistocene channel deposits, burying fluvial terraces with 5 to 30 m of piedmont alluvium (Johnpeer and others, 1985). Gile and others (1981) report a similar pattern of fan extension and axial-channel

Geological Society of America Bulletin, v. 100, p. 928–937, 7 figs., 4 tables, June 1988.

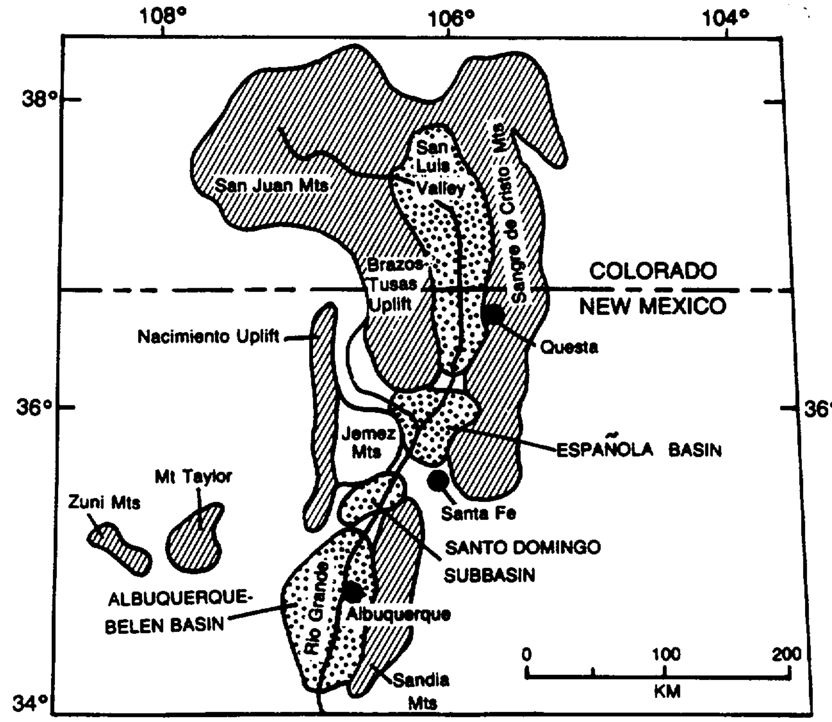


Figure 1. Maps showing the location of the Española basin and the area of this report (after Manley, 1979). a. Map of basins along the Rio Grande in northern New Mexico and southern Colorado (stippled areas), and surrounding mountains.

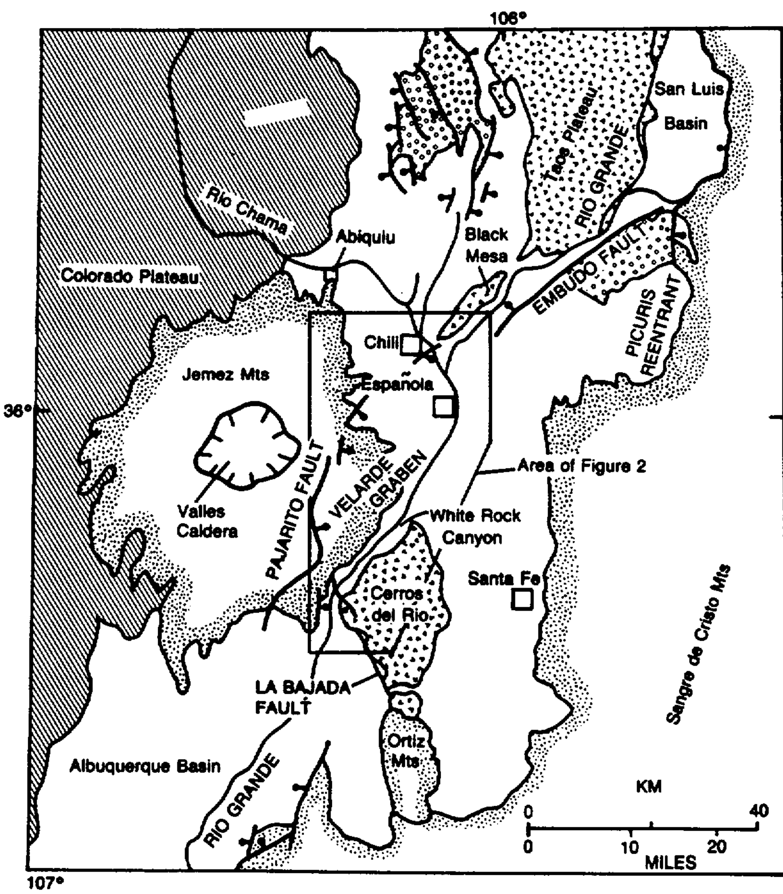


Figure 1. (*Continued*). b. Generalized geology of the Española basin, which extends from the La Bajada fault to the southeast edge of the Taos Plateau. Basin is bounded by Precambrian and lower Paleozoic rocks of the Sangre de Cristo Mountains, Mesozoic rocks of the Colorado Plateau, and Tertiary and Quaternary volcanic rocks of the Jemez Mountains. Principal rock types exposed in the basin are Precambrian metamorphic and igneous rocks (circle pattern), upper Tertiary sedimentary rocks (unpatterned), and upper Miocene and Pliocene basaltic rocks (angle pattern).

alluviation in the southern Rio Grande rift during latest Pleistocene and Holocene time. Major episodes of incision are not well documented but may have been driven by increased discharge in major rivers, such as the Grande and Rio Chama, during pluvial periods correlated with ad-.ces of the continental ice sheets (Richmond, 1965; Hawley and others, 1976). In New Mexico, pluvial periods coincided with cooler temperatures (Phillips and others, 1986), lowered tree line, and more extensive vegetative cover in areas now characterized by communities of mixed, semidesert grassland and desert scrub (Spaulding and others, 1983; Spaulding, 1984). The timing and duration of interpluvial and pluvial climates, however, is not known. Uplift of the Colorado Plateau, Rio Grande rift, and adjacent areas (Eaton, 1979) and increases in the drainage area of the Rio Grande (Kelson and others, 1986) may also have played an important role in incision.

Periods when late Cenozoic erosion surfaces formed along the Rio Grande can be estimated from regional and local studies. Basalt flows beneath and above the highest erosion surfaces in northern New Mexico have K-Ar ages that cluster near 3 Ma (Bachman and Mehnert, 1978; Manley, 1979). Their areal and stratigraphic relations demonstrate that the Rio Grande was an integrated drainage by that time. Manley (1976, 1979) mapped Lower Bandelier Tuff (1.4 Ma; Doell and others, 1968) on surfaces incised more than 80 m below the highest erosion surfaces east of Española. The distribution of Upper Bandelier Tuff (1.1 Ma; Doell and others, 1968) indicates that significant downcutting did not resume until sometime after eruption of the tuff (Dethier and Demsey, 1984). Dethier and Demsey (1984) used the mass of carbonate in soils to estimate that surfaces mapped by Dethier and Manley (1985) along the Rio del Oso (northwestern Española basin) formed, respectively, before about 350, 240, 130, and 80 ka. Thorium/uranium ages of soil carbonate demonstrate that surfaces between the Rio del Oso and Santa Clara Canyon ned before about 145, 105, and 20 ka (Harrington and Aldrich, 1984). e ages are minimum values, because erosion surfaces require time to bilize, thick carbonate rinds take tens of thousands of years to form, and because of assumptions inherent to Th/U dating.

The degree of soil development suggests that the Holocene landscape in southern New Mexico stabilized at about 10 ka and again at about 4 ka (Gile and others, 1981); data from northern New Mexico are less extensive. At a site near Santa Fe, radiocarbon ages of charcoal in alluvium indicate two periods of aggradation and three times when arroyos incised during the past 2,300 yr (Miller and Wendorf, 1958). In the Española area, drilling, trenching, and seismic evidence show that Holocene fans have prograded over latest Pleistocene Rio Grande gravels. Radiocarbon ages from buried organic matter suggest that the most recent period of aggradation began before about 3 ka and ended in the 19th century (Johnpeer and others, 1985).

SETTING

The western Española basin is filled with Miocene sedimentary rock and with Pliocene to Holocene volcanic rocks and sediment derived from the Jemez Mountains, from the Sangre de Cristo Range, and from uplands to the north (Fig. 1). Pleistocene surfaces 15 to 180 m above present arroyos slope gently toward the Rio Chama and Rio Grande and are generally flanked by boulder-mantled slopes. Holocene surfaces are within 10 m of present grade.

Annual precipitation near the Rio Grande ranges from about 220 mm at Cochiti Lake to 250 mm at Española. More than 50% of the precipitation falls in intense local thunderstorms during July–September, whereas frontal disturbances produce precipitation of moderate intensity during the rest of the year. The highest erosion surfaces are covered with a dense pinon-juniper forest near the mountain front; lower and easterly parts of the high surfaces support grasses, sage, cholla cactus, and sparse juniper.

METHODS

Field

Our field investigations focused on mapping and dating of some 30 surface remnants west of the Rio Grande between Chili and Cochiti Lake (Fig. 2) and their underlying deposits. We placed particular emphasis on using varnish-cation ratios for correlating surfaces and collected the most strongly varnished clasts at four to ten sites on each of the remnants (Harrington and Whitney, 1987). We described the best-preserved soils from most surfaces, and Dethier and Demsey (1984) sampled soil carbonate at ten sites on four surfaces. In addition, we collected carbonate rinds from clasts at seven sites for Th/U dating, and we sampled gastropods from four deposits beneath three different surfaces for amino-acid racemization analyses. Stratigraphic control in most of the area was provided by the Lower and Upper Bandelier Tuff, and by the El Cajete tephra, which erupted from a dome in the Valles Caldera at about 130 ka (J. N. Gardner, Los Alamos National Laboratory, 1987, personal commun.). Two undated mid-Pleistocene tephras from unidentified sources provided local control west of Española.

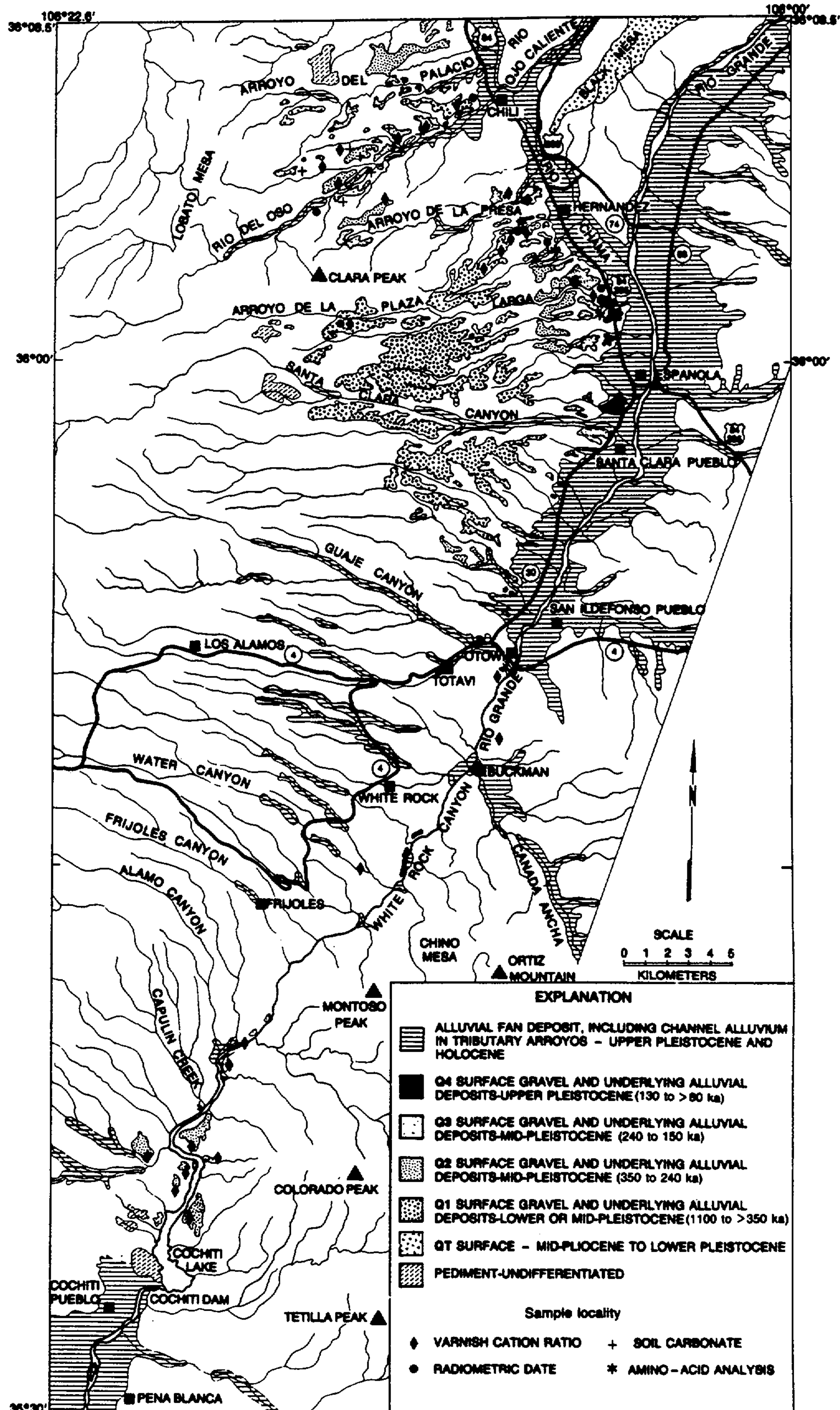
Laboratory

We analyzed the chemistry of rock-varnish samples following scanning electron microscope methods described by Harrington and Whitney (1987). Varnish-cation ratios were calculated as Ca + K/Ti (Dorn, 1983), where each element was reported in weight percent. We used the lowest ratios determined for a geomorphic surface ($\pm 1\sigma$) for correlation and age calculations except when the varnish contained (1) more than 2.5% Ti and more than 3.0% P or (2) more than 3% Ti-magnetite grains in the 5-μ to 100-μ size range. Such samples were excluded from our calculations. For most erosion surfaces, varnish ratios measured for at least four clasts agreed within 10% of each other.

We calculated the amount of pedogenic carbonate in a soil (cS) using methods described by Machette (1985). As soils commonly were eroded, ages were estimated using the maximum values of cS for a geomorphic surface. We used the rate of $CaCO_3$ accumulation at Albuquerque, 0.22 $gcm^{-2}ka^{-1}$ (Machette, 1985), for the western Española basin because (1) annual precipitation and temperatures near Española are similar to those at Albuquerque, (2) soils are developed in deposits similar to those near Albuquerque, and (3) the Albuquerque sites used by Machette (1985) for calibration are within 125 km of our study sites. Because carbonate probably accumulated at rates of about 0.35 $gcm^{-2}ka^{-1}$ during interpluvial periods (Machette, 1985, Fig. 7), our age estimates for late Pleistocene soils are slightly too old. Samples of dense, inner carbonate rinds from the bottoms of clasts in the soils were collected for Th/U analysis according to the methods of Ku and Liang (1984).

Amino-acid ratios for gastropods were determined by W. D. McCoy, University of Massachusetts. We collected gastropods from silty sand beneath three of the erosion surfaces south of the Arroyo de la Presa (Fig. 2). For analysis, the gastropods were cleaned ultrasonically in distilled water

Figure 2. Map showing late Cenozoic geomorphic surfaces of the western Española basin. Varnish-cation ratios were measured at all of the soil-carbonate sample sites along the Rio del Oso.



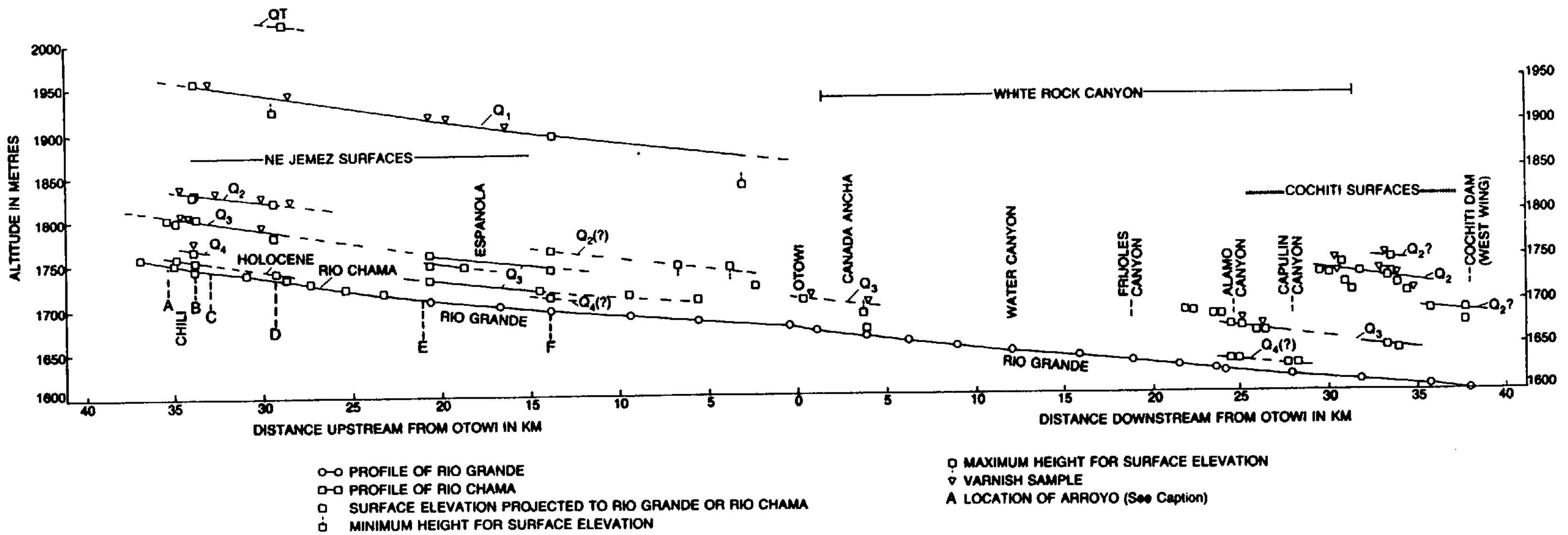


Figure 3. Profiles of geomorphic surfaces projected to the Rio Chama and Rio Grande systems, western Española basin. Arroyo junctions are designated by letters as follows: Arroyo del Palacio (A), Rio del Oso (B), Rio Ojo Caliente (C), Arroyo de la Presa (D), Arroyo de la Plaza Larga (E), and Santa Clara Creek (F).

TABLE 1. SELECTED AGE-RELATED CHARACTERISTICS OF QUATERNARY SURFACES, WESTERN ESPAÑOLA BASIN

Surface	Elevation above grade (m)	Soil-carbonate		Varnish-cation ratio	Estimated age (ka)					Remarks
		Stage	cS		Range	Control				
						cS	Th/U	Varnish	AA	
Holocene (several surfaces)	3–10	I–II	n.d.	4.5–6.5	0.1 1.0 2.3 10.0?	n.d.	n.d.	0.1–15?	n.d.	Historic accounts >0.3 (^{14}C) Miller and Wendorf (1958) 10.3 (^{14}C)
Q_4	10–20	III-	17	2.7–3.2	75–135	>77	>22	75–135	60–130	Older than El Cajete tephra (130 ka)
Q_3	25–50	III, III+	28	2.4–2.8	125–240	>130	>105	125–210	180–250	Older than El Cajete tephra (130 ka)
Q_2	55–90	IV	52	1.7–2.2	240–550	>235	>31	240–550	500–700	
Highest Cochiti surfaces	90–120	IV	n.d.	1.7–2.0	300–550	n.d.	n.d.	300–550	n.d.	Older than El Cajete tephra (130 ka)
Q_1	150–200	IV	78	1.5–1.8	350–1,100	>350	>144	500–700	n.d.	Younger than Upper Bandelier Tuff (1.1 m.y.)

Note: n.d. means not determined; stage is diagnostic measure of carbonate morphology in soil (compare Gile and others, 1981); cS is soil-carbonate accumulation, in gcm^{-2} soil column (method of Machette, 1985); varnish-cation ratios are the range for the 5 rock surfaces which gave the lowest ratios of Ca + K/Ti (Dorn, 1983) at 15 Kev, by energy-dispersive analysis; estimated age from cS calculated as age (ka) = cS/(0.22 gcm^{-2}), Machette (1985); Th/U age from Table 3; varnish age calculated from Figure 5; AA age calculated from amino-acid analyses in Table 2. Values are maximum-limiting ages for surfaces.

and dissolved in HCl. The isoleucine and alloisoleucine content of this solution was analyzed after drying (*free fraction*) or pyrolization (*hydrolyzate*) using a cation-exchange liquid chromatograph (McCoy, 1987).

Gradients of the Rio Grande, Rio Chama, and their western tributary arroyos were determined from the thalweg (channel) distance measured on 1:24,000-scale maps that have a 20-ft contour interval. We plotted gradients and projected surface elevations using techniques described by Hack (1957). Projections of older surfaces to the axial drainage are approximate because (1) the ancestral positions of the Rio Grande and Rio Chama are incompletely known, (2) some older surfaces have been regraded or deformed, and (3) gradients cannot be drawn accurately from isolated remnants. The maximum uncertainty in the elevation of the oldest surface, however, is probably <30 m.

DATA AND DISCUSSION

Spatial Relations

We mapped four groups of piedmont surfaces of Pleistocene age, undifferentiated fans of latest Pleistocene to Holocene age, and two Holocene terraces in the western Española basin. The surfaces are well preserved near arroyos tributary to the Rio Chama, near Santa Clara Canyon, and north of Cochiti Lake (Fig. 2). Erosion surfaces are poorly preserved in White Rock Canyon between Cañada Ancha and Alamo Canyon because of steep valley walls and extensive slumping (Fig. 3). Our estimates of age depend on relative and isotopic dating of erosion surfaces and their associated deposits. The estimates are minima because erosion surfaces often were modified by subsequent deposition or erosion.

Most erosion surfaces between Chili and Española (here called the "northwestern Española basin") are underlain by a mantle of piedmont gravel, which rests unconformably on Miocene bedrock or on Quaternary axial-channel alluvium. For instance, surfaces Q_1 through Q_4 along the Rio del Oso (Fig. 4) are underlain by 3–8 m of gravel on Miocene sandstone. The surface of intermediate elevation apparently represents a temporary period of lateral planation during downcutting that followed Q_1 time. North of Arroyo de la Plaza Larga, surfaces Q_2, Q_3, and Q_4 are underlain by piedmont gravels that truncate axial-river deposits. Each deposit under a surface consists of basal cobble-gravel overlain by 1–5 m of pumiceous sand and sparsely fossiliferous silty sand. Gastropods were collected from the silty sand for amino-acid analyses. Surface Q_2 is preserved only locally south of Arroyo de la Plaza Larga; in most areas, surface Q_4 cannot be distinguished from fans of latest Pleistocene and Holocene age.

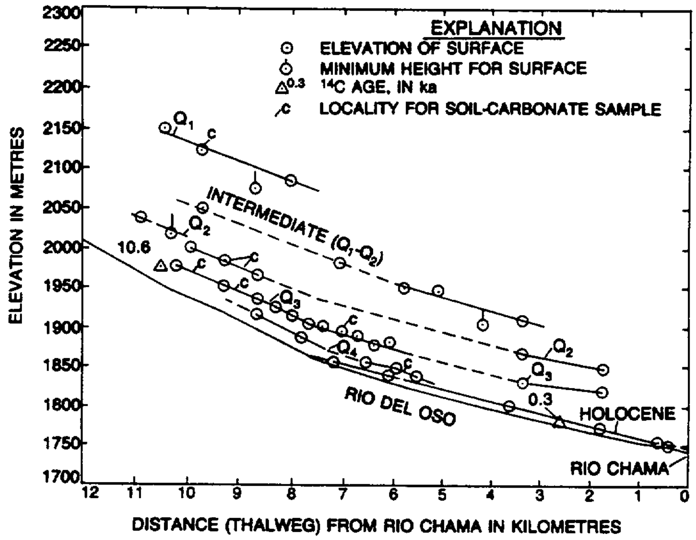


Figure 4. Profiles of Pleistocene erosion surfaces and a Holocene terrace along the Rio del Oso (Rio Chama tributary), showing sample sites for ^{14}C ages and soil-carbonate accumulation.

Erosion surfaces near Cochiti Lake are underlain either by 2–6 m of piedmont gravel or by axial-river deposits composed of 10–40 m of boulder gravel. Surfaces are preserved at elevations of 90 to 130 m (Q_2?), at about 50 m (Q_3), and at 8 to 15 m above the pre-reservoir grade of the Rio Grande (Q_4?). El Cajete tephra overlies the highest surfaces (Q_2?), which have elevations similar to that of the intermediate surface along the Rio del Oso. Surface Q_3, best exposed 12 km north of Cochiti Dam, also is covered with El Cajete tephra. Near the mouth of Alamo Canyon, Q_3 surfaces are cut on a Quaternary flood (?) gravel 20 m thick that contains clasts larger than 4 m. The lowest surface (Q_4?) is visible on air photos and topographic maps, but it is covered by water during most years. Its soils, tephra, and rock varnish have been stripped or altered by fluctuating water levels.

TABLE 2. AMINO-ACID ANALYSES, WESTERN ESPAÑOLA BASIN

Sample	Location	Altitude (m)	Overlying surface	Genus	Amino-acid ratios		Estimated age (ka)
					Free	Hydrolysate	
D-85-132	36°1.51'N 106°5.48'W	1,747	Q_4	*Succinea*	0.38 ± 0.02(3)	0.20 ± 0.01(3)	60–130
D-86-13	36°2.93'N 106°7.12'W	1,795	Q_3	*Pupilla, Zonitoides*	n.d.	0.35 ± 0.02(2)	180–250
D-83-5	36°3.21'N 106°7.93'W	1,830	Q_2	*Succinea*	1.08	0.69 ± 0.03(2)	500–700
D-86-11a	36°2.61'N 106°7.80'W	1,830	Q_2	*Succinea*	1.09 ± 0.03(2)	0.65 ± 0.02(1)*	500–700

Note: n.d. means not determined; altitude for top of axial-channel gravel deposited by the Rio Chama; amino-acid ratios for isoleucine and alloisoleucine, W. D. McCoy, University of Massachusetts, 9 June 1986, written commun. Number of specimens analyzed in parentheses; ages older than 250 ka are estimated by comparing the degree of racemization with that of molluscs at other sites in the semiarid western United States: (1) where Lava Creek or Bishop tephra are found, (2) which have modern temperatures similar to those at Española (~10°C), and (3) where the range of Quaternary temperature is thought to be comparable to that of the western Española basin. Ages younger than about 250 ka were computed from ages and amino-acid ratios for genera (*Amnicola*; *Lymnaea*) that racemize at rates similar to those for *Succinea*, *Zonitoides*, and *Pupilla* (W. D. McCoy, University of Massachusetts, unpub. data).

*One specimen gave a ratio of 0.82 (for two splits). The specimen is thought to have been reworked from older deposits 200 m north of 86-11a and is excluded from the results.

We have correlated surfaces north and south of White Rock Canyon using elevation despite significant differences in river gradient and channel shape, and the proximity of surfaces in the Cochiti area to the La Bajada fault-zone (Kelley, 1977). These correlations are consistent with varnish-cation ratios, which indicate that the Q_2 surfaces of the Cochiti area have been exposed for about the same time as the oldest Q_2 or intermediate surface of the northwestern Española basin. Ratios also indicate that Q_3 surfaces in both areas are of similar age. We tentatively correlate the submerged Cochiti surface with Q_4 north of White Rock Canyon.

Latest Pleistocene and early Holocene surfaces are younger than Q_4 and consist mainly of alluvial fans graded to low terraces along the Rio Grande. The surfaces are best developed north of White Rock Canyon, from Otowi to Española. Alluvial terraces also are preserved along the Rio del Oso and other channels that drain Miocene sandstone. The degree of soil development on isolated terraces 4 to 8 m above arroyos suggests that these surfaces became stable before late Holocene time (D. P. Dethier, unpub. data). Terraces within 4 m of grade record a period of aggradation that began before about 300 yr ago, followed by incision after about 1900 A.D. (Dethier and Demsey, 1984).

Surface Ages

Geologic dating (Tables 1, 2) indicates that Pleistocene erosion surfaces in the Española basin formed at successively decreasing altitudes during four periods: 1100 to 350 ka, 350 to 240 ka, 240 to 130 ka, and 130 to 80 ka. We calculated the approximate ages of surfaces at some 30 localities (Fig. 2), using the curve for varnish-cation ratios determined for the Española basin (Fig. 5). Calibration was provided by four Th/U ages (Table 3: samples 4-84-, 2-84-, 3-84-, and 1-85-MJA) from sites where we also analyzed varnish-cation ratios. The varnish technique gave results consistent with the geologic evidence and with other dating methods used in this study. The highest surfaces had the lowest varnish-cation ratios and largest cS values (Table 1), and the erosion surfaces truncated deposits that gave the highest (oldest) amino-acid ratios (Table 2). Surfaces Q_3 and Q_4 gave higher varnish-cation ratios (Table 1), lower cS values, and cut younger fossiliferous deposits. Varnish-cation ratios were considerably higher than those listed in Table 1 near scarps in gullied areas (for instance, 3-84-MJA) and in other zones where surfaces showed evidence of reworking. Samples for Th/U analyses were collected at localities near scarps (Harrington and Aldrich, 1984), and varnish-cation ratios at these sites were higher than ratios from more stable areas of the surface. The line defined by the varnish-catio ratios at the Th/U localities, however, is only slightly different than that defined by varnish-cation ratios at the soil-carbonate localities (Fig. 5).

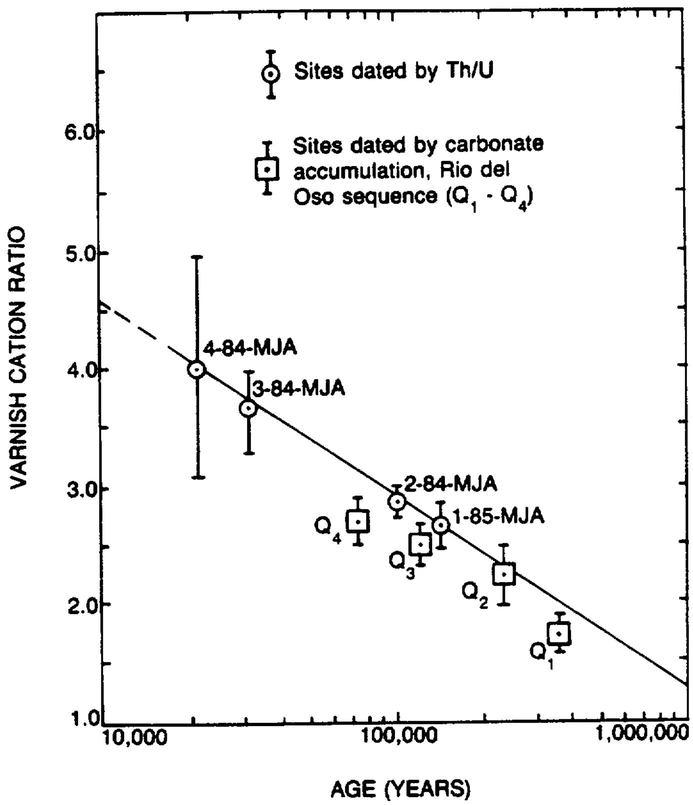


Figure 5. Relation between ages of geomorphic surfaces and varnish-cation ratios (determined at 15 Kev), western Española basin, New Mexico. Line is the least-squares fit through the Th/U-dated points (Harrington and Whitney, 1987). Varnish-cation ratios were measured at four to ten locations (points are mean ±1σ values for the five lowest varnish-cation ratios; Harrington and Whitney, 1987) on each surface. Ages of surfaces Q_1, Q_2, Q_3, and Q_4 along the Rio del Oso were estimated from their maximum amounts of soil-carbonate (Dethier and Demsey, 1984) and an estimated $CaCO_3$ accumulation rate of 0.22 $gcm^{-2}ka^{-1}$.

Amino-acid ratios from three sequences of axial-river deposits (Table 2) help to limit maximum ages for surfaces Q_2, Q_3, and Q_4. Gastropods from axial deposits beneath surface Q_2 gave amino-acid ratios (Table 2; samples D-86-11a and D-83-5) that suggest deposition between 700 and 500 ka. Amino-acid ratios show that surface Q_3 is younger than 250 ka

TABLE 3. Th/U AGE DETERMINATIONS OF CARBONATE RINDS ON CLASTS FROM THE ESPAÑOLA BASIN

Surface	Location			Activity ratios			Age ka	Field no.
	USGS 7½' quadrangle	Latitude (N)	Longitude (W)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$		
Q_4	San Juan Pueblo	36°01'27"	106°05'27"	1.19 ± 0.11	0.18 ± 0.19	n.d.	22 ± 3	4-84-MJA
Q_3	San Juan Pueblo	36°03'07"	106°07'21"	1.31 ± 0.14	0.63 ± 0.06	n.d.	103 ± 17	2-84-MJA
Q_3	Chili	36°03'20"	106°07'50"	1.33 ± 0.15	0.25 ± 0.03	n.d.	31 ± 4	3-84-MJA
Q_1	Chili	36°01'13"	106°13'45"	1.14 ± 0.40	0.81 ± 0.03	7.35 ± 0.46	144 ± 15	1-85-MJA
Santa Cruz	Cundiyo	35°59'00"	105°54'36"	1.16 ± 0.44	0.37 ± 0.14	12.04 ± 1.04	42 ± 4	13-85-MJA
Q_1	Puye	35°57'20"	106°07'45"	1.13 ± 0.04	0.47 ± 0.01	49.33 ± 11.6	66 ± 3	17-85-MJA
Q_1	Chili	36°02'03"	106°08'31"	1.13 ± 0.18	0.06 ± 0.12	n.d.	7^{+15}_{-7}	1-84-MJA

Note: n.d. means not determined; Th/U ages were determined by Teh-Lung Ku, University of California, Los Angeles, in 1984 and 1985. Data for samples 2-84-MJA and 4-84-MJA are from Harrington and Aldrich (1984) and are included here for completeness; sample 3-84-MJA was collected on a low-angle scarp separating Q_3 and Q_2; Santa Cruz surface is east of Española; see Manley (1979) and Kelley (1979).

and that surface Q_4 is younger than 130 ka (Table 2), ages similar to those calculated from varnish-cation ratios (Table 1). These data suggest that alluvial fans built across the flood plain and that surfaces Q_3 and Q_4 ·came stable within a few tens of thousands of years. Deposits truncated .y surface Q_2, however, may have accumulated as much as several hundred thousand years earlier than the erosion surface.

Varnish-cation ratios, used in conjunction with other dating techniques, help to define periods when geomorphic surfaces were modified by local aggradation or erosion. For instance, a cS of 78 gcm^{-2} demonstrates that an isolated remnant of surface Q_1 north of the Rio del Oso (Fig. 2) has been accumulating $CaCO_3$ for more than 350,000 yr. We did not obtain a Th/U age at this site, but the varnish-cation ratio was 1.7, equivalent to an age of about 500 ka (Fig. 5). The Th/U age of surface Q_1 was 144 ka (Table 3; 85-1-MJA) at a site south of Clara Peak where the varnish-cation ratio was about 2.7, equivalent to an age of about 150 ka. We did not use the Th/U technique to date surface Q_2, but varnish-cation ratios show that the surface formed before about 250 ka, and possibly as early as about 550 ka (Table 1). Soil-carbonate accumulation demonstrates that parts of the surface have been stable for 235,000 yr. The ages of surfaces Q_3 and Q_4 are constrained by the data in Table 2 and by the varnish-cation ratios and cS values listed in Table 1. The Th/U ages of 105 ka for Q_3 and 22 ka for Q_4 do not date formation of the surfaces but do record when the sample sites became stable. The last three Th/U ages listed in Table 3 probably reflect periods of local surface degradation or aggradation, but we have not analyzed varnish from these sites. The lowest varnish-cation ratios generally give close limiting ages for the time when a surface was last modified. Ages calculated from rock varnish must be used in conjunction with other dating techniques, however, to estimate the age of formation of geomorphic surfaces.

·ision History

Net incision in the Española basin probably is driven by regional uplift, but cycles of incision and aggradation caused by Quaternary climatic change also have produced substantial changes in local base level. Elevations and ages of erosion surfaces show that the net incision rate since about 2.8 Ma has averaged about 10 cm/1,000 yr and that more rapid incision has characterized the past 500,000 yr. Late Pliocene and early Pleistocene changes in base level are poorly documented in the western Española basin, but times of incision are approximately known in a few areas. Stratigraphic relations near White Rock Canyon, for instance, suggest that base level was relatively stable from 3 Ma to about 2 Ma (Waresback, 1986). In the northeastern Española basin, a series of pediments were cut between about 2.8 and 1.4 Ma when local base level fell some 80 m (Manley, 1976, 1979). Catastrophic deposition of the Lower and Upper Bandelier Tuff interrupted Pleistocene incision in the northwestern Española basin. Canyons tens of metres deep were cut locally in Bandelier Tuff between 1.4 and 1.1 Ma (Griggs, 1964), but rapid incision did not begin until after 1.1 Ma in both White Rock Canyon (D. P. Dethier, unpub. data) and the Rio del Oso area (Dethier and Demsey, 1984).

Ages and elevations of erosion surfaces in the northwestern Española basin indicate that incision rates increased dramatically after about 500 ka. Between about 500 ka and 100 ka, base level fell about 150 m. The average rate of incision over that period was almost four times the rate calculated from 1.1 Ma to present. Net incision ended sometime after 100 ka, and latest Pleistocene and Holocene fans buried the Pleistocene Rio Grande channel near Española. Many surfaces that formed during the climatic change at the end of the Pleistocene were buried along the Rio ·de elsewhere in New Mexico (Gile and others, 1981; Machette, ·). Late Pleistocene terraces related to the Pinedale glaciation are preserved, however, along rivers draining the northern Sangre de Cristo Range and Brazos upland (for instance, see Scott and Marvin, 1985; Wesling and McFadden, 1986; Kelson and others, 1986), and locally along the upper Rio Grande.

Ages and elevations of surfaces in the Rio Chama/Rio Grande drainage (Fig. 6) are broadly comparable to those reported for the Albuquerque-Belen basin by Machette (1985). Combined data from the Española and Albuquerque-Belen basins suggest that rapid incision began sometime after about 600 ka and lasted until at least 100 ka. Data from the Española basin are similar to those reported elsewhere in the region, which implies fairly uniform regional climatic or tectonic influences (Fig. 7). We have no direct evidence that climate controlled development of Pleistocene erosion surfaces along the Rio Grande. Axial-channel deposits covered by piedmont gravel, however, suggest that surfaces near Española and along the southern Rio Grande were active zones of transport during transitional and interpluvial climates and were relatively stable during pluvial periods (Gile and others, 1981).

Personius and Machette (1984) noted rapid downcutting along the Rio Grande near Taos, New Mexico, beginning after about 600 ka. They attributed the downcutting to either drainage integration or uplift. Studies by Kelson and others (1986) in the same general area led them to favor drainage integration or capture for the rapid downcutting. Gillam and others (1984) suggested that elevations of surfaces along the Animas River were a function of uplift. We believe that drainage integration may have increased incision rates in northern New Mexico, but widespread downcutting between 500 and 100 ka implies a change in a regional variable such as a shift to wetter climate.

Denudation Rates

Although incision was relatively uniform in the western Española basin during the late Quaternary, denudation (incision integrated over area) was strongly influenced by different rock types (Table 4). We calculated denudation rates from hypsometric measurements for test areas of about 35 km^2 located 2–6 km from the axial drainage in each of three 7.5′

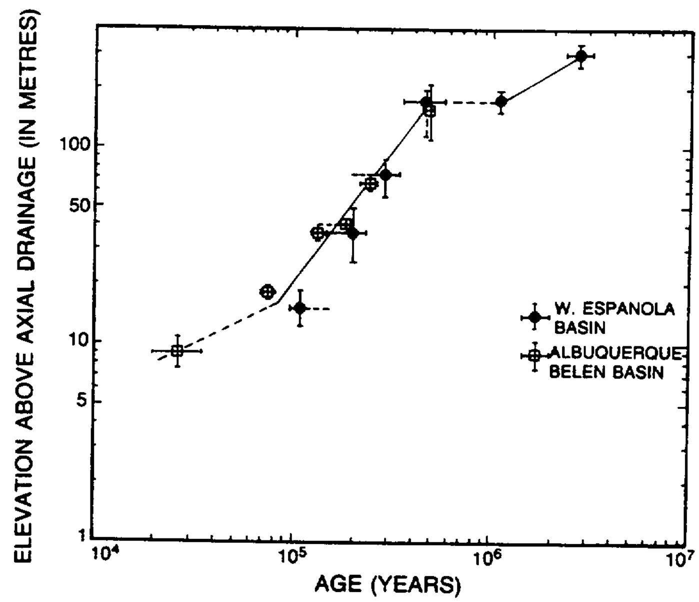


Figure 6. Elevation of erosion surfaces above the Rio Grande, western Española and Albuquerque-Belen basins, New Mexico. Line indicates net incision history since 2.8 Ma. Other data for the western Española basin are given in Table 1. Data for Albuquerque-Belen basin from Machette (1985), except for the elevation of the youngest point, which is from Lambert (1968). Age and elevation ranges are shown as solid lines (dashed where uncertain) about the data points.

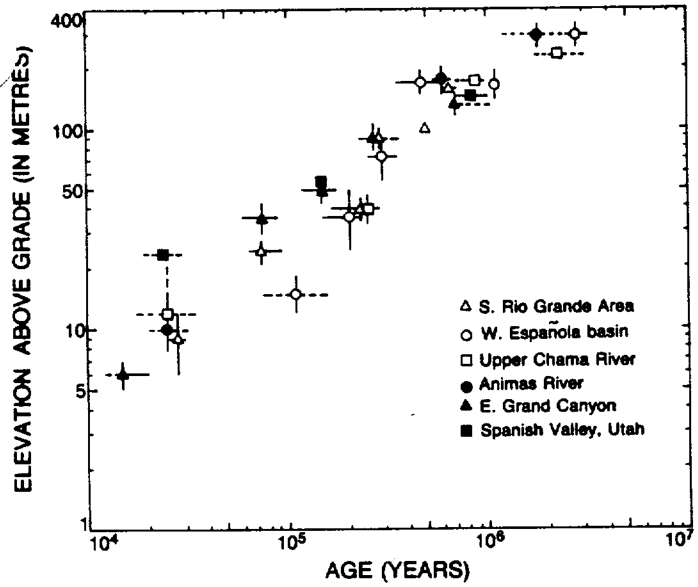


Figure 7. Net Pliocene-Pleistocene incision along the Rio Grande and other selected major drainages in the southwestern United States. Sources are Machette, 1985 (southern Rio Grande: Las Cruces area); this study (western Española basin); Scott and Marvin, 1985 (Upper Chama River); Gillam and others, 1984 (Animas River); Machette and others, 1986 (eastern Grand Canyon); and Harden and others, 1985 (Spanish Valley, Utah). Age and elevation ranges given in the original studies are shown as solid lines (dashed where uncertain) about the data points.

TABLE 4. SUMMARY OF QUATERNARY DENUDATION RATES, WESTERN ESPAÑOLA BASIN, NEW MEXICO

Time period and reference surface (in parentheses)	Denudation rates in cm/1,000 yr		
	Weakly lithified sandstone (Chili quad.)	Indurated tuff/ boulder gravel (Puye quad.)	Indurated tuff/ basalt (White Rock quad.)
1.1 Ma (pre-Q_1) to present	10	<7	4
1.1 Ma (pre-Q_1) to 500 ka(Q_1)	<10	10	n.d.
500 ka(Q_1) to present	20–35	>3	n.d.
500 ka(Q_1) to 250 ka(Q_2)	30–100	n.d.	n.d.
250 ka(Q_2) to present	>10; <30	n.d.	n.d.
250 ka(Q_2) to 160 ka(Q_3)	>13; <30	n.d.	n.d.
160 ka(Q_3) to present	> 7; <20	n.d.	n.d.

Note: n.d. means not determined; denudation rates calculated as volume of material removed in each period/test area; test areas in each quadrangle were as follows: Chili quadrangle (36°06.00′N, 106°15.00′W; 36°07.00′N, 106°12.50′W; 36°03.50′N, 106°10.00′W; 36°02.50′N, 106°13.00′W); Puye quadrangle (36°00.00′N, 106°13.80′W; 36°00.00′N, 106°10.00′W; 35°56.00′N, 106°10.00′W; 35°56.00′N, 106°13.8′W); White Rock quadrangle (35°52.50′N, 106°15.00′W; 35°52.50′N, 106°10.00′W; 35°47.50′N, 106°13.80′W; 35°47.50′N, 106°15.00′W).

quadrangles along the western margin of the Española basin. The principal rock types were (1) slightly lithified Miocene sandstone (Chili quadrangle), (2) indurated Quaternary tuff overlying Pliocene boulder gravel (Puye quadrangle), and (3) indurated Quaternary tuff overlying Pliocene basalt (White Rock quadrangle). Denudation rates were calculated as (cubic metres of rock removed/size of test area, in m^2)/(time interval, in thousands of years) for the time intervals listed in Table 4. We assumed that when incision began, each reference surface tested in Table 4 had a slope similar to preserved remnants, and that erosion from the remnants has been minimal. Each of the geomorphic surfaces was well preserved in the Chili quadrangle; in the Puye quadrangle, only the top of the Bandelier Tuff and surface Q_1 were defined, and only the top of the Bandelier Tuff served as a reference point in the White Rock quadrangle. We can best constrain denudation rates for the Chili quadrangle, but the effect of differential rock resistance is clear in all three quadrangles for rates integrated from 1.1 Ma to the present.

Different rates of denudation and varied rock resistance have strongly affected the landscape exposed in the northwestern Española basin. For instance, weakly cemented sandstone along the Rio del Oso was removed twice as rapidly as the more resistant tuff, boulder gravel, and basalt near the Arroyo de la Presa. The well-defined surfaces cut on soft sandstone near Chili are a direct consequence of rapid erosion, followed by armoring of surfaces with gravel transported in paleochannels. Erosion surfaces younger than Q_1 are less sharply defined and less extensive in the areas of tuff and boulder gravel south of Guaje Canyon (Fig. 2). South of Los Alamos Canyon, narrow, steep-walled canyons eroded into tuff and basalt preserve only a few erosion surfaces, although fans older than 130 ka are present locally. Relatively slow rates of denudation and limited preservation of erosion surfaces are typical of the resistant rocks exposed in most of the southwestern Española basin, the White Rock Canyon area, and near Cochiti Dam.

Denudation rates calculated for the Chili quadrangle (Table 4) indicate a long-term sediment loss of about 10 cm/1,000 yr (200 $Tkm^{-2}yr^{-1}$), and peak rates (Q_1 to Q_2 time) of 50 cm/1,000 yr (900 $Tkm^{-2}yr^{-1}$), assuming a sediment density of 2.0 gcm^{-3}. Denudation rates in areas of more resistant rocks are less well constrained but are probably less than 5 cm/1,000 yr (<100 $Tkm^{-2}yr^{-1}$). The higher rates are comparable to late Holocene denudation rates and to contemporary sediment yield for the Rio Grande. Miller and Wendorf (1958) used the volume of sediment stored beneath terraces to estimate that late Holocene denudation rates from weakly cemented Miocene sandstone ranged from 11.5 to 43 cm/1,000 yr (330 to 860 $Tkm^{-2}yr^{-1}$). They suggested that present rates of denudation and flood-plain aggradation in northern New Mexico are comparable to those for the late Holocene period of aggradation. Sediment yield for the Rio Grande catchment at Otowi is about 200 to 500 $Tkm^{-2}yr^{-1}$ (U.S. Geol. Survey, Albuquerque, New Mexico, 1986, unpub. records), equivalent to a denudation rate of 10 to 25 cm/1,000 yr. Contemporary rates of denudation thus are comparable to rates calculated from 500 ka to the present.

Uplift Rate and Climate Change

Incision recorded by erosion surfaces in the western Española basin could reflect uplift, climate change, drainage capture, or a combination of factors. If incision was dominated by uplift, rates were slow to moderate (5 to 35 cm/1,000 yr) in late Cenozoic time. Such rates are comparable to those estimated for the southern Rocky Mountains in Colorado (Scott, 1975) and southern San Juan Mountains of Colorado (M. L. Gillam, University of Colorado, unpub. data). Slow regional uplift of parts of the western United States apparently is caused by either regional extension and upward bulging of the lithosphere (Eaton, 1979) or subduction of a lithospheric plate (Damon, 1983). Increased rates of incision (Figs. 6, 7) after about 500 ka could suggest a change in rates of regional uplift, but we ve a climatic explanation is more likely.

Increased runoff in the Rio Grande may have contributed to the pparent increase in rates of downcutting at 500 ka. Drainage capture could explain increases in runoff along the Rio Grande, but we are not aware of any evidence that suggests capture in the basins of the Rio Chama, Animas River, and eastern Grand Canyon (Colorado River), which also record more rapid incision. Global change to a wetter climate after about 600 ka, suggested by some terrestrial and deep-sea records (Sarnthein and others, 1986; Jansen and others, 1986), could have increased peak or average discharge in rivers. Climatic models for the southwestern United States demonstrate that temperature and effective moisture changed substantially in the late Pleistocene and early Holocene (Phillips and others, 1986; Spaulding and others, 1983; Galloway, 1983; Brakenridge, 1978). No comparable records of paleoclimate, however, are available for the period of changed incision rates. Incision of basin-filling alluvium (Camp Rice Formation and correlative units) along the central and southern Rio Grande valley after about 500 ka is attributed mainly to integration of middle and lower river segments (Gile and others, 1981; Seager and others, 1984), rather than solely to a climatic shift. The importance of climate change to downcutting along the Rio Grande is thus not clear.

We suggest that regional uplift produced late Cenozoic downcutting by drainages such as the Rio Grande in the Española basin and that changes to a wetter climate increased rates of incision at about 500 ka. Proof of wetter climate and increased discharge requires studies that emphasize palynologic, paleontologic, and stable-isotope techniques, coupled with paleohydraulic data. Better understanding of the erosional history of the Rio Grande will come when we can predict how major rivers in rid zones respond to climatic changes, still a poorly understood ct (Schumm, 1977; Bull, 1979; Howard, 1982).

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TRW

TRW Environmental
Safety Systems Inc.

Civilian Radioactive Waste Management System

Management and Operating Contractor

Contract #: DE-AC01-91RW00134
LV.SC.BWD.8/92-103

Erosion Rates at Yucca Mountain

Technical Assessment Qualification of Data

August 31, 1992

9303110103 21pp.

WBS: 1.2.5.2.4
QA: QA

CIVILIAN RADIOACTIVE WASTE MANAGEMENT SYSTEM

MANAGEMENT AND OPERATING CONTRACTOR

To: J. Russell Dyer, Director
Regulatory & Site Evaluation Division
Yucca Mountain Site Characterization Project Office
U. S. Department of Energy

Date: August 31, 1992

M&O Program: Technical Assessment
Qualification of Technical Data Collected and Evaluated Prior to NRC Acceptance of YMPO Quality Assurance Program.

Submitted by: B. William Distel
Technical Assessment Chairperson — date
(702) 794-1827

M&O Review

Technical Reviewer — Date 9/7/92

Technical Reviewer — Date 9/8/92

Approved:

C. Thomas Statton, M&O Site Characterization Manager — Date 14 Sept '92

This Technical Assessment has been done in accordance with YMPO QMP-02-08, and M&O Procedure QAP-3-5.

TABLE OF CONTENTS

WBS: 1.2.5.2.4
QA: QA

EXECUTIVE SUMMARY

Data Qualification of Existing Data for Erosion

The Erosion Data has been subjected to technical assessment to establish that: Equivalent QA existed during data gathering and evaluation, that corroborative data exists to substantiate the Erosion Data, and that an independent Peer Review of leading geomorphologists has examined the varnish cation-ratio age dating process used by the Principal Investigators on erosion at Yucca Mountain and find it the best technique currently available.

The Nuclear Regulatory Commission (NRC) published NUREG-1298 (Generic Technical Position on Qualification of Existing Data for High-Level Waste Repositories) to provide guidance to the DOE regarding the process by which existing data should be qualified to meet the requirements of 10 CFR 60, Subpart G. DOE has implemented Administrative Procedure 5.9Q (Qualification of Data or Data Analyses Not Developed Under the Yucca Mountain Project Quality Assurance Plan) to allow a qualification process for Project data gathered prior to the NRC's acceptance of Yucca Mountain Project Office's (YMPO) Quality Assurance Requirements Document (QARD) guidelines.

A Technical Exchange was held on May 27, 1992 between DOE, and the NRC to present the technical basis for a DOE Topical Report (TR) on Erosion. In line with DOE issuing a TR, this Technical Assessment has been conducted to demonstrate the QA acceptability of Erosion Data.

This Technical Assessment was completed in accordance with Yucca Mountain Project Office (YMPO) Quality Management Procedure (QMP) 02-08, Rev. 1 and with YMPO Administrative Procedure (AP) 5.9Q, Rev. 1, Sections 4.5, 5.3.2.1, and 5.3.2.5. Just prior to summarization of this Technical Assessment, AP 5.9Q, Rev. 2 has been implemented. AP 5.9Q, Rev. 2 was being developed during the Assessment period, and was actually a result of working with Rev. 1 and NUREG-1298 in the Assessment effort. The Technical Assessment method is consistent with Rev. 2 requirements, as well as the requirements of Rev. 1.

This Technical Assessment, and all directly related Technical and QA Procedures, TATM qualifications, correspondence, Assessment results, the LANL Independent Peer Panel Review, and the Technical Assessment Notice, Rev. 0 and Rev. 1 have been entered in the YMPO Records Information System.

WBS: 1.2.5.2.4
QA: QA

TECHNICAL ASSESSMENT RESULTS

This Technical Assessment was conducted in two (2) phases. Phase one consisted of having the Technical Assessment Team Members (TATM) review Technical and QA Procedures in-place for the U. S. Geological Survey (USGS), and Los Alamos National Laboratory (LANL) guiding sample collecting and analysis, and field measurements against current Technical and QA Procedures for the USGS and LANL which control field and laboratory processes today. The second Phase of this Technical Assessment verified that the Scientific Notebooks showing field work and laboratory work conformed to, and followed those relevant Procedures in-place during the time the Notebooks were developed.

The Technical Assessment Team consisted of:

Dr. John C. Dohrenwend
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Menlo Park, California

Dr. Peter W. Birkeland
University of Colorado
Boulder, Colorado

August C. Matthusen
SAIC
Las Vegas, Nevada

Jeff McCleary
Woodward-Clyde Federal Services
Moab, Utah

B. Robert Justice
Duke Engineering & Services, Inc.
CRWMS/Management and Operating Contractor
Las Vegas, Nevada

These Team Members were chosen based on their professional standing in the geomorphological field and/or their expertise in High Level Waste Site Characterization work. None of these people have worked within the Erosion Study Program on Yucca Mountain except as independent reviewers of specific portions of the Study.

WBS: 1.2.5.2.4
QA: QA

Conclusions and Recommendations

The Technical Assessment Team has compared current and previous QA and Technical Procedures that control erosion samples collection and analyses, and field measurements for ero.ion. In addition, field and laboratory notebooks of the Principal Investigators (Dr.'s Whitney and Harrington) were examined and compared to these Procedures.

Conclusion

It is unanimously agreed by all five Technical Assessment Team Members that data collection and evaluation completed prior to NRC acceptance of the YMPO Quality Assurance Program can be qualified under current YMPO QARD requirements.

Recommendation

The Technical Assessment Team does recommend to DOE YMPO that the technical data on Erosion be formally accepted as **qualified** under current YMPO QARD, Rev. 4 guidelines.

Peter W. Birkeland Date

John C. Dohrenwend Date

B. Robert Justice Date

Jeff R. McCleary Date

August C. Matthusen Date

TECHNICAL ASSESSMENT

Qualification of Technical Data - Extreme Erosion

INTRODUCTION

On May 1, 1992, the Regulatory & Site Evaluation Division (RSED) of the Department of Energy (DOE) Yucca Mountain Project Office (YMPO) initiated a Technical Assessment to evaluate the ability of DOE to accept as "Qualified" the technical data on extreme erosion. This data was collected and evaluated prior to NRC acceptance of the YMPO Quality Assurance Program. The scope of the Technical Assessment has been to evaluate the Quality Assurance (QA) and Technical Procedures guiding sample collecting and analysis, and field measurements against current procedures in-place for the U. S. Geological Survey (USGS) and Los Alamos National Laboratory (LANL), under the DOE Quality Assurance Requirements Document (QARD) acceptable to the Nuclear Regulatory Commission (NRC).

In accordance with YMPO Administrative Procedure (AP) 5.9Q, Rev. 1, Section 4.5, this Technical Assessment has been carried out to provide review and evaluation of the data and data analyses in line with AP-5.9Q, Rev. 1, Sections, 5.3.2.1 and 5.3.2.5. AP-5.9Q, Rev. 2 has been implemented soon after this Technical Assessment was completed. AP-5.9Q, Rev. 2 was in development during the Assessment period, and was a result of working with AP-5.9Q, Rev. 1 and NUREG 1298 in the Assessment effort. The Assessment method is consistent with AP-5.9Q, Rev. 2 requirements. This Technical Assessment has been done in accordance with YMPO Quality Management Procedure (QMP) 02-08, Rev. 1, to establish technical merit.

The Technical Assessment Notices, Revision 0 and Revision 1, are included as Attachment I. The Technical Assessment Team (TAT) initially consisted of four (4) members, then was expanded on June 12, 1992, to include one additional member. These TAT members are identified in Attachment II, as are their qualifications to perform this Technical Assessment.

Communications between the Technical Assessment Chairperson (TAC) and the Technical Assessment Team Members, (TATM) are included in Attachment III, as are the initial comments by TAT Members.

This Technical Assessment has been conducted in two (2) phases. Phase I consisted of having the TATM review the Procedures described above in the first Paragraph. As a result of the Phase I evaluation, a second Phase was initiated during which two members of the TAT visited the Principal Investigators for the Erosion studies on the Yucca Mountain Site, Dr. Whitney (USGS), and Dr. Harrington (LANL) at their respective offices. These visits were for the purpose of examining field and laboratory scientific notebooks, and interviewing Dr. Whitney and Dr. Harrington.

SUMMARY - PHASE I

The Technical Assessment Notices of May 1, 1992, and June 22, 1992 asked the TATM to evaluate the QA and Technical Procedures in-place in the U. S. Geological Survey (USGS), and Los Alamos National Laboratory (LANL), during the time that sample collection, analysis, and field measurements were performed. These were compared against procedures currently in place at the USGS and LANL under the DOE QARD guidelines. The purpose was to examine any differences between these procedures in order to answer the following questions:

- Would data collection and evaluation under current Participant technical procedures differ from those procedures actually followed?
- Are any differences significant enough to affect technical results?
- Can a recommendation be made to DOE YMPO that the procedures used to gather and evaluate samples, and guide field measurements are acceptable to allow the technical data to be qualified under current QARD guidelines?

This Assessment has been conducted in line with the Instructions for Assessment included in Attachment I.

ASSESSMENTS

Dr. John C. Dohrenwend
U. S. Geological Survey
Menlo Park, California

I have examined the differences between those procedures that were in place during collection and evaluation of samples for rock varnish analysis (for the purpose of assessing extreme erosion as an issue at Yucca Mountain) and current procedures under the DOE QARD that are applicable to such collection and evaluation activities. As a result of this examination, I have reached the following conclusions:

- *Current sample collection and evaluation procedures are nearly the same as the procedures actually followed during sample collection and evaluation.*
- *None of the procedural differences that do exist are significant enough to affect the technical results of the extreme erosion study.*
- *Therefore, a recommendation can be made to DOE YMPO that the procedures used to collect and evaluate samples are acceptable and that the technical data pertaining to the extreme erosion study should be qualified under current QARD guidelines.*

Dr. Peter W. Birkeland
University of Colorado
Boulder, Colorado

In summary, in answer to the three questions posed:

- *I think the sample collection and evaluation was not significantly different under both procedures.*

- *The differences are not significant enough to effect technical results.*

- *I recommend that the procedures used to gather and evaluate samples are acceptable to allow the technical data to be qualified under current QARD guidelines.*

I should add, however, that it is very difficult to make these judgements without knowing the kind of data that were collected. It would help to see the report that resulted from the field work, or lab work.

The rest of Dr. Birkeland's assessment is contained in Attachment IV.

August C. Matthusen
SAIC
Las Vegas, Nevada

- *From the procedures reviewed, it is not possible to determine if the technical results would differ from the results that were determined. The procedures reviewed govern mainly the documentation of results and not the gathering and analysis processes.*

- *(Requires verification of technical data to reviewed procedures).*

- *There do not appear to be any valid reasons why any of these data can not be qualified under current QARD guidelines.*

The rest of Mr. Matthusen's assessment on equivalent QA is contained in Attachment IV. Resolution of Mr. Matthusen's comments are addressed further into this Summary Report on pages 6-7.

Jeff McCleary
Woodward-Clyde Federal Services
Moab, Utah

- *In summary, based on the information provided, because of the unknown criteria for sample collection prior to 5/1/87 it is possible that technical results could differ if current procedures were followed. Similarly, potential shipping damage should be considered in accepting the technical results. I feel that if recommendations 1 and 2 are followed these issues can be resolved.*

Recommendations

1. The LANL notebooks developed under the R and D procedures should be reviewed in order to determine how samples were selected in the field prior to 5/1/87. If it can be shown that the same criteria for site and sample selection were followed *prior to 5/1/89, as after the sample collection procedure for rock varnish studies was issued, then all samples can be considered valid.*

2. *All samples shipped should be examined for abrasion or other shipping damage to the varnish surface. If all samples show an intact varnish surface they can be considered valid.*

The rest of Mr. McCleary's assessment on equivalent QA is contained in Attachment IV Resolution of Mr. McCleary's comments are addressed further into this Summary Report on pages 7-10.

B. Robert Justice
CRWMS Management & Operating Contractor
Las Vegas, Nevada

- *Would sample collection and evaluation under current participant technical procedures differ from those procedures actually followed?*

  Response - Inconclusive in that procedures for collection did not exist until 5/1/87 and until 5/3/88 did not adequately address the handling of samples. The guidelines for determining collection areas were less restrictive than current requirements and could have led to samples being collected from areas which may be unsuitable under current procedures. Additionally, there is no evidence of procedural guidelines for conducting the rock varnish for erosion analysis.

- *Are there any differences significant enough to affect technical results?*

  Response - Yes, in the area of handling the samples once they were collected. There was not any specific guidelines provided for the handling of samples until 5/3/88 when change Request #29 to procedure TWS-ESS-DP-114, Rev. 0 became effective. Also, the lack of procedural processes for the collection and analysis of samples raises questions with respect to what processes were actually used and the consistency with which those processes were repeated.

- *A recommendation to accept the data based on the procedures provided for this assessment cannot be made. The obvious lack of procedural guidance in the early stages of this activity supports this conclusion. Other evidence may be available to support the processes used to accomplish the collection and analysis of samples. The notebooks, which have been used throughout this activity to document the work that was performed, may contain enough information to identify the processes used and the consistency with which they were repeated.*

The rest of Mr. Justice's assessment on equivalent QA is contained in Attachment IV. Resolution of Mr. Justice's comments are addressed further into this Summary Report on pages 10-14.

After evaluating the TATM Phase I comments (excerpted above and provided in full in Attachment IV), it was apparent that:

a. All of the TAT Members recognized that the two sets of procedures (those prior to DOE QARD guidelines, and those after) provided to them for evaluation are very similar.

b. Mr.'s McCleary and Justice recognized that samples were collected prior to 5/1/87 before the initial sample collection procedure became effective. Handling and shipping controls were not well addressed before 5/3/88.

c. Mr.'s Matthusen, McCleary, Justice, and Dr. Birkeland, all commented that it would be desirable to see data and results (i.e. field and laboratory notebooks) in order to compare data entries to the reviewed procedures.

SUMMARY - PHASE II

In order to resolve the concerns and questions identified in the Phase I procedures review, the following assignments were given to Mr. McCleary and Mr. Matthusen of the TATM:

Mr. McCleary went to interview Dr. Whitney at the USGS offices in Denver on July 14, 1992, and examine his field notebooks relating to the erosion studies, particularly those sections on sampling for cation ratio dating of desert varnish.

Mr. Matthusen went to interview Dr. Harrington at the LANL offices in Albuquerque on July 14, 1992, and examine his field and laboratory notebooks.

The results of these examinations were quite positive. Mr. McCleary concluded ". . . it is my opinion that cation-ratio dating of desert varnish can be used to support the Project position on erosion rates at Yucca Mountain."

Mr. Matthusen has stated "The procedures (which includes the methodology reflected in field and laboratory notebooks) for gathering and evaluating samples, and the documentation of the gathering and evaluation of samples, allow the data to be qualified."

The full text of Mr.'s McCleary's and Matthusen's observations and evaluations are in Attachment V.

In the following Section, point by point resolutions are provided for each TATM comment.

RESOLUTION OF ASSESSMENT COMMENTS

Dr. John C. Dohrenwend

Dr. Dohrenwend has answered the three questions posed by the Technical Assessment in recommending "to DOE YMPO that the procedures used to collect and evaluate samples are acceptable and that the technical data pertaining to the extreme erosion study should be qualified . . .".

Dr. Peter W. Birkeland

Dr. Birkeland has also recommended that the technical data pertaining to the extreme erosion study should be qualified. Dr. Birkeland's one concern was the kind of data (samples) that were collected, and the results (documentation) of field work, or lab work. Mr. McCleary and Mr. Matthusen have resolved Dr. Birkeland's concern by inspecting the scientific field and laboratory notebooks.

August C. Matthusen

First Comment:

- *From the procedures reviewed, it is not possible to determine if the technical results would differ from the results that were determined. The procedures reviewed govern mainly the documentation of results and not the gathering and analysis process.*

Resolution of Mr. Matthusen's comment is addressed in the verification of data to procedures which was carried out by Mr. Matthusen, at LANL and Mr. McCleary, at the USGS, subsequent to the Procedures Assessment.

Proposed Resolution - Mr. Matthusen:

Additionally, the purpose of the Technical Assessment Notice requested that I assess three questions. These are assessed as follows:

Would sample collection and evaluation under current participant technical procedures differ from those procedures actually followed?

No, they would not differ.

Are any differences significant enough to affect technical results?

No, there are not significant differences.

Can a recommendation be made to DOE YMPO that the procedures used to gather and evaluate samples are acceptable to allow the technical data to be qualified under current QARD guidelines?

Yes. The procedures for gathering and evaluating samples and the documentation of the gathering and evaluation of samples allow the data to be qualified. The documentation of sample and data collection would allow a knowledgeable person to retrace the investigation and confirm the results. The same documentation would allow a peer of Dr. Harrington to repeat the investigation and achieve comparable results without recourse to Dr. Harrington. From my review of the documentation I recommend that the data be accepted.

The rest of Mr. Matthusen's verification report is contained in Attachment V.

Proposed Resolution - Mr McCleary:

Based on the above observations of the procedures and notebooks and my discussions with John Whitney, it is my opinion that if the early sampling were repeated under current procedures, the results would not be significantly different.

It is also worth noting that the early samples collected by the USGS alone have, in general, yielded age estimates that are younger than average. Therefore, eliminating the use of these samples would only support older deposits and slower erosion rates, a less conservative position relative to the regulations. In addition the overall argument on erosion rates does not hinge on the cation-ratio dating technique. U-series, U-trend, Cl-36, and tephrachronology studies were also carried out on early samples collected by the USGS and are in general agreement with the cation-ratio data.

In summary, I have made the following observations:

- *USGS field notebooks document to a reasonable extent that the samples collected early in the study would also have been selected under the 5/1/87 procedure.*
- *Inclusion of the early data produces a slightly more conservative erosion rate relative to the regulations.*
- *Other dating studies carried out to address the erosion issue generally support the results of the desert varnish studies.*

Therefore, it is my opinion that the cation-ratio dating of desert varnish can be used to support the project position on erosion rates at Yucca Mountain. If other assessment team members, or the project, still have concerns, other evaluations can be made with existing information and examination of the samples at LANL.

Resolved: Based on the documentation in the scientific notebooks of the Principal Investigators it is apparent that sample collection and evaluation procedures followed during the investigation were not different from those currently in place. Therefore, technical results would not be significantly different.

Second comment:

- *Requires verification of technical data to reviewed procedures.*

Resolved - This comment has been resolved by the verification of data to procedures by Mr. Matthusen and Mr. McCleary.

Jeff McCleary

First Comment:

- *In summary, based on the information provided, because of the unknown criteria for sample collection prior to 5/1/87 it is possible that technical results could differ if current procedures were followed.*

Proposed Resolution by comparison of field notebooks to procedures provided the following:

Proposed Resolution - Mr. Matthusen:

The documentation materials reviewed include the following:

- *Field Notebooks. Two of Dr. Harrington's field notebooks document samples, sample collection , field sample identification numbers assigned, dates of collection, field personnel, collection rationale, hypotheses, and descriptions of sample collection localities for rock varnish samples for the Yucca Mountain Project. The first notebook (NB1) covered the period from 10/2/85 to 5/13/87. This notebook also included information on rock varnish projects not related to Yucca Mountain. The second field notebook (NB2) covers the period from 1/10/87 to 1990 and includes only Yucca Mountain related information. NB1 contains copies of pages from the field notebook of J. Whitney (USGS) documenting rock varnish sample collection activities in 6/84, 10/85, 11/85, and 7/86. NB1 also contains notes by Dr. Harrington regarding sample collection done in conjunction with J. Whitney for the previously mentioned dates after 10/85. NB2 is more detailed than NB1 and contains more detailed descriptions of samples, sample locations, collection rationales, and hypotheses. Samples and locations recorded in NB1 and NB2 are further documented in a Sample Tracking Notebook and on topographic maps.*

- *Sample Tracking Notebook for rock varnish samples. Samples are recorded with field sample identification number, lab disk identification number (two disks of rock are cut from the field samples and cemented onto a glass slide for use in the scanning electron microscope (SEM) and a new lab disk identification number is assigned to the slide as the field sample identification is often too long to fit on the slide), geologic deposit name, description of sample, and samples are keyed to collection locations documented on topographic maps.*

- *NNWSI Log Book. This notebook documents sample transfers and handlings for the ESS-1 group of Los Alamos National Laboratory from the time period 5/14/86 to 10/2/91. The first entry by Dr. Harrington was 6/3/87. The notebook has been technically reviewed five times between 1/15/88 to 10/2/91.*

Proposed Resolution - Mr McCleary:

The following observations were made:

- *The current procedure requires that samples be collected:*
  - *from stabilized deposits or outcrops*
  - *that exhibit mature varnish development (darker)*

- *that avoids cracks, lichens, etc.*
- *that are not wind abraded or spalled.*

- *Samples were collected by the USGS (John Whitney) alone in 1984 and by the USGS and LANL jointly in 1985 and later. I therefore concentrated my examination on the 1984 notebooks.*
  - *The stabilized deposits are well described (slope angle, thickness, etc.) in each case.*
  - *Varnish maturity is not always described but it is noted often and it is apparent from the notebook as a whole that the intent was to sample darker (more mature) varnish.*
  - *The physical condition of the sample relative to cracks, lichens, abrasion, etc. was not well described. However, if necessary, the rock samples actually collected could be examined at LANL to determine their physical condition.*

Resolved: Documentation available in the field and laboratory notebooks of the Principal Investigators at the USGS and LANL demonstrates that the same sample collection procedures were followed prior to 5/1/87 as after. Therefore, technical results would not be significantly different.

Second Comment:

- *The LANL notebooks developed under the R and D procedures should be reviewed in order to determine how samples were selected in the field prior to 5/1/87. If it can be shown that the same criteria for site and sample collection were followed prior to 5/1/87 as after the "sample collection procedure for rock varnish studies" was issued, then all samples can be considered valid.*

Proposed Resolution has been done by Mr. Matthusen in verifying that samples collected prior to 5/1/87 were selected using the same guidelines as were established in the subsequent sampling procedure.

Proposed Resolution - Mr. Matthusen:

What techniques were used for sample collection?

Discussions with Dr. Harrington elicited that the technique used for sample collection was as described in Harrington and Whitney (1987) and in the Sample Collection Procedure for Rock Varnish Samples (TWS-ESS-DP-114).

Was a procedure followed?

The Sample Collection Procedure for Rock Varnish Samples was implemented in 5/87. Prior to that time the work was being done under the Quality Assurance Procedure for One-time Research and Development Work (TWS-MSTQA-QP-14, R0) implemented in 5/85, and the Research and Development (Experimental) Procedure (TWS-MSTQA-QP-14, R1) implemented in 2/86. These procedures allow development work to be done and documented in notebooks.

Resolved: As noted previously, documentation is available to demonstrate that the same procedures were followed pre and post the 5/1/87 issue date of the sample collection procedure.

Third Comment:

- *All samples shipped should be examined for abrasion or other shipping damage to the varnish surface. If all samples show an intact varnish surface they can be considered valid.*

Proposed Resolution has been done by Mr. Matthusen.

Proposed Resolution - Mr. Matthusen:

- *The SEM samples (the rock disks on slides). These are retained in a locked cabinet in Dr. Harrington's office. The cabinet was opened and I observed the samples. One sample was checked for ID number and the ID number could be tracked to corresponding numbers in notebooks, maps, etc. In discussion, Dr. Harrington indicated that the rock samples from which the disks had been cut are also maintained in storage. Dr. Harrington stated that all rock varnish samples have been hand carried to Los Alamos, so use of the procedure for shipping samples has not been needed.*

Resolved: Observation of the samples and the careful handling of the samples (i.e. all hand carried) demonstrates that the varnish surface is intact and the samples can be considered valid.

B. Robert Justice

First Comment:

1. *Would sample collection and evaluation under current Participant technical procedures differ from those procedures actually followed?*

   Response - Inconclusive in that procedures for collection did not exist until 5/1/87. The procedure used for collection (TWS-ESS-DP-114, Rev. 0) from 5/1/87 until 5/3/88 did not adequately address the handling of samples. The guidelines for determining collection areas were less restrictive than current requirements and could have led to samples being collected from areas which may be unsuitable under current procedures. Additionally, there is no evidence of procedural guidelines for conducting the rock varnish for erosion analysis.

Proposed Resolution - August Matthusen

Prior to 1987 LANL and the USGS were evolving defined (specific locations) sample sites, and the analysis process.

The Sample Collection Procedure for Rock Varnish Samples was implemented in 4/87. Prior to that time the work was being done under the Quality Assurance Procedure for One-time Research and Development Work (TWS-MSTQA-QA-14, R0) implemented in 5/85, and the Research and Development (Experimental) Procedure (TWS-MSTQA-QP-14, R1) *implemented in 2/86. These procedures allow development work to be done and documented in notebooks.*

1. *Field Notebooks. Two of Dr. Harrington's field notebooks document samples, sample collection, field sample identification numbers assigned, dates of collection, field personnel, collection rationale, hypotheses, and descriptions of sample collection localities for rock varnish samples for the Yucca Mountain Project. The first notebook (NB1) covered the period from 10/2/85 to 5/13/87. This notebook also included information on rock varnish projects not related to Yucca Mountain. The second field notebook (NB2) covers the period from 1/10/87 to 1990 and includes only Yucca Mountain related information. NB1 contains copies of pages from the field notebook of J. Whitney (USGS) documenting rock varnish sample collection activities in 6/84, 10/85, 11/85, and 7/86. NB1 also contains notes by Dr. Harrington regarding sample collection done in conjunction with J. Whitney for the previously mentioned dates after 10/85. NB2 is more detailed than NB1 and contains more detailed descriptions of samples, sample locations, collection rationales, and hypotheses. Samples and locations are recorded in NB1 and NB2 and further documented in a Sample Tracking Notebook and on topographic maps.*

2. *Sample Tracking Notebook for rock varnish samples. Samples are recorded with field sample identification number, lab disk identification number (two disks of rock are cut from the field samples and cemented onto a glass slide for use in the scanning electron microscope [SEM] and a new lab disk identification number is assigned to the slide as the field sample identification is often too long to fit on the slide), geologic deposit name, description of sample, and samples are keyed to collection locations documented on topographic maps.*

3. *NNWSI Log Book. This notebook documents sample transfers and handlings for the ESS-1 group of Los Alamos National Laboratory from the time period 5/14/86 to 10/2/91. The first entry by Dr. Harrington was 6/3/87. The notebook has been technically reviewed five times between 1/15/88 to 10/2/91.*

4. *SEM Notebook Rock Varnish. Begun in 6/86 to document the SEM and energy dispersive X-ray analyzer (EDAX) work performed on the rock varnish samples. It begins referencing the initial analytic procedure (Harrington and Whitney, in review; later published as Harrington and Whitney, 1987, "Scanning electron microscope method for rock-varnish dating", Geology, Vol.15, pp. 967-970) and briefly describing the initial analytic procedure in the notebook. It described specifics of analyses and analytic results. The notebook also documents much additional pertinent information (e.g., on 9/22/86 the SEM machine was moved to a new location, a new run was done with a previously analyzed sample to verify/compare new results to previous analytic results). Therefore, for a new series of runs, an old sample would be re-run to ensure similarity of results. Over the course of the experiment, the experimental methodology was refined. All changes in SEM settings in response to methodological refinements are documented (e.g., on 9/22/86 - the procedure was modified to ascertain penetration for the varnish coating without inclusion of the rock substrate, that is, to ensure that only the varnish is being sampled) and previous samples retested. The notebook has undergone frequent technical review by technical staff from Los Alamos (Carlos, Vaniman, Broxton, Maassen). Thirteen reviews are documented between 7/1/86 to 1/18/91. The last technical entry in this notebook is 11/14/90, it was reviewed*

1/18/91, and was closed out 2/10/92. Additionally, the notebook documents changes in the SEM program used to deconvolute the data, hypotheses, changes in hypotheses, problems encountered, investigations pursued to resolve problems, data, and assumptions in methods.

Proposed Resolution - Jeff McCleary

The current procedure requires that samples be collected:

- *from stabilized deposits or outcrops*
- *that exhibit mature varnish development (darker)*
- *that avoid cracks, lichens, etc.*
- *That are not wind abraded or spalled.*

Samples were collected by the USGS (John Whitney) alone in 1984 and by the USGS and LANL jointly in 1985 and later. I therefore concentrated my examination on the 1984 notebooks.

- *The stabilized deposits are well described (slope, angle, thickness, etc.) in each case.*
- *Varnish maturity is not always described but it is noted often and it is apparent from the notebook as a whole that the intent was to sample darker (more mature) varnish.*
- *The physical condition of the sample relative to cracks, lichens, abrasion, etc. was not well described. However, if necessary the samples (at LANL) could be examined to determine their physical condition.*

Based on the above observations of the procedures and notebooks and my discussions with John Whitney, it is my opinion that if the early sampling were repeated under current procedures, the results would not be significantly different.

It is also worth noting that the early samples collected by the USGS alone have, in general, yielded age estimates that are younger than average. Therefore, eliminating the use of these samples would only support older deposits and slower erosion rates, a less conservative position relative to the regulations. In addition the overall argument on erosion rates does not hinge on the cation-ration dating technique. U-series, U-trend, Cl-36, and tephrachronology studies were also carried out and are in general agreement with cation-ratio data.

Resolved: That the sampling process, and sample analysis process (via the documentation in the Notebooks) is the same as would be done under current procedures (which were developed from the processes demonstrated in the Notebooks).

Therefore, there would be only minimal differences, if any, for sample collection and evaluation under current LANL and USGS procedures.

Second Comment:

2. *Are there any differences significant enough to affect technical results?*

   Response - Yes, in the area of handling the samples once they were collected. There were not any specific guidelines provided for the handling of samples until 5/3/88 when Change Request #29 to procedure TWS-ESS-DP-114, Rev. 0 became *effective. Also, the lack of procedural processes for the collection and analysis of samples raises questions with respect to what processes were actually used and the consistency with which those processes were repeated.*

Proposed Resolution - August Matthusen

The field notebooks, the sample tracking notebook, the NNWSI Log Book, the maps, and the samples themselves (all discussed prior) exist to document the sample collection and handling. Dr. Harrington stated that all rock varnish samples have been hand carried to Los Alamos, so use of the procedure for shipping samples has not been needed.

Sample handling used a "best practices" approach to protect samples being "hand carried" by Dr. Harrington.

The data, documentation, and work comply to procedures governing scientific notebooks (Quality Assurance Procedure for One-time Research and Development Work [TWS-MSTQA-QA-14, R0] implemented in 5/85; Research and Development Work (Experimental) Procedure [TWS-MSTQA-QP-14, R1] implemented in 2/86; and Procedure for Documenting Scientific Investigations [TWS-QAS-AP-03.5, R0] implemented 3/10/89). These procedures allow development work to be done and documented in notebooks.

Proposed Resolution - Jeff McCleary

In summary, I have made the following observations:

- *USGS field notebooks document to a reasonable extent that the samples collected early in the study would also have been selected under the 5/1/87 procedure.*
- *Inclusion of the early data produces a slightly more conservative erosion rate relative to the regulations.*
- *Other dating studies carried out to address the erosion issue generally support the results of the desert varnish studies.*

Therefore, it is my opinion that the cation-ratio dating of desert varnish can be used to support the project position on erosion rates at Yucca Mountain. If other assessment team members, or the project, still have concerns, other evaluations can be made with existing information and examination of the samples at LANL.

The question of what processes were actually used (to collect samples and evaluate samples), and the consistency with which these processes were repeated, is answered in resolution of Comment #1.

Resolved: That the sampling and evaluation processes actually used, and the consistency of repeating these processes is documented, and demonstrated in the Scientific Notebooks available from Dr. Harrington. Therefore, in that current procedures have been developed from the processes demonstrated within these Scientific Notebooks, there would not be significantly different data obtained if tests were performed today.

Third Comment:

3. *Can a recommendation be made to DOE YMPO that the procedures used to gather and evaluate samples are acceptable to allow the technical data to be qualified under current QARD guidelines?*

Response - A recommendation to accept the data based on the procedures provided for this assessment cannot be made. The obvious lack of procedural guidance in the early stage of this activity supports this conclusion. Other evidence may be available to support the processes used to accomplish the collection and analysis of samples. The notebooks, which have been used throughout this activity to document the work that was performed, may contain enough information to identify the processes used and the consistency with which they were repeated. These notebooks were not provided as part of the review package.

Resolved: That the Scientific Notebooks verify that the processes used would conform to current procedures. Therefore, a recommendations <u>can</u> be made to DOE YMPO to accept the erosion technical data as qualified under current DOE QARD guidelines.

Conclusions and Recommendations

The Technical Assessment Team has evaluated current and previous QA and Technical Procedures that relate to sample collection and analysis, and field measurements for cation ratio dating. In addition, field and laboratory notebooks of the Principal Investigators were examined and compared to the procedures.
Three questions have been answered:

1. Would data collection and evaluation under current Participant technical procedures differ from those procedures actually followed?

2. Are any differences significant enough to affect technical results?

3. Can a recommendation be made to DOE YMPO that the procedures used to gather and evaluate samples, and guide field measurements are acceptable to allow the technical data to be qualified under current QARD guidelines?

First question

It has been unanimously agreed by all five Technical Assessment Team Members (TATM) that data collection and evaluation would not differ under current QA and Technical Procedures for LANL and the USGS.

Second question

The TATM unanimously agrees that no significant differences would result from data collection and evaluation under current QA and Technical Procedures.

Third Question

The Technical Assessment Team Members do recommend to DOE YMPO to allow the technical data on Extreme Erosion be formally accepted as qualified under current YMPO QARD guidelines.

In June 1989 LANL organized a peer review group of leading geomorphologists to examine the VCR (varnish cation-ratio) age dating technique and "critically reviewed rock-varnish studies within the LANL Yucca Mountain Project". This Peer Review Panel concluded ". . . that the VCR age determinations by Dr. Harrington and collaborators are the best presently being done." This Panel also stated: "We are impressed with the excellent work being done on VCR age determination by the LANL research and technical staff and their associates at the USGS and the University of New Mexico. The members of this high-quality team, primarily in the ESS-1 Group (LANL), are extremely careful in all phases of the work, from the initial field sampling, through the laboratory work, to the final age estimation." This peer review supports the results of this Technical Assessment. The report by this Panel is included as Attachment VI.

Geology of the Ash Meadows Quadrangle Nevada-California

By CHARLES S. DENNY and HARALD DREWES

CONTRIBUTIONS TO GENERAL GEOLOGY

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The history of a desert basin and its bordering highlands

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ILLUSTRATIONS

GEOLOGY OF THE ASH MEADOWS QUADRANGLE, NEVADA-CALIFORNIA

By Charles S. Denny and Harald Drewes

ABSTRACT

The Ash Meadows quadrangle lies about 25 miles east of Death Valley and includes the southern part of the Amargosa Desert, a broad lowland adjacent to the Amargosa River. The southeastern spur of the Funeral Mountains projects a short distance into the quadrangle from the west, and the northern end of the Resting Spring Range lies in the southeast corner. The mountains rise 2,000–3,000 feet above the adjoining piedmonts that are largely coalescing alluvial fans. The Ash Meadows, located in the northeastern part of the quadrangle, contain several flowing springs such as Devils Hole, a large sink in Middle Cambrian limestone and dolomite.

Within the quadrangle, about 5,000 feet of Silurian to Mississippian limestone and dolomite forms the backbone of the Funeral Mountains and is overlain by 3,000–5,000 feet of fluvial and lacustrine deposits of Tertiary, perhaps Oligocene age. The spur is an eastward-dipping fault block bounded on the south by the Furnace Creek fault zone. The block itself is broken by two sets of normal faults.

Volcanic rocks, part of those that form much of the Greenwater Range to the southwest, form a small butte in the southwestern corner of the quadrangle.

On the east side of the Amargosa Valley lies Shadow Mountain, which forms the end of the Resting Spring Range, and a group of isolated hills near Devils Hole. Both highlands consist of about 5,000 feet of gently dipping Cambrian rocks, chiefly quartzite, limestone, and dolomite. The rocks of Shadow Mountain form an east-dipping fault block overlain at its north end by fanglomerate and finer grained beds of Tertiary age. The rocks of the hills near Devils Hole are broken by numerous steep faults of small displacement.

The rocks of the mountains and hills throughout the quadrangle are overlapped by alluvial-fan deposits of Quaternary age, largely undeformed beds of gravel, sand, and breccia. Away from the highlands the fan deposits intertongue with playa and spring deposits, largely silt and lesser amounts of sand or clay. No fossils have been found in these arid-basin sediments, but Pleistocene fossils are known from similar deposits in the Amargosa Valley about 30 miles to the south. Surficial deposits of limited extent include dune sand, scree, and landslide breccia. Alluvium floors the lowlands along the Amargosa River and its principal tributaries. Artifacts associated with the alluvium suggest that most of it is at least 2,000 years old. Some alluvium and some of the dune sand, however, are younger.

The piedmonts between mountain and lowland include four geomorphic units: desert pavement, pediment, and washes, the last divisible into washes floored with unweathered gravel and those where the stones on the surface have a coating of desert varnish. The size of a piedmont and the proportion of pavement, wash, or pediment on its surface depend upon the structural history of mountain and basin and the processes acting upon them. The configuration of the piedmont may represent an approach toward a steady state of balance or dynamic equilibrium between the rate at which detritus is brought to the piedmont from the adjacent highland and the rate at which it is removed by erosion.

Patterned ground, reminiscent of that found in cold climates, occurs throughout the quadrangle. The patterns are due to the orderly arrangement of such features as desiccation cracks, shrubs, terracettes, and linear or oval-shaped areas of large and small fragments of rock.

INTRODUCTION

The Ash Meadows quadrangle, in the southern part of the Amargosa Desert, is a broad area of sloping piedmonts bordered by small mountain ranges. The Amargosa River flows southward through the desert for more than 100 miles (fig. 1), roughly parallel to and about 25 miles east of Death Valley, until it reaches the point where it turns westward into Death Valley and there flows northwestward for about 40 miles until it loses itself on the saltpan near Badwater. The Ash Meadows are largely a wide expanse of swamp or meadow, but includes some areas of sand dunes and bare ground. The name connotes extensive areas of salt crust or white clay which give an ashen color to the landscape. Within the Meadows are several large flowing springs, one of which, Devils Hole, has been set aside as a part of Death Valley National Monument.

In 1956–58, Denny, with the able assistance of H. F. Barnett, Jack Rachlin, and J. P. D'Agostino, mapped the Quaternary deposits of the quadrangle and the older rocks in the northern end of the Resting Spring Range. He was especially concerned with the form and origin of the alluvial fans (Denny, 1964). Drewes, in 1955, mapped the Tertiary and Paleozoic rocks of the eastern spur of the Funeral Mountains and of the hills near Devils Hole. Previously he had completed a study of the Funeral Peak quadrangle which adjoins the Ash Meadows area on the southwest (Drewes, 1963). We are grateful for criticism of this report by several of our colleagues in the Geological Survey and also by Charles B. and Alice P. Hunt.

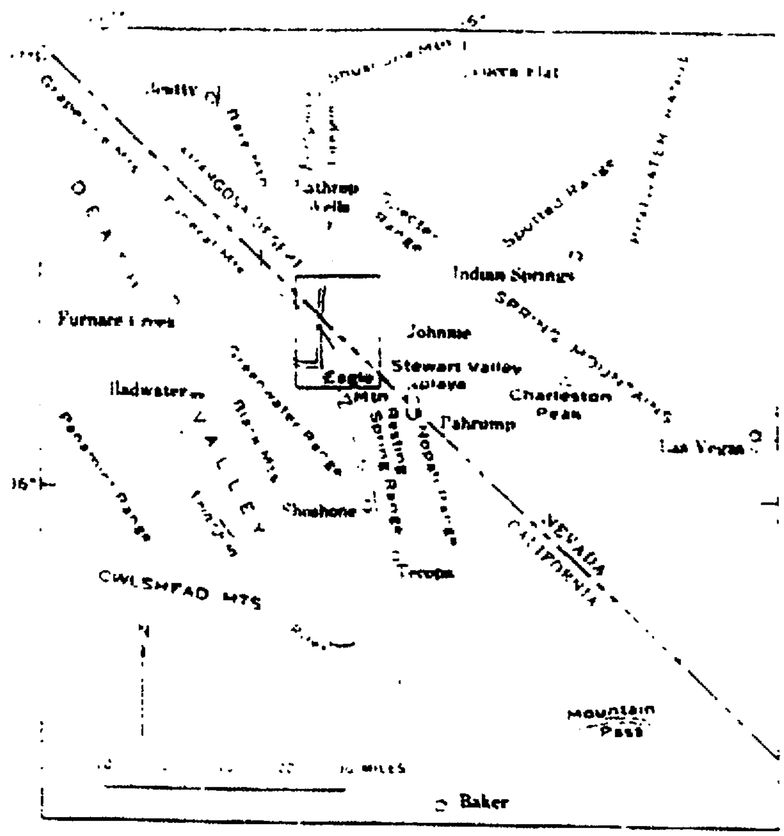


FIGURE 1.—Index map of parts of Nevada and California showing location of Ash Meadows quadrangle.

GEOGRAPHY

The Ash Meadows quadrangle (pl. 1) lies within the Amargosa Valley and includes Death Valley Junction, an abandoned mining settlement on the dismantled Tonopah and Tidewater Railroad. The junction is at the terminus of one of the principal access routes into Death Valley from the east (fig. 1). One of the two highways leading southward from Tonopah and Beatty, Nev., to Baker, Calif., transects the quadrangle; the other follows the length of Death Valley.

The quadrangle is largely a plains area; only about 10 percent is mountain or hill. Local relief on the plains is rarely more than 50 feet. The average gradient of the Amargosa River is about 14 feet per mile. Shadow Mountain, the higest peak (alt 5,071 ft), lies about 3,000 feet above Alkali Flat, the lowest point. The mountain fronts are both linear and embayed.

The highlands are bordered by sloping piedmonts, largely coalescing fans that range from 1 to 6 miles in length. There are only small areas of pediment cut on rocks of late Tertiary age and commonly veneered with gravel. The fans have slopes near their apices that range from about 300 to 800 feet per mile. Downfan, slope decreases to less than 100 feet per mile.

The surface of most fans is not smooth but is cut by washes that lie many feet below the surrounding gravel plain. Such dissection reaches depths of as much as 60 feet near the highlands. Near the toes, however, the surface approaches a plain, and the floors of the larger washes may actually lie slightly above their surroundings. The skin of most fans is a mosaic of areas of desert pavement and of wash.

The piedmonts lead down to broad lowlands such as the flood plains of the Amargosa River and of Carson Slough or the playa of Alkali Flat and of a second unnamed playa in the northeast corner of the quadrangle. Both of these playas are no longer enclosed but drain to the Amargosa River. Marshlands border the upper reaches of Carson Slough.

The surface of the Amargosa Desert exhibits patterns formed by surface features of many kinds: arrangements of salt efflorescences, of stones and finer material, or of miniature terraces; mosaics composed of braided channels and areas of desert pavement; and groups of shrubs.

The hills and mountains in the quadrangle have bare slopes of 3,000–5,000 feet per mile or roughly 30°–45°. Small deposits of scree are found in many places, but most of the mapped scree is on Shadow Mountain. Dark-gray quartzite forms the upper slopes of Shadow Mountain; its lower flanks are of similar but slightly paler colored rock. Viewed from the west, the contact between these rocks of differing color is horizontal, and the mountain's summit appears in the late afternoon light as if in shadow. A tongue-shaped landslide projects eastward from the base of the Funeral Mountains just south of Bat Mountain, and on the piedmont northeast of the mountain, landslide masses of Tertiary limestone form low white hills (Denny, 1961).

Sand dunes supporting a scattered growth of mesquite occur in the northern half of the quadrangle; the largest sand-covered areas are on the plains east of Carson Slough where the dunes reach heights of 50 feet. A small butte, capped by a spring deposit, rises about 150 feet above Fairbanks Spring near the head of Carson Slough; other, less conspicuous mesas of similar material lie south of Longstreet Spring. Still other small unmapped bodies of spring deposits occur in the Ash Meadows.

There are nearly 20 flowing springs in or near the Ash Meadows (Lyle, 1878; Ball, 1907; Stearns, Stearns, and Waring, 1937; Hunt and Robinson, 1960). Most of these springs, including several circular pools 20–40 feet in diameter and 5-20 feet deep, are in Cenozoic rocks. Two springs, Point of Rocks and Devils Hole, are in Paleozoic limestone and dolomite. Devils Hole is a rectangular opening about 50 feet deep that contains a pool about 10 feet wide by 65 feet long. Many of the springs contain the *Cyprinodont* fish whose presence in such isolated places led Hubbs and Miller (Miller, 1946, 1948; Hubbs and Miller, 1948) to postulate the existence of very extensive pluvial lakes and connecting drainageways over much of western United States during the Pleistocene.

The water table is near the surface in much of the Ash Meadows and at Death Valley Junction. Loeltz (1960) estimates that the annual discharge from the springs is about 18,000 acre feet of water annually. The limestones and dolomites of the northeast part of the quadrangle provide channelways to bring water into the area. Although similar rocks apparently form the treeless hills between Devils Hole and Johnnie (fig. 1), it is doubtful that these hills receive sufficient precipitation to produce such a discharge. The spring water probably has its ultimate source in precipitation on the northern part of the Spring Mountains about 20 miles to the east. Hunt and Robinson (written commun., 1962) suggest that the springs in the Ash Meadows have their source in the lowlands near Pahrump, which in turn derive their water from the Spring Mountains. The lowest part of these lowlands is a playa, known as Stewart Valley, which is about 300 feet higher than and about 10 miles southeast of Ash Meadows.

The only mining in the quadrangle is a small bentonite prospect north of Bat Mountain. The numerous clay pits in the Meadows and near Clay Camp have not been worked for many years, probably at least since the railroad was dismantled about 1940.

The climate is warm and dry. The average annual precipitation probably is between 3 and 4 inches per year in the lowland (Troxell and Hofmann, 1954; U.S. Weather Bureau, 1932) and slightly higher on the adjacent mountains. Snow seldom reaches the Amargosa Desert but mantles the neighboring mountains for short periods in winter. On the valley floor, the average maximum monthly temperature for July is more than 100°F; minimum winter temperatures are below freezing in December and January. The highest temperature recorded at Clay Camp near the center of the quadrangle was 118° F in July; the lowest was 3°F in December. A thermometer resting on a desert pavement southwest of Grapevine Springs, the bulb covered by a layer of fine sand about one grain thick, registered a high of 162° F during the period from May 1957 to February 1958.

[illegible]

The region is virtually treeless, but desert shrubs are scattered over the surface of the fans. Mesquite grows on all sand dunes and along the Amargosa River west of California State Highway 127. A mesquite tree near Franklin Well is about 15 feet high, and some in the Ash Meadows reach heights of 10 feet.

STRATIGRAPHY

Rocks of Paleozoic and of Tertiary age make up the highlands; the lowlands are mantled by Quaternary deposits. Shadow Mountain and the hills near Devils Hole include about 5,000 feet of Cambrian strata, chiefly quartzite and massive limestone or dolomite. An equal thickness of Silurian to Mississippian limestone and dolomite forms the backbone of the northern part of the spur of the Funeral Mountains that lies within the quadrangle. Bat Mountain and the remainder of the spur comprise 3,000 to 5,000 feet of fluvial and lacustrine deposits of Tertiary age. Similar rocks are exposed in the hills at the north end of the Resting Spring Range. The volcanic rocks of the Greenwater Range project into the southwest corner of the quadrangle to form a small butte.

Arid-basin sediments of Quaternary age cover the lowlands. Gravel, breccia, sand, and silt form alluvial fans; silt and clay underlie playas. Quaternary deposits of limited extent include spring or swamp deposits, scree, sand dunes, landslide breccia, and alluvial deposits along washes.

PALEOZOIC ROCKS

The areal extent of the Palesozoic rocks in the highlands is small. These formations were not studied in detail, and their description is perforce brief. Dark-gray or banded medium-gray and dark-gray dolomite, limestone, and quartzite are the most abundant rocks. In this area, somber colors are typical of the Paleozoic rocks and brighter yellowish-brown or reddish-brown hues are characteristic of outcrops of the younger formations. The formation names assigned to the Paleozoic rocks on the east side of the quadrangle are based on similarity of the rocks to those described by Hazzard (1937) in the Nopah and Resting Spring Ranges. The rock units recognized in the Funeral Mountains on the west side are based on similarity to rocks described by McAllister (1952) in the northern Panamint Range and elsewhere in the Funeral Mountains (McAllister, written commun., 1961).

ROCKS OF THE RESTING SPRING RANGE

QUARTZITE OF SHADOW MOUNTAIN

Shadow Mountain[1] is composed of quartzite and minor amounts of micaceous shale and quartzite-pebble conglomerate. The total thickness of these rocks is probably several thousand feet. Beneath this massive quartzite and adjacent to the block of unidentified limestone and dolomite at the west base of the mountain are about 250 feet of interbedded quartzite and phyllitic shale and a few thin beds of light-brown dolomite. The quartzite under the lower slopes of the mountain is light gray to grayish orange pink; under the upper slopes which simulate the shadow, the quartzite is a more somber pale red to pale yellowish brown. On fresh surfaces the rocks are more varied in color, with light values of red, purple, brown, and green in the lower part of the section and dark values of brown and purple in the upper part. The individual strata are commonly 1–5 feet thick, and crossbedding, ripple marks, and scour features are characteristic. Most of the quartz grains are coarse to medium-coarse sand, but granule beds and pebble beds are present also. Micaceous silty beds are intercalated with some of the quartzite.

This sequence of quartzite is lithologically similar to the Stirling Quartzite as described by Hazzard (1937, p. 306–307). Noble and Wright (1954), however, believe that both the Wood Canyon Formation and the Stirling Quartzite are present in Shadow Mountain (Quartzite Peak). The thin-bedded rocks near the west base of the mountain may be the top of the Johnnie Formation.

UNIDENTIFIED LIMESTONE AND DOLOMITE

A small fault block of interbedded limestone and dolomite lies at the west base of Shadow Mountain. The limestone is medium light gray to pale yellow brown, and the dolomite is light gray to medium dark gray. Chert is absent except for a few siliceous nodules and stringers. The bedding planes in these much-deformed rocks are inconspicuous or discontinuous, and breccia zones are abundant. The minimum thickness of rock exposed is perhaps 200 feet. These strata are possibly of Middle Cambrian or Upper Cambrian age because the older carbonate rocks are brown or very pale orange and because most younger carbonate rocks of Paleozoic age contain abundant chert.

ROCKS OF THE DEVILS HOLE AREA

The hills near Devils Hole in the northeast part of the quadrangle are underlain by three sequences of Cambrian limestone and dolomite, which are separated by two thin but conspicuous clastic units contain-

[1] Called Quartzite Peak on other maps. See Hazzard (1937, fig. 2), Noble (1941, pl. 1), Noble and Wright (1954, pl. 7), Jennings (1958).

ing abundant fossils. The whole section is 2,000–3,000 feet thick. The upper clastic unit and overlying limestone and dolomite are part of the Nopah Formation. The middle sequence of carbonate rocks and the lower clastic unit together form the upper division of the Bonanza King Formation of Palmer and Hazzard (1956). The lower sequence of limestone and dolomite, part of the lower division of the Bonanza King Formation, crops out only in one small area at the edge of the quadrangle east of Devils Hole. The adjacent hills further to the east are composed of the rocks of the Devils Hole area and older beds of Cambrian age.

BONANZA KING FORMATION

Only about 100 feet of the lower division of the Bonanza King Formation is exposed in the quadrangle. Cliff-forming medium- to dark-gray limestone and dolomite form beds 1–3 feet thick. The clastic unit at the base of the upper division is 100–200 feet thick and consists of shale and siltstone intercalated with thin fossiliferous limestone beds; it forms a pale yellow-brown ledge between the gray cliffs of carbonate rock. The bulk of the upper division is banded light-gray and medium-gray limestone and dolomite in units 100–200 feet thick. About 60 percent of the rock is limestone and 40 percent dolomite. This proportion is reversed for correlative rocks in the Nopah Range (Hazzard, 1937, p. 277) east of Shoshone (fig. 1).

The trilobites in the lower clastic unit, identified by A. R. Palmer, U.S. Geological Survey, are a Middle Cambrian assemblage (USGS colln. 2456-CO) that includes *Alokistocare* sp. and "*Ehmania*" sp. The same lithology and fauna occur in Hazzard's (1937) unit 7A, the base of the Cornfield Springs Formation in the Nopah Range. Palmer and Hazzard (1956) revised this part of the section and dropped the name Cornfield Springs Formation. Although the name is no longer valid in the type area, the lithologic division found there is practical in the Nopah Range and at least as far north as the Devils Hole area. The uniform gray dolomite beneath the lower clastic unit in the latter area is correlative with the Bonanza King Formation of Hazzard (1937) and the lower division of the Bonanza King Formation of Palmer and Hazzard (1956). The banded limestone and dolomite is correlative with the Cornfield Spring Formation of Hazzard (1937) and the upper division of the Bonanza King Formation of Palmer and Hazzard (1956).

NOPAH FORMATION

In the northernmost of the hills near Devils Hole, about a mile southeast of Longstreet Spring, the Nopah Formation rests conformably on the Bonanza King Formation. The basal unit, the upper clastic beds mentioned above, is a yellowish-brown shaly limestone that is about 150 feet thick. It contains several highly fossiliferous bioclastic brown limestone units 4–8 feet thick. Other bioclastic limestone beds near the top of the shaly limestone unit and in the bottom of the overlying dolomite and limestone unit are sparsely fossiliferous. The top of the shaly unit also contains some nodular limestone. The dolomite and limestone above the basal unit are similar to the upper division of the Bonanza King Formation. The total thickness of the formation exposed is about 1,000 feet, the top half or more being absent.

The basal shaly limestone unit contains a trilobite assemblage that has been identified by A. R. Palmer as belonging to the Nopah Formation. The assemblage comes from two collections. The lower one (USGS colln. 2457–CO) from near the base of the formation contains:

Cernuolimbus cf. *C. semigranulosus* Palmer
Dunderbergia cf. *D. variagranula* Palmer
Homagnostus obesus (Belt)
Minupeltis cf. *M. conservator* Palmer
Pelagiella sp.
Prehousia sp.
Pseudagnostus cf. *P. communis* (Hall and Whitfield)
Chancelloria sp.

According to Palmer, this collection is characteristic of the Dunderberg Shale at Eureka, Nev.

The upper collection (USGS colln. 2458–CO), from near the top of the shaly limestone unit and 80 feet above the lower collection, contains:

Cheilocephalus sp.
Dellea? sp.
Elviniella sp.
Homagnostus sp.
Oligometopus breviceps (Walcott)
Pseudagnostus sp.
Pterocephalia cf. *P. sanctisabae* Roemer
Pseudosaratogia leptogranulata Palmer
Sigmocheilus sp.
Linnarssonella sp.

According to Palmer, these fossils are typical of the assemblage found just above the middle of the Dunderberg Shale in central Nevada.

ROCKS OF THE FUNERAL MOUNTAINS

HIDDEN VALLEY DOLOMITE

Near the north end of the southeast spur of the Funeral Mountains, about 500 feet of thick-bedded medium-gray dolomite including some darker and lighter beds underlies two small areas west and southeast of a knob at altitude 4,377 feet. The dolomite contains a little chert but no fossils and is assigned to the upper part of the Hidden Valley Dolomite because it lies beneath a sandstone-bearing and quartzite-bearing dolomite identified by J. F. McAllister (written commun., 1961) as the base of the Lost Burro Formation. The dark-gray Ely Springs Dolomite is not exposed.

LOST BURRO FORMATION

A light- and medium-gray dolomite that contains a little clastic limestone and is 2,000–3,000 feet thick is assigned to the Lost Burro Formation. It overlies the Hidden Valley Dolomite with apparent conformity. The basal 225 feet of the formation contains clastic rocks. The lowest 150 feet of the basal unit is gray dolomite that contains some brown dolomitic sandstone and sandy dolomite and underlies a bench. Above these rocks is 75 feet of medium-gray dolomite and some light-gray, blackish-brown-weathering quartzite in beds 1–3 feet thick. The basal clastic unit is identified as the Lippincott Member of the Lost Burro Formation by J. F. McAllister (written commun., 1961).

Dominantly light gray to yellowish gray, slightly cherty dolomite about 1,000 feet thick overlies the Lippincott Member of the Lost Burro Formation. About 250 feet above the clastic rocks there is a 50-foot-thick unit of dark-gray dolomite beds, and about 750 feet above the clastic rocks some dark-gray limestone containing horn corals, algae, and stromatoporoids is interbedded with the dolomite.

Medium-gray thick-bedded dolomite and limestone about 1,500 feet thick form a cliffy unit near the top of the formation. A particularly dark banded dolomite occurs at the base of the unit, and at the top of the unit there is some interbedded limestone. The uppermost 50 feet of the formation, as identified by McAllister, consists of medium-dark-gray platy limestone that contains silty partings, light-gray sandstone, and purplish-gray quartzite. Some limestone beds interbedded with or just above the quartzite are crinoidal and contain fragments of cephalopods and gastropods.

TIN MOUNTAIN LIMESTONE

A dark-gray cherty limestone, about 450 feet thick, that forms much of the crest of the southeasternmost spur of the Funeral Mountains is assigned to the Tin Mountain Limestone. It lies comformably on, and grades up from, the underlying silty limestone and interbedded quartzite. At the base of the formation some crinoidal limestone contains fragments of cephalopods and gastropods. A little pale-yellow-brown dolomite overlies the crinoidal limestone. The bulk of the formation contains silty partings, though fewer than in the underlying rock;

some of the silty partings are reddish brown. The amount of chert increases upward.

Corals, Bryozoa, and brachiopods are common throughout the formation and were collected in two places. Helen Duncan, U.S. Geological Survey, identified the corals and Bryozoa; Mackenzie Gordon, Jr., U.S. Geological Survey, identified the other forms. The first collection (USGS 20579-PC) was made near the southernmost tip of the southeastern spur of the Funeral Mountains a quarter of a mile S. 70° E. of a knob 2,997 feet in altitude in the Ryan quadrangle. This location is at or near the site mentioned by Noble (1934, p. 177) and Noble and Wright (1954, p. 155). The collection contains:

Rylstonia? sp. indet.
Cyathaxonia sp.
Cladochonus sp. indet.
Fenestella sp. indet.
Pelmatozoan debris
Productoid cf. *Levitusia* sp. indet.
Rhipidomella sp.
Punctospirifer sp.
Spirifer 2 spp.
Straparollus (*Euomphalus*) sp.

The second collection (USGS 20580-PC) is from a site in the Ash Meadows quadrangle at elevation 3,680 feet, half a mile S. 10° W. of a knob (alt 4,756 ft) and contains:

Enygmophyllum sp.
Amplexus? sp. indet.
Cyathaxonia sp.
Cladochonus sp.
Fenestella 3 spp. indet.
Penniretepora 2 spp. indet.
Diploporaria? sp.
Rhipidomella sp.
Leiorhynchus? sp.
Crurithyris sp.

According to Duncan and Gordon, these faunas are dated as Early Mississippian and are typical of the Tin Mountain Limestone.

PERDIDO(?) FORMATION

The southeast spur of the Funeral Mountains has two peaks about three-quarters of a mile apart; both are less than a quarter of a mile inside the adjoining Ryan quadrangle. The southern peak (alt 4,962 ft) is built of a very cherty limestone tentatively assigned to the Perdido Formation. The east slope of the peak within the Ash Meadows quadrangle is underlain by 400–500 feet of these cherty rocks, a medium-dark-gray silty limestone that weathers pale yellow brown. The base of the formation is taken as the lowest unit that contains abundant chert; the top is not present in the area. No fossils were collected, and the reliability of the chert as a formation indicator is questionable.

TERTIARY ROCKS

Rocks of Tertiary age are exposed on the east flank of the Funeral Mountains and at the north end of the Resting Spring Range. The total area of outcrop is only about 6 percent of the area of the quadrangle, roughly 15 square miles, but Tertiary rocks probably lie beneath a veneer of Quaternary deposits throughout much of the lowlands. The rocks are largely alluvial-fan and playa deposits but include some volcanic rocks. Sedimentary units grade laterally over short distances from shale to conglomerate or from limestone to fanglomerate. Such facies changes and an absence of index fossils make it impossible to correlate the Tertiary rocks from place to place. Description of these rocks is by their geographic area.

ROCKS OF THE FUNERAL MOUNTAINS

Tertiary sedimentary rocks underlie about 5 square miles of the southeast spur of the Funeral Mountains that lies within the Ash Meadows quadrangle. Seven major lithologic units include, from bottom upward: lower fanglomerate, lower shale, lower limestone, lower conglomerate, upper limestone and shale, upper fanglomerate, and upper conglomerate. A major unconformity separates the lower units from the upper ones, and minor unconformities that have only a slight angular discordance underlie the lower conglomerate and the upper fanglomerate. The composite maximum thickness of the units is about 5,000 feet. The strata rest unconformably on Paleozoic rocks, are tilted eastward about 30°, and are broken by normal faults of at least two ages. These Tertiary beds were mapped by Noble and Wright (in Jennings, 1958) as of Oligocene age, a part of their sequence of older Tertiary sedimentary rocks, including the Titus Canyon Formation (Stock and Bode, 1935). Similar rocks, also mapped by Noble and Wright (in Jennings, 1958), crop out in the foothills to the west in the Ryan quadrangle and to the south in the Eagle Mountain quadrangle. At the north end of the spur in the Ash Meadows quadrangle, the three units at the base of the Tertiary sequence are the lower fanglomerate, the lower shale, and the lower limestone. In the Ryan quadrangle, about 2 miles to the west, a similar succession of rocks form a long, north-trending ridge (Jennings, 1958) and may be correlative with the rocks of the spur.

LOWER FANGLOMERATE

The thick fanglomerate near a knob (alt 3,377 ft) at the north end of the spur of the Funeral Mountains is the lowest stratigraphic unit of Tertiary age in the spur. It is as much as 600 feet thick near the knob, but thins southeastward and probably pinches out less than a mile from the knob. The fanglomerate is thick bedded to massive, grayish red to brownish gray. The boulders and cobbles within it are chiefly gray dolomite, pale-yellow-orange dolomite, purplish coarse-grained quartzite, and limestone. A few shale particles are also present. The association of these lithologies suggests a source in the Stirling Quartzite and the Noonday Dolomite, neither of which are now exposed nearby. The fragments of gray dolomite may have come from rocks of Middle Cambrian to Devonian age, for most older rocks contain only brown dolomite, and few younger rocks contain any dolomite. The lower fanglomerate is similar to but not correlative with the upper fanglomerate, which caps the south end of the spur.

LOWER SHALE

A section of reddish shale and associated rocks underlies the north-sloping valley east of the 3,777-foot knob and is present in small fault blocks south and southwest of the knob. The section is largely white to light-red shale and siltstone, plus small amounts of sandstone, fine-grained conglomerate, limestone, tuffaceous rocks, bentonite, and one bed of indurated rhyolite tuff. The rocks are poorly exposed. The bedding planes are commonly a few inches apart, except for the tuffaceous rocks which are thick bedded. The layer of indurated tuff is 10–40 feet thick and weathers into blocks. Unweathered tuff is light brownish black to grayish pink; its weathered surface is brownish black. More than 90 percent of the tuff consists largely of glass shards, brown cryptocrystalline material, and alteration material. Imbedded in the tuff are fragmental crystals of sanidine, quartz, plagioclase (albite or sodic oligoclase), biotite, titaniferous magnetite, and a few rock fragments. Sanidine forms large subhedral fragments, and some of the fragments contain fresh plagioclase. Most plagioclase is partly altered to sericite and has lost the fresh appearance of sanidine. Some biotite is oxidized or replaced by sericite. The shard structure of the groundmass has not been stretched (not welded), but the glass of the shards has crystallized to a radial, fibrous material. Similar devitrified material is scattered in the groundmass. The lower shale unit can be separated from the upper limestone and shale unit because the older unit contains bentonite and tuff.

LOWER LIMESTONE

More than 50 feet of yellowish-gray fine-grained limestone overlies the lower shale north and west of the 3,377-foot knob. It is thick bedded and forms prominent cliffs and knobs. The limestone contains some fossils that resemble algae and plant stems. North of the knob, the limestone grades laterally into a conglomerate whose cobbles, pebbles, and matrix are a similar limestone. The unit is probably correlative with the thick limestone on the ridge to the west of the quadrangle and is distinguishable from the upper limestone only by its stratigraphic position.

LOWER CONGLOMERATE

A conspicuously red pebble conglomerate and sandstone, more than 1,500 feet thick, lies unconformably on the lower shale unit. The basal unconformity truncates the lower limestone unit, more than 100 feet of the underlying shale, and the indurated tuff. Most of the conglomerate is uniformly red, but in the area of outcrop west of the large landslide masses, a tongue of yellowish-brown conglomerate lies between red beds. The lower conglomerate contains well-rounded pebbles and scattered cobbles of reddish-gray felsite, quartzite, and some granitic rocks. Beds range from 1/2 to 3 feet thick. The unit is distinguishable from the upper conglomerate only by its stratigraphic position.

UPPER LIMESTONE AND SHALE

A varicolored shale and overlying yellowish-gray limestone have a combined thickness of 150–200 feet and unconformably overlie the lower conglomerate (fig. 2A). The basal unconformity is large, for the unit truncates a postlower conglomerate horst and graben. The shale is thin bedded and dominantly red, locally green or olive gray. Intercalated with the shale are a few beds of siltstone, sandstone, limestone, tuffaceous rocks, and gypsum. Outcrops of the shale are badly slumped. The thickness is generally about 75 feet, but in a few places may be much thicker.

Above the shale is about 60 feet of thick-bedded cliff-forming limestone that thickens northward to perhaps 200 feet. Algal markings are abundant, and, in a few places, silicified plant stems as large as 1/2 by 3 inches are common, but diagnostic fossils are absent. Toward the north the limestone interfingers with the overlying fanglomerate; toward the south it is overlain by about 50 feet of tuffaceous siltstone and limestone.

UPPER FANGLOMERATE

A poorly bedded boulder fanglomerate lies with slight angular discordance on the upper limestone and shale. As much as 1,500 feet of fanglomerate forms the southernmost ridge of the spur, but thins northward to less than 100 feet and interfingers with the overlying conglomerate. The basal unconformity truncates the thin tuffaceous beds capping the underlying unit to the south and truncates a jumble

A

B

[illegible] ... Tertiary ... alluvial-fan ... Perdido ... upper limestone ... the lime ... cliffs in right ... the near eastern ... mudflow ... NE¼SE¼ sec. 28 ... [illegible] of large blocks of the underlying limestone to the north. However, south of the landslide to the south of Bat Mountain, the fanglomerate appears to interfinger with the underlying limestone. The fanglomerate consists of subangular cobbles, boulders, and subordinate pebbles set in a limy and sandy matrix. The fragments are chiefly purplish quartzite, gray dolomite, and very pale orange dolomite; limestone and shale are also present. This assemblage of fragments suggests a source in lower Paleozoic rocks, particularly the Cambrian sequence.

UPPER CONGLOMERATE

A few hundred feet of moderate-red pebble conglomerate and sandstone overlie and intertongue with the upper fanglomerate along the east base of the mountains. The pebbles are well rounded and consist of quartzite, volcanic rocks, and granitic rocks, much like those in the lower conglomerate.

AGE AND CORRELATION

The Tertiary rocks of the Funeral Mountains are perhaps as old as the Oligocene Epoch. These largely clastic rocks resemble the Titus Canyon Formation of Stock and Bode (1935) which occupies similar structural troughs to the northwest along the eastern edge of the Funeral Mountains and their northern extension, the Grapevine Mountains (fig. 1). Correlation between the Titus Canyon Formation, which is well dated as early Oligocene, seems probable but is not as yet demonstrable. If the boulders in the upper and lower fanglomerates of the spur are, in fact, from the lower Paleozoic rocks of the region, these fanglomerates are probably older than the Miocene or Pliocene Furnace Creek Formation, for the source area of lower Paleozoic rocks was to the west of the Ash Meadows quadrangle in an area now buried beneath the Furnace Creek Formation and younger beds.

ORIGIN AND ENVIRONMENT

The Tertiary rocks of the spur of the Funeral Mountains within the Ash Meadows quadrangle were deposited in a basin occupied by a fluctuating or intermittent lake. Alluvial fans bordered the mountains that formed the western side of the basin, and volcanoes that ejected pyroclastic material of rhyolitic composition lay to the northeast. The fanglomerates were derived from highlands whose base was not more than 3–4 miles distant and probably was close by. Within the quadrangle, the lower fanglomerate thins southward, but in the Ryan quadrangle about 2 miles to the west it is tremendously thickened. The upper fanglomerate thins rapidly to the northeast, and north of the landslides intertongues with conglomerate. Both fanglomerates are largely poorly sorted, coarse-grained detritus from sedimentary rocks of Cambrian age and possibly also from other Paleozoic rocks. In the main body of the Funeral Mountains to the west, Cambrian rocks are largely buried beneath younger Paleozoic sediments. The fanglomerates, therefore, were probably derived from highlands southwest of the Furnace Creek fault zone and perhaps in the position of the modern Greenwater Range and the Black Mountains to the southwest. Part of the source area of older Paleozoic rocks is now buried beneath the volcanic and sedimentary rocks of Tertiary and Quaternary ages, but in much of the source area rocks of Precambrian age are exposed and the rocks of Paleozoic age have been removed (Drewes 1963).

The two bodies of red conglomerate are probably stream deposits. The sorting, rounding, and small size of the fragments suggest a distant source, at least distant with respect to the provenance of the fanglomerate. The pebbles of felsitic, granitic, and sedimentary rocks are an assortment that may have come from the mountains north of Lathrop Wells (fig. 1). The limestone and shale units were deposited in and along the edge of a fluctuating lake or playa. The trace of gypsum suggests at least a brief period during which the lake had no outlet. Explosive eruptions of rhyolitic volcanoes northeast of the quadrangle spread tuff and ash throughout the area.

ROCKS OF THE RESTING SPRING RANGE

A sequence of Tertiary rocks having a total thickness of several thousand feet crops out at the north end of the range. About 2 miles north of Shadow Mountain a reddish-brown fanglomerate rests unconformably on Cambrian rocks and forms low hills. Overlying the fanglomerate is a thick section of rocks that are chiefly sandstone and claystone. These finer grained clastics are in turn capped by another fanglomerate that makes up the hills east of Grapevine Springs. No fossils have been found in the Tertiary rocks north of Shadow Mountain. The younger fanglomerate is perhaps early Pleistocene. The older fanglomerate and the overlying fine-grained beds are similar lithologically to some of the Tertiary rocks on Bat Mountain.

FANGLOMERATE

Low hills along the state line south of the Old Traction Road are composed of reddish, firmly cemented boulder fanglomerate which contains cobbles and boulders of quartzite and of Paleozoic carbonate rocks as much as several feet in maximum diameter. The basal 30–50 feet of the unit is a breccia of quartzite blocks in a gray but locally reddish matrix. The fragments are commonly 2–3 feet in diameter; a few are as large as 6 feet. The breccia grades upward into faintly bedded or massive reddish fanglomerate. Toward the top, the largest fragments are of pebble size and the beds of fanglomerate are separated by lenses of brown pebbly sandstone. The fanglomerate is about 800 feet thick and rests with angular unconformity on quartzite that is strongly brecciated. The top of the unit is placed at the top of the uppermost bed of fanglomerate.

The fanglomerate was deposited as gravel on an alluvial fan. The basal breccia is probably scree derived from an adjacent steep face or cliff composed of quartzite. Weathering broke the upper few feet of the quartzite into blocks, and those near the surface accumulated as talus. The others still remain more or less in place on top of less-weathered quartzite. Perhaps some of the breccia slid downslope, such movement contributing to the shattering of the blocks.

The highland source was Shadow Mountain, and the areas of carbonate rocks were probably more extensive than at present. If the reddish color of the fanglomerate matrix is inherited from that of the weathered source rocks, it suggests an episode of weathering unlike any during the later Quaternary. Throughout the Death Valley region, Quaternary alluvial deposits composed of fragments of Paleozoic carbonate rocks have not weathered to red colors.

The fanglomerate is nonfossiliferous, but it is without doubt of Tertiary age. Lithologically it is indistinguishable from the Oligocene(?) fanglomerate of the Funeral Mountains about 10 miles distant.

SANDSTONE AND CLAYSTONE

The lowlands north and northwest of the Resting Spring Range are underlain by a thick sequence of fine clastic rocks largely concealed beneath younger formations. Moderate-brown to very light gray, locally yellow or green, sandstone and claystone predominate, but subordinate amounts of conglomerate, siltstone, tuff, and limestone are present also. The rocks are loose to moderately cemented and are well bedded, the individual layers ranging from paper-thin to several feet thick. The sandstone is locally pebbly and shows crossbedding and ripple marks. Claystone and siltstone are gray, and the individual beds are commonly not more than an inch thick. In a few places the claystone is gypsiferous. Scattered conglomerate beds contain pebbles of quartzite, limestone, dolomite, and tuff; one such bed contains many cigar-shaped pebbles that are fractured. Layers of white tuff containing pumice fragments are common. One or two beds of pale-yellow-orange, very fine grained limestone occur in the lower part of the formation not far from the state line.

In the north-central part of the quadrangle, clastic rocks, mapped as part of the sandstone and claystone unit, apparently lie unconformably beneath the surrounding Quaternary sediments. Near Clay

Camp, both flat-lying and inclined layers of sandstone, siltstone, conglomerate, and fanglomerate are poorly exposed. The coarser grained beds contain pebbles of quartzite, limestone, dolomite, conglomerate, and volcanic rocks.

In the hills east of where the Old Traction Road crosses the State line, the sandstone and claystone unit rests conformably on and is interbedded with the uppermost pebble beds of the underlying fanglomerate. On the north flank of these hills the unit is overlain by and interbedded with the fanglomerate near Grapevine Springs. The total thickness of the unit may be as much as 2,000 feet.

The sandstone and claystone unit includes both fluvial and lacustrine deposits. The mapping outlines a depositional basin at least 12 miles long in a northwest direction. The bordering highlands were either low or far removed in comparison with those of the preceding or the following epochs of fanglomerate deposition. Limestone and evaporites are scarce; apparently during much of the time the depositional basin did not include a playa. Now and then there were showers of ash.

No fossils have been found in the sandstone and claystone unit. These rocks closely resemble some of the rocks of Oligocene(?) age in the southeast spur of the Funeral Mountains, such as the upper limestone and shale unit.

ORIGIN AND ENVIRONMENT

The Tertiary rocks at the north end of the Resting Spring Range were deposited both as alluvial fans and as lake sediments. The depositional basin was occupied by a playa only for short periods. The present-day configuration of mountain and basin has existed almost unchanged since these rocks began to be deposited. While the sandstone and claystone unit was being laid down, the north end of the Shadow Mountain block was lower and less extensive in relation to the surrounding basin than it was during the time of accumulation of the fanglomerate near Grapevine Springs. A more profound departure from the present is suggested by the presence of deformed fanglomerate in the central lowlands near Clay Camp.

ROCKS OF HILL SOUTHWEST OF DEATH VALLEY JUNCTION

FURNACE CREEK FORMATION

The isolated butte in the southwest corner of the quadrangle includes a few beds of tuff and siltstone assigned to the Furnace Creek Formation of Miocene and Pliocene age (Drewes, 1963). Fine-grained tuff and siltstone form thin beds, and coarse-grained material makes thick beds that contain pumice fragments as much as 1 inch in diameter.

TERTIARY AND QUATERNARY ROCKS

FANGLOMERATE NEAR GRAPEVINE SPRINGS

Boulder-covered hills extending from Grapevine Springs southeastward to the Old Traction Road are underlain by brown thickbedded or massive fanglomerate. Although poorly exposed, the unit apparently includes many hundreds of feet of fanglomerate and intercalated thin beds of pumice and of tuffaceous sandstone. The pebbles and boulders are chiefly subangular fragments of quartzite and Paleozoic carbonate rocks in about equal proportions. The fanglomerate near Grapevine Springs is well indurated, but less so than the older underlying reddish fanglomerate, a few boulders of which are found in the younger fanglomerate unit. Similar fanglomerate, included with that near Grapevine Springs, occurs in a small downfaulted basin just south of Shadow Mountain, in a small area west of the mountain, and in the hills south of Last Chance Spring near the Ash Meadows Rancho. At the north end of the Resting Spring Range the fanglomerate may be as much as 1,000 feet thick. Although over much of the area the rocks appear to be undeformed, the hills east of Grapevine Springs are a cuesta of southward-dipping fanglomerate overlying finer clastic rocks.

On the south slope of Shadow Mountain a narrow downfaulted wedge of brown fanglomerate extends for about half a mile into the quadrangle from the east, and small caps of fanglomerate cover two bedrock spurs a short distance to the west. At least 100 feet of southward-dipping boulder fanglomerate rests unconformably on the quartzite of Shadow Mountain. The fanglomerate includes abundant subangular fragments of quartzite and micaceous shale and also a few fragments of Paleozoic carbonate rocks and of a reddish fanglomerate that resembles the older fanglomerate unit north of the mountain. The fanglomerate is moderately well indurated, is massive or well bedded, and contains conspicuous lenses of white pumice.

In a small area west of Shadow Mountain, a well-bedded pebble fanglomerate rests conformably on finer grained, tuffaceous rocks. In the hills south of Last Chance Spring, at least 500 feet of gray fanglomerate and intercalated tuffaceous sandstone rests with apparent conformity on finer grained beds. This pebbly to bouldery fanglomerate forms clearly defined beds and contains fragments of quartzite and Paleozoic carbonate rocks.

In some places the fanglomerate near Grapevine Springs is clearly unconformable on the underlying rocks; elsewhere its stratification appears to be parallel with that of the underlying sandstone and claystone unit. Near the state line the fanglomerate is not deformed.

The fanglomerate was derived from the Resting Spring Range, and the source may have been about the same size as Shadow Mountain although perhaps not in the same place. The width of outcrop of the fanglomerate at the northwest end of the range is about equal to the distance that bouldery gravel is carried at the present time from the apex of the fan northwest of Shadow Mountain. The fanglomerate accumulated at a time of frequent showers of pumice and ash. The abundance of fragments of reddish fanglomerate in the beds near Grapevine Springs and their scarcity in the Quaternary alluvial fan deposits suggest that the area of outcrop of the older fanglomerate unit north of Shadow Mountain was more extensive during the accumulation of the fanglomerate near Grapevine Springs than at present. The undeformed part of the fanglomerate, which is largely in California west of the Old Traction Road, may be part of a fan that sloped northwestward from Shadow Mountain and had its apex in the NW¼ NE¼ sec. 24, T. 25 N., R. 6 E. If the fanglomerate in Nevada, including the hills near Grapevine Springs and those south of Last Chance Spring, is part of the same fan, it was a little larger than the modern fan northwest of Shadow Mountain.

The few small remnants of the fanglomerate near Grapevine Springs south of Shadow Mountain suggest that an extensive fanglomerate unit once covered that area also.

The fanglomerate near Grapevine Springs is nonfossiliferous. It is perhaps of early Pleistocene age but may belong to the close of the Pliocene Epoch. Because a considerable part of it has been removed by erosion or has been downfaulted and buried beneath later Quaternary deposits, the unit is probably older than the late Pleistocene.

ROCKS OF HILL SOUTHWEST OF DEATH VALLEY JUNCTION

FUNERAL FORMATION

A butte in the southwest corner of the quadrangle is an eastern outlier of the volcanic rocks that form much of the Greenwater Range to the west (Drewes, 1963). About 40 feet of dark vesicular basalt, assigned to the Funeral Formation of Pliocene and Pleistocene(?) age, rests conformably on tuff of the Furnace Creek Formation. Boulders of the basalt mantle the slopes of the butte.

QUATERNARY ROCKS

Most of the Ash Meadows quadrangle is underlain by unconsolidated or, at most, weakly indurated rocks of Quaternary age, largely alluvial-fan and playa deposits accumulated in a desert basin. Surficial deposits of limited extent include dune sand, scree, spring deposits, and landslide breccia. Over broad areas the rocks are not exposed in section; only in a few places have they been dissected to depths of as much as 50 feet. The Quaternary rocks are virtually undeformed and unfossiliferous. Artifacts are found on or in the sand dunes, in alluvium along the Amargosa River, and on low terraces along the river and one or two of the larger washes.

The total thickness of the Quaternary rocks is unknown. The drillers' log of a water well at Death Valley Junction lists 25 feet of coarse gravel, in part cemented, resting on about 120 feet of clay that includes two thin, water-bearing gravel beds (Pacific Coast Borax Co., written commun., 1957). A second well nearby is said to have been drilled to a depth of 800 feet, the lower 700 feet entirely in clay (Ben Barlow, oral commun., 1956). Several drillers' logs (Office of State Engineer, Carson City, Nev.) of water wells in the Amargosa Desert near the T and T Ranch, a few miles northwest of the quadrangle, report "gravel and clay" to depths of as much as 700 feet. Whether these wells penetrate Tertiary rocks is unknown.

ARID-BASIN SEDIMENTS

Virtually undeformed strata of Quaternary age, including alluvial-fan, spring, and playa deposits, floor the Amargosa Desert. White clay and silt in the Ash Meadows, for example, intertongue to the east with gravel and sand, part of an alluvial apron that surrounds the hills near Devils Hole. The gravelly alluvium rests unconformably on the Paleozoic rocks of the Devils Hole area, although the hills themselves doubtless owe their existence to faulting. Spring deposits rest on and are intercalated in the clastic sediments.

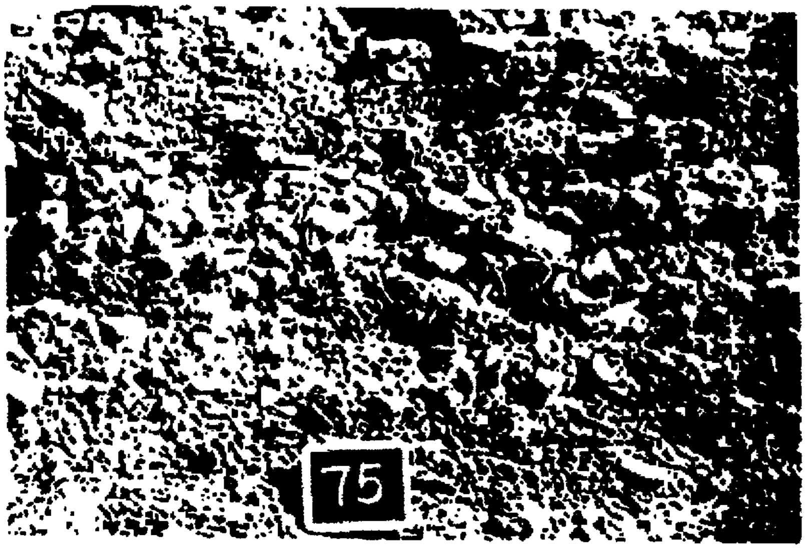
FAN DEPOSITS

The fan deposits include gravel, breccia, sand, silt, and a little clay and are divided into those containing many fragments of quartzite, limestone, and dolomite and those that include abundant pieces of volcanic rock. The fragments are angular and subangular. Boulders are most abundant near the mountain front. The pebbly gravel is commonly crossbedded and is interlayered with coarse, pebbly sand. The bouldery gravel is poorly sorted and irregularly stratified, and forms massive beds several feet thick. Along the strike, the fan deposits may change from bouldery gravel to sand within distances of only a few feet. The lenses of breccia, probably mudflow debris that makes up only a small part of the deposit, are unsorted mixtures of all sizes and shapes; they range from 1 to about 10 feet thick. Where exposed, the fan deposits are cemented by caliche, but over much of the quadrangle the deposits are dissected to depths of not more than 3 feet, and only near the mountain front are there continuous exposures as much as 10 feet high. In general, large highlands are bordered by more extensive fan deposits than are small hills, but the spatial relations of mountain and basin or the occurrence of Recent deformation may upset this generalization.

Much of the surface of the fan deposits is desert pavement. These smooth, gently sloping pavements are composed of closely packed angular fragments of rock whose exposed surfaces are either coated with varnish or etched by solution, depending upon their lithologic composition. Fragments of quartzite, of sandstone, and of volcanic rocks have a coating of desert varnish; basalt and andesite have darker coatings than quartz-rich rocks. Carbonate rocks on a pavement are etched and grooved by solution. The rest of the surface of the fan deposits consists of braided channels and gravel bars whose constituents are also slightly weathered.

Quartzite is the dominant constituent of the coarse fan deposits west of the Resting Spring Range, but quartzite conglomerate and micaceous shale are also present. The deposits include a few lenses of breccia or mudflow debris, chaotic assemblages of slabs of quartzite in a pale-gray silty matrix (figs. 2*B* and 3*A*). In the reentrant north of Shadow Mountain, Quaternary gravel rests unconformably on the older rocks. At the north end of the area underlain by the unidentified limestone and dolomite unit, slightly deformed bouldery gravel, mapped as of Quaternary age, lies against brecciated and discolored carbonate rocks, the contact being either a fault plane or a buried fault scarp. The gravel is well indurated and may belong to the fanglomerate near Grapevine Springs, which crops out about three-quarters of a mile to the southwest. Alluvial deposits southwest of Ash Meadows Rancho are at the mouth of a large wash that drains a large area to the east of the quadrangle.

The alluvial-fan deposits surrounding the eastern prong of the Funeral Mountains are similar to those adjacent to Shadow Mountain (fig. 3*B*). The gravel, however, contains a variety of rock types including limestone, dolomite, quartzite, fanglomerate, sandstone, and tuff. Fan deposits rest unconformably on the Paleozoic rocks of the hills near Devils Hole. The small bedrock hill east of Longstreet Spring, for example, is surrounded by a narrow apron of gravel that, within about 500 feet of the base of the hill, intertongues with white clay. Further from the hill, the deposits are largely fine grained and contain only a few lenses of limestone and dolomite pebbles. The extent of the gravel apron around the hills near Devils Hole is, of course, related to their size. Measurements, discussed in another publication (Denny, 1964), show that the area of the individual gravel fan around these hills is about equal to the size of its source area. Gravel



A

B

[illegible] deposits of Quaternary age. A, Pebble and cobble [illegible] caused by varying proportions of pebbles [illegible]. B, Faintly [illegible] pebble and [illegible] of Bat Mountain. [illegible] desert pavement [illegible] and sand form the plains south and west of Death Valley Junction and are composed largely of volcanic debris from the Greenwater Range which lies to the southwest outside of the quadrangle.

Pebble gravel and sand, the fragments dominantly of volcanic rock, mantle a considerable part of the plains between Amargosa River and Carson Slough. The gravel is coarser grained to the north outside the quadrangle and is the southern end of a broad alluvial plain that rises gradually northward into the hills north of Lathrop Wells (fig. 1). The deposit is crossbedded, and the pebbles in most outcrops are less than 2 inches in diameter. The sandy layers are weakly indurated. Throughout much of the uplands the deposit is only a few feet thick; the maximum observed thickness is about 25 feet in the bluffs overlooking Carson Slough (NE¼ sec. 19, T. 17 S., R. 50 E.) where the gravel contains a few boulders of vesicular basalt.

Estimates of the size of the material on the fans in the Ash Meadows quadrangle were made as part of a general study of fans in the Death Valley region (Denny, 1964). These estimates are an attempt to characterize the gravel on the surface of a fan and to compare the material from fan to fan. The numerical estimates are based on samples selected by means of a grid laid on the surface of the ground (Wolman, 1954). No size estimates were made of the fan debris exposed in cross section, nor were any bulk samples analyzed. The estimates of size of material were made at selected points along a traverse from apex to toe. Values obtained from four such traverses on three fans are shown in the semilogarithmic graph of figure 4.

Two traverses are on the piedmont northwest of Shadow Mountain, on the fan that heads in the reentrant northwest of the peak and that has its apex in the NE¼NE¼NW¼ sec. 18, T. 25 N., R. 7 E. The size estimates of one traverse are based on samples of unweathered gravel mapped as Recent alluvium, although some of the deposits sampled are so small that on plate 1 they are included in the surrounding alluvial-fan deposits. Samples from the second traverse on Shadow Mountain are of gravel on the surface of the alluvial-fan deposits (outside of areas of desert pavement) where the fragments are slightly weathered, having a coating of desert varnish. Thus the values from the first traverse characterize unweathered alluvium that is in transit downfan at present, and those from the second characterize material that has not been moved since it was coated. The fact that the weathered gravel is slightly coarser grained than the unweathered alluvium suggests that transportation and deposition of gravel was more active in the past than at present.

The third traverse is on the surface of Recent alluvium in a wash on a fan in the Devils Hole area, and the fourth is on Recent alluvium on a fan south of Bat Mountain on the west side of the quadrangle.

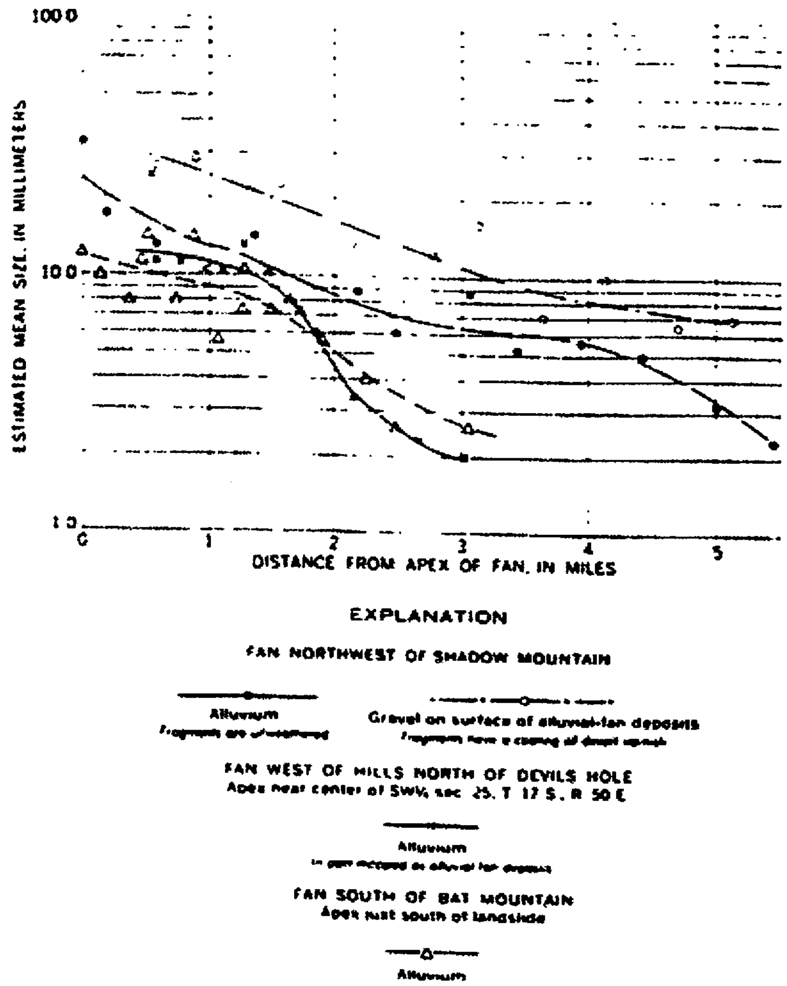


FIGURE 4.—Estimated mean size of samples of material on surface of alluvial fans in Ash Meadows quadrangle. Semilogarithmic scatter diagram showing the relation between the estimated mean size of samples from selected sites and the distance of these sites from apex of fan.

Inspection of figure 4 shows that the rate of decrease in size of material downfan varies from fan to fan. The two highlands on the east side of the Amargosa Valley are both composed of massive sedimentary rocks, and both furnish coarse detritus to the apices of their fans. At distances of more than 1–2 miles downfan, however, the size estimates on the smaller fan decline more rapidly than on the larger one. The small hills do not furnish sufficient water in flood to move the debris very far.

To generalize, the fan deposits adjacent to highlands of massive sedimentary rocks of Paleozoic age are coarse and bouldery. The fan debris gradually decreases in size away from the highland for perhaps two-thirds or three-quarters of the distance to the toe of the fan, where size rapidly decreases. Most of the fan debris at the foot of the Funeral Mountains is slightly finer grained than debris at the base of the other hills because the Funeral Mountains include a slightly greater amount of fine-grained or thin-bedded rocks than the other highlands.

The alluvial-fan deposits in the northwestern and southwestern parts of the area are dominantly of volcanic rock and have relatively distant sources. Within the quadrangle the material is chiefly pebble gravel and sand, although many boulders are present in the deposits west of Death Valley Junction, especially in the area north of the bed of the dismantled Death Valley Railroad. This pebbly gravel contains many boulders of vesicular basalt, and the matrix is tuffaceous.

The spatial relations of mountain and basin are as important as bedrock lithology in alluvial-fan formation. The alluvial deposits of the small fans that spread southward from the Funeral Mountains near the quadrangle boundary have about the same range in size at the mountain front as at the toe of the fan. The material travels southward to the toe and is then carried eastward in the large washes of a fan that heads in the Greenwater Range to the west. The toe of the coalescing fans that surround the southern part of the Funeral Mountains is also the lateral margin on the much larger fan from the Greenwater Range. Eastward from the west edge of the quadrangle, the toe of the Funeral fans lies progressively further from the mountain front and the debris near the toe decreases in size.

PLAYA DEPOSITS

Sand, silt, and clay underlie the lowlands in much of the Nevada part of the quadrangle. The strata are white or pale shades of gray and brown, are loose to weakly cemented, and contain a few lenses of fine pebble gravel. These fine-grained sediments, locally including tuffaceous materials and evaporites, probably accumulated in part near the distal end of an alluvial fan and in part on a playa. Fan gravel is gradational into playa deposits. The contact between them is placed where more than half of the material is sand, silt, and clay.

The playa deposits are well exposed. Numerous excavations—the clay pits—have been dug in the Ash Meadows and in the Amargosa Desert near Clay Camp. Natural exposures occur along the wash east of Rogers Spring, near Fairbanks Spring, along the west side of Carson Slough from 2 to 3 miles north-northeast of Clay Camp, and near Franklin Well. In the northeast corner of the quadrangle (S½ sec.

7, T. 17 S., R. 51 E.), white silty clay underlies the remnant of a playa, now isolated by dissection on all sides except to the south, and a larger playa lies about 2 miles to the east beyond the quadrangle boundary. The following section describes the Quaternary deposits exposed in the bluffs about 1 mile east of Rogers Spring.

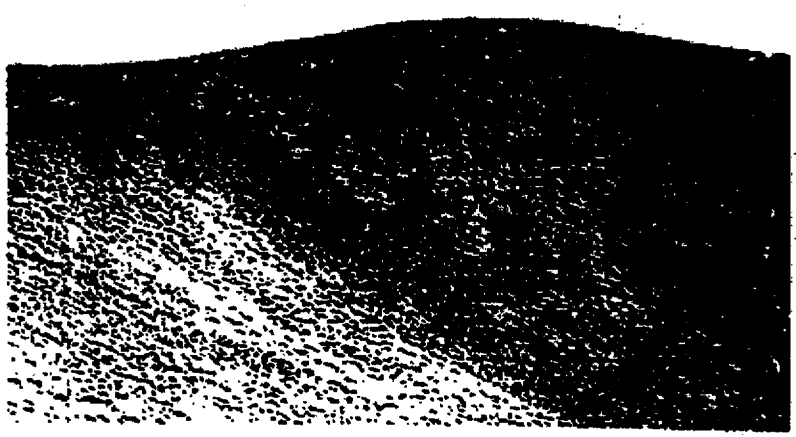
Section of Quaternary deposits exposed in bluff on south bank of wash about 1 mile east of Rogers Spring (SW¼ NE¼ sec. 11, T. 17 S., R. 50 E.)

	Approximate thickness (feet)
1. Spring deposits(?), pale-yellow (5Y 8/3 to 7/3), hard, massive, and very fine grained. Numerous tubular openings ranging from 1/16 to ¼ in. in diameter. Surface of outcrop is rough and pitted	3
2. Sand, pale-yellow (2.5Y 8/4), medium- to fine-grained, loose, friable	2½
3. Gravel, gray, pebbly, crossbedded, friable, loose; contains some lenses of sand and fragments of clay. Pebbles are angular and slightly rounded; rock types include quartzite, chert, sandstone, limestone, and dolomite. Near top of unit, gravel is sandy and is interbedded with sand resembling that which overlies it	4
4. Clay, white, massive; hard when dry; blocky structure; contains nodular masses of evaporites(?). Includes thin beds of fine-grained sand that are most abundant near base of unit. At east end of section, unit 4 is only 3 feet thick because base of overlying gravel (unit 3) cuts down across the clay	5
5. Sand and gravel, loose, friable, thin-bedded. Sand, medium to very coarse grained; many grains well rounded; contains a few pebbles. Stratification locally wavy and broken. Gravel composed of angular and slightly rounded pebbles ranging from granule size to 1 inch in diameter; most are less than a half an inch in diameter. Pebbles are of quartzite, chert, and dark-gray carbonate rock. Unit contains a few mudballs and small white nodular masses of evaporites(?). Upper contact sharp, wavy	2
6. Clay, pale-yellow, pale-olive, and white (5Y 6/4 — 7/4 — 7/6), sandy; contains numerous small white nodules of evaporites(?). Structure blocky and massive. Upper contact sharp, wavy; local relief of 10 inches	3½
Total thickness exposed	20

Units 4 and 6 are believed to be playa sediments separated by fine-grained alluvial-fan debris; the position of the toe of the fan fluctuated from time to time. The stream that deposited the gravel of unit 3 apparently eroded the top of the underlying playa clay.

In some of the clay pits, pale-olive clay occurs as irregular masses and lenses in white fine sand to silty clay that is commonly massive and weakly to firmly cemented (figs. 5.1 and 7). The olive clay apparently was the material mined; blocks of the enclosing white indurated material were dumped nearby. The olive clay may have filled irregular openings in the enclosing white material, or the interfinger-

A



B

FIGURE 5.—Playa deposits [illegible] M[illegible]tion. A, White massive nodular silty [illegible] materials similar to those shown in [illegible] boulder scree on rounded north slope of [illegible]

ing may have been subsequent to the deposition of both materials, perhaps related to repeated wetting and drying of the surface of a playa.

SPRING DEPOSITS

Firmly cemented clastic material, largely sand and silt, occurs near the flowing springs. In places the material is porous and finely crystalline. The deposits are pale gray or pale brown and include many casts and molds of plant stems. Broad areas of wet, turfy meadow constitute a considerable part of the Ash Meadows. On the bottom of small pools the stems of reeds or sedges are now being buried by clay or silt, presumably material blown into the pool. The draining and drying of such a pool may cause the sediment to become indurated, leaving molds of the stems when the organic matter has disappeared. Gradual dissection by Carson Slough is an adequate explanation for these relic spring deposits; it is unnecessary to postulate any change in the total discharge of all the springs in the Meadows. Spring deposits mantle low ridges and extend down to the floor of the intervening washes. Similar deposits cap buttes as much as 100 feet high or are intercalated in the finer clastic sediments. Only some of the larger and more conspicuous spring deposits are shown as a separate unit on plate 1.

Just west of Devils Hole a sheet of spring deposits, not shown on plate 1, measures roughly 500 by 1,500 feet and mantles ridges and shallow gullies. The edge of the sheet is lobate, and the fingers point

FIGURE 6.—Indurated caprock (spring deposits?) overlying a fine pebble gravel, resting with local angular discordance on clay, silt, and sand.

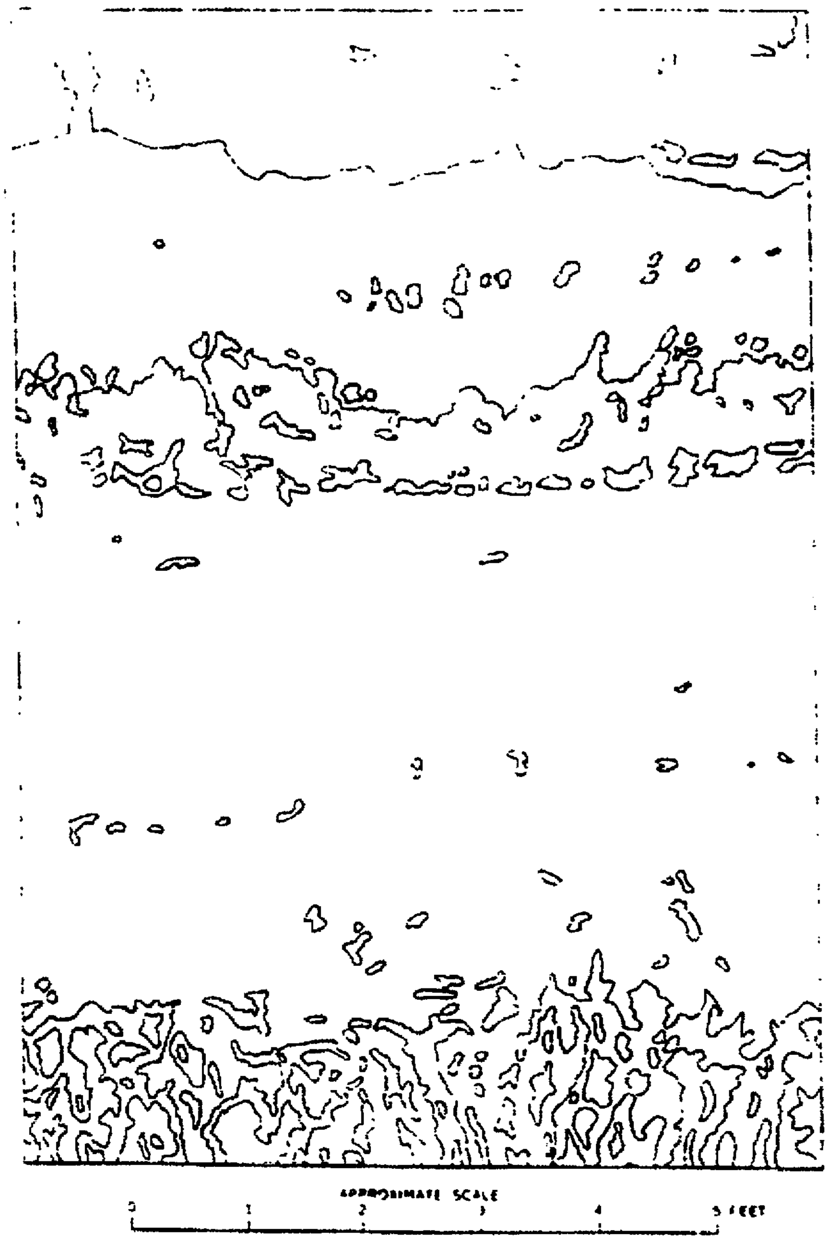


FIGURE 7.—Cross section of playa deposits. Olive clay (dark areas) and enclosing white clay that is massive and slightly indurated. Exposure is in prospect pit about 2 miles northwest of Devil Hole (center sec. 26, T. 17 S., R. 50 E.).

downwash. The deposits are at least 2 feet thick, thinning to a few inches near their borders; on ridges they overlie a desert pavement. An east-trending narrow band of slightly more massive deposits suggests seepage along a fissure. The sheet is draped over the landscape and is perhaps the relic of a wet meadow which surrounded a flowing spring.

The prominent butte northeast of Fairbanks Spring has a hard massive cap of spring deposits that is nearly 20 feet thick. Conformably below the caprock is nearly a hundred feet of brown and light-brown sandy silt and clay containing nodular masses of evaporites(?). The great thickness of the caprock suggests that it was deposited around a spring and is not merely a weathered crust, though no sign of such an opening was found. The Quaternary rocks near Fairbanks Springs are undeformed, and the caprock is isolated and exposed because of dissection by Carson Slough.

Three small mesas south of Longstreet Spring have indurated caprocks and are mapped as spring deposits (pl. 1). The caprock is largely a massive pale-brown, very fine grained sandstone 2–3 feet thick; locally the material is coarse grained and faintly stratified. Below the cap of the eastern mesa is about 2 feet of fine pebble gravel that thins westward and rests on clay, silt, and sand. The contact locally shows a slight angular discordance (fig. 6). No gravel occurs beneath the caprock of the two mesas just to the west. The tops of the mesas slope westward, parallel to that of the apron of alluvial-fan deposits to the south. The caps of the mesas are remnants of westward-sloping sheets of alluvial-fan debris. The eastern mesa lies at about the western limit of gravel on the ancient fan; further westward, perhaps near the toe of the ancient fan, the material was largely sand. The location of these caprocks near present-day springs suggests that the alluvial apron west of the hills was once the site of a swampy meadow which is now drained.

ORIGIN AND ENVIRONMENT

The alluvial fan, playa, and spring deposits accumulated in an arid basin whose bordering highlands were almost the same as they are today. The small clay-covered flat in the northeast corner of the area may be a remnant of the ancestral playa. Alluvial fans spread out from the highlands to an extensive playa that, in the Pleistocene, occupied much of the Nevada segment of the quadrangle. Springs in the Ash Meadows probably supplied water to the playa and the Meadows were areas of swamp, much as they are today. The ancestral playa apparently extended southward into California probably as far as Eagle Mountain (fig. 1). Dissection of the playa probably began in the late Pleistocene, and in the Nevada part of the quadrangle reached to depths of at least 100 feet. Washes from volcanic mountains to the north (fig. 1) spread a layer of gravel on top of the playa deposits in the northern part of the area. Erosion has now removed or redistributed part of this cover.

Alkali Flat, at the southern edge of the quadrangle, is almost undissected. In late Recent time the Amargosa River was dammed west of Eagle Mountain, and a small playa—Alkali Flat—was built in the river valley just north of the mountain. The construction of the Flat coincides with the dissection of the much more extensive "ancestral" playa mentioned above. The building of the Flat may be due to the rise of Eagle Mountain or perhaps to the growth of the adjacent fans at a time of increased flood flow from the neighboring highlands.

AGE AND CORRELATION

The arid-basin sediments probably include deposits of both Pleistocene and Recent ages. No fossils have been found. Similar materials in the Amargosa Valley to the south include "dissected playa or lake beds * * * [which] between Shoshone and Tecopa contain elephant remains that, according to Curry (personal comm.), who collected them, are Pleistocene" (Noble, 1941, p. 957–958). Along the Amargosa River west of Franklin Well the alluvium that overlies the playa and the fan deposits has been dated archeologically by Alice Hunt (1960, p. 65) as about 2,000 years old. Most of the arid-basin sediments are probably of Pleistocene age.

LANDSLIDE BRECCIA

Tongue-shaped masses of landslide breccia, including some brecciated sheets of limestone or megabreccia (Longwell, 1951), lie on the piedmont east of the Funeral Mountains. Northeast of Bat Mountain several masses of breccia form conspicuous low hills on the piedmont east of the mountains. South of Bat Mountain a mass of breccia is largely within the range, and just east of the peak is another small slide. Detailed maps of the several slides are published elsewhere (Denny, 1961).

The landslide breccia is either a disordered mass of fanglomerate and limestone blocks or large plates of limestone resting on breccia, on gravel, or directly on Oligocene(?) rocks stratigraphically above those included in in the plates (pl. 1, section *A–A'*). The southern slide filled a narrow gully near the mountain front and spread out over the apex of the adjacent fan. The single or forked tongues of breccia northeast of Bat Mountain are separate landslides that moved down gullies on the piedmont which has since been lowered 30 to 40 feet by erosion.

All the landslides came from the steep eastward-dipping beds of fanglomerate and limestone (upper fanglomerate unit and upper limestone and shale unit, pl. 1) that have shale and other thin-bedded rocks beneath them. Uplift of Bat Mountain along high-angle faults set the stage for the erosion of cliffs on its northern and western sides. Material from these cliffs descended into gullies and moved out onto the piedmont. The individual tongues are discrete slides that moved down the piedmont in shallow gullies carved partly in bedrock and partly in gravel. Sliding occurred more than once, but the precise age of any one of the slides is unknown. Subsequent erosion has left the slides standing above their surroundings.

SCREE

Much of the quartzite of Shadow Mountain lies beneath a discontinuous mantle of scree, but only the larger masses of this bouldery deposit are shown on the map (pl. 1). A scree of basalt boulders mantles the slopes of the small butte in the southwest corner of the quadrangle. Unmapped bodies of scree lie on the slopes of the Funeral Mountains and of the hills near Devils Hole.

The typical scree on Shadow Mountain is composed of cobbles and boulders of quartzite, and the stones on the surface have a dark coating of desert varnish. Scree occurs on all sides of the peak, chiefly as tongue-shaped masses in the heads of gullies. Only near the summit does scree mantle ridge crests (fig. 5*B*). Between the tongues of boulder scree are bands of pebble scree whose stones are not varnished and are imbedded in a sandy matrix. In the upper foot of the boulder scree most of the fragments are varnished on all sides and there is no matrix between them. From a depth of 1–1½ feet the stones are not varnished but are coated with sand. In the few pits excavated to greater depths, the material consisted of pebbles of quartzite imbedded in a fine sandy matrix.

The estimated mean size of the fragments on the surface of three bodies of scree on Shadow Mountain is given below; the estimates were determined by the method noted on page L25.

Kind of surface	*Slope* (°)	*Estimated mean size* (mm)
Varnished fragments and no fines	29	80
Do	31	175
Unvarnished fragments and a little fine sand	29	10

The rounded crests of the high ridges on Shadow Mountain are draped with dark bands of scree. Stripes of varnished boulders are separated by areas of fine scree with abundant shrubs. On gentle slopes near the summit, masses of fine scree have moved within the last few years. Unweathered fragments of quartzite are piled up behind bushes to a height of several inches, or form a tongue that has moved down over varnished boulder scree (fig. 84). Tongue-shaped masses of scree in a gully are dissected along their lower edges by a wash that heads in the same gully or in a neighboring one. Scree forms low ridges that trend downslope and are surfaced with either varnished boulders or pebbly sand in which scattered shrubs grow. Fine pebbly scree floors gullies cut in coarse boulder scree, or rests on top of and is completely surrounded by boulder scree.

The scree on the butte southwest of Death Valley Junction forms an almost continuous mantle of boulders that conceals the underlying tuff. These basalt boulders have a black coating of desert varnish. The surface of the deposit has the form of low ridges and shallow gullies trending downslope. Mantles of varnished boulders, largely talus, are, of course, characteristic of many areas of basaltic rocks in the western United States.

In the hills of the Devil's Hole area, the largely bare-rock surface of the hills is separated from the adjacent piedmont by a narrow band of many closely spaced gullies that are walled by coarse and fine scree. Such patterns of gullies and intervening spurs are characteristic of the transition from hills to piedmont and are perhaps an expression of a dynamic equilibrium between the rate at which scree is produced by weathering on the bare mountain slope and the rate at which scree is eroded and the material carried down onto the piedmont. The gradual wearing back of the bedrock slope above the band of gullies causes them to deepen and thereby isolate masses of scree downslope from further sedimentation. In this way, the amount of scree separated from its source gradually increases. These abandoned deposits of scree are eroded and the material transported down onto the piedmont. If we assume that the rate of the supply of detritus to form scree is constant, in time the rate at which the scree is removed will equal the rate at which material is supplied to it. Thereafter, this system of erosion and deposition will remain in balance until upset by some change in process or in geometric relation of mountain slope to piedmont.

The scree in the Ash Meadows quadrangle is detritus from an adjacent bedrock slope or from older scree. Much of it has accumulated as individual blocks at the base of a cliff to form talus. The localization of some scree in gullies suggests a casual relation to running water. Such scree—boulder colluvium is perhaps a more appropriate term—may accumulate to a considerable thickness before a high flow of water moves the debris down the gully and out onto the adjacent fan. Scree on divides is derived by weathering from adjacent bedrock or older scree.

A

B

FIGURE [illegible].—Scree on Shadow Mountain and patterned salt crust. A, Tongue-shaped mass of unvarnished fragments (light colored) outlined by hammer, ruler, and slate, that rests on older varnished scree; shrub in foreground; summit cone of Shadow Mountain, altitude [illegible] feet. B, Polygonal arrangement of pebbles on salt-encrusted surface of playa deposits. The slate is about [illegible] inches long. Locality is south of Ash Meadows Road, [illegible] east of Carson Slough (NE¼SW¼ sec. [illegible], T. [illegible] N., R. [illegible] E.).

The varnished coatings on the exposed fragments of most deposits of scree suggest that they are old, but how old is a moot question. Present-day frost action is doubtless responsible for the fine scree on the summit of Shadow Mountain, and perhaps the coarse scree dates from a time of more effective frost action in the past, either in the late Pleistocene or about 2,000 years ago during a moist-climate episode when there was a shallow lake on the floor of Death Valley (C. B. Hunt, written comm., 1960).

The occurrence of varnished or solution-faceted pieces of rock in the upper few feet of scree suggests that the stones were weathered prior to burial. Accumulation may have been piece by piece over a long interval of time. A weathered boulder moves down off a bedrock face from time to time, and gradually scree accumulates at the base of the steep slope. Given sufficient time, such a slow process could form a thick deposit.

The occurrence of coarse and fine scree reflects in part at least the presence, under the adjacent slope, of both thin-bedded or well-jointed rocks and thick-bedded or massive rocks. A bouldery surface, however, may be only superficial. Exposures show that the coarse material at the surface becomes finer grained at depth, and a similar relationship can be inferred from the occurrence of fine scree completely surrounded by boulder scree. The presence of both coarse and fine scree in the same gully suggests that both large and small fragments weather out of the bedrock upslope. The sorting may reflect differences in runoff intensity from storm to storm.

GRAVEL ALONG AMARGOSA RIVER

A low gravel terrace occurs along the Amargosa River from about State Route 126 southward to Ash Meadows Road. In some places the surface of the terrace is a desert pavement. A gray pebble gravel contains abundant fragments of volcanic rocks and a subordinate number of quartzite, chert, limestone, dolomite, and sandstone fragments. The pebbles commonly range from 1/4 to 1 inch in diameter. The deposit is crossbedded and includes layers of coarse- to medium-grained sand and sandy silt. Locally it is overlain by 2–3 feet of fine, crossbedded sand. The terrace is perhaps as much as 6 feet above the dry river bed and 2–4 feet above the toe of the fans from the Funeral Mountains.

Pebbles in the gravel come both from the mountains north of Lathrop Wells and from the Funeral Mountains. The pebbles of volcanic rock were reworked presumably from the gravel that mantles the uplands near Clay Camp. The pebbles of sedimentary rock came either directly from the Funeral Mountains or were reworked out of the adjacent fan deposits. The gravel extends only a short distance upriver from the highway crossing and probably did not come down the river from the northwest. The sand that overlies the gravel contains a few pieces of charcoal and chipped flakes of rock. This sand is probably part of the Recent alluvium that west of Franklin Well is overlain by archeological material believed by Alice Hunt (1960) to be about 2,000 years old.

DUNE SAND

Sand dunes are on the alluvial plains or near the toes of fans and are composed of coarse- to medium-grained sand. The largest areas of dunes are on the east bank of Carson Slough and the adjacent plains. A few small dunes occur on the uplands north of Clay Camp. Many dunes are underlain by playa deposits, and most of them are not far removed from springs or swamps. The dunes have irregular shapes: most are 5–10 feet high, but some are as much as 30 feet high. Some of them are slightly elongate in plan. The dunes are bare, except for scattered mesquite, and change shape from time to time. None of the dunes, however, appear to be moving across the plains. In a few places near dunes the surface of the playa deposits has been slightly eroded by wind-driven sand.

Archeological remains on the surface of the dunes belong to the Death Valley III and Death Valley IV stages (A. P. Hunt, 1960, p. 65, 168–171), which span the last 2,000 years. The dune sand is apparently derived from alluvium. Perhaps the sand north of Clay Camp came from the adjacent alluvial-fan deposits. Gravel fans with extensive areas of pavement are devoid of dunes, probably because the surface of the gravel is not a good source of sand.

The largest area of dune sand, west of Crystal Pool, has a straight and abrupt east face that lines up with that of smaller dunes to the north. The arm of alluvium east of these dunes suggest that their linear front is an erosional feature. It is tempting, neverthess, to speculate that this alinement reflects a structure in the underlying rocks.

During times of high wind, sand can be seen moving across the surface of the Amargosa Desert. There is no evidence in the quadrangle that the dunes were ever more extensive or more actively moving than they are at present. Whether the presence of mesquite is a contributor to dune formation or merely a result thereof is not clear. All the dunes support mesquite, but extensive areas of mesquite are on plains where dunes are virtually absent.

ALLUVIUM

Material that ranges in texture from boulders to silt floors narrow washes and broad flood plains. The amount of clay in the alluvium appears to be small but was not determined by mechanical analysis. The lithology of the deposit reflects that of the adjacent rocks. The coarse fragments are mostly unweathered and lack a coating of desert varnish. Along the Amargosa River and Carson Slough, the alluvium is largely sand or silt. Large areas along Carson Slough have a salt crust. Near Ash Meadows Road the crust disappeared during heavy rains in the spring of 1958, but the white coloration returned within a week or two after the rains had ceased. On the fans, the alluvium is chiefly sand and gravel. The delineation of alluvium on the fans (pl. 1) is a generalized portrayal of what is actually a mosaic of small bodies of unweathered alluvium and of weathered fan deposits, the latter including areas of wash floored with varnished fragments and areas of desert pavement.

The alluvium on the fans is confined in narrow channels of which a few head in the mountains, but most head in an area of desert pavement. Many of the elongate bodies of alluvium do not extend as far as the toes of the fans. Near the toes, however, other small elongate bodies of alluvium are separated by small areas of desert pavement. This distribution of alluvium suggests that some of the deposits come from catchment basins on the adjacent steep mountain slopes and others from smooth areas of desert pavement where runoff is rapid.

The recent alluvium on the fans is finer grained than the varnished gravel on adjacent alluvial-fan deposits (fig. 4). The weathered gravel is more extensive than the alluvium, and the floods that moved the latter were probably not as extensive as those that moved the older gravel.

The thickness of the alluvium is unknown. Few exposures reach depths of more than 10 feet. No fossils have been found.

In her study of the archeology of Death Valley, Alice Hunt (1960, p. 65) mentions briefly sites along the Amargosa River in the Ash Meadows quadrangle:

> * * * Late Death Valley II (Amargosa) sites are numerous along and near the Amargosa River, which is now dry most of the year, in the valley next east of Death Valley. Some crudely shaped tools, a washed fireplace, and numerous flakes were found in the alluvial bank of the river to depths 3 feet below the surface. Diagnostic tools were not found in the alluvium but the artifacts almost certainly are from the numerous Late Death Valley II sites along the edge of the river floodplain. Sites with pottery and arrowheads are few along the river and are largely restricted to the existing springs.

The Late Death Valley II occupation is believed by Alice Hunt to have ended at about the beginning of the Christian era, and to have been contemporaneous with a Recent pluvial lake which covered the floor of Death Valley to a depth of about 30 feet (C. B. Hunt, written commun., 1960). In Death Valley, occupation sites of this same stage are found around springs that are now dry but presumably were flowing at the time of occupation. It is likely, therefore, that much of the alluvium along the Amargosa River is at least 2,000 years old.

STRUCTURE

FUNERAL MOUNTAINS

Within the Ash Meadows quadrangle, the southeastern spur of the Funeral Mountains is an eastward-dipping fault block, bounded on the northwest by a fault that we have named the Bat Mountain fault. Smaller faults within the block strike either parallel to it or terminate against it at a low angle. At least two periods of deformation occurred.

The Funeral Mountains (fig. 1) are bounded on the southwest by the Furance Creek fault zone, one of the master faults of the region. The zone follows the southwest base of the Grapevine Mountains and the Funeral Mountains to the Amargosa Valley, where it turns southward to extend perhaps as far as the point where the Amargosa River crosses the Shoshone-Baker highway (Noble and Wright, 1954, pl. 7; Jennings, 1958). The fault zone is concealed in the Ash Meadows quadrangle, but probably lies close to the southern end of the spur, where the northeasterly strike of the Tertiary rocks changes abruptly to the east.

The Bat Mountain fault northwest of the spur extends southwest into the Ryan quadrangle and is inferred to terminate in the Furnace Creek fault zone. Both faults are largely concealed beneath the Quaternary deposits. The rocks of the spur are uplifted several thousand feet relative to those to the west, and the displacement increases toward the Furnace Creek fault zone.

Within the spur, which is bounded on the west by the Furnace Creek fault zone and the Bat Mountain fault, the older of the two sets of small normal faults strikes northward and joins the Bat Mountain fault obliquely. On the northeast slope of Bat Mountain a horst of Paleozoic limestone and dolomite is separated from the adjacent Tertiary rocks by high-angle faults (section *B–B'*, pl. 1). The upper limestone and shale unit lies unconformably on the beveled top of the underlying horst and graben structure.

The younger set of normal faults trends northeast in the southern part of the spur and swings north and northwest in the northern part. Many of the faults dip about 65° west, or about normal to the bedding in the upper fanglomerate unit. The western blocks generally dropped relative to those to the east. Toward the south, some of the younger faults become a zone of faults and the throw increases, but even here is not more than a few hundred feet. Near the northwest side of the spur the younger faults join some of the older set. Here the movement apparently took place along both sets at the same time. The throw of the fault immediately east of the knob at altitude 3,377 feet decreases southward from about 400 feet at a point three-quarters of a mile from the Bat Mountain fault to about 50 feet 1½ miles from it.

The oldest movement on the faults at the southeastern spur of the Funeral Mountains is inferred to be Oligocene. The area southwest of the Furnace Creek fault zone was raised at least twice to supply the debris for the two bodies of fanglomerate at Bat Mountain. Probably during this same time movement took place along subsidiary faults in the older rocks of the spur. By Miocene or Pliocene time the Funeral Mountains were raised relative to the area southwest of the Furnace Creek fault zone, and the lacustrine and volcanic rocks of the Furnace Creek Formation were deposited west of Death Valley Junction. The rocks of the spur were broken again by many faults during this interval. The abrupt west face of the spur, largely outside of the Ash Meadows quadrangle, suggests that the youngest movement on the Bat Mountain fault is no older than the Quaternary Period. No movement has taken place along the small faults mantled by landslide breccia since the breccia was deposited, perhaps in late Pleistocene time.

DEVILS HOLE AREA

The unnamed range, largely outside the northeast edge of the Ash Meadows quadrangle but extending into it at a point about 2 miles northeast of Point of Rocks Springs, is in general a gently northeast dipping block that contains one or two thrust faults of undetermined size. Along the westernmost of these faults, gently dipping Middle and Upper Cambrian rocks moved over steeply dipping Lower and Middle Cambrian rocks. The rocks of the Devils Hole area appear to be extensions of the upper plate.

Alluvial deposits overlap the Paleozoic rocks of the hills near Devils Hole in the northeast part of the quadrangle, and the faults along which the hills are believed to have been elevated relative to the adjacent plains are nowhere exposed. The rocks of the hills are broken by numerous north- to northwest-trending steep faults, which have displacements rarely exceeding 200 feet. In the hill north of Devils Hole, the eastern fault blocks are dropped with respect to the western ones. Three sinkholes, of which Devils Hole is the largest, lie on or close to small faults; very likely their solution was structurally controlled. The rocks in the hill north of Point of Rocks Springs are gently arched and are also broken by north- to northeast-trending steep faults. The blocks along the crest of the anticline are upthrown.

The rocks in the spur along the eastern edge of the area are broken in a less systematic manner along northwest-trending steep faults.

On the gently sloping surface of the playa deposits about a mile southwest of Devils Hole, small areas of gravel are shown bordering the trace of an inferred fault. Areas of gravel abut against playa deposits along a north-trending line. The distribution of gravel and playa deposits suggests differential erosion along some sort of structural break. The trace of the doubtful fault lines up with two springs about a mile to the north.

RESTING SPRING RANGE

Shadow Mountain is a block of east-dipping Paleozoic rocks (section *E–E'*, pl. 1) that has risen relative to its surroundings. The border faults are nowhere exposed, for on all sides fanglomerates of Cenozoic age rest unconformably on the older rocks. West of the peak a small mass of disordered blocks of limestone and dolomite has apparently been dropped down relative to the main body of the mountain along a northeast-trending fault. The range diminishes in altitude northward, presumably because the amount of displacement along its concealed border faults also decreases. At the north end of the range, the surface of the block passes beneath the older of the fanglomerates that is displaced a few hundred feet by movement along high-angle faults that strike northward and die out in the overlying finer grained beds.

The Paleozoic rocks of the range are apparently displaced along other north-trending faults that were not mapped. South of Shadow Mountain, a small southward-dipping wedge of fanglomerate has been dropped relative to the Paleozoic rocks along an east-trending high-angle fault.

South of Grapevine Springs, the nearly straight western limit of the younger fanglomerate suggests faulting, but exposures on the south side of the broad wash near the state line (sec. 11, T. 25 N., R. 6 E.) show the fanglomerate near Grapevine Springs resting unconformably on the sandstone and clay unit. At the north end of the range the Tertiary rocks form a broad anticline whose axis lies close to the broad wash entering the quadrangle from the east.

GEOMORPHOLOGY

ALLUVIAL FANS

Alluvial fans are accumulations of detritus at a place where a debris-carrying wash from a highland becomes free to migrate from side to side. The fan-building wash has a smooth profile and passes without a break in slope from highland out onto fan. The point at which the wash leaves its confined channel and moves from side to side varies from fan to fan. On some it is at the mountain front, on others half-way down to the toe of the fan. Deposition will take place where the channel is unconfined, if the gradient at that place is less than that upstream, and the wash will thus acquire a smooth profile from headwaters to toe of fan.

The mountains and hills of the Ash Meadows quadrangle are surrounded by coalescing alluvial fans that have a complex surface—a mosaic of desert pavements and of washes. On the geologic map (pl. 1) the areas where the surface of the alluvial-fan deposits is desert pavement are shown by pattern. The rest of the surface of the alluvial-fan deposits consists of abandoned washes that have not carried water for some time. The surface form and origin of two fans in the quadrangle and others nearby are discussed in detail elsewhere (Denny, 1964).

WASHES

The modern washes, the Recent alluvium of plate 1, differ from the abandoned washes in topographic form and in the nature of the material at the surface. Braided channels and gravel bars constitute the modern washes. Desert shrubs are absent, and the stones on the surface are mostly unweathered. The channels and bars of the abandoned washes support a growth of desert shrubs and are floored with stones that have a coating of desert varnish. The surface material is coarser grained, and the microrelief between channel and bar is greater than in the modern washes.

As has just been stated, the distinction between modern and abandoned washes is based in part on the presence or absence of desert varnish. Such black coatings are found on quartzite, sandstone, and volcanic rocks: the volcanic rocks commonly have darker coatings than the other rock types. These thin coatings are removed from a stone when it is moved by running water. Thus, if we knew when a stone had been coated with varnish, or perhaps how long a time is required for a stone to acquire such a coating, we would have a minimum age for the last movement of the stone. This age would be the minimum length of time since the last flood came down the wash in which the stone lies.

Observations that have a bearing on the age of desert varnish were made along the Old Traction Road (pl. 1), which crosses the fans west of Shadow Mountain. Stones overturned during the building of the road about 1905 have not acquired a coating of varnish since that time. At a locality in the Mohave Desert, however, varnish has formed on rhyolite fragments during a 25-year period (Engel and Sharp, 1958). The Hunts (A. P. Hunt, 1960; C. B. Hunt, 1954, 1961) present impressive archeological and geological evidence that much desert varnish has considerable antiquity. They believe that in Death Valley most varnish was formed not later than about the beginning of the Christian era. The weight of the evidence certainly indicates that many deposits whose surface stones are varnished are much more than 2,000 years old.

DESERT PAVEMENT

Pavements are segments of fans that have received no additions of detritus for a long time and serve as an armor that protects the underlying material from removal by water or by wind. The areas of desert pavement on the fans are smooth, gently sloping surfaces composed of closely packed angular fragments of rock that range in size from pebbles to large boulders. Most of the stones are varnished, except those of carbonate rock that are etched by solution. The exposed surface of a boulder of carbonate rock is eroded, and material is deposited beneath it. As a result, many such fragments on a pavement have smooth and etched upper surfaces and a buried surface that is rounded or irregular depending on the original shape of the fragment (Bryan, 1929, p. 194). Pavements rest on and in a silt that is several inches thick.

The silt beneath the stone armor is firm in place but very friable in hand specimen and has conspicuous circular cavities that give it a vesicular structure. Origin of the silt is unknown; apparently it is formed by both chemical and mechanical weathering of gravel and sand similar to that which underlies it.

Pavements are broken by miniature terraces with risers less than an inch high and lengths ranging from a foot to more than 10 feet. After a prolonged rain, when the silt is saturated with water, the silt at the edge of a pavement next to a gully tends to flow down into it. This movement places the silt that is further away from the gully under tension. Some of the risers of the miniature terraces are believed to be tension cracks produced by the downslope movement of a 1–2-inch layer of silt on which the armor of stones rode. Movements of this sort on an abandoned segment of a fan carry material from high points and fill low spots. Debris is also transported by surface wash and by wind action. These processes combine to transform the channels and bars of a desert wash into a smooth pavement.

Pavements are born dissected. Although at first glance, a smooth desert pavement may appear to be an end point in the evolution of the surface form of a fan, all pavements are dissected irrespective of their location or history. All the larger areas of pavement are cut by narrow washes that head in them. These gullies have probably been in existence at all times and do not record a specific climatic or tectonic episode of accelerated erosion.

PIRACY

On the piedmont at the north end of the Resting Spring Range a spectacular piracy has taken place. A wash floored with alluvium heads in the quartzite hills along the State line and lies along the contact between Quaternary and Paleozoic rocks. The wash turns southwestward into a narrow gully (SW¼NW¼NE¼ sec. 24, T. 25 N., R. 6 E.) and passes through a large area of desert pavement to emerge on another broad wash. At one time, however, the wash did not turn southwest but followed a northwesterly course, roughly parallel to the State line. The point of diversion is where the present wash leaves the alluvium and turns southwestward to pass through a small inlier of fanglomerate. Between the inlier and the hills of fanglomerate a few hundred feet to the northeast, alluvial-fan deposits form a 2-foot bank on the north side of the alluvium. The exposed fragments on top of the bank have a coating of desert varnish. The diversion is a recent event. A large flood from the quartzite hills might discharge both into the gully and over the low bank to the northwest. Southwest of the point of diversion, the floors of narrow washes that head in the pavement are slightly below that of the broad wash. This wash apparently cut back its south bank in the vicinity of the fanglomerate inlier and intersected the head of a gully in the pavement.

Piracies have taken place repeatedly on the larger fans in the Death Valley region and are responsible for the development of many large areas of desert pavement. Piracy may occur wherever washes from a mountain have steep gradients and a coarse bedload compared with washes that head on the adjacent piedmont. Such piedmonts consist of areas of gravel deposits, derived usually from highlands of resistant rock and separated by gullies or small valleys carved by local washes either in gravel or in bedrock less resistant than that of the highlands. The erosion of the gullies is due in part to piracy of the sort just described. Great local relief is characteristic of such piedmonts, which have been clearly described and illustrated from the Henry Mountains region, Utah, by Hunt (in Hunt, Averitt, and Miller, 1953, p. 191), whose analysis was based in part on an earlier study by Rich (1935, p. 1002–1003). An example from the Shenandoah Valley, Virginia, is described by Hack (1960, p. 91–94). In the Ash Meadows quadrangle, the topography of the inner part of many piedmonts close to the mountain front is one of narrow ridges and deep ravines. North and northwest of the Resting Spring Range, for example, the outcrops of the sandstone and claystone unit are largely on the lower sides of deep gulches where these weakly consolidated rocks adjoin hills of firmly cemented fanglomerate.

An example of possible future piracy is at the north end of the Resting Spring Range, where a broad wash, floored with alluvium, parallels the State line and emerges onto the piedmont at a point about 1 mile south of Grapevine Springs. This wash has a much larger drainage area than a small one just south of it that, west of the hills, is carved in the sandstone and claystone unit. At the west front of the hills, the surface of the broad wash lies 25–30 feet above the floor of the small wash to the south and is separated from it by a narrow ridge of gravel. If the broad wash were to widen its bed by cutting back its south bank a few hundred feet, it would breach the gravel ridge and flow down into the small wash. The broad wash would then deposit its load in the more gently sloping channel of the small wash, perhaps burying it completely.

RECENT HISTORY

That the fans were at one time flooded more extensively than they are at present is shown by the greater areal extent of abandoned washes compared with that of modern washes. Many of the modern washes, the Recent alluvium of plate 1, do not reach the toe but end on the fan. The piedmont northwest of Shadow Mountain, for example, is a complex grouping of pavement, abandoned wash, modern wash, and pediment. The proportions of these four geomorphic units and their equivalents on the geologic map (pl. 1) are tabulated below. The area of deposition on the fan at present—the modern washes—is about 15 percent of the total area of the piedmont.

Geomorphic unit	*Geologic unit (pl. 1)*	*Estimated proportion of total area of piedmont (percent)*
Pavement	Alluvial-fan deposits	35
Abandoned washes	Alluvial-fan deposits	40
Modern washes	Alluvium	15
Pediment	Sandstone and claystone unit and playa deposits.	10

On the north side of Shadow Mountain, a narrow wash floored with alluvium runs westward from the mountain front for about half a mile (SW¼SW¼ sec. 7, T. 25 N., R. 7 E.). The wash fingers out on the edge of an oval-shaped area of fan deposits that is almost completely surrounded by desert pavement (largely in N½ sec. 25, T. 25 N., R. 6 E.). The surface of the pavement lies many feet above the oval except on its southwest side where the fan deposits of the oval overlap the desert pavement. The stones on the surface of the gravel that floors the oval are varnished and are slightly coarser grained than those on the surface of the alluvium in the narrow wash to the east. Present-day floods from the mountain drop their load before reaching the oval. The now-varnished gravel in the oval was deposited by floods that were more extensive and carried slightly coarser material than those of recent years. Thus, for some time, perhaps for the last several thousand years, most of the coarse detritus from the mountain has been deposited within about a mile of its front.

On the central part of the fan northwest of Shadow Mountain, ribbons of alluvium head in areas of desert pavement. Runoff on a pavement is more rapid than on the surface of a wash (C. B. Hunt, written commun., 1960) and probably facilitates the erosion of gullies in the weathered gravel beneath the pavement. This alluvium is finer grained than that near the mountain front or on the surface of the adjacent alluvial-fan deposits (fig. 4). The slope of the fan decreases in its central part, perhaps because of this decrease in size of its debris.

ORIGIN

The larger fans in the quadrangle and elsewhere in the Death Valley region have a complex surface of pavements and washes. Denny (1964) has suggested that these fans approximate or are approaching a condition of dynamic equilibrium wherein their surface form is so adjusted that the rate at which detritus is supplied to them from the adjacent mountains equals the rate at which material is removed from them by erosion. Let us assume, for example, that material is supplied by Shadow Mountain to the fan north of it at a constant rate and is deposited near the apex. Elsewhere on the piedmont, large areas of pavement and small areas of pediment are being eroded, and material is being carried off the fan to the flood plain of Carson Slough. Piracies take place, such as the one of Recent date described earlier. The locus of deposition shifts downfan, and additional segments of the fan are abandoned. Thus the area of the fan's surface that is being eroded, that is, the amount of material being removed, will increase until it equals the amount supplied. The processes of deposition and erosion will thereafter be in a steady state of balance and will remain so as long as the topographic position of mountain and basin and the geologic processes remain the same (Nikiforoff, 1942). The total volume of detrital material on the fan will not change, the volume of fine material reaching the adjacent flood plain being balanced by the amount of coarse detritus supplied by the highland.

If position of mountain and basin and the geologic processes change in the future as they have in the past, a change will occur in the rates of deposition, weathering, and erosion. The equilibrium between erosion and deposition will be shifted, and changes in the form and size of the piedmont will result. In the Death Valley region, the variations in piedmonts from range to range suggest that they tend to adjust rapidly to changes in the equilibrium of which they are a part.

Pavements, as already mentioned, are born dissected. The transformation of an abandoned wash into a smooth pavement involves the movement of debris down into the gullies that dissect the pavement where the material remains until carried down the gully and on down the fan. If the gullies ramify and grow deeper, they may approach a condition where the rate at which material is removed from the area of pavement by way of the gully balances the rate at which material is supplied to the gully from the adjacent pavement. Thus, a pavement, once formed, may persist for some time. Pavements occur in diverse locations, in one place partly buried by younger alluvium, elsewhere on a ridge 50 feet above the neighboring wash. It would be a remarkable coincidence if all pavements began to form at the same time; rather, the ubiquitous occurrence of dissected pavements suggests that they formed at various times in the past and have persisted to the present.

The processes of weathering, erosion, and deposition operate concurrently on the fans. It is only the intensity of these processes that varies from one segment of the fan to another. Pavements and associated gullies, as already noted, are the places where weathering and erosion dominate over deposition. They are segments of fans that have received no additions of detritus for a long time. The locations of these segments of fans change with time because of piracy. The formation of a complex mosaic of pavement and wash is conditioned by the local geology and is not primarily dependent on changes in the intensity of weathering, erosion, and deposition caused by changes in climate. Such changes doubtless have occurred, but it cannot be demonstrated that they have radically altered the history of any fan in the quadrangle.

To demonstrate that any of the alluvial fans in the quadrangle are in a steady state of balance or dynamic equilibrium requires actual measurements of the rates of erosion and deposition. None are available. Measurements of the size of many fans in the Death Valley region, however, indicate that, for this region, the area of a fan is roughly equal to one-third to one-half of its source area. This relation holds true for fans composed of different rock types and with diverse geologic histories, suggesting that perhaps these fans are approaching a condition of dynamic equilibrium. If so, the fans will not grow much larger in the future, but will maintain more or less their present size. The location of pavement, wash, or pediment will change from time to time, but the proportion of these three geomorphic units will remain about the same. The configuration of these fans may depend primarily upon some functional relation between the bedrock and the processes acting upon it, rather than upon their stage of development in an evolutionary sequence. The existing highlands have remained nearly unchanged for a long time, perhaps since the mid-Pleistocene. No fault scarps cut the arid-basin sediments.

The outcrop pattern (pl. 1) of the alluvial-fan and playa deposits is the result of the dissection of the ancestral playa (p. L32), whose surface was at least 100 feet above the bed of Carson Slough or the Amargosa River. The pattern depends ultimately on the local geology, which sets limits to mountain and piedmont and thereby determines the size of the adjacent fans. For example, alluvial-fan deposits cover the entire piedmont that extends westward from Shadow Mountain to Alkali Flat. To the north, however, playa deposits crop out in a narrow belt between the toe of the alluvial apron of Shadow Mountain and the alluvium along Carson Slough. The fact that these playa deposits intertongue with alluvial-fan deposits shows that the limit to which gravel was carried from the northwest slope of Shadow Mountain to the ancestral playa was the same as it is today. The gradual lowering of the piedmont west of Shadow Mountain during the dissection of the ancestral playa has not altered the limits of gravel transport on the piedmont.

This restricted belt, east of Carson Slough and south of Ash Meadows Road, consists of narrow finger-shaped areas of playa deposits, desert pavement, and alluvium (pl. 1). Similar belts of pavement fingers occur near the toes of many of the fans, such as those north and east of the Funeral Mountains. The belt west of the Resting Spring Range does not extend south to the quadrangle boundary, but is coextensive with the playa deposits. Perhaps where a wash has banks of sand and silt (playa deposits) the channel tends to maintain its position because it can easily move the fine material on its bed. On the other hand, where the wash is flowing entirely in gravel, as on the piedmont east of Alkali Flat, the occasional flows are more effective in eroding the banks of a wash than in moving the material on its bed. The wash tends to cut laterally and forms a wide, gravel-covered plain.

PEDIMENTS

Between fans are small areas of pediment. On the piedmont surrounding the Resting Spring Range the pediments are underlain by the sandstone and claystone unit. These weakly consolidated but deformed rocks are exposed in shallow gullies and are overlain unconformably by a few feet of alluvial-fan deposits. The unconformity at the base of these deposits is an erosion surface that bevels the deformed rocks. The unconformity is a pediment mantled by a younger gravel, which has since been dissected. These areas of pediment are places where erosion has dominated over deposition to the extent that rocks of early Pleistocene or older age are exposed beneath only a few feet of gravel.

PATTERNED GROUND

The Amargosa Desert exhibits patterns due to the orderly arrangement of various features such as desert shrubs, desiccation cracks, salt crusts, small terraces, or large and small fragments of rock. On many abandoned washes and on some pavements, desert shrubs are spaced uniformly, and the resulting design may be noticeable on aerial photographs. The surface forms portrayed by the stripes of boulder scree on Shadow Mountain or the terracettes that run across many pavements simulate ground patterns found in arctic or alpine regions.

Patterned ground in the Ash Meadows quadrangle is most conspicuous on alluvium or playa deposits, or on alluvial fan deposits where they veneer playa deposits. The optimum development of patterns in such areas is perhaps due to the presence of fine-grained silty material and a high content of soluble salts (carbonates and sulfates?). As with the patterns found in cold climates, those in arid regions can be grouped into more or less equidimensional forms on gently sloping land and elongate structures on steeper slopes.

Sorted polygons (Washburn, 1956) several feet in diameter occur in a few places on the surface of the playa deposits (fig. 9). Small stones, commonly less than 1 inch in diameter, fill shallow cracks or troughs a few inches deep. The adjacent material is a clayey silt. The pattern resembles others found in Death Valley (Hunt and Wash-

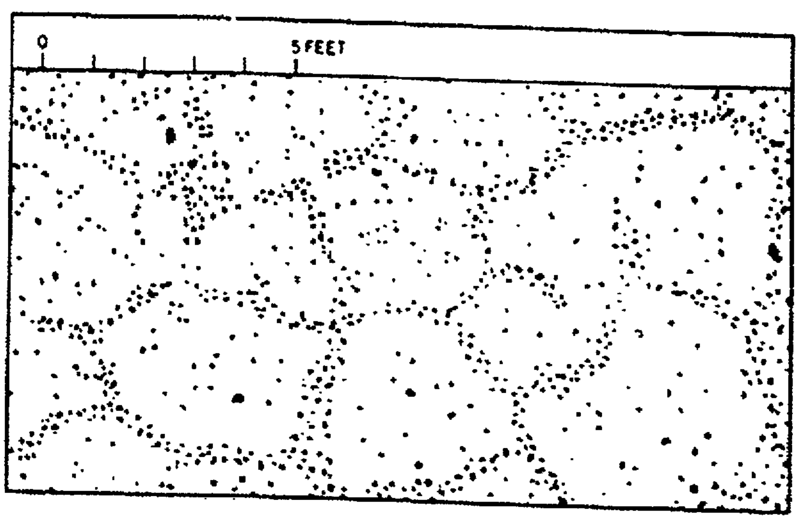


FIGURE 9.—Sorted polygons on surface of playa deposits north of Ash Meadows Rancho. Stones fill shallow cracks and are scattered over intervening fine material. Surface of playa deposits is almost level, and is probably flooded during rains; nearby ground is swampy. Sketched from high-angle oblique photograph, scale not uniform. Locality is a few hundred feet northeast of southwest corner sec. 13, T. 18 S., R. 50 E.

burn, 1960, fig. 185.1A) and presumably is caused by desiccation. These polygons were not excavated. Many of the centers appear to have a very slightly domed surface; the troughs widen at the top.

Areas of salt-encrusted alluvium also show ground patterns. A pebble-covered surface of alluvium may be interrupted by areas of salt crust to give a patterned surface, and these areas of salt crust may themselves show a network of small stones (fig. 8*B*). In some places where an armor of stones rests on silty deposits, a spotted pattern is visible that is reminiscent of stone circles. Large fragments, ½–3 inches a common size, form circular or oval bands surrounding areas 2–3 feet in diameter where the fragments are smaller. White salt crusts appear between the stones of the circles, whose centers are very shallow basins less than an inch deep.

Small terraces are a common feature in the Amargosa Desert and indicate that sliding or slumping has taken place. Such lobate forms are most common where the underlying materials are fine grained. At a point about 2½ miles west of Ash Meadows Rancho (NE. cor. sec. 28, T. 18 S., R. 50 E.), terraces occur on a south-facing, 6° slope underlain by silty material. The individual terraces contour the slope and can be traced for distances of 5 to 30 feet. The risers are from a few inches to nearly a foot high and are faced with pebbles. The treads are of loose puffy silt containing a few small pebbles. Jeep tracks made in 1957 across other areas of puffy ground nearby were partially obliterated a year later.

Somewhat larger and more lobate terraces lie on the south-facing 10° slope of a ridge near Clay Camp (NW. cor. NE¼NW¼ sec. 1, T. 18 S., R. 49 E.). A pebble gravel composed of quartzite, sandstone, limestone, dolomite, conglomerate, and porphyry forms a pavement that mantles the hill. Near the base of the ridge a white salt crust caps prominent lobate terraces (figs. 10 and 11*A*). The risers, from a few inches to 1½ feet high, are faced with pebbles and cobbles. A few shrubs grow on the lower slopes of the ridge.

The material exposed in a trench dug through one of the terraces is illustrated in figure 12, and the accompanying photograph (fig. 11*B*) shows the right-hand terrace of the cross section prior to excavation. The treads have a firm but friable crust on which rest a few pebbles; the risers are of loose sand mantled by pebbles and cobbles, some of which lie on the face in an unstable position. Bedrock is within about 1 foot of the surface. The treads are underlain by loose sandy material that contains particles of white caliche. The risers are partially weathered bedrock, a mixture of sand, silt, and rock fragments.

We believe that the downslope movement recorded by these terraces was largely caused by the addition of water to the underlying material, perhaps partly by the formation of salts in the ground. The water

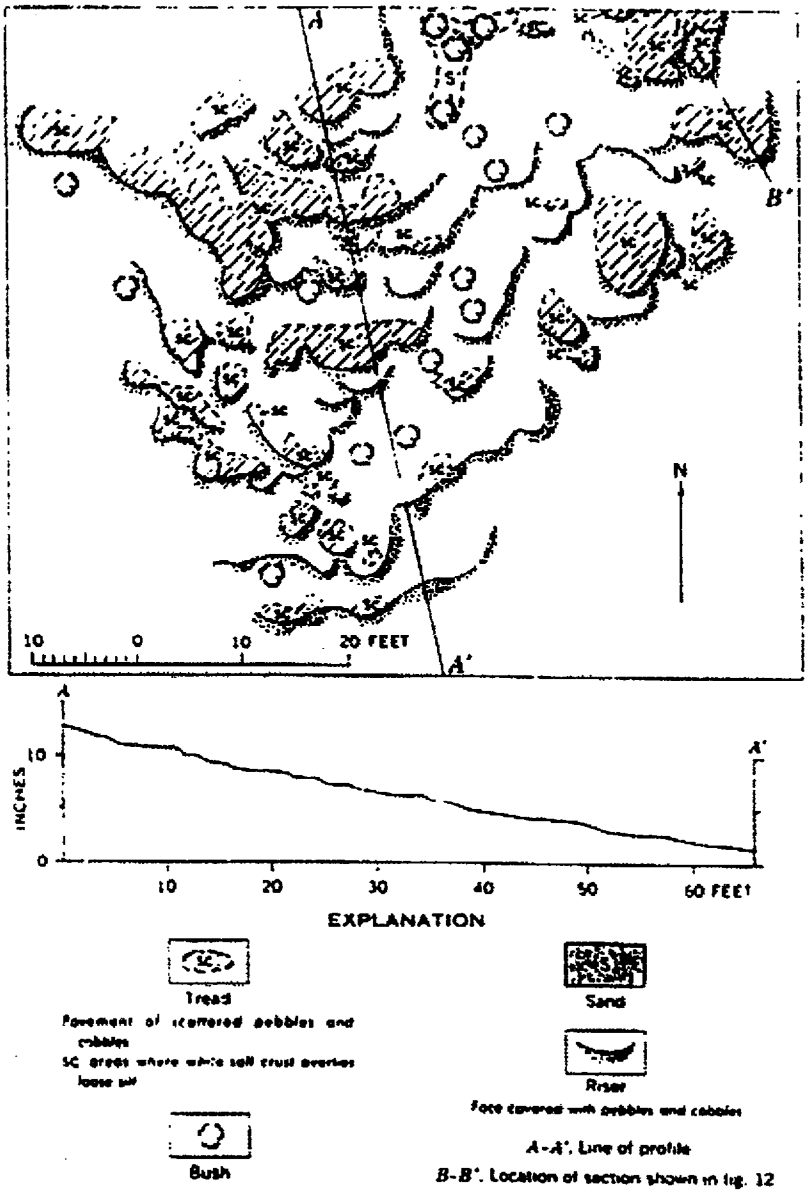


FIGURE 10.—Sketch map and profile of small terraces near Clay Camp. Material exposed in trench (section B-B') is shown in figure 12. Datum assumed.

A

B

FIGURE 11.—Small terraces near Clay Camp. A, Small terraces with curving risers faced with pebbles and cobbles; treads commonly have covering of scattered pebbles and cobbles interspersed with white areas of salt crust. Terrace is on south-facing side of ridge about half a mile northwest of Clay Camp. (For map and profile, see fig. 10.) B, Tongue-shaped terrace with pebble-faced riser and white salt-encrusted tread; cross section through this terrace is shown in figure 12.

may have come from occasional rains or from a rise in the ground-water table because of reduced evaporation and transpiration. Such a rise has been observed in Death Valley at times of cloudy weather in winter (C. B. Hunt, written commun., 1960).

Whether the terraces are forming today or are largely relics from a moister climatic episode is debatable. Hunt and Washburn (1960) hold that similar terraces in Death Valley are the result of past movements when the climate was more favorable than it is today. They observed rows of pegs across terraces in Death Valley and could find no evidence of movement during a 4-year period.

We believe that some of the terracettes in the Amargosa Valley are forming at present. The relation of terracettes to vegetation suggests present-day movement. On the east side of the hills north of Point of Rocks Springs are many small lobate terraces near the inner

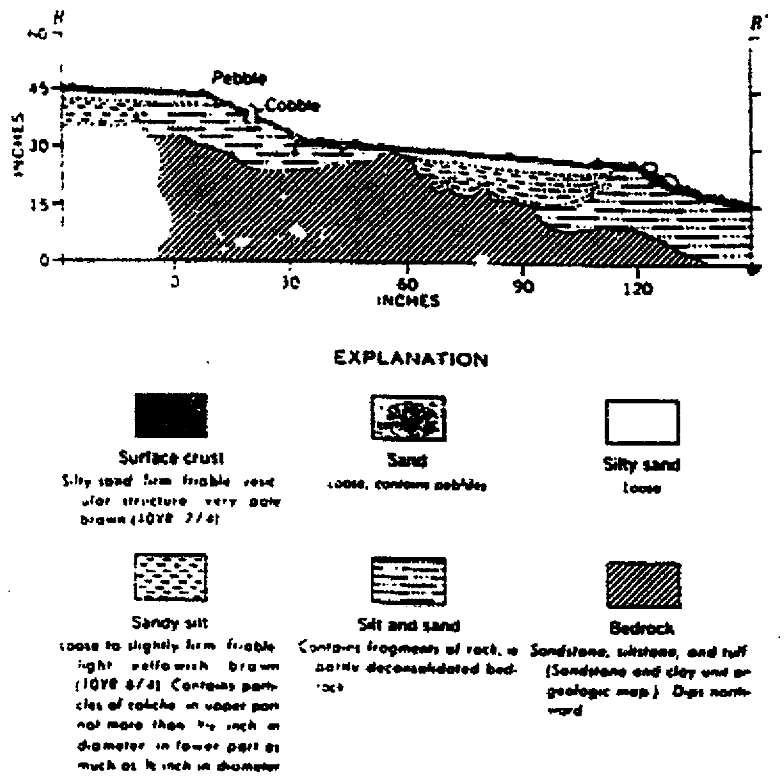


FIGURE 12.—Section through small terraces near Clay Camp. For map of terraces and location of section, see figure 10.

edge of the pediment next to the mountain front. Some of the lobes appear to have moved around the base of adjacent shrubs. Some of the stones associated with the lobes lean against the stem of a shrub as if they had slid or rolled up against the stem. The uneroded or otherwise unmodified form of some terraces made of loose material suggest that no cloudburst has occurred since such terraces were formed. Stones on the risers of some terraces are loosely packed; a slight touch will send them rolling downslope. It is unlikely that a stone would have maintained such an unstable position for a long time. These stones probably have been pushed into their present attitude by movement of the terrace front within the last few years.

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Late Cenozoic rates of erosion in the western Española basin, New Mexico: Evidence from geologic dating of erosion surfaces

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ABSTRACT

Erosion surfaces in the Española basin formed before 350 ka and between 350 and 240, 240 and 130, and 130 and 80 ka, probably in response to climatic change and regional uplift. The surfaces are cut on Miocene, Pliocene, and Pleistocene deposits and range from about 200 m to 15 m above the present Rio Chama/Rio Grande system. Periods when the surfaces formed were dated using varnish-cation ratios from exposed clasts, the mass of soil carbonate, and amino-acid ratios in Pleistocene gastropods from underlying deposits. Thorium/uranium ages from soil carbonate were used to calibrate a local curve for varnish-cation ratios. The range in age determined for a given surface, although derived from different dating techniques, implies that parts of the surface were sites of erosion or aggradation after the surface formed.

From 1.1 Ma to present, denudation rates averaged 10 cm/1,000 yr from weakly lithified sandstone, less than 7 cm/1,000 yr from indurated tuff and boulder gravel, and about 4 cm/1,000 yr from tuff and basalt. Erosion surfaces were preserved as upland benches and terraces by stream incision during periods of pluvial climate and regional uplift, but our data do not permit clear separation of the two causes.

INTRODUCTION

Erosion surfaces in the Española basin, New Mexico, that cut across late Cenozoic bedrock and surficial deposits provide strong evidence for climatic change and regional uplift. Prominent Quaternary surfaces are preserved along the western margin of the basin at elevations 180–15 m above the Rio Grande and its tributaries. This paper reports geologic data for major surfaces of Quaternary age west of the Rio Grande and Rio Chama. We correlate these surfaces and estimate their ages from a curve of varnish-cation ratios (Harrington and Whitney, 1987), which has been calibrated with $^{230}Th/^{234}U$ ages of soil carbonate. These ages are supplemented by those calculated from amounts of soil carbonate, amino-acid ratios from gastropods, the distribution of Quaternary tephra, and radiocarbon dates. Our data suggest that late Cenozoic incision rates in the Española basin are similar to those reported from several nearby areas in the semiarid western United States.

This study demonstrates that varnish-cation ratios (Dorn, 1983; Harrington and Whitney, 1987), when used with other dating methods, are useful for correlating and dating surfaces in arid and semiarid areas. Ages calculated from varnish-cation ratios also can provide indications about when specific areas on surfaces became stable. Local erosion and aggradation occur frequently on geomorphic surfaces, and it is often difficult to recognize evidence for such reworking. Under optimal conditions, the lowest varnish-cation ratio from an erosion surface provides a close minimum age for cutting of the surface (Harrington and Whitney, 1987). Groups of higher ratios indicate subsequent periods when other areas of the surface became stable. Varnish-cation ratios can thus be integrated with soil morphology, soil-carbonate accumulation, and isotopic ages to infer episodes or areas of reworking on erosion surfaces.

Erosion surfaces are cut across Miocene, Pliocene, and Pleistocene deposits that fill the Española basin, one in a series of structural troughs that comprise the Rio Grande rift in northern New Mexico. The rift was internally drained until the Rio Grande formed an integrated drainage system between 4.5 and 3.0 Ma. Upper Pliocene and Pleistocene deposits record alternating periods of erosion and aggradation in the basin, punctuated by eruption of the upper Pleistocene Bandelier Tuff. Quaternary surfaces consist mainly of (1) paleochannels preserved by coarse gravel and calcrete, (2) pediments that truncate late Tertiary and Quaternary deposits, (3) alluvial fans, and (4) terraces near present channels. The surfaces variously record periods of lateral cutting (Bull, 1979), episodic dissection of the basin fill, aggradation, and local warping associated with faults (Kelley, 1979; Harrington and Aldrich, 1984). Surface ages and elevations provide evidence for the history of river incision during the Quaternary. Inset relations of surfaces enable us to measure denudation rates (average rate of surface lowering, expressed in cm/1,000 yr) during several periods of the Pleistocene. By comparing denudation rates in areas of different lithology, we can also assess the significance of rock resistance for erosion rates integrated over hundreds of thousands of years.

Episodic aggradation and incision are correlated with climate change during the past 500 ka in New Mexico (Gile and others, 1981; Machette, 1985). Aggradation along the Rio Grande has occurred during transitions from periods of higher effective moisture (pluvial) to more arid conditions (interpluvial), such as the transition from the latest Pleistocene to Holocene. For example, the width of the Rio Grande meander belt near Española has narrowed substantially since about 15 ka, as alluvial fans prograded over Pleistocene channel deposits, burying fluvial terraces with 5 to 30 m of piedmont alluvium (Johnpeer and others, 1985). Gile and others (1981) report a similar pattern of fan extension and axial-channel

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Figure 1. Maps showing the location of the Española basin and the area of this report (after Manley, 1979). a. Map of basins along the Rio Grande in northern New Mexico and southern Colorado (stippled areas), and surrounding mountains.

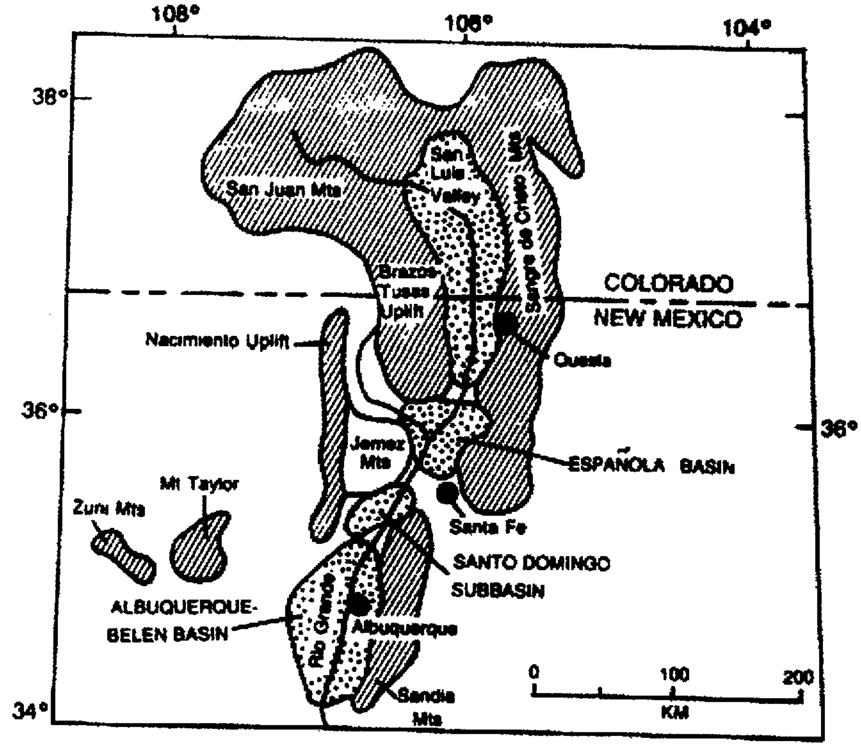
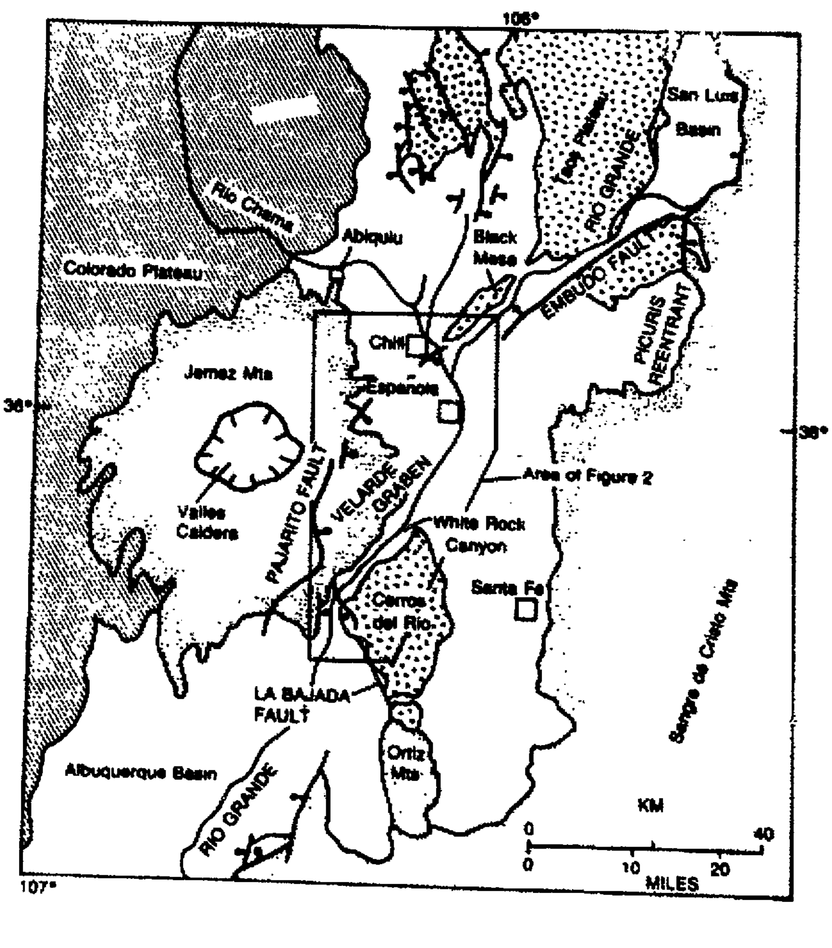


Figure 1. (*Continued*). b. Generalized geology of the Española basin, which extends from the La Bajada fault to the southeast edge of the Taos Plateau. Basin is bounded by Precambrian and lower Paleozoic rocks of the Sangre de Cristo Mountains, Mesozoic rocks of the Colorado Plateau, and Tertiary and Quaternary volcanic rocks of the Jemez Mountains. Principal rock types exposed in the basin are Precambrian metamorphic and igneous rocks (circle pattern), upper Tertiary sedimentary rocks (unpatterned), and upper Miocene and Pliocene basaltic rocks (angle pattern).



alluviation in the southern Rio Grande rift during latest Pleistocene and Holocene time. Major episodes of incision are not well documented but may have been driven by increased discharge in major rivers, such as the Rio Grande and Rio Chama, during pluvial periods correlated with advances of the continental ice sheets (Richmond, 1965; Hawley and others, 1976). In New Mexico, pluvial periods coincided with cooler temperatures (Phillips and others, 1986), lowered tree line, and more extensive vegetative cover in areas now characterized by communities of mixed, semidesert grassland and desert scrub (Spaulding and others, 1983; Spaulding, 1984). The timing and duration of interpluvial and pluvial climates, however, is not known. Uplift of the Colorado Plateau, Rio Grande rift, and adjacent areas (Eaton, 1979) and increases in the drainage area of the Rio Grande (Kelson and others, 1986) may also have played an important role in incision.

Periods when late Cenozoic erosion surfaces formed along the Rio Grande can be estimated from regional and local studies. Basalt flows beneath and above the highest erosion surfaces in northern New Mexico have K-Ar ages that cluster near 3 Ma (Bachman and Mehnert, 1978; Manley, 1979). Their areal and stratigraphic relations demonstrate that the Rio Grande was an integrated drainage by that time. Manley (1976, 1979) mapped Lower Bandelier Tuff (1.4 Ma; Doell and others, 1968) on surfaces incised more than 80 m below the highest erosion surfaces east of Española. The distribution of Upper Bandelier Tuff (1.1 Ma; Doell and others, 1968) indicates that significant downcutting did not resume until sometime after eruption of the tuff (Dethier and Demsey, 1984). Dethier and Demsey (1984) used the mass of carbonate in soils to estimate that surfaces mapped by Dethier and Manley (1985) along the Rio del Oso (northwestern Española basin) formed, respectively, before about 350, 240, 130, and 80 ka. Thorium/uranium ages of soil carbonate demonstrate that surfaces between the Rio del Oso and Santa Clara Canyon formed before about 145, 105, and 20 ka (Harrington and Aldrich, 1984). These ages are minimum values, because erosion surfaces require time to stabilize, thick carbonate rinds take tens of thousands of years to form, and because of assumptions inherent to Th/U dating.

The degree of soil development suggests that the Holocene landscape in southern New Mexico stabilized at about 10 ka and again at about 4 ka (Gile and others, 1981); data from northern New Mexico are less extensive. At a site near Santa Fe, radiocarbon ages of charcoal in alluvium indicate two periods of aggradation and three times when arroyos incised during the past 2,300 yr (Miller and Wendorf, 1958). In the Española area, drilling, trenching, and seismic evidence show that Holocene fans have prograded over latest Pleistocene Rio Grande gravels. Radiocarbon ages from buried organic matter suggest that the most recent period of aggradation began before about 3 ka and ended in the 19th century (Johnpeer and others, 1985).

SETTING

The western Española basin is filled with Miocene sedimentary rock and with Pliocene to Holocene volcanic rocks and sediment derived from the Jemez Mountains, from the Sangre de Cristo Range, and from uplands to the north (Fig. 1). Pleistocene surfaces 15 to 180 m above present arroyos slope gently toward the Rio Chama and Rio Grande and are generally flanked by boulder-mantled slopes. Holocene surfaces are within 10 m of present grade.

Annual precipitation near the Rio Grande ranges from about 220 mm at Cochiti Lake to 250 mm at Española. More than 50% of the precipitation falls in intense local thunderstorms during July–September, whereas frontal disturbances produce precipitation of moderate intensity during the rest of the year. The highest erosion surfaces are covered with a dense pinon-juniper forest near the mountain front; lower and easterly parts of the high surfaces support grasses, sage, cholla cactus, and sparse juniper.

METHODS

Field

Our field investigations focused on mapping and dating of some 30 surface remnants west of the Rio Grande between Chili and Cochiti Lake (Fig. 2) and their underlying deposits. We placed particular emphasis on using varnish-cation ratios for correlating surfaces and collected the most strongly varnished clasts at four to ten sites on each of the remnants (Harrington and Whitney, 1987). We described the best-preserved soils from most surfaces, and Dethier and Demsey (1984) sampled soil carbonate at ten sites on four surfaces. In addition, we collected carbonate rinds from clasts at seven sites for Th/U dating, and we sampled gastropods from four deposits beneath three different surfaces for amino-acid racemization analyses. Stratigraphic control in most of the area was provided by the Lower and Upper Bandelier Tuff, and by the El Cajete tephra, which erupted from a dome in the Valles Caldera at about 130 ka (J. N. Gardner, Los Alamos National Laboratory, 1987, personal commun.). Two undated mid-Pleistocene tephras from unidentified sources provided local control west of Española.

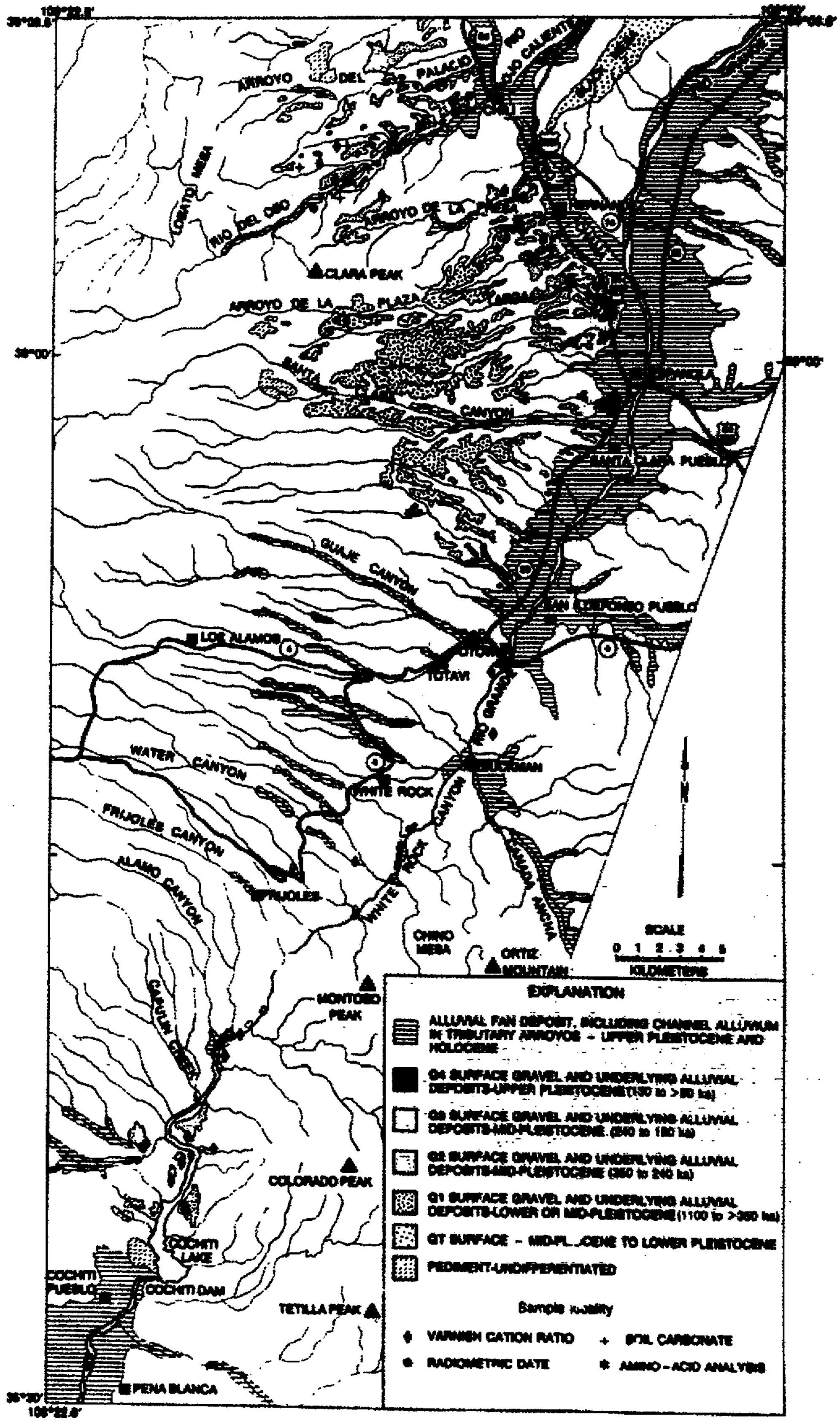
Laboratory

We analyzed the chemistry of rock-varnish samples following scanning electron microscope methods described by Harrington and Whitney (1987). Varnish-cation ratios were calculated as Ca + K/Ti (Dorn, 1983), where each element was reported in weight percent. We used the lowest ratios determined for a geomorphic surface ($\pm 1\sigma$) for correlation and age calculations except when the varnish contained (1) more than 2.5% Ti and more than 3.0% P or (2) more than 3% Ti-magnetite grains in the 5-μ to 100-μ size range. Such samples were excluded from our calculations. For most erosion surfaces, varnish ratios measured for at least four clasts agreed within 10% of each other.

We calculated the amount of pedogenic carbonate in a soil (cS) using methods described by Machette (1985). As soils commonly were eroded, ages were estimated using the maximum values of cS for a geomorphic surface. We used the rate of $CaCO_3$ accumulation at Albuquerque, 0.22 $gcm^{-2}ka^{-1}$ (Machette, 1985), for the western Española basin because (1) annual precipitation and temperatures near Española are similar to those at Albuquerque, (2) soils are developed in deposits similar to those near Albuquerque, and (3) the Albuquerque sites used by Machette (1985) for calibration are within 125 km of our study sites. Because carbonate probably accumulated at rates of about 0.35 $gcm^{-2}ka^{-1}$ during interpluvial periods (Machette, 1985, Fig. 7), our age estimates for late Pleistocene soils are slightly too old. Samples of dense, inner carbonate rinds from the bottoms of clasts in the soils were collected for Th/U analysis according to the methods of Ku and Liang (1984).

Amino-acid ratios for gastropods were determined by W. D. McCoy, University of Massachusetts. We collected gastropods from silty sand beneath three of the erosion surfaces south of the Arroyo de la Presa (Fig. 2). For analysis, the gastropods were cleaned ultrasonically in distilled water

Figure 2. Map showing late Cenozoic geomorphic surfaces of the western Española basin. Varnish-cation ratios were measured at all of the soil-carbonate sample sites along the Rio del Oso.



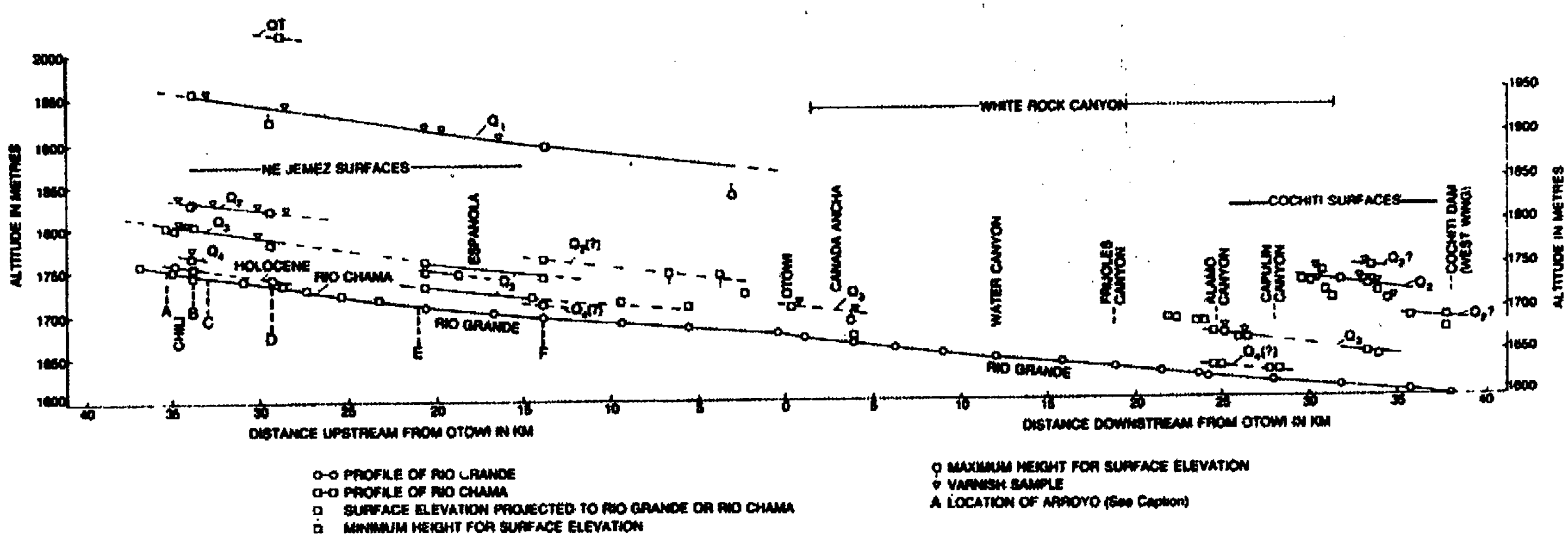


Figure 3. Profiles of geomorphic surfaces projected to the Rio Chama and Rio Grande systems, western Española basin. Arroyo junctions are designated by letters as follows: Arroyo del Palacio (A), Rio del Oso (B), Rio Ojo Caliente (C), Arroyo de la Presa (D), Arroyo de la Plaza Larga (E), and Santa Clara Creek (F).

TABLE 1 SELECTED AGE-RELATED CHARACTERISTICS OF QUATERNARY SURFACES, WESTERN ESPAÑOLA BASIN

Surface	Elevation above grade (m)	Soil-carbonate Stage	Soil-carbonate cS	Varnish-cation ratio	Estimated age (ka) Range	Control cS	Control Th/U	Control Varnish	Control AA	Remarks
					0.1					Historic accounts >0.3 (^{14}C)
Holocene (several surfaces)	3-10	I-II	n.d.	4.5-6.5	1.0 2.3 10.0?	n.d.	n.d.	0.1-15?	n.d.	Miller and Wendorf (1958) 10.3 (^{14}C)
Q_4	10-20	III	17	2.7-3.2	75-135	>77	>22	75-135	60-130	Older than El Cajete tephra (130 ka)
Q_3	25-50	III, III+	28	2.4-2.8	125-240	>130	>105	125-210	180-250	Older than El Cajete tephra (130 ka)
Q_2	55-90	IV	52	1.7-2.2	240-550	>235	>31	240-550	500-700	
Highest Cochiti surfaces	90-120	IV	n.d.	1.7-2.0	300-550	n.d.	n.d.	300-550	n.d.	Older than El Cajete tephra (130 ka)
Q_1	150-200	IV	78	1.5-1.8	350-1,100	>350	>144	500-700	n.d.	Younger than Upper Bandelier Tuff (1.1 m.y.)

Note: n.d. means not determined; stage is diagnostic measure of carbonate morphology in soil (compare Gile and others, 1981); cS is soil-carbonate accumulation, in $g\,cm^{-2}$ soil column (method of Machette, 1985); varnish-cation ratios are the range for the 5 rock surfaces which gave the lowest ratios of Ca + K/Ti (Dorn, 1983) at 15 Kev, by energy-dispersive analysis; estimated age from cS calculated as age (ka) = cS/(0.22 $g\,cm^{-2}$), Machette (1985); Th/U age from Table 3; varnish age calculated from Figure 5; AA age calculated from amino-acid analyses in Table 2. Values are maximum-limiting ages for surfaces.

and dissolved in HCl. The isoleucine and alloisoleucine content of this solution was analyzed after drying (*free fraction*) or pyrolization (*hydrolysate*) using a cation-exchange liquid chromatograph (McCoy, 1987).

Gradients of the Rio Grande, Rio Chama, and their western tributary arroyos were determined from the thalweg (channel) distance measured on 1:24,000-scale maps that have a 20-ft contour interval. We plotted gradients and projected surface elevations using techniques described by Hack (1957). Projections of older surfaces to the axial drainage are approximate because (1) the ancestral positions of the Rio Grande and Rio Chama are incompletely known, (2) some older surfaces have been regraded or deformed, and (3) gradients cannot be drawn accurately from isolated remnants. The maximum uncertainty in the elevation of the oldest surface, however, is probably <30 m.

DATA AND DISCUSSION

Spatial Relations

We mapped four groups of piedmont surfaces of Pleistocene age, undifferentiated fans of latest Pleistocene to Holocene age, and two Holocene terraces in the western Española basin. The surfaces are well preserved near arroyos tributary to the Rio Chama, near Santa Clara Canyon, and north of Cochiti Lake (Fig. 2). Erosion surfaces are poorly preserved in White Rock Canyon between Cañada Ancha and Alamo Canyon because of steep valley walls and extensive slumping (Fig. 3). Our estimates of age depend on relative and isotopic dating of erosion surfaces and their associated deposits. The estimates are minima because erosion surfaces often were modified by subsequent deposition or erosion.

Most erosion surfaces between Chili and Española (here called the "northwestern Española basin") are underlain by a mantle of piedmont gravel, which rests unconformably on Miocene bedrock or on Quaternary axial-channel alluvium. For instance, surfaces Q_1 through Q_4 along the Rio del Oso (Fig. 4) are underlain by 3–8 m of gravel on Miocene sandstone. The surface of intermediate elevation apparently represents a temporary period of lateral planation during downcutting that followed Q_1 time. North of Arroyo de la Plaza Larga, surfaces Q_2, Q_3, and Q_4 are underlain by piedmont gravels that truncate axial-river deposits. Each deposit under a surface consists of basal cobble-gravel overlain by 1–5 m of pumiceous sand and sparsely fossiliferous silty sand. Gastropods were collected from the silty sand for amino-acid analyses. Surface Q_2 is preserved only locally south of Arroyo de la Plaza Larga; in most areas, surface Q_4 cannot be distinguished from fans of latest Pleistocene and Holocene age.

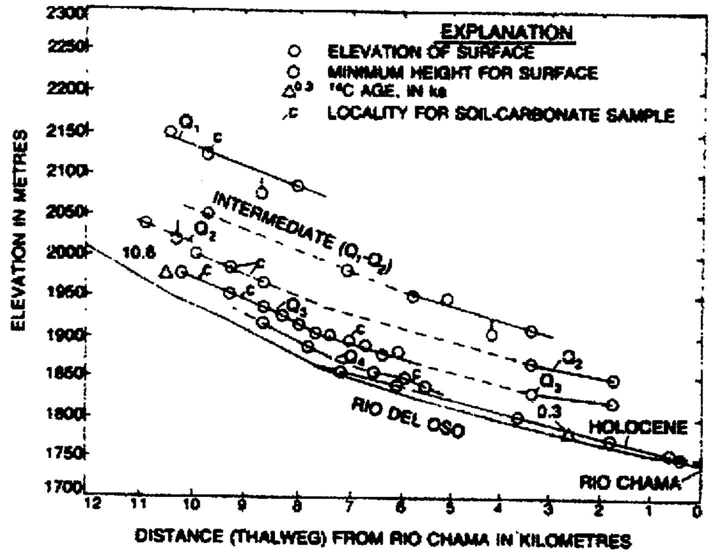


Figure 4. Profiles of Pleistocene erosion surfaces and a Holocene terrace along the Rio del Oso (Rio Chama tributary), showing sample sites for ^{14}C ages and soil-carbonate accumulation.

Erosion surfaces near Cochiti Lake are underlain either by 2–6 m of piedmont gravel or by axial-river deposits composed of 10–40 m of boulder gravel. Surfaces are preserved at elevations of 90 to 130 m (Q_2?), at about 50 m (Q_3), and at 8 to 15 m above the pre-reservoir grade of the Rio Grande (Q_4?). El Cajete tephra overlies the highest surfaces (Q_2?), which have elevations similar to that of the intermediate surface along the Rio del Oso. Surface Q_3, best exposed 12 km north of Cochiti Dam, also is covered with El Cajete tephra. Near the mouth of Alamo Canyon, Q_3 surfaces are cut on a Quaternary flood (?) gravel 20 m thick that contains clasts larger than 4 m. The lowest surface (Q_4?) is visible on air photos and topographic maps, but it is covered by water during most years. Its soils, tephra, and rock varnish have been stripped or altered by fluctuating water levels.

TABLE 2. AMINO-ACID ANALYSES, WESTERN ESPAÑOLA BASIN

Sample	Location	Altitude (m)	Overlying surface	Genus	Amino-acid ratios		Estimated age (ka)
					Free	Hydrolysate	
D-85-132	36°1.31'N 106°5.48'W	1,747	Q_4	*Succinea*	0.38 ± 0.02(3)	0.20 ± 0.01(3)	60–130
D-86-13	36°2.93'N 106°7.12'W	1,795	Q_3	*Pupilla, Zonitoides*	n.d.	0.35 ± 0.02(2)	180–250
D-83-5	36°3.21'N 106°7.93'W	1,830	Q_2	*Succinea*	1.08	0.69 ± 0.03(2)	500–700
D-86-11a	36°2.61'N 106°7.80'W	1,830	Q_2	*Succinea*	1.09 ± 0.03(2)	0.65 ± 0.02(1)*	500–700

Note: n.d. means not determined; altitude for top of axial-channel gravel deposited by the Rio Chama; amino-acid ratios for isoleucine and alloisoleucine, W. D. McCoy, University of Massachusetts, 9 June 1986, written communication. Number of specimens analyzed in parentheses; ages older than 250 ka are estimated by comparing the degree of racemization with that of molluscs at other sites in the semiarid western United States (1) where Lava Creek or Bishop tephra are found, (2) which have modern temperatures similar to those at Española (~10°C), and (3) where the range of Quaternary temperature is thought to be comparable to that of the western Española basin. Ages younger than about 250 ka were computed from ages and amino-acid ratios for genera (*Anguispira, Lymnaea*) that racemize at rates similar to those for *Succinea, Zonitoides,* and *Pupilla* (W. D. McCoy, University of Massachusetts, unpub. data).

*One specimen gave a ratio of 0.82 (for two splits). The specimen is thought to have been reworked from older deposits 200 m north of 86-11a and is excluded from the results.

We have correlated surfaces north and south of White Rock Canyon using elevation despite significant differences in river gradient and channel shape, and the proximity of surfaces in the Cochiti area to the La Bajada fault-zone (Kelley, 1977). These correlations are consistent with varnish-cation ratios, which indicate that the Q_2 surfaces of the Cochiti area have been exposed for about the same time as the oldest Q_2 or intermediate surface of the northwestern Española basin. Ratios also indicate that Q_3 surfaces in both areas are of similar age. We tentatively correlate the submerged Cochiti surface with Q_4 north of White Rock Canyon.

Latest Pleistocene and early Holocene surfaces are younger than Q_4 and consist mainly of alluvial fans graded to low terraces along the Rio Grande. The surfaces are best developed north of White Rock Canyon, from Otowi to Española. Alluvial terraces also are preserved along the Rio del Oso and other channels that drain Miocene sandstone. The degree of soil development on isolated terraces 4 to 8 m above arroyos suggests that these surfaces became stable before late Holocene time (D. P. Dethier, unpub. data). Terraces within 4 m of grade record a period of aggradation that began before about 300 yr ago, followed by incision after about 1900 A.D. (Dethier and Demsey, 1984).

Surface Ages

Geologic dating (Tables 1, 2) indicates that Pleistocene erosion surfaces in the Española basin formed at successively decreasing altitudes during four periods: 1100 to 350 ka, 350 to 240 ka, 240 to 130 ka, and 130 to 80 ka. We calculated the approximate ages of surfaces at some 30 localities (Fig. 2), using the curve for varnish-cation ratios determined for the Española basin (Fig. 5). Calibration was provided by four Th/U ages (Table 3: samples 4-84-, 2-84-, 3-84-, and 1-85-MJA) from sites where we also analyzed varnish-cation ratios. The varnish technique gave results consistent with the geologic evidence and with other dating methods used in this study. The highest surfaces had the lowest varnish-cation ratios and largest cS values (Table 1), and the erosion surfaces truncated deposits that gave the highest (oldest) amino-acid ratios (Table 2). Surfaces Q_3 and Q_4 gave higher varnish-cation ratios (Table 1), lower cS values, and cut younger fossiliferous deposits. Varnish-cation ratios were considerably higher than those listed in Table 1 near scarps in gullied areas (for instance, 3-84-MJA) and in other zones where surfaces showed evidence of reworking. Samples for Th/U analyses were collected at localities near scarps (Harrington and Aldrich, 1984), and varnish-cation ratios at these sites were higher than ratios from more stable areas of the surface. The line defined by the varnish-catio ratios at the Th/U localities, however, is only slightly different than that defined by varnish-cation ratios at the soil-carbonate localities (Fig. 5).

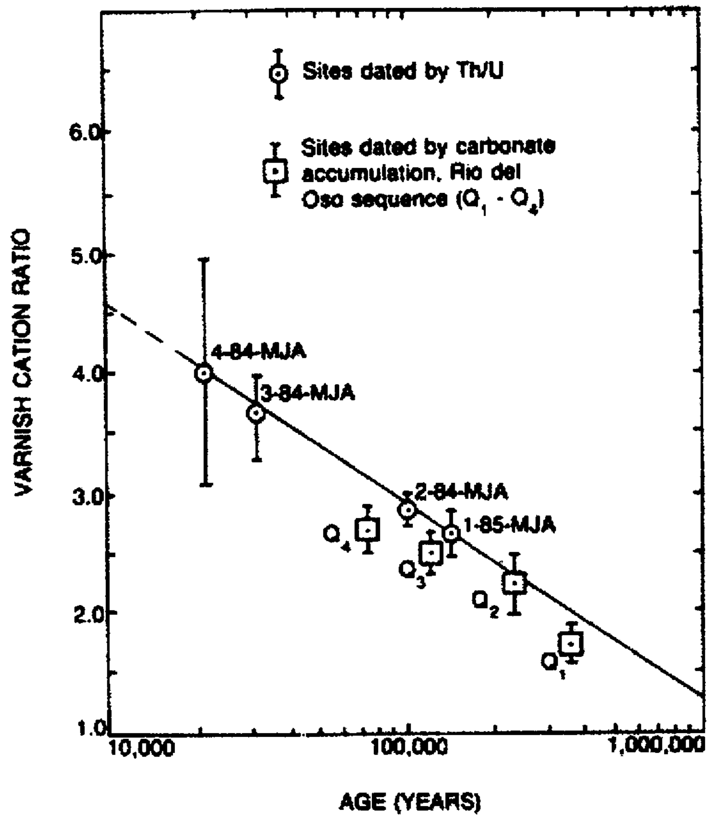


Figure 5. Relation between ages of geomorphic surfaces and varnish-cation ratios (determined at 15 Kev), western Española basin, New Mexico. Line is the least-squares fit through the Th/U-dated points (Harrington and Whitney, 1987). Varnish-cation ratios were measured at four to ten locations (points are mean ±1σ values for the five lowest varnish-cation ratios; Harrington and Whitney, 1987) on each surface. Ages of surfaces Q_1, Q_2, Q_3, and Q_4 along the Rio del Oso were estimated from their maximum amounts of soil-carbonate (Dethier and Demsey, 1984) and an estimated $CaCO_3$ accumulation rate of 0.22 gcm^{-2}ka^{-1}.

Amino-acid ratios from three sequences of axial-river deposits (Table 2) help to limit maximum ages for surfaces Q_2, Q_3, and Q_4. Gastropods from axial deposits beneath surface Q_2 gave amino-acid ratios (Table 2; samples D-86-11a and D-83-5) that suggest deposition between 700 and 500 ka. Amino-acid ratios show that surface Q_3 is younger than 250 ka

TABLE 3. TH/U AGE DETERMINATIONS OF CARBONATE RINDS ON CLASTS FROM THE ESPAÑOLA BASIN

Surface	Location			Activity ratios			Age ka	Field no.
	USGS 7½' quadrangle	Latitude (N)	Longitude (W)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$		
Q_4	San Juan Pueblo	36°01'27"	106°05'27"	1.19 ± 0.11	0.18 ± 0.19	n.d.	22 ± 3	4-84-MJA
Q_3	San Juan Pueblo	36°03'07"	106°07'21"	1.31 ± 0.14	0.63 ± 0.06	n.d.	103 ± 17	2-84-MJA
Q_3	Chili	36°03'20"	106°07'50"	1.33 ± 0.15	0.25 ± 0.03	n.d.	31 ± 4	3-84-MJA
Q_3	Chili	36°01'13"	106°13'45"	1.14 ± 0.40	0.81 ± 0.03	7.35 ± 0.46	144 ± 15	1-85-MJA
Santa Cruz	Cundiyo	35°59'00"	105°54'36"	1.16 ± 0.44	0.37 ± 0.14	12.04 ± 1.04	42 ± 4	13-85-MJA
Q_2	Puye	35°57'20"	106°07'45"	1.13 ± 0.04	0.47 ± 0.01	40.33 ± 11.6	66 ± 3	17-85-MJA
Q_1	Chili	36°02'03"	106°08'31"	1.13 ± 0.18	0.06 ± 0.12	n.d.	7^{+11}_{-7}	1-84-MJA

Note: n.d. means not determined; Th/U ages were determined by Teh-Lang Ku, University of California, Los Angeles, in 1984 and 1985. Data for samples 2-84-MJA and 4-84-MJA are from Harrington and Aldrich (1984) and are included here for completeness; sample 3-84-MJA was collected on a low-angle scarp separating Q_3 and Q_2. Santa Cruz surface is east of Española; see Manley (1979) and Kelley (1979).

and that surface Q_4 is younger than 130 ka (Table 2), ages similar to those calculated from varnish-cation ratios (Table 1). These data suggest that alluvial fans built across the flood plain and that surfaces Q_3 and Q_4 became stable within a few tens of thousands of years. Deposits truncated by surface Q_2, however, may have accumulated as much as several hundred thousand years earlier than the erosion surface.

Varnish-cation ratios, used in conjunction with other dating techniques, help to define periods when geomorphic surfaces were modified by local aggradation or erosion. For instance, a cS of 78 gcm^{-2} demonstrates that an isolated remnant of surface Q_1 north of the Rio del Oso (Fig. 2) has been accumulating $CaCO_3$ for more than 350,000 yr. We did not obtain a Th/U age at this site, but the varnish-cation ratio was 1.7, equivalent to an age of about 500 ka (Fig. 5). The Th/U age of surface Q_1 was 144 ka (Table 3; 85-1-MJA) at a site south of Clara Peak where the varnish-cation ratio was about 2.7, equivalent to an age of about 150 ka. We did not use the Th/U technique to date surface Q_2, but varnish-cation ratios show that the surface formed before about 250 ka, and possibly as early as about 550 ka (Table 1). Soil-carbonate accumulation demonstrates that parts of the surface have been stable for 235,000 yr. The ages of surfaces Q_3 and Q_4 are constrained by the data in Table 2 and by the varnish-cation ratios and cS values listed in Table 1. The Th/U ages of 105 ka for Q_3 and 22 ka for Q_4 do not date formation of the surfaces but do record when the sample sites became stable. The last three Th/U ages listed in Table 3 probably reflect periods of local surface degradation or aggradation, but we have not analyzed varnish from these sites. The lowest varnish-cation ratios generally give close limiting ages for the time when a surface was last modified. Ages calculated from rock varnish must be used in conjunction with other dating techniques, however, to estimate the age of formation of geomorphic surfaces.

Incision History

Net incision in the Española basin probably is driven by regional uplift, but cycles of incision and aggradation caused by Quaternary climatic change also have produced substantial changes in local base level. Elevations and ages of erosion surfaces show that the net incision rate since about 2.8 Ma has averaged about 10 cm/1,000 yr and that more rapid incision has characterized the past 500,000 yr. Late Pliocene and early Pleistocene changes in base level are poorly documented in the western Española basin, but times of incision are approximately known in a few areas. Stratigraphic relations near White Rock Canyon, for instance, suggest that base level was relatively stable from 3 Ma to about 2 Ma (Waresback, 1986). In the northeastern Española basin, a series of pediments were cut between about 2.8 and 1.4 Ma when local base level fell some 80 m (Manley, 1976, 1979). Catastrophic deposition of the Lower and Upper Bandelier Tuff interrupted Pleistocene incision in the northwestern Española basin. Canyons tens of metres deep were cut locally in Bandelier Tuff between 1.4 and 1.1 Ma (Griggs, 1964), but rapid incision did not begin until after 1.1 Ma in both White Rock Canyon (D. P. Dethier, unpub. data) and the Rio del Oso area (Dethier and Demsey, 1984).

Ages and elevations of erosion surfaces in the northwestern Española basin indicate that incision rates increased dramatically after about 500 ka. Between about 500 ka and 100 ka, base level fell about 150 m. The average rate of incision over that period was almost four times the rate calculated from 1.1 Ma to present. Net incision ended sometime after 100 ka, and latest Pleistocene and Holocene fans buried the Pleistocene Rio Grande channel near Española. Many surfaces that formed during the climatic change at the end of the Pleistocene were buried along the Rio Grande elsewhere in New Mexico (Gile and others, 1981; Machette, 1985). Late Pleistocene terraces related to the Pinedale glaciation are preserved, however, along rivers draining the northern Sangre de Cristo Range and Brazos upland (for instance, see Scott and Marvin, 1985; Wesling and McFadden, 1986; Kelson and others, 1986), and locally along the upper Rio Grande.

Ages and elevations of surfaces in the Rio Chama/Rio Grande drainage (Fig. 6) are broadly comparable to those reported for the Albuquerque-Belen basin by Machette (1985). Combined data from the Española and Albuquerque-Belen basins suggest that rapid incision began sometime after about 600 ka and lasted until at least 100 ka. Data from the Española basin are similar to those reported elsewhere in the region, which implies fairly uniform regional climatic or tectonic influences (Fig. 7). We have no direct evidence that climate controlled development of Pleistocene erosion surfaces along the Rio Grande. Axial-channel deposits covered by piedmont gravel, however, suggest that surfaces near Española and along the southern Rio Grande were active zones of transport during transitional and interpluvial climates and were relatively stable during pluvial periods (Gile and others, 1981).

Personius and Machette (1984) noted rapid downcutting along the Rio Grande near Taos, New Mexico, beginning after about 600 ka. They attributed the downcutting to either drainage integration or uplift. Studies by Kelson and others (1986) in the same general area led them to favor drainage integration or capture for the rapid downcutting. Gillam and others (1984) suggested that elevations of surfaces along the Animas River were a function of uplift. We believe that drainage integration may have increased incision rates in northern New Mexico, but widespread downcutting between 500 and 100 ka implies a change in a regional variable such as a shift to wetter climate.

Denudation Rates

Although incision was relatively uniform in the western Española basin during the late Quaternary, denudation (incision integrated over area) was strongly influenced by different rock types (Table 4). We calculated denudation rates from hypsometric measurements for test areas of about 35 km^2 located 2–6 km from the axial drainage in each of three 7.5′

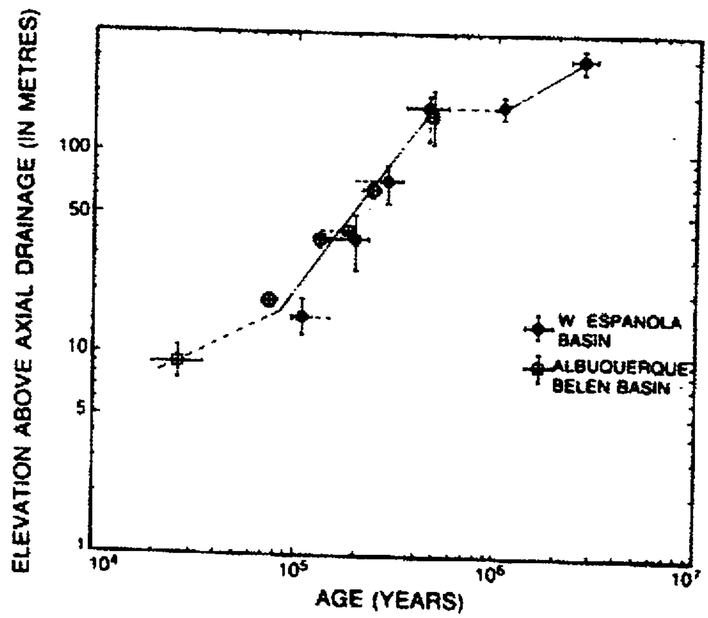


Figure 6. Elevation of erosion surfaces above the Rio Grande, western Española and Albuquerque-Belen basins, New Mexico. Line indicates net incision history since 2.8 Ma. Other data for the western Española basin are given in Table 1. Data for Albuquerque-Belen basin from Machette (1985), except for the elevation of the youngest point, which is from Lambert (1968). Age and elevation ranges are shown as solid lines (dashed where uncertain) about the data points.

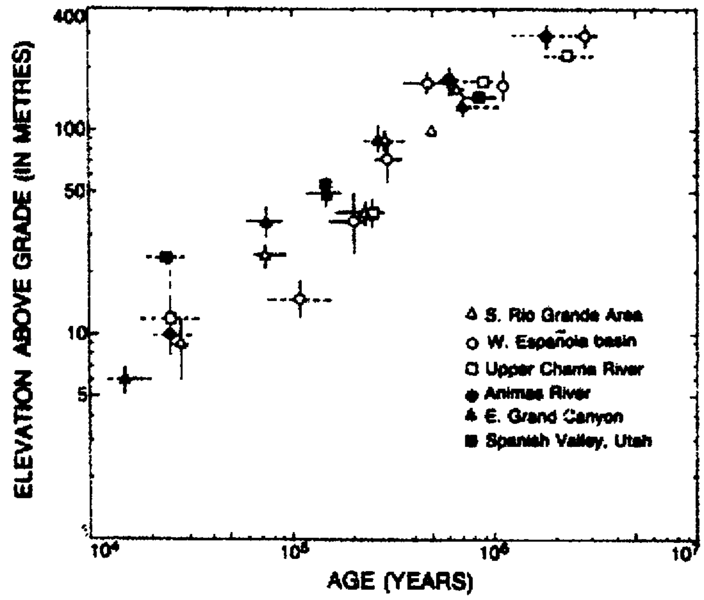


Figure 7. Net Pliocene-Pleistocene incision along the Rio Grande and other selected major drainages in the southwestern United States. Sources are Machette, 1985 (southern Rio Grande: Las Cruces area); this study (western Española basin); Scott and Marvin, 1985 (Upper Chama River); Gillam and others, 1984 (Animas River); Machette and others, 1986 (eastern Grand Canyon); and Harden and others, 1985 (Spanish Valley, Utah). Age and elevation ranges given in the original studies are shown as solid lines (dashed where uncertain) about the data points.

TABLE 4. SUMMARY OF QUATERNARY DENUDATION RATES, WESTERN ESPAÑOLA BASIN, NEW MEXICO

Time period and reference surface (in parentheses)	Denudation rates in cm/1,000 yr		
	Weakly lithified sandstone (Chili quad.)	Indurated tuff/ boulder gravel (Puye quad.)	Indurated tuff/ basalt (White Rock quad.)
1.1 Ma (pre-Q_1) to present	10	<7	4
1.1 Ma (pre-Q_1) to 500 ka(Q_1)	~10	10	n.d.
500 ka(Q_1) to present	20–35	~3	n.d.
500 ka(Q_1) to 250 ka(Q_2)	30–100	n.d.	n.d.
250 ka(Q_2) to present	>10; <30	n.d.	n.d.
250 ka(Q_2) to 160 ka(Q_3)	>13; <30	n.d.	n.d.
160 ka(Q_3) to present	> 7, <20	n.d.	n.d.

Note: n.d. means not determined; denudation rates calculated as volume of material removed in each period/test area; test areas in each quadrangle were as follows: Chili quadrangle (36°06.00'N, 106°15.00'W; 36°07.00'N, 106°12.50'W; 36°03.50'N, 106°10.00'W; 36°02.50'N, 106°13.00'W); Puye quadrangle (36°00.00'N, 106°13.00'W; 36°00.00'N, 106°10.00'W, 35°56.00'N, 106°10.00'W, 35°56.00'N, 106°13.[illegible]'W); White Rock quadrangle (35°52.50'N, 106°15.00'W, 35°52.50'N, 106°10.00'W; 35°47.50'N, 106°13.00'W; 35°47.50'N, 106°15.00'W).

quadrangles along the western margin of the Española basin. The principal rock types were (1) slightly lithified Miocene sandstone (Chili quadrangle), (2) indurated Quaternary tuff overlying Pliocene boulder gravel (Puye quadrangle), and (3) indurated Quaternary tuff overlying Pliocene basalt (White Rock quadrangle). Denudation rates were calculated as (cubic metres of rock removed/size of test area, in m^2)/(time interval, in thousands of years) for the time intervals listed in Table 4. We assumed that when incision began, each reference surface tested in Table 4 had a slope similar to preserved remnants, and that erosion from the remnants has been minimal. Each of the geomorphic surfaces was well preserved in the Chili quadrangle; in the Puye quadrangle, only the top of the Bandelier Tuff and surface Q_1 were defined, and only the top of the Bandelier Tuff served as a reference point in the White Rock quadrangle. We can best constrain denudation rates for the Chili quadrangle, but the effect of differential rock resistance is clear in all three quadrangles for rates integrated from 1.1 Ma to the present.

Different rates of denudation and varied rock resistance have strongly affected the landscape exposed in the northwestern Española basin. For instance, weakly cemented sandstone along the Rio del Oso was removed twice as rapidly as the more resistant tuff, boulder gravel, and basalt near the Arroyo de la Presa. The well-defined surfaces cut on soft sandstone near Chili are a direct consequence of rapid erosion, followed by armoring of surfaces with gravel transported in paleochannels. Erosion surfaces younger than Q_1 are less sharply defined and less extensive in the areas of tuff and boulder gravel south of Guaje Canyon (Fig. 2). South of Los Alamos Canyon, narrow, steep-walled canyons eroded into tuff and basalt preserve only a few erosion surfaces, although fans older than 130 ka are present locally. Relatively slow rates of denudation and limited preservation of erosion surfaces are typical of the resistant rocks exposed in most of the southwestern Española basin, the White Rock Canyon area, and near Cochiti Dam.

Denudation rates calculated for the Chili quadrangle (Table 4) indicate a long-term sediment loss of about 10 cm/1,000 yr (200 $Tkm^{-2}yr^{-1}$), and peak rates (Q_1 to Q_2 time) of 50 cm/1,000 yr (900 $Tkm^{-2}yr^{-1}$), assuming a sediment density of 2.0 gcm^{-3}. Denudation rates in areas of more resistant rocks are less well constrained but are probably less than 5 cm/1,000 yr (<100 $Tkm^{-2}yr^{-1}$). The higher rates are comparable to late Holocene denudation rates and to contemporary sediment yield for the Rio Grande. Miller and Wendorf (1958) used the volume of sediment stored beneath terraces to estimate that late Holocene denudation rates from weakly cemented Miocene sandstone ranged from 11.5 to 43 cm/1,000 yr (330 to 860 $Tkm^{-2}yr^{-1}$). They suggested that present rates of denudation and flood-plain aggradation in northern New Mexico are comparable to those for the late Holocene period of aggradation. Sediment yield for the Rio Grande catchment at Otowi is about 200 to 500 $Tkm^{-2}yr^{-1}$ (U.S. Geol. Survey, Albuquerque, New Mexico, 1986, unpub. records), equivalent to a denudation rate of 10 to 25 cm/1,000 yr. Contemporary rates of denudation thus are comparable to rates calculated from 500 ka to the present.

Uplift Rate and Climate Change

Incision recorded by erosion surfaces in the western Española basin could reflect uplift, climate change, drainage capture, or a combination of factors. If incision was dominated by uplift, rates were slow to moderate (5 to 35 cm/1,000 yr) in late Cenozoic time. Such rates are comparable to those estimated for the southern Rocky Mountains in Colorado (Scott, 1975) and southern San Juan Mountains of Colorado (M. L. Gillam, University of Colorado, unpub. data). Slow regional uplift of parts of the western United States apparently is caused by either regional extension and upward bulging of the lithosphere (Eaton, 1979) or subduction of a lithospheric plate (Damon, 1983). Increased rates of incision (Figs. 6, 7) after about 500 ka could suggest a change in rates of regional uplift, but we believe a climatic explanation is more likely.

Increased runoff in the Rio Grande may have contributed to the apparent increase in rates of downcutting at 500 ka. Drainage capture could explain increases in runoff along the Rio Grande, but we are not aware of any evidence that suggests capture in the basins of the Rio Chama, Animas River, and eastern Grand Canyon (Colorado River), which also record more rapid incision. Global change to a wetter climate after about 600 ka, suggested by some terrestrial and deep-sea records (Sarnthein and others, 1986; Jansen and others, 1986), could have increased peak or average discharge in rivers. Climatic models for the southwestern United States demonstrate that temperature and effective moisture changed substantially in the late Pleistocene and early Holocene (Phillips and others, 1986; Spaulding and others, 1983; Galloway, 1983; Brakenridge, 1978). No comparable records of paleoclimate, however, are available for the period of changed incision rates. Incision of basin-filling alluvium (Camp Rice Formation and correlative units) along the central and southern Rio Grande valley after about 500 ka is attributed mainly to integration of middle and lower river segments (Gile and others, 1981; Seager and others, 1984), rather than solely to a climatic shift. The importance of climate change to downcutting along the Rio Grande is thus not clear.

We suggest that regional uplift produced late Cenozoic downcutting by drainages such as the Rio Grande in the Española basin and that changes to a wetter climate increased rates of incision at about 500 ka. Proof of wetter climate and increased discharge requires studies that emphasize palynologic, paleontologic, and stable-isotope techniques, coupled with paleohydraulic data. Better understanding of the erosional history of the Rio Grande will come when we can predict how major rivers in semiarid zones respond to climatic changes, still a poorly understood subject (Schumm, 1977; Bull, 1979; Howard, 1982).

ACKNOWLEDGMENTS

Dethier was supported by the Associated Western Universities Sabbatical Program and Williams College while on leave at Los Alamos National Laboratory. The comments of J. N. Gardner, J. W. Hawley, H. E. Malde, M. N. Machette, and T. Rockwell greatly improved a previous version of this manuscript.

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TRW

TRW Environmental
Safety Systems Inc

Civilian Radioactive Waste Management System

Management and Operating Contractor

Contract #: DE-AC01-91RW00134
LV.SC.BWD.8/92-103

Erosion Rates at Yucca Mountain

Technical Assessment Qualification of Data

August 31, 1992

WBS: 1.2.5.2.4
QA: QA

CIVILIAN RADIOACTIVE WASTE MANAGEMENT SYSTEM

MANAGEMENT AND OPERATING CONTRACTOR

To: J. Russell Dyer, Director
Regulatory & Site Evaluation Division
Yucca Mountain Site Characterization Project Office
U. S. Department of Energy

Date: August 31, 1992

M&O Program: Technical Assessment
Qualification of Technical Data Collected and Evaluated Prior to NRC Acceptance of YMPO Quality Assurance Program.

Submitted by: B. William Distel
Technical Assessment Chairperson — date
(702) 794-1827

M&O Review

Technical Reviewer — Date 9/?/92

Technical Reviewer — Date 9/8/92

Approved:

C. Thomas Statton, M&O Site Characterization Manager — Date 14 Sept '92

This Technical Assessment has been done in accordance with YMPO QMP-02-08, and M&O Procedure QAP-3-5.

TABLE OF CONTENTS

WBS: 1.2.5.2.4
QA: QA

EXECUTIVE SUMMARY

Data Qualification of Existing Data for Erosion

The Erosion Data has been subjected to technical assessment to establish that: Equivalent QA existed during data gathering and evaluation, that corroborative data exists to substantiate the Erosion Data, and that an independent Peer Review of leading geomorphologists has examined the varnish cation-ratio age dating process used by the Principal Investigators on erosion at Yucca Mountain and find it the best technique currently available.

The Nuclear Regulatory Commission (NRC) published NUREG-1298 (Generic Technical Position on Qualification of Existing Data for High-Level Waste Repositories) to provide guidance to the DOE regarding the process by which existing data should be qualified to meet the requirements of 10 CFR 60, Subpart G. DOE has implemented Administrative Procedure 5.9Q (Qualification of Data or Data Analyses Not Developed Under the Yucca Mountain Project Quality Assurance Plan) to allow a qualification process for Project data gathered prior to the NRC's acceptance of Yucca Mountain Project Office's (YMPO) Quality Assurance Requirements Document (QARD) guidelines.

A Technical Exchange was held on May 27, 1992 between DOE, and the NRC to present the technical basis for a DOE Topical Report (TR) on Erosion. In line with DOE issuing a TR, this Technical Assessment has been conducted to demonstrate the QA acceptability of Erosion Data.

This Technical Assessment was completed in accordance with Yucca Mountain Project Office (YMPO) Quality Management Procedure (QMP) 02-08, Rev. 1 and with YMPO Administrative Procedure (AP) 5.9Q, Rev. 1, Sections 4.5, 5.3.2.1, and 5.3.2.5. Just prior to summarization of this Technical Assessment, AP 5.9Q, Rev. 2 has been implemented. AP 5.9Q, Rev. 2 was being developed during the Assessment period, and was actually a result of working with Rev. 1 and NUREG-1298 in the Assessment effort. The Technical Assessment method is consistent with Rev. 2 requirements, as well as the requirements of Rev. 1.

This Technical Assessment, and all directly related Technical and QA Procedures, TATM qualifications, correspondence, Assessment results, the LANL Independent Peer Panel Review, and the Technical Assessment Notice, Rev. 0 and Rev. 1 have been entered in the YMPO Records Information System.

TECHNICAL ASSESSMENT RESULTS

This Technical Assessment was conducted in two (2) phases. Phase one consisted of having the Technical Assessment Team Members (TATM) review Technical and QA Procedures in-place for the U. S. Geological Survey (USGS), and Los Alamos National Laboratory (LANL) guiding sample collecting and analysis, and field measurements against current Technical and QA Procedures for the USGS and LANL which control field and laboratory processes today. The second Phase of this Technical Assessment verified that the Scientific Notebooks showing field work and laboratory work conformed to, and followed those relevant Procedures in-place during the time the Notebooks were developed.

The Technical Assessment Team consisted of:

Dr. John C. Dohrenwend
U. S. Geological Survey
Menlo Park, California

Dr. Peter W. Birkeland
University of Colorado
Boulder, Colorado

August C. Matthusen
SAIC
Las Vegas, Nevada

Jeff McCleary
Woodward-Clyde Federal Services
Moab, Utah

B. Robert Justice
Duke Engineering & Services, Inc.
CRWMS/Management and Operating Contractor
Las Vegas, Nevada

These Team Members were chosen based on their professional standing in the geomorphological field and/or their expertise in High Level Waste Site Characterization work. None of these people have worked within the Erosion Study Program on Yucca Mountain except as independent reviewers of specific portions of the Study.

WBS: 1.2.5.2.4
QA: QA

Conclusions and Recommendations

The Technical Assessment Team has compared current and previous QA and Technical Procedures that control erosion samples collection and analyses, and field measurements for ero .ion. In addition, field and laboratory notebooks of the Principal Investigators (Dr.'s Whitney and Harrington) were examined and compared to these Procedures.

Conclusion

It is unanimously agreed by all five Technical Assessment Team Members that data collection and evaluation completed prior to NRC acceptance of the YMPO Quality Assurance Program can be qualified under current YMPO QARD requirements.

Recommendation

The Technical Assessment Team does recommend to DOE YMPO that the technical data on Erosion be formally accepted as qualified under current YMPO QARD, Rev. 4 guidelines.

Peter W. Birkeland Date

John C. Dohrenwend Date

B. Robert Justice Date

Jeff R. McCleary Date

August C. Matthusen Date

TECHNICAL ASSESSMENT

Qualification of Technical Data - Extreme Erosion

INTRODUCTION

On May 1, 1992, the Regulatory & Site Evaluation Division (RSED) of the Department of Energy (DOE) Yucca Mountain Project Office (YMPO) initiated a Technical Assessment to evaluate the ability of DOE to accept as "Qualified" the technical data on extreme erosion. This data was collected and evaluated prior to NRC acceptance of the YMPO Quality Assurance Program. The scope of the Technical Assessment has been to evaluate the Quality Assurance (QA) and Technical Procedures guiding sample collecting and analysis, and field measurements against current procedures in-place for the U. S. Geological Survey (USGS) and Los Alamos National Laboratory (LANL), under the DOE Quality Assurance Requirements Document (QARD) acceptable to the Nuclear Regulatory Commission (NRC).

In accordance with YMPO Administrative Procedure (AP) 5.9Q, Rev. 1, Section 4.5, this Technical Assessment has been carried out to provide review and evaluation of the data and data analyses in line with AP-5.9Q, Rev. 1, Sections, 5.3.2.1 and 5.3.2.5. AP-5.9Q, Rev. 2 has been implemented soon after this Technical Assessment was completed. AP-5.9Q, Rev. 2 was in development during the Assessment period, and was a result of working with AP-5.9Q, Rev. 1 and NUREG 1298 in the Assessment effort. The Assessment method is consistent with AP-5.9Q, Rev. 2 requirements. This Technical Assessment has been done in accordance with YMPO Quality Management Procedure (QMP) 02-08, Rev. 1, to establish technical merit.

The Technical Assessment Notices, Revision 0 and Revision 1, are included as Attachment I. The Technical Assessment Team (TAT) initially consisted of four (4) members, then was expanded on June 12, 1992, to include one additional member. These TAT members are identified in Attachment II, as are their qualifications to perform this Technical Assessment.

Communications between the Technical Assessment Chairperson (TAC) and the Technical Assessment Team Members, (TATM) are included in Attachment III, as are the initial comments by TAT Members.

This Technical Assessment has been conducted in two (2) phases. Phase I consisted of having the TATM review the Procedures described above in the first Paragraph. As a result of the Phase I evaluation, a second Phase was initiated during which two members of the TAT visited the Principal Investigators for the Erosion studies on the Yucca Mountain Site, Dr. Whitney (USGS), and Dr. Harrington (LANL) at their respective offices. These visits were for the purpose of examining field and laboratory scientific notebooks, and interviewing Dr. Whitney and Dr. Harrington.

SUMMARY - PHASE I

The Technical Assessment Notices of May 1, 1992, and June 22, 1992 asked the TATM to evaluate the QA and Technical Procedures in-place in the U. S. Geological Survey (USGS), and Los Alamos National Laboratory (LANL), during the time that sample collection, analysis, and field measurements were performed. These were compared against procedures currently in place at the USGS and LANL under the DOE QARD guidelines. The purpose was to examine any differences between these procedures in order to answer the following questions:

- Would data collection and evaluation under current Participant technical procedures differ from those procedures actually followed?
- Are any differences significant enough to affect technical results?
- Can a recommendation be made to DOE YMPO that the procedures used to gather and evaluate samples, and guide field measurements are acceptable to allow the technical data to be qualified under current QARD guidelines?

This Assessment has been conducted in line with the Instructions for Assessment included in Attachment I.

ASSESSMENTS

Dr. John C. Dohrenwend
U. S. Geological Survey
Menlo Park, California

I have examined the differences between those procedures that were in place during collection and evaluation of samples for rock varnish analysis (for the purpose of assessing extreme erosion as an issue at Yucca Mountain) and current procedures under the DOE QARD that are applicable to such collection and evaluation activities. As a result of this examination, I have reached the following conclusions:

- *Current sample collection and evaluation procedures are nearly the same as the procedures actually followed during sample collection and evaluation.*
- *None of the procedural differences that do exist are significant enough to affect the technical results of the extreme erosion study.*
- *Therefore, a recommendation can be made to DOE YMPO that the proce[illegible]res used to collect and evaluate samples are acceptable and that the technical data pertaining to the extreme erosion study should be qualified under current QARD guidelines.*

Dr. Peter W. Birkeland
University of Colorado
Boulder, Colorado

In summary, in answer to the three questions posed:

- *I think the sample collection and evaluation was not significantly different under both procedures.*
- *The differences are not significant enough to effect technical results.*
- *I recommend that the procedures used to gather and evaluate samples are acceptable to allow the technical data to be qualified under current QARD guidelines.*

I should add, however, that it is very difficult to make these judgements without knowing the kind of data that were collected. It would help to see the report that resulted from the field work, or lab work.

The rest of Dr. Birkeland's assessment is contained in Attachment IV.

August C. Matthusen
SAIC
Las Vegas, Nevada

- *From the procedures reviewed, it is not possible to determine if the technical results would differ from the results that were determined. The procedures reviewed govern mainly the documentation of results and not the gathering and analysis processes.*
- *(Requires verification of technical data to reviewed procedures).*
- *There do not appear to be any valid reasons why any of these data can not be qualified under current QARD guidelines.*

The rest of Mr. Matthusen's assessment on equivalent QA is contained in Attachment IV. Resolution of Mr. Matthusen's comments are addressed further into this Summary Report on pages 6-7.

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Woodward-Clyde Federal Services
Moab, Utah

- *In summary, based on the information provided, because of the unknown criteria for sample collection prior to 5/1/87 it is possible that technical results could differ if current procedures were followed. Similarly, potential shipping damage should be considered in accepting the technical results. I feel that if recommendations 1 and 2 are followed these issues can be resolved.*

Recommendations

1. *The LANL notebooks developed under the R and D procedures should be reviewed in order to determine how samples were selected in the field prior to 5/1/87. If it can be shown that the same criteria for site and sample selection were followed*

prior to 5/1/89, as after the sample collection procedure for rock varnish studies was issued, then all samples can be considered valid.

2. *All samples shipped should be examined for abrasion or other shipping damage to the varnish surface. If all samples show an intact varnish surface they can be considered valid.*

The rest of Mr. McCleary's assessment on equivalent QA is contained in Attachment IV Resolution of Mr. McCleary's comments are addressed further into this Summary Report on pages 7-10.

B. Robert Justice
CRWMS Management & Operating Contractor
Las Vegas, Nevada

- *Would sample collection and evaluation under current participant technical procedures differ from those procedures actually followed?*

  Response - Inconclusive in that procedures for collection did not exist until 5/1/87 and until 5/3/88 did not adequately address the handling of samples. The guidelines for determining collection areas were less restrictive than current requirements and could have led to samples being collected from areas which may be unsuitable under current procedures. Additionally, there is no evidence of procedural guidelines for conducting the rock varnish for erosion analysis.

- *Are there any differences significant enough to affect technical results?*

  Response - Yes, in the area of handling the samples once they were collected. There was not any specific guidelines provided for the handling of samples until 5/3/88 when change Request #29 to procedure TWS-ESS-DP-114, Rev. 0 became effective. Also, the lack of procedural processes for the collection and analysis of samples raises questions with respect to what processes were actually used and the consistency with which those processes were repeated.

- *A recommendation to accept the data based on the procedures provided for this assessment cannot be made. The obvious lack of procedural guidance in the early stages of this activity supports this conclusion. Other evidence may be available to support the processes used to accomplish the collection and analysis of samples. The notebooks, which have been used throughout this activity to document the work that was performed, may contain enough information to identify the processes used and the consistency with which they were repeated.*

The rest of Mr. Justice's assessment on equivalent QA is contained in Attachment IV. Resolution of Mr. Justice's comments are addressed further into this Summary Report on pages 10-14.

After evaluating the TATM Phase I comments (excerpted above and provided in full in Attachment IV), it was apparent that:

a. All of the TAT Members recognized that the two sets of procedures (those prior to DOE QARD guidelines, and those after) provided to them for evaluation are very similar.

b. Mr.'s McCleary and Justice recognized that samples were collected prior to 5/1/87 before the initial sample collection procedure became effective. Handling and shipping controls were not well addressed before 5/3/88.

c. Mr.'s Matthusen, McCleary, Justice, and Dr. Birkeland, all commented that it would be desirable to see data and results (i.e. field and laboratory notebooks) in order to compare data entries to the reviewed procedures.

SUMMARY - PHASE II

In order to resolve the concerns and questions identified in the Phase I procedures review, the following assignments were given to Mr. McCleary and Mr. Matthusen of the TATM·

Mr. McCleary went to interview Dr. Whitney at the USGS offices in Denver on July 14, 1992, and examine his field notebooks relating to the erosion studies, particularly those sections on sampling for cation ratio dating of desert varnish.

Mr. Matthusen went to interview Dr. Harrington at the LANL offices in Albuquerque on July 14, 1992, and examine his field and laboratory notebooks.

The results of these examinations were quite positive. Mr. McCleary concluded " . . . it is my opinion that cation-ratio dating of desert varnish can be used to support the Project position on erosion rates at Yucca Mountain."

Mr. Matthusen has stated "The procedures (which includes the methodology reflected in field and laboratory notebooks) for gathering and evaluating samples, and the documentation of the gathering and evaluation of samples, allow the data to be qualified."

The full text of Mr.'s McCleary's and Matthusen's observations and evaluations are in Attachment V.

In the following Section, point by point resolutions are provided for each TATM comment.

RESOLUTION OF ASSESSMENT COMMENTS

Dr. John C. Dohrenwend

Dr. Dohrenwend has answered the three questions posed by the Technical Assessment in recommending "to DOE YMPO that the procedures used to collect and evaluate samples are acceptable and that the technical data pertaining to the extreme erosion study should be qualified . . .".

Dr. Peter W. Birkeland

Dr. Birkeland has also recommended that the technical data pertaining to the extreme erosion study should be qualified. Dr. Birkeland's one concern was the kind of data (samples) that were collected, and the results (documentation) of field work, or lab work. Mr. McCleary and Mr. Matthusen have resolved Dr. Birkeland's concern by inspecting the scientific field and laboratory notebooks.

August C. Matthusen

First Comment:

- *From the procedures reviewed, it is not possible to determine if the technical results would differ from the results that were determined. The procedures reviewed govern mainly the documentation of results and not the gathering and analysis process.*

Resolution of Mr. Matthusen's comment is addressed in the verification of data to procedures which was carried out by Mr. Matthusen, at LANL and Mr. McCleary, at the USGS, subsequent to the Procedures Assessment.

Proposed Resolution - Mr. Matthusen:

Additionally, the purpose of the Technical Assessment Notice requested that I assess three questions. These are assessed as follows:

Would sample collection and evaluation under current participant technical procedures differ from those procedures actually followed?

No, they would not differ.

Are any differences significant enough to affect technical results?

No, there are not significant differences.

Can a recommendation be made to DOE YMPO that the procedures used to gather and evaluate samples are acceptable to allow the technical data to be qualified under current QARD guidelines?

Yes. The procedures for gathering and evaluating samples and the documentation of the gathering and evaluation of samples allow the data to be qualified. The documentation of sample and data collection would allow a knowledgeable person to retrace the investigation and confirm the results. The same documentation would allow a peer of Dr. Harrington to repeat the investigation and achieve comparable results without recourse to Dr. Harrington. From my review of the documentation I recommend that the data be accepted.

The rest of Mr. Matthusen's verification report is contained in Attachment V.

Proposed Resolution - Mr McCleary:

Based on the above observations of the procedures and notebooks and my discussions with John Whitney, it is my opinion that if the early sampling were repeated under current procedures, the results would not be significantly different.

It is also worth noting that the early samples collected by the USGS alone have, in general, yielded age estimates that are younger than average. Therefore, eliminating the use of these samples would only support older deposits and slower erosion rates, a less conservative position relative to the regulations. In addition the overall argument on erosion rates does not hinge on the cation-ratio dating technique. U-series, U-trend, Cl-36, and tephrachronology studies were also carried out on early samples collected by the USGS and are in general agreement with the cation-ratio data.

In summary, I have made the following observations:

- *USGS field notebooks document to a reasonable extent that the samples collected early in the study would also have been selected under the 5/1/87 procedure.*
- *Inclusion of the early data produces a slightly more conservative erosion rate relative to the regulations.*
- *Other dating studies carried out to address the erosion issue generally support the results of the desert varnish studies.*

Therefore, it is my opinion that the cation-ratio dating of desert varnish can be used to support the project position on erosion rates at Yucca Mountain. If other assessment team members, or the project, still have concerns, other evaluations can be made with existing information and examination of the samples at LANL.

Resolved: Based on the documentation in the scientific notebooks of the Principal Investigators it is apparent that sample collection and evaluation procedures followed during the investigation were not different from those currently in place. Therefore, technical results would not be significantly different.

Second comment:

- *Requires verification of technical data to reviewed procedures.*

Resolved - This comment has been resolved by the verification of data to procedures by Mr. Matthusen and Mr. McCleary.

Jeff McCleary

First Comment:

- *In summary, based on the information provided, because of the unknown criteria for sample collection prior to 5/1/87 it is possible that technical results could differ if current procedures were followed.*

Proposed Resolution by comparison of field notebooks to procedures provided the following:

Proposed Resolution - Mr. Matthusen:

The documentation materials reviewed include the following:

- *Field Notebooks. Two of Dr. Harrington's field notebooks document samples, sample collection , field sample identification numbers assigned, dates of collection, field personnel, collection rationale, hypotheses, and descriptions of sample collection localities for rock varnish samples for the Yucca Mountain Project. The first notebook (NB1) covered the period from 10/2/85 to 5/13/87. This notebook also included information on rock varnish projects not related to Yucca Mountain. The second field notebook (NB2) covers the period from 1/10/87 to 1990 and includes only Yucca Mountain related information. NB1 contains copies of pages from the field notebook of J. Whitney (USGS) documenting rock varnish sample collection activities in 6/84, 10/85, 11/85, and 7/86. NB1 also contains notes by Dr. Harrington regarding sample collection done in conjunction with J. Whitney for the previously mentioned dates after 10/85. NB2 is more detailed than NB1 and contains more detailed descriptions of samples, sample locations, collection rationales, and hypotheses. Samples and locations recorded in NB1 and NB2 are further documented in a Sample Tracking Notebook and on topographic maps.*

- *Sample Tracking Notebook for rock varnish samples. Samples are recorded with field sample identification number, lab disk identification number (two disks of rock are cut from the field samples and cemented onto a glass slide for use in the scanning electron microscope (SEM) and a new lab disk identification number is assigned to the slide as the field sample identification is often too long to fit on the slide), geologic deposit name, description of sample, and samples are keyed to collection locations documented on topographic maps.*

- *NNWSI Log Book. This notebook documents sample transfers and handlings for the ESS-1 group of Los Alamos National Laboratory from the time period 5/14/86 to 10/2/91. The first entry by Dr. Harrington was 6/3/87. The notebook has been technically reviewed five times between 1/15/88 to 10/2/91.*

Proposed Resolution - Mr McCleary:

The following observations were made:

- *The current procedure requires that samples be collected:*
  - *from stabilized deposits or outcrops*
  - *that exhibit mature varnish development (darker)*

- *that avoids cracks, lichens, etc.*
- *that are not wind abraded or spalled.*

- *Samples were collected by the USGS (John Whitney) alone in 1984 and by the USGS and LANL jointly in 1985 and later. I therefore concentrated my examination on the 1984 notebooks.*
  - *The stabilized deposits are well described (slope angle, thickness, etc.) in each case.*
  - *Varnish maturity is not always described but it is noted often and it is apparent from the notebook as a whole that the intent was to sample darker (more mature) varnish.*
  - *The physical condition of the sample relative to cracks, lichens, abrasion, etc. was not well described. However, if necessary, the rock samples actually collected could be examined at LANL to determine their physical condition.*

Resolved: Documentation available in the field and laboratory notebooks of the Principal Investigators at the USGS and LANL demonstrates that the same sample collection procedures were followed prior to 5/1/87 as after. Therefore, technical results would not be significantly different.

Second Comment:

- *The LANL notebooks developed under the R and D procedures should be reviewed in order to determine how samples were selected in the field prior to 5/1/87. If it can be shown that the same criteria for site and sample collection were followed prior to 5/1/87 as after the "sample collection procedure for rock varnish studies" was issued, then all samples can be considered valid.*

Proposed Resolution has been done by Mr. Matthusen in verifying that samples collected prior to 5/1/87 were selected using the same guidelines as were established in the subsequent sampling procedure.

Proposed Resolution - Mr. Matthusen:

What techniques were used for sample collection?

Discussions with Dr. Harrington elicited that the technique used for sample collection was as described in Harrington and Whitney (1987) and in the Sample Collection Procedure for Rock Varnish Samples (TWS-ESS-DP-114).

Was a procedure followed?

The Sample Collection Procedure for Rock Varnish Samples was implemented in 5/87. Prior to that time the work was being done under the Quality Assurance Procedure for One-time Research and Development Work (TWS-MSTQA QP-14, R0) implemented in 5/85, and the Research and Development (Experimental) Procedure (TWS-MSTQA-QP-14, R1) implemented in 2/86. These procedures allow development work to be done and documented in notebooks.

Resolved: As noted previously, documentation is available to demonstrate that the same procedures were followed pre and post the 5/1/87 issue date of the sample collection procedure.

Third Comment:

- *All samples shipped should be examined for abrasion or other shipping damage to the varnish surface. If all samples show an intact varnish surface they can be considered valid.*

Proposed Resolution has been done by Mr. Matthusen.

Proposed Resolution - Mr. Matthusen:

- *The SEM samples (the rock disks on slides). These are retained in a locked cabinet in Dr. Harrington's office. The cabinet was opened and I observed the samples. One sample was checked for ID number and the ID number could be tracked to corresponding numbers in notebooks, maps, etc. In discussion, Dr. Harrington indicated that the rock samples from which the disks had been cut are also maintained in storage. Dr. Harrington stated that all rock varnish samples have been hand carried to Los Alamos, so use of the procedure for shipping samples has not been needed.*

Resolved: Observation of the samples and the careful handling of the samples (i.e. all hand carried) demonstrates that the varnish surface is intact and the samples can be considered valid.

B. Robert Justice

First Comment:

1. *Would sample collection and evaluation under current Participant technical procedures differ from those procedures actually followed?*

   Response - Inconclusive in that procedures for collection did not exist until 5/1/87. The procedure used for collection (TWS-ESS-DP-114, Rev. 0) from 5/1/87 until 5/3/88 did not adequately address the handling of samples. The guidelines for determining collection areas were less restrictive than current requirements and could have led to samples being collected from areas which may be unsuitable under current procedures. Additionally, there is no evidence of procedural guidelines for conducting the rock varnish for erosion analysis.

Proposed Resolution - August Matthusen

Prior to 1987 LANL and the USGS were evolving defined (specific locations) sample sites, and the analysis process.

The Sample Collection Procedure for Rock Varnish Samples was implemented in 4/87. Prior to that time the work was being done under the Quality Assurance Procedure for One-time Research and Development Work (TWS-MSTQA-QA-14, R0) implemented in 5/85, and the Research and Development (Experimental) Procedure (TWS-MSTQA-QP-14, R1) *implemented in 2/86. These procedures allow development work to be done and documented in notebooks.*

1. *Field Notebooks. Two of Dr. Harrington's field notebooks document samples, sample collection, field sample identification numbers assigned, dates of collection, field personnel, collection rationale, hypotheses, and descriptions of sample collection localities for rock varnish samples for the Yucca Mountain Project. The first notebook (NB1) covered the period from 10/2/85 to 5/13/87. This notebook also included information on rock varnish projects not related to Yucca Mountain. The second field notebook (NB2) covers the period from 1/10/87 to 1990 and includes only Yucca Mountain related information. NB1 contains copies of pages from the field notebook of J. Whitney (USGS) documenting rock varnish sample collection activities in 6/84, 10/85, 11/85, and 7/86. NB1 also contains notes by Dr. Harrington regarding sample collection done in conjunction with J. Whitney for the previously mentioned dates after 10/85. NB2 is more detailed than NB1 and contains more detailed descriptions of samples, sample locations, collection rationales, and hypotheses. Samples and locations are recorded in NB1 and NB2 and further documented in a Sample Tracking Notebook and on topographic maps.*

2. *Sample Tracking Notebook for rock varnish samples. Samples are recorded with field sample identification number, lab disk identification number (two disks of rock are cut from the field samples and cemented onto a glass slide for use in the scanning electron microscope [SEM] and a new lab disk identification number is assigned to the slide as the field sample identification is often too long to fit on the slide), geologic deposit name, description of sample, and samples are keyed to collection locations documented on topographic maps.*

3. *NNWSI Log Book. This notebook documents sample transfers and handlings for the ESS-1 group of Los Alamos National Laboratory from the time period 5/14/86 to 10/2/91. The first entry by Dr. Harrington was 6/3/87. The notebook has been technically reviewed five times between 1/15/88 to 10/2/91.*

4. *SEM Notebook Rock Varnish. Begun in 6/86 to document the SEM and energy dispersive X-ray analyzer (EDAX) work performed on the rock varnish samples. It begins referencing the initial analytic procedure (Harrington and Whitney, in review; later published as Harrington and Whitney, 1987, "Scanning electron microscope method for rock-varnish dating", Geology, Vol.15, pp. 967-970) and briefly describing the initial analytic procedure in the notebook. It described specifics of analyses and analytic results. The notebook also documents much additional pertinent information (e.g., on 9/22/86 the SEM machine was moved to a new location, a new run was done with a previously analyzed sample to verify/compare new results to previous analytic results). Therefore, for a new series of runs, an old sample would be re-run to ensure similarity of results. Over the course of the experiment, the experimental methodology was refined. All changes in SEM settings in response to methodological refinements are documented (e.g., on 9/22/86 - the procedure was modified to ascertain penetration for the varnish coating without inclusion of the rock substrate, that is, to ensure that only the varnish is being sampled) and previous samples retested. The notebook has undergone frequent technical review by technical staff from Los Alamos (Carlos, Vaniman, Broxton, Maassen). Thirteen reviews are documented between 7/1/86 to 1/18/91. The last technical entry in this notebook is 11/14/90. it was reviewed*

11/8/91, and was closed out 2/10/92. Additionally, the notebook documents changes in the SEM program used to deconvolute the data, hypotheses, changes in hypotheses, problems encountered, investigations pursued to resolve problems, data, and assumptions in methods.

Proposed Resolution - Jeff McCleary

The current procedure requires that samples be collected:

- *from stabilized deposits or outcrops*
- *that exhibit mature varnish development (darker)*
- *that avoid cracks, lichens, etc.*
- *That are not wind abraded or spalled.*

Samples were collected by the USGS (John Whitney) alone in 1984 and by the USGS and LANL jointly in 1985 and later. I therefore concentrated my examination on the 1984 notebooks.

- *The stabilized deposits are well described (slope, angle, thickness, etc.) in each case.*
- *Varnish maturity is not always described but it is noted often and it is apparent from the notebook as a whole that the intent was to sample darker (more mature) varnish.*
- *The physical condition of the sample relative to cracks, lichens, abrasion, etc. was not well described. However, if necessary the samples (at LANL) could be examined to determine their physical condition.*

Based on the above observations of the procedures and notebooks and my discussions with John Whitney, it is my opinion that if the early sampling were repeated under current procedures, the results would not be significantly different.

It is also worth noting that the early samples collected by the USGS alone have, in general, yielded age estimates that are younger than average. Therefore, eliminating the use of these samples would only support older deposits and slower erosion rates, a less conservative position relative to the regulations. In addition the overall argument on erosion rates does not hinge on the cation-ration dating technique. U-series, U-trend, Cl-36, and tephrachronology studies were also carried out and are in general agreement with cation-ratio data.

Resolved: That the sampling process, and sample analysis process (via the documentation in the Notebooks) is the same as would be done under current procedures (which were developed from the processes demonstrated in the Notebooks).

Therefore, there would be only minimal differences, if any, for sample collection and evaluation under current LANL and USGS procedures.

Second Comment:

2. *Are there any differences significant enough to affect technical results?*

Response - Yes, in the area of handling the samples once they were collected. There were not any specific guidelines provided for the handling of samples until 5/3/88 when Change Request #29 to procedure TWS-ESS-DP-114, Rev. 0 became *effective. Also, the lack of procedural processes for the collection and analysis of samples raises questions with respect to what processes were actually used and the consistency with which those processes were repeated.*

Proposed Resolution - August Matthusen

The field notebooks, the sample tracking notebook, the NNWSI Log Book, the maps, and the samples themselves (all discussed prior) exist to document the sample collection and handling. Dr. Harrington stated that all rock varnish samples have been hand carried to Los Alamos, so use of the procedure for shipping samples has not been needed.

Sample handling used a "best practices" approach to protect samples being "hand carried" by Dr. Harrington.

The data, documentation, and work comply to procedures governing scientific notebooks (Quality Assurance Procedure for One-time Research and Development Work [TWS-MSTQA-QA-14, R0] implemented in 5/85; Research and Development Work (Experimental) Procedure [TWS-MSTQA-QP-14, R1] implemented in 2/86; and Procedure for Documenting Scientific Investigations [TWS-QAS-AP-03.5, R0] implemented 3/10/89). These procedures allow development work to be done and documented in notebooks.

Proposed Resolution - Jeff McCleary

In summary, I have made the following observations:

- *USGS field notebooks document to a reasonable extent that the samples collected early in the study would also have been selected under the 5/1/87 procedure.*
- *Inclusion of the early data produces a slightly more conservative erosion rate relative to the regulations.*
- *Other dating studies carried out to address the erosion issue generally support the results of the desert varnish studies.*

Therefore, it is my opinion that the cation-ratio dating of desert varnish can be used to support the project position on erosion rates at Yucca Mountain. If other assessment team members, or the project, still have concerns, other evaluations can be made with existing information and examination of the samples at LANL.

The question of what processes were actually used (to collect samples and evaluate samples), and the consistency with which these processes were repeated, is answered in resolution of Comment #1.

Resolved: That the sampling and evaluation processes actually used, and the consistency of repeating these processes is documented, and demonstrated in the Scientific Notebooks available from Dr. Harrington. Therefore, in that current procedures have been developed from the processes demonstrated within these Scientific Notebooks, there would not be significantly different data obtained if tests were performed today.

Third Comment:

3. *Can a recommendation be made to DOE YMPO that the procedures used to gather and evaluate samples are acceptable to allow the technical data to be qualified under current QARD guidelines?*

Response - A recommendation to accept the data based on the procedures provided for this assessment cannot be made. The obvious lack of procedural guidance in the early stage of this activity supports this conclusion. Other evidence may be available to support the processes used to accomplish the collection and analysis of samples. The notebooks, which have been used throughout this activity to document the work that was performed, may contain enough information to identify the processes used and the consistency with which they were repeated. These notebooks were not provided as part of the review package.

Resolved: That the Scientific Notebooks verify that the processes used would conform to current procedures. Therefore, a recommendations can be made to DOE YMPO to accept the erosion technical data as qualified under current DOE QARD guidelines.

Conclusions and Recommendations

The Technical Assessment Team has evaluated current and previous QA and Technical Procedures that relate to sample collection and analysis, and field measurements for cation ratio dating. In addition, field and laboratory notebooks of the Principal Investigators were examined and compared to the procedures.
Three questions have been answered:

1. Would data collection and evaluation under current Participant technical procedures differ from those procedures actually followed?

2. Are any differences significant enough to affect technical results?

3. Can a recommendation be made to DOE YMPO that the procedures used to gather and evaluate samples, and guide field measurements are acceptable to allow the technical data to be qualified under current QARD guidelines?

First question

It has been unanimously agreed by all five Technical Assessment Team Members (TATM) that data collection and evaluation would not differ under current QA and Technical Procedures for LANL and the USGS.

Second question

The TATM unanimously agrees that no significant differences would result from data collection and evaluation under current QA and Technical Procedures.

Third Question

The Technical Assessment Team Members do recommend to DOE YMPO to allow the technical data on Extreme Erosion be formally accepted as qualified under current YMPO QARD guidelines.

In June 1989 LANL organized a peer review group of leading geomorphologists to examine the VCR (varnish cation-ratio) age dating technique and "critically reviewed rock-varnish studies within the LANL Yucca Mountain Project". This Peer Review Panel concluded " . . . that the VCR age determinations by Dr. Harrington and collaborators are the best presently being done." This Panel also stated: "We are impressed with the excellent work being done on VCR age determination by the LANL research and technical staff and their associates at the USGS and the University of New Mexico. The members of this high-quality team, primarily in the ESS-1 Group (LANL), are extremely careful in all phases of the work, from the initial field sampling, through the laboratory work, to the final age estimation." This peer review supports the results of this Technical Assessment. The report by this Panel is included as Attachment VI.