Open-File Report 80-942 Open-File Report 80-942

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOLOGY OF THE SYNCLINE RIDGE AREA RELATED TO NUCLEAR WASTE DISPOSAL, NEVADA TEST SITE, NYE COUNTY, NEVADA

By

D. L. Hoover[1] and J. N. Morrison[2]

[1]U.S. Geological Survey, Denver, Colo.
[2]Fenix & Scisson, Inc., Mercury, Nev.

CONTENTS

CONTENTS--Continued

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

GEOLOGY OF THE SYNCLINE RIDGE AREA RELATED TO NUCLEAR WASTE DISPOSAL, NEVADA TEST SITE, NYE COUNTY, NEVADA

By

D. L. Hoover and J. N. Morrison

ABSTRACT

The Syncline Ridge area is in the western part of Yucca Flat, Nye Co., Nev. Drill holes, geophysical surveys, mapping, and laboratory studies during 1976 through 1978 were used to investigate argillite in unit J (Mississippian) of the Eleana Formation (Devonian and Mississippian) as a possible nuclear waste repository site.

Argillite in unit J has a minimum stratigraphic thickness of at least 700 m. The argillite underlies most of the Syncline Ridge area east of the Eleana Range, and is overlain by Quaternary alluvium and the Tippipah Limestone (Pennsylvanian and Permian(?)) of Syncline Ridge. At the edges of the Syncline Ridge area, alluvium and volcanic rocks overlie the argillite. The argillite is underlain by more than 1,000 m of quartzite, siliceous argillite, and minor limestone in older units of the Eleana Formation. These older units crop out in the Eleana Range.

The Syncline Ridge area is defined by poorly exposed faults of Mesozoic and Tertiary age. The area is divided into southern, central, and northern structural blocks by two lateral faults. The southern and central blocks either have volumes of argillite too small for a repository site, or have irregular-shaped volumes caused by Mesozoic high-angle faults that make the structure too complex for a repository site. The northern block appears to contain thick argillite within an area of 6 to 8 km^2.

Tertiary or Quaternary faults are present only at the periphery of the Syncline Ridge area. A few faults displace older Quaternary alluvium north of Red Canyon in the northern structural block. The postvolcanic history of the Syncline Ridge area indicates that the area has undergone less deformation than other areas in Yucca Flat. Most of the late Tertiary and Quaternary deformation consisted of uplift and eastward tilting in the Syncline Ridge area.

Preliminary engineering geology investigations indicate that although the competency of the argillite is low, the argillite may be feasible for construction of a nuclear waste disposal facility. Physical, thermal, chemical, and mineralogical properties of the argillite appear to be within acceptable limits for a nuclear waste repository.

INTRODUCTION

During 1976-78, the Eleana Formation (Devonian and Mississippian) at the Nevada Test Site (NTS) was investigated as a potential nuclear waste repository medium. After review of all outcrops of the Eleana Formation at NTS, the Syncline Ridge area (fig. 1) was selected as the area with the best potential for a nuclear waste repository site. This report summarizes the geology and engineering geology in the Syncline Ridge area as it relates to a potential repository site. Details of individual investigations are given in reports on drill holes, hydrology, and geophysical surveys.

Geography

The Syncline Ridge area is located on the west side of Yucca Flat (fig. 1). The area is about 60 km north and west of Mercury, Nev., by paved road. The Pahute Mesa paved highway approximately bisects the area from east to west. Otherwise, only a few short dirt roads to drill holes and the paved road to the U16a tunnel penetrate the area. Most of the structural boundaries that define the Syncline Ridge area (fig. 2) are concealed beneath alluvium or volcanic rocks.

The topography of the Syncline Ridge area can be divided from east to west into four north-northeast-trending units. The easternmost unit consists mainly of alluvial fans with low, relatively smooth slopes. The fans range in elevation from about 1,250 to approximately 1,500 m. The next unit west is Syncline Ridge with rugged steep slopes ranging from 1,400 to just over 1,675 m in elevation. The third unit, between Syncline Ridge and the Eleana Range, is a dissected pediment and fan surface that slopes eastward. This surface has about the same range in elevation as Syncline Ridge. The westernmost unit contains the Eleana Range and volcanic hills with moderate to steep slopes, ranging in elevation from 1,500 to slightly less than 2,200 m.

Two major drainages, Gap Wash and Red Canyon, are deeply incised into the area. Gap Wash is incised 10-20 m into alluvium. This wash has cut through both the Eleana Range and Syncline Ridge to depths of approximately 170 and 210 m, respectively, below the tops of the adjacent ridges. Red Canyon has cut through the Eleana Range to a similar depth. Red Canyon Wash is incised from 3-10 m into the alluvium. Vegetation in Red Canyon indicates that underflow in the gravels in the floor of the canyon may extend 1 1/2 km beyond the east edge of the Eleana Range. The underflow may come from springs on the west side of the range; low permeability of the Eleana Formation that lies within a meter or two of the floor of Red Canyon probably prevents downward percolation of the underflow. Between Syncline Ridge and the Eleana Range, Pediment Wash and its tributaries have dissected the pediment and alluvial fans to depths of 3-25 m.

Investigations

After review of the sparse literature on the Syncline Ridge area and brief field investigations, a detailed gravity survey was conducted in 1976 to locate faults north and east of Syncline Ridge concealed by alluvium. Seven holes were drilled in 1976 through the alluvium to provide control for the gravity survey and to determine the stratigraphic position of the rocks beneath the alluvium. Drill hole UE17a was deepened in 1976 to obtain hydrologic data. One shallow drill hole, UE1m (fig. 2), was drilled in early 1976 on an outcrop of the

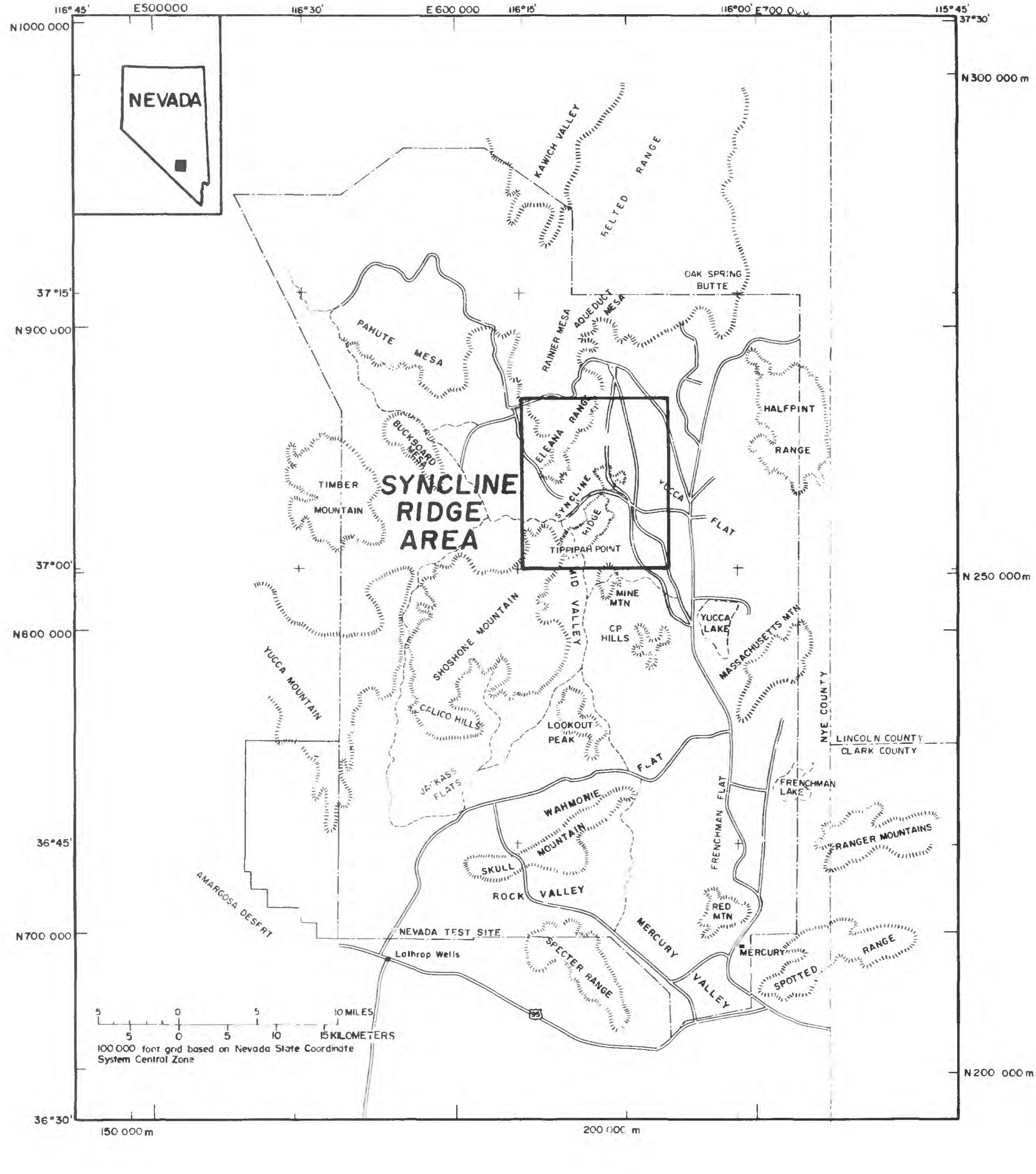


Figure 1.--Index map showing location of the Nevada Test Site and the Syncline Ridge area.

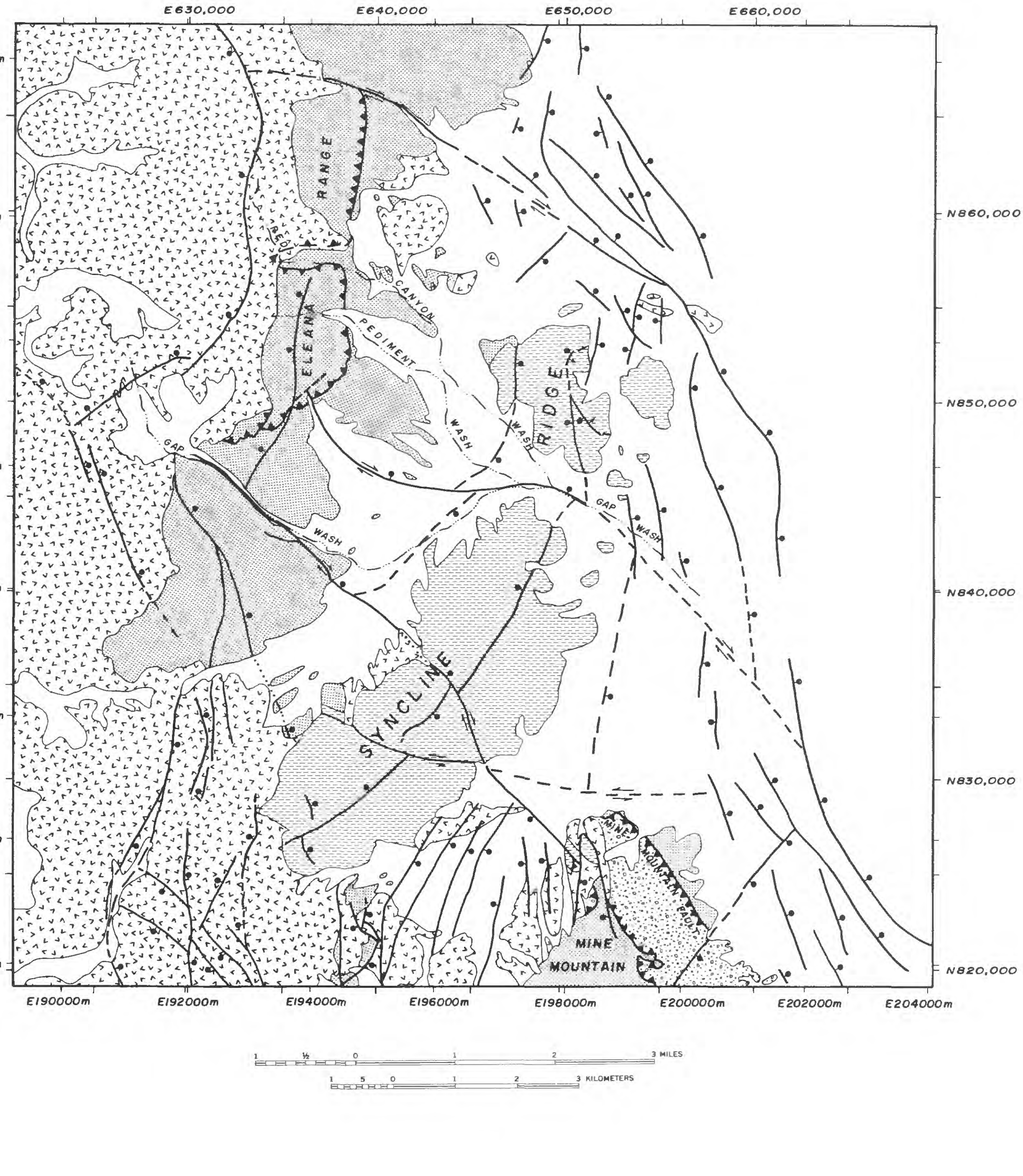
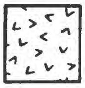


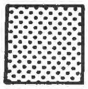
Figure 2.--Geologic map of the Syncline Ridge area showing principal stratigraphic units and major structures.

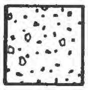
EXPLANATION

 Alluvium (Quaternary)

 Volcanic rocks (Tertiary)

 Tippipah Limestone (Permian(?) and Pennsylvanian)

 Eleana Formation (Mississippian and Devonian)

 Older rocks (Paleozoic)

 FAULT (Tertiary)--Bar and ball on downthrown side, dashed where inferred

 THRUST FAULT (Mesozoic)--Teeth are on upper plate, dashed where inferred

 LATERAL FAULT (Mesozoic)--Bar and ball on downthrown side, dashed where inferred; arrows indicate direction of relative lateral movement

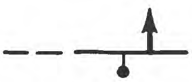
 FAULT--Bar and ball on downthrown side, dashed where inferred; arrows indicate direction of dip for reverse fault

Figure 2.--Continued

Eleana Formation to investigate a location for a heating experiment. In late 1976, UE17e was cored to a depth of 914.4 m to obtain samples for laboratory studies as well as structural and stratigraphic information related to a waste repository site. Core samples from UE17e were analyzed by Sandia National Laboratories, and by other laboratories under the direction of Sandia, for physical, mechanical, thermal, chemical, and mineralogical properties.

In 1977 and 1978, the Syncline Ridge area was investigated by electrical, seismic, gravity, and magnetic surveys to determine subsurface structure. Detailed data and interpretations are presented in separate reports, but some of the conclusions are summarized in this report. Holes UE16d and UE16f were drilled in 1977 as hydrologic test holes. Lithologic logs and results of hydrologic testing are presented in other reports; stratigraphic and structural information from the holes is summarized in this report. Syncline Ridge faults and Quaternary deposits west of Syncline Ridge were also mapped during 1977 and 1978. Mapping was not completed because the investigation of Syncline Ridge was terminated, but the conclusions from this mapping program are presented in this report.

Previous work

Ball (1907) mapped much of southern Nevada and eastern California. He identified the Eleana Formation as the Weber conglomerate, identified the Tippipah Limestone (Pennsylvanian and Permian(?)) as Pennsylvanian limestone and recognized Syncline Ridge as a synclinal structure. Johnson and Hibbard (1957) named the Eleana Formation and the Tippipah Limestone and described their general lithologies. They described the Syncline Ridge syncline and the Mine Mountain thrust fault, and recognized the thrust faults in the Eleana Range. Detailed mapping (scale: 1:24,000) of the quadrangles that include the Syncline Ridge area was done by Orkild (1963, 1968), Gibbons and others (1963), McKeown and others (1976) and Colton and McKay (1966). Poole and others (1961) described the lithology and stratigraphy of the Eleana Formation and divided the formation into 10 units, A-J. Fossil collections from their work showed the age of the Eleana Formation to be Late Devonian to Early Pennsylvanian. Gordon and Poole (1968) found evidence for a Late Mississippian age of the uppermost part of unit J and evidence for an unconformity between the Eleana Formation and the overlying lower part of the Tippipah Limestone of Early Pennsylvanian age. Poole (1974) described the depositional history of the Eleana Formation and its equivalents in the Western U.S.

The Mesozoic deformation of the Paleozoic rocks and the Tertiary and Quaternary faulting are complex in the Syncline Ridge area. Barnes and Poole (1968) described the Mine Mountain, CP, and Tippinip thrust faults. Ekren and others (1968) found that the Tertiary faults are of two ages; an older northwest- and northeast-trending set and a younger north-south set. Carr (1974) synthesized the tectonics and determined the Quaternary regional stress orientation for Yucca Flat. He concluded that Yucca Flat and the surrounding region are undergoing northwest-southeast extension. Unpublished gravity data (D. L. Healey and others, 1978, written commun.) indicate that the Syncline Ridge area is bounded on the north and east by Quaternary faults concealed by alluvium.

Studies of Quaternary alluvium at NTS have been concerned mainly with engineering geology for underground nuclear tests. Gravity and drill-hole data have provided detailed maps of the thickness of Quaternary deposits and faults displacing these deposits for much of Yucca Flat. Fernald and others (1968) mapped the Quaternary deposits of Yucca Flat on the basis of depositional environment, slope, grain size, and bedding quality. They recognized the pediment between Syncline Ridge and the Eleana Range.

Acknowledgments

Much of the data summarized in the engineering geology section was compiled by geologists of Fenix & Scisson, Inc. Their help in assembling the large amount of data is gratefully acknowledged. The interpretation of the subsurface structure would not have been possible without the numerous geophysical data made available by colleagues. In particular, L. A. Anderson, V. J. Flanigan, W. F. Hanna, D. B. Hoover, and L. W. Pankratz unreservedly furnished data, maps, and a valuable exchange of interpretations. P. P. Orkild and F. G. Poole added greatly to our understanding of Eleana Formation stratigraphy and engineering geology.

SITE POTENTIAL SUMMARY

Surface, drill-hole, and geophysical data indicate that the Syncline Ridge area contains thick sections of argillite within the Eleana Formation at depths between 300 and 1,000 m. The maximum area that contains the thick sections of argillite is 6-8 km^2. Mesozoic and Tertiary deformations have limited the size of potential repository site areas.

Most of the physical, thermal, chemical, and mineralogical properties that might affect the suitability of the argillite for nuclear waste disposal appear to be within acceptable ranges. The compressive strength of thin (less than 1 m average) intervals is less than $4.5X10^3$ MPa. This low compressive strength can affect construction, but intervals of argillite with strengths of 20 to $65X10^3$ MPa are thick enough to contain presently proposed underground facilities. Prediction of low-strength argillite intervals is uncertain because of structural deformation in the argillite and because the origin of the low-strength argillite has not been fully determined.

The Syncline Ridge area is defined by fault zones that separate an area with few Tertiary and Quaternary faults from surrounding areas with numerous Tertiary and Quaternary faults. The Syncline Ridge area is defined on the north and south by northwest-trending fault zones. These fault zones are Mesozoic lateral faults that have been reactivated in the Tertiary period as normal faults. Quaternary faulting has not been seen, but it is probably present along part of these fault zones. The eastern boundary is defined by a north- to northwest-trending fault zone of Tertiary and Quaternary age. The western boundary is defined by arcuate faults trending approximately north-south paralleling the Timber Mountain caldera faults farther west.

The Syncline Ridge area is divided into three structural blocks by two Mesozoic lateral faults. These faults have a northwest trend. Except for a short segment between Syncline Ridge and Mine Mountain on the southern fault, no evidence of Tertiary or Quaternary movement has been found on these faults. The Quaternary history of the Syncline Ridge area indicates that Quaternary deformation and probably late Tertiary deformation consisted of eastward tilting and uplift of the entire area. Between Syncline Ridge and Mine Mountain a graben was formed during the Tertiary and Quaternary Periods.

The three structural blocks, called the southern, central, and northern blocks, have undergone the same structural deformation, but differ greatly in their individual structures and in the thickness and continuity of the argillite in unit J of the Eleana Formation. The southern block contains numerous Tertiary faults. Seismic reflection surveys indicate several large high-angle faults that are probably Mesozoic in age. The argillite varies greatly in thickness and may be absent in much of the southern block.

The central block contains as much as 800 m of argillite at depths of 300-1,000 m but geophysical surveys indicate that the argillite alternately thins and thickens from west to east. This alternation is caused by high-angle Mesozoic faults that parallel the north-northeast trend of Syncline Ridge. Most of these faults are concealed by alluvium or by the Tippipah Limestone of Syncline Ridge that forms a thrust plate overlying the Eleana Formation. The high-angle faults limit areas of continuous argillite to narrow bands that probably have an area of less than 5 km^2.

The northern block contains argillite ranging from 160 m to more than 800 m thick in a 6-8 km^2 area between Syncline Ridge and the Eleana Range. Geophysical surveys indicate that Mesozoic high-angle faults do not greatly affect the thickness of the argillite in this area. Beneath Syncline Ridge and to the east, high-angle faults probably thin and thicken the argillite as in the central block. A few Quaternary faults have been found north of Red Canyon and its former channel north of Syncline Ridge. No Quaternary faults have been found south of Red Canyon where older Quaternary deposits and a pediment are well exposed. The northern block west of Syncline Ridge is the only location in the Syncline Ridge area that might contain a possible nuclear waste disposal site in argillite.

STRATIGRAPHY

Rocks exposed in the Syncline Ridge area range from Ordovician to Quaternary in age. Most of the outcrops are the Eleana Formation, the Tippipah Limestone, and Quaternary alluvium. Tertiary volcanic rocks crop out or underlie alluvium around the periphery of the area. In adjacent areas, thrust plates of Ordovician and Devonian rocks overlie the Eleana Formation and the Tippipah Limestone. These older Paleozoic rocks crop out on Mine Mountain and underlie Tertiary volcanic rocks and (or) Quaternary alluvium adjacent to the Syncline Ridge area on the north, east, and south. Older Paleozoic rocks are probably concealed by the volcanic rocks west of the Syncline Ridge area.

Older Paleozoic rocks

Older Paleozoic rocks (pre-Eleana Formation) have not been found within the Syncline Ridge area. These older rocks, predominantly carbonates, are present in adjacent structural blocks (figs. 2, 3). Where present, all of the older Paleozoic rocks overlie the Eleana Formation or the Tippipah Limestone as thrust plates.

South and southeast of Syncline Ridge in Mid Valley and on Mine Mountain, dolomite and minor amounts of quartzite of Silurian through Devonian age overlie units H-J of the Eleana Formation and the Tippipah Limestone (figs. 2, 3). These rocks are the upper plate of either the Mine Mountain or the CP thrust faults. East of Mine Mountain in drill hole UE1p and further north or east in drill holes UE1c, UE1d, UE1e, UE1h, and UE1j limestone, dolomite, and quartzite of Ordovician through Devonian age lie beneath alluvium or Tertiary volcanic rocks. These older Paleozoic rocks are probably part of the upper plate of the CP thrust fault that overlies the Mine Mountain thrust plate. The CP thrust plate is preserved by Tertiary faults along the east side of the Syncline Ridge block.

Holes drilled northeast and north of Syncline Ridge have penetrated only older Paleozoic carbonates in the upper plate of the CP thrust fault beneath alluvium or Tertiary volcanic rocks. Older Paleozoic carbonates in this upper plate crop out between the Eleana Range and Rainier Mesa. West of the Syncline Ridge structural block, these carbonates have not been seen and may lie beneath Tertiary volcanic rocks at depths of 300 m or more. The eastern edge of the Timber Mountain caldera may displace these carbonates down 1,000 m or more to the west.

The older Paleozoic rocks beneath Syncline Ridge probably are more than 2,000 m beneath the surface and are overlain by all or most of the Eleana Formation. Those rocks were not penetrated by the UE1L drill hole at the total depth of 1,627 m. Geophysical surveys have not indicated the presence of carbonate rocks beneath the structural block at similar depths.

The presence of older Paleozoic carbonates immediately adjacent to the Syncline Ridge area places limits on a repository site and its buffer zone, because the carbonates are the principal aquifer draining Yucca Flat into the Amargosa discharge area. Steep hydraulic gradients from the Syncline Ridge area toward the center of Yucca Flat indicate that any ground water in the Syncline Ridge area would enter the carbonates within a short distance of the boundaries of the Syncline Ridge structural block (Winograd and Thordarson, 1975). Thus, retardation of radionuclides would have to be based on hydraulic or ion-exchange properties of the Eleana Formation.

Eleana Formation

The Eleana Formation is a series of predominantly clastic rocks at least 2,350 m thick and possibly 3,000-4,000 m thick. The Eleana is divided into 10 units from A at the base to J at the top (Poole, Houser and Orkild, 1961). Only units G-J crop out or have been penetrated in drill holes in the Syncline Ridge area. Units E and F (fig. 3) are outside the Syncline Ridge area.

Depositional Environment and Rock Types

The Eleana Formation was deposited in a deep marine basin that extended from southern California northward through Idaho into British Columbia (Poole, 1974). Compression of Devonian and older eugeosynclinal rocks caused the uplift of the Antler orogenic highland and formation of the Antler depositional trough (fig. 4). The Eleana Formation and its equivalents were deposited in this trough in Late Devonian and Mississippian time. Rapid

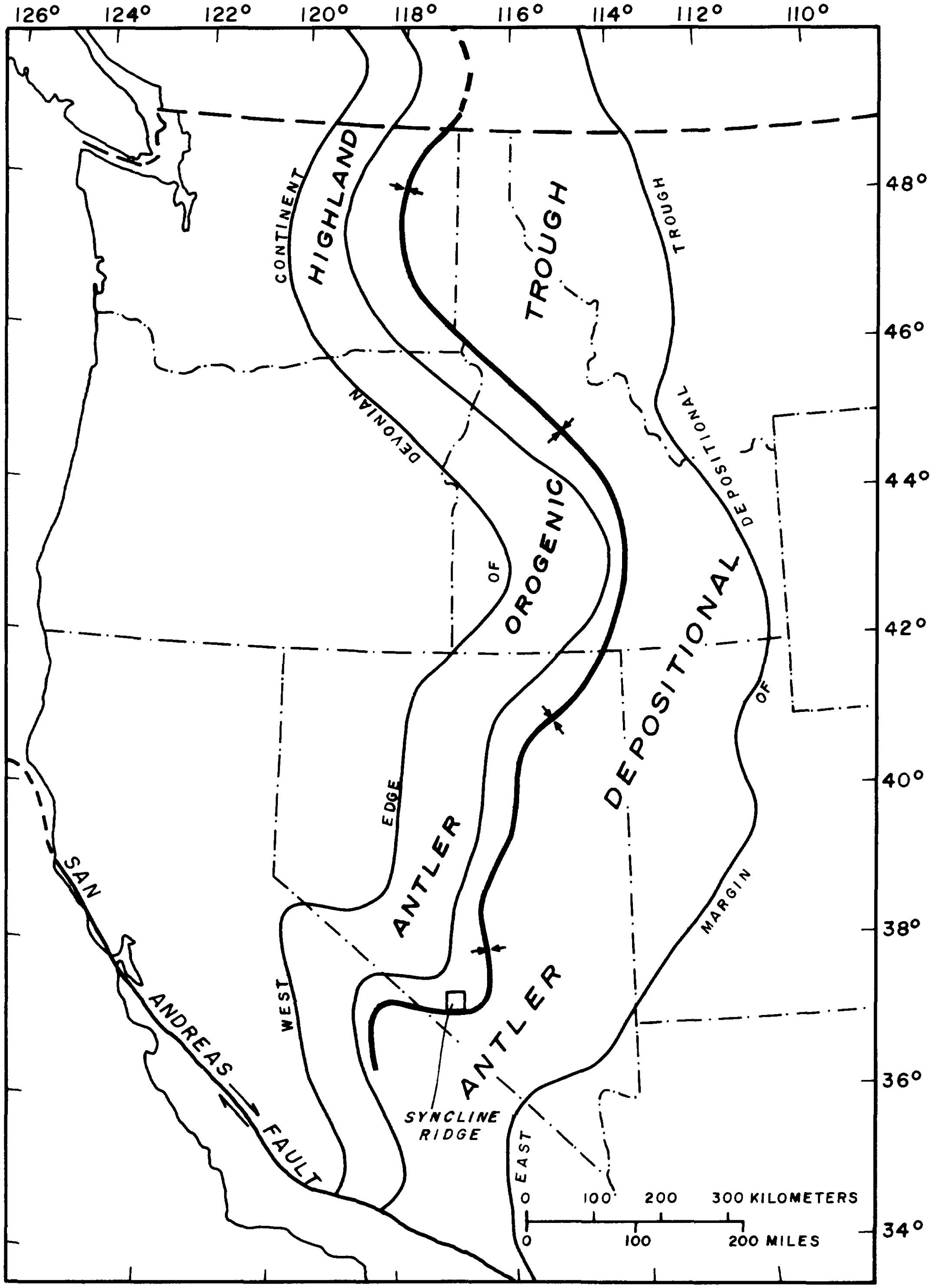


Figure 4.--Structural and depositional framework of the Eleana Formation and its Late Devonian and Mississippian equivalents in the Western U.S. [Modified from Poole, 1974]

uplift of the highland and rapid subsidence of the basin caused deposition of thick sequences of predominantly siliceous sediments derived from cherts and volcanic and granitic rocks of the highland. Quiescence of the basin caused deposition of limestones in units A and I. Near the end of the Antler orogeny, a low highland and deep weathering resulted in deposition of predominantly clay minerals in unit J. Rapid deposition of the Eleana Formation in deep water produced uniform rocks with thicknesses and extent more than sufficient for a repository site.

The rock types in units G-J in the Syncline Ridge area include both siliceous and argillaceous clastic sediments. Only unit I contains significant amounts of limestone. The siliceous clastic sediments, almost entirely quartz, were deposited as mudstones, siltstones, sandstones, and conglomerates. Regional deformation and metamorphism transformed these rocks into siliceous argillite[1], siltstone, quartzite, and conglomerite that fracture across grain boundaries. Thin limestone beds were recrystallized to medium- to coarse-grained textures.

Argillaceous (clay-rich) clastic sediments were transformed by regional deformation and metamorphism into soft, thoroughly sheared argillite. Much of this shearing is not visible in a fresh core, but on exposure and release of stress, the core will commonly break along closely spaced shear planes. Argillite is easily distinguished from siliceous argillite; a knife will readily groove argillite, but will only grate over the surface of siliceous argillite. Argillite in drill holes in the Syncline Ridge area generally has a resistivity of less than 30 ohm-m whereas siliceous argillite has a resistivity of more than 50 ohm-m. Resistivities between 30 and 50 ohm-m are rarely seen.

---

[1]In the Eleana Formation, argillites are of two types: siliceous, containing more than 90 percent quartz, and argillaceous, generally containing less than 45 percent quartz with clay minerals, other sheet-structure minerals, and carbonates. The siliceous argillites were derived from the thick sequences of chert in the highlands. The term argillite is defined as "A compact rock, derived either from mudstone or shale (claystone or siltstone), that has undergone a somewhat higher degree of induration than is present in mudstone or shale....." (Gary and others, 1972). Because most mudstones and shales contain predominantly clay minerals, the term argillite is normally thought of as containing predominantly clay minerals or other sheet-structure minerals. However, the definition of mudstone and shale is based on grain size, not mineralogy.

To avoid confusion of siliceous and argillaceous argillites, the term "siliceous argillite" is used in this report for argillites containing more than 90 percent quartz and breaking along fractures into small angular blocks. "Argillite" refers to those rocks generally containing less than 45 percent quartz and breaking along shear surfaces into thin chips.

Argillite is divided further into low-quartz argillite (less than 25 percent quartz) and high-quartz argillite (25-45 percent quartz). Low-quartz argillite is a much weaker rock than high-quartz argillite. The significance of high- and low-quartz argillite is discussed in detail in the Engineering Geology section.

Unit G

Unit G crops out only in the northwest corner of the Syncline Ridge area on the west side of the Eleana Range (fig. 3). The stratigraphic thickness is about 450 m. The base of the unit is not exposed in the Syncline Ridge area, but just north of Grouse Canyon, unit G lies unconformably on unit E. Unit G is seen within the Syncline Ridge area only in the upper plate of a thrust fault. It may be more than 2,000 m below the surface beneath the central part of the area because of folding within stratigraphically higher units.

Unit G is predominantly brown, grayish-brown, and yellowish-brown quartzite (75-80 percent) with conglomerite (15-20 percent) and small amounts of siliceous argillite and argillite (5 percent or less). The unit characteristically forms prominent brown to grayish-brown hills with steep sides. The argillite is present in intervals a few meters thick.

Unit H

Unit H crops out in the Eleana Range as a thrust plate, below the thrust plate, and also in the center of the anticline that forms Mine Mountain. Unit H has a stratigraphic thickness of about 425 m at Mine Mountain (fig. 3). This unit has not been penetrated in drill holes within the Syncline Ridge area. Unit H probably is at least 2,000 m below the surface in the central part of the Syncline Ridge area.

Unit H is predominantly gray to brownish-gray siliceous argillite (80-85 percent) with interbedded finely to coarsely crystalline limestone (10 percent) and quartzite and conglomerite (5-10 percent). In the Mine Mountain area hydrothermal alteration has changed the normal medium gray to brownish-gray color to a mottled red and gray appearance. The limestones, quartzites, and conglomerites are a few meters thick. On outcrop, unit H forms prominent hills with moderate to mostly steep slopes.

Unit I

Unit I crops out in the Eleana Range north of Red Canyon and on the west side of Mine Mountain (fig. 3). It is present in both the upper and lower thrust plates in the Eleana Range. The stratigraphic thickness of unit I is about 160 m. This unit has not been penetrated in drill holes within the Syncline Ridge area. It is at least 2,000 m below the surface in the central part of the area; less than 1,000 m at the western edge, and 1,000-2,000 m at the eastern edge.

Unit I is predominantly gray to brownish-gray limestone in beds less than 1-2 m thick. Thin intervals of argillite are present in the top of unit I in the Eleana Range and in the top and bottom of the unit on Mine Mountain. On outcrop, unit I is distinguished from other units by its banded appearance. Unit I forms predominantly moderate slopes with ledges.

Unit J

Outcrops of the Eleana Formation in the Syncline Ridge area are mostly unit J. Unit J also crops out on the flanks of the Mine Mountain anticline (fig. 3). The total stratigraphic thickness of unit J is approximately 1,100 m. Due to structural deformation, the base of unit J is 1,000-1,500 m or more below the surface in the Syncline Ridge area.

Unit J has been divided into lower, argillite, and quartzite subunits, in ascending order. These subunits are easily identified not only throughout the Syncline Ridge area, but also in the Calico Hills area in southwestern NTS (fig. 1). The subunits in drill holes are identified by cuttings and correlated by electric logs. Comparisons to the Calico Hills section are made to demonstrate the continuity of the subunits and lithologies of unit J.

Lower subunit.--The lower subunit forms most of the Eleana Range on either side of the Pahute Mesa road (fig. 3). Further north in the range, the subunit crops out east of the thrust fault forming the crest of the range. The lower subunit also crops out on the flanks of Mine Mountain. The stratigraphic thickness is estimated to be 300 m.

The lower subunit is predominantly dark gray to black siliceous argillite and siltstone. The upper 50-100 m of the subunit may contain argillite. Limestone, quartzite, or conglomerite that are a few meters thick are scattered through the subunit. The lower subunit is similar to unit H in lithology and appearance, but it is lighter in color and contains fewer interbeds of limestone, quartzite, and conglomerite than unit H. The lower subunit weathers into subsequent blocky fragments in contrast to the platy fragments typical of unit H. Slopes in the lower subunit range from gentle to steep and the hills are more rounded than those of unit H. The lower subunit in the Calico Hills appears to be similar but it has been highly faulted and is hydrothermally altered at many locations.

The lower subunit is at depths of more than 1,000 m in UE17e and at a depth of 1,414 m in UE1L; at the eastern edge of the Syncline Ridge area it may be 500-1,000 m or more below the surface. Complex structure may bring the lower subunit within 500 m of the surface within part of the Syncline Ridge area.

Argillite subunit.--This subunit is the only lithologic unit at NTS that may have thickness, uniformity, and engineering properties suitable for a repository site. The subunit crops out between the Eleana Range and Syncline Ridge, north of Red Canyon at the eastern foot of the Eleana Range, and on both sides of the Pahute Mesa road west of the Eleana Range (fig. 3). The subunit is easily eroded and is therefore exposed only along washes and on steep slopes of ridges capped by early Quaternary alluvium.

The stratigraphic thickness of this subunit is estimated to be about 700 m. Due to deformation, thicknesses in drill holes may be more than 850 m. In the UE17e drill hole, an incomplete section 841 m thick was corrected to a true thickness of 533 m using core dips. Folds significantly increasing the stratigraphic thickness are unlikely, but numerous faults of unknown displacement are present in the UE17e drill hole (Hodson and Hoover, 1979) that may decrease (or increase) the thickness. Correlation of UE17e with UE1L, which penetrated the entire subunit, indicates that 700 m is a reasonable estimate.

The argillite subunit is predominantly argillite with one quartzite bed near the middle of the subunit and at least three quartzite intervals near the base. Quartzite makes up less than 5 percent of the subunit. The base of the subunit is at the top of a recrystallized limestone containing fossil fragments and rounded black chert pebbles and cobbles. The lithologic section is the same in both the Syncline Ridge area and in the Calico Hills (fig. 5). The position of the quartzites is only an approximation because of faulting and alluvial cover that prevent the accurate location.

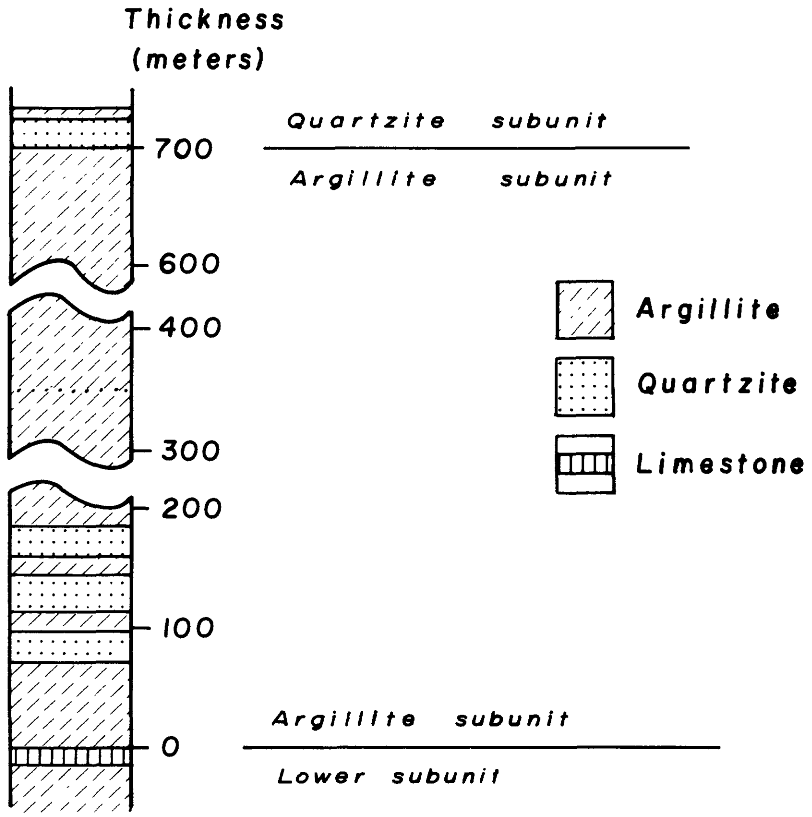


Figure 5.--Lithology of argillite subunit, unit J, Eleana Formation, showing approximate locations of quartzites in subunit.

The argillite is dark gray to black and ranges from laminated to thick bedded. Bedding planes tend to be obscured and can be seen only by wetting the core. It would appear that bedding planes are marked at the planes by small differences in composition, such as organic content or source materials. In the upper 50 m of the subunit, evidence of deposition by turbidity currents is sometimes present in the form of disoriented bedded fragments.

The original mineralogy of the argillite probably included montmorillonite, kaolinite, quartz, carbonates, and small amounts of feldspar. Regional metamorphism at low temperatures has transformed the original minerals to illite and mixed layer illite-montmorillonite, kaolinite, siderite, quartz, ankerite, pyrophyllite, feldspar, and small amounts of chlorite, calcite,and pyrite. Pyrite is present as sparse clots as much as 5 cm in diameter and disseminations near bedding planes. Fractures contain calcite, quartz, and clay minerals. Iron staining is present in fractures in the weathered zone.

The argillite subunit contains thin layers of low-quartz argillite (less than 25 percent quartz) separated by high-quartz argillite (25 to 45 percent quartz). In the UE17e core, the two types of argillite were visually distinguished by their appearance. Low-quartz argillite is soft, easily deformed by handling, has a heavy mud cake when freshly removed from the core barrel, and cracks irregularly upon drying. When immersed in water, the dry core will decompose into mud with a few lumps. High-quartz argillite, when freshly cored, is solid, undeformed, and has little or no mud cake. Unless fractured, high-quartz argillite does not crack after drying. Immersion in water has no apparent effect on high-quartz argillite.

The incompetency of low-quartz argillite might affect construction of a repository facility. The possible origin, abundance, frequency, and thickness of low-quartz argillite are discussed in the Engineering Geology section.

Quartz veins in the argillite subunit contain white, coarsely crystalline quartz. Small amounts of very fine grained pyrite and calcite occur in a few veins. The veins are 1 to 65 mm wide; most are less than 5 mm wide. Undeformed quartz crystals range from 1 mm and equidimensional to 3X3X10 cm. A tensional origin of the quartz veins is indicated by:

1. Angular fragments of argillite enclosed by quartz.
2. En echelon pattern of some veins.
3. Pinching and swelling of some veins.

Formation of the quartz veins prior to Mesozoic compressional deformation is indicated by:

1. Gentle to tight folding of numerous veins.
2. Brecciation of quartz in some veins.
3. Shearing at the edges of, or along selvedges within, some veins.

Lack of brecciation in many veins and the coarsely crystalline nature of the quartz indicates recrystallization after much of the Mesozoic deformation.

Quartzites in the argillite subunit were originally deposited as pure, well-sorted quartz grains. Lithologies now range from quartzitic sandstone with quartz grains welded at their contacts and visible porosity to dense, glassy quartzites without visible porosity. The quartzite bed near the middle of the subunit ranges from 1.2 to 2 m in thickness. The quartzite intervals in the basal part of the subunit range from 3 to 20 m in thickness.

The quartzites in the argillite subunit have few, if any, siltstones or very fine grained quartzite in contrast to this association in the overlying quartzite subunit. The quartzites are white to gray in color and weather to orangish brown to grayish brown. They form low ridges standing a few meters above the enclosing argillite. The continuity of the quartzites over a large area is indicated by their similar stratigraphic position in both the Syncline Ridge area and the Calico Hills.

The base of the argillite subunit was placed at the top of a solitary fragmental limestone. The limestone is light to medium gray in color and 3 to 5 m thick. It contains at least 95 percent fossil fragments and 5 percent or less black, rounded chert pebbles and cobbles from 0.5 to 10 cm in diameter. The fossil fragments can be seen only on weathered surfaces due to recrystallization of the limestone. The base of the argillite subunit was placed at the top of this limestone because it forms a readily recognizable unconformity. Argillite immediately below the limestone is included in the lower subunit. The limestone has been identified on both sides of the Eleana Range south of the Pahute Mesa road and in the Calico Hills.

Quartzite subunit.--This subunit is the uppermost lithologic unit of the Eleana Formation. It crops out at the northwest corner of Syncline Ridge and in the Calico Hills. The subunit lies directly beneath the Tippipah Limestone in the UE16d, UE16f, and UE17a drill holes. The quartzite subunit was also penetrated in the UE16b and UE16c drill holes beneath Tertiary volcanic rocks and Quaternary alluvium, respectively.

On outcrop, the unit forms low, narrow ridges or ledges of quartzite a meter or less in height separated by intervals of argillite. In the UE17e core, a descending sequence of limestone, quartzite or quartzitic sandstone, siltstone, alternating argillite and siltstone, and finally, argillite, was repeated, or partly repeated, four times. The limestone beds are about 0.3 m thick and grade from pure limestone at the top to calcareous quartzite at the base. The quartzite beds range from dense, glassy quartzite without visible porosity to a quartzitic sandstone that is welded only at grain contacts. The sandstones have pore spaces that range from open to partially or totally filled with iron oxides, calcite, or both. The quartzites and sandstones contain only sand-sized grains and appear to be entirely quartz. The siltstones are light to medium gray and apparently contain only quartz when not finely interbedded with argillite. Some of the siltstones, when interbedded with argillite, may have partings or inclusions of argillite. Siliceous argillite and argillite, both high-quartz and low-quartz, are present in the quartzite subunit. Low-quartz argillite is more abundant where argillite predominates over siltstone.

Fossils are present in a few limestone, argillite, and siltstone beds. The most conspicuous depositional features are incomplete "Bouma" structures like those described by Poole (1974); these structures indicate deposition by turbidity currents. The most prominent evidence of deposition by turbidity currents are ripped-up fragments of beds, ripple laminae, and wavy or convoluted laminae. These structures are present in interbedded siltstone and argillite with a few occurrences in quartzite.

The thickness of the quartzite subunit is estimated to be about 100 m. The quartzite subunit in the UE17e drill hole is incomplete and has a stratigraphic thickness of 65 m. The

Tippipah Limestone is about 50 m stratigraphically above the drill-hole collar; a thrust fault may be present or near the contact of the quartzite subunit and the Tippipah Limestone. Elsewhere in Syncline Ridge, at least two thrust faults are present near the contact with the Tippipah Limestone and parts of the subunit are repeated.

The base of the quartzite subunit is placed either at the bottom of the lowest quartzite or siltstone in the subunit or at the bottom of the lowest unit on the electric log that has a resistivity significantly higher than the underlying argillite subunit. The top of the subunit is placed at the top of the uppermost quartzite wherever the Eleana Formation is overlain by the Tippipah Limestone. Lateral variation in lithology is probable in the quartzite subunit, but use of the preceding criteria for correlation of the UElL, UE16d and UE16f drill holes indicates no apparent large variations in thickness of the quartzite subunit.

Tippipah Limestone

The Tippipah Limestone forms Syncline Ridge and crops out on the northwest flank of Mine Mountain and west of the Eleana Range (figs. 2, 3). The contact with the Eleana Formation at the northwest corner of Syncline Ridge and on the northwest flank of Mine Mountain are mapped as normal contacts. Drill-hole and stratigraphic evidence indicate that these contacts may be thrust faults or near thrust faults that omit part of the Tippipah Limestone.

The lower 100 to 200 m of the Tippipah Limestone is a series of interbedded limestones, siltstones, and argillites. Most of the limestones are argillic or silty; the siltstones and argillites are calcareous. A few limestones contain quartz grains. The limestones are light to dark gray and black; the siltstones and argillites are dark gray or black. Beds are usually less than 0.5 m thick. Lack of the lower part of the Tippipah Limestone near Eleana outcrops or just above the Eleana in drill holes indicates previously unrecognized thrust faults. The upper part of the Tippipah Limestone is relatively pure, light- to medium-gray limestone in contrast to the clastic rocks in the lower part. Individual beds generally range from 1 to 10 m in thickness. The thickness of this upper part is 850 to 900 m. The upper part of the Tippipah Limestone forms most of Syncline Ridge and a thrust plate west of the Eleana Range.

Tertiary Rocks

The Tertiary rocks include alluvial deposits, zeolitized bedded tuffs and nonwelded ash-flow tuffs, vitric bedded tuffs,and welded tuffs. Outcrops of Tertiary rocks are sparse and confined to the edges of the Syncline Ridge area (figs. 2, 3). Tertiary volcanic rocks crop out around the southern end of Syncline Ridge and south and west of the Eleana Range. Tertiary alluvium and volcanic rocks are present beneath Quaternary alluvium on the north and east sides of the Syncline Ridge area.

Alluvium

Tertiary alluvium was penetrated in the UE17c drill hole beneath the welded tuff of the Rainier Mesa Member of the Timber Mountain Tuff (Miocene). The upper 31 m of this alluvium contains volcanic rock fragments, but the lower 93 m is a limestone conglomerate containing only Paleozoic rock fragments. The limestone is Tippipah Limestone, probably from a thrust plate in the Eleana Range. Only a small remnant of this thrust plate remains west of the Eleana Range.

Volcanic rocks west of the UE17c drill hole are underlain by a conglomerate containing cobbles and large boulders of Tippipah Limestone. This conglomerate is probably equivalent to the limestone conglomerate in UE17c. The conglomerate rests on a surface cut on the Eleana Formation between Red and Grouse Canyons. The surface slopes relatively smoothly to the east, and is roughly parallel in slope to the Quaternary alluvium, but at a higher elevation. Parallel to slope, sparse outcrops indicate a gently rolling topography with an estimated relief of 5 to 10 m.

In the UE17c drill hole the Tertiary alluvium is 122 m thick, but in the conglomerate outcrops to the west it is less than 10 m thick. Drill holes east of Syncline Ridge have penetrated alluvium beneath volcanic rocks that is similar and probably equivalent to the conglomerate.

Volcanic Rocks

Tertiary volcanic rocks, in ascending order, include the welded tuff of Red Rock Valley north of Red Canyon and west of the Eleana Range, and zeolitized equivalents of the tunnel beds of Rainier Mesa, the Paintbrush Tuff,and the Rainier Mesa Member of the Timber Mountain Tuff on the north, west, and south sides of the Syncline Ridge area (table 1). All of the volcanic rocks are Miocene in age. Similar rocks are present in the subsurface beneath Quaternary alluvium on the north and east edges of the area. Tertiary volcanic rocks have been eroded from within most of the structural block. The thickness of these rocks is less than 200 m within most of the Syncline Ridge area. The thickness may be 200 to 500 m at the south and west edge of the Syncline Ridge area and in the valley between Mine Mountain and Syncline Ridge.

Quaternary Deposits

Quaternary alluvial deposits include either a weathered zone or a pediment gravel as basal stratigraphic units and seven different alluvial map units (fig. 6). Much of the area between Syncline Ridge and the Eleana Range from Gap Wash north to Grouse Canyon was mapped in detail. Although the mapping was not completed, it has provided most of the data in this section of this report and the Geomorphology section. Some of these deposits may be Tertiary in age. All of the alluvial deposits are mapped as Quaternary until ages can be determined for these units. Alluvial units, older than those in the Syncline Ridge area, that contain Pliocene ash-fall tuff have been found beneath Yucca Flat.

Table 1.--Stratigraphy of Tertiary rocks in the Syncline Ridge area (modified from Gibbons and others, 1963; Orkild, 1963, 1968; Colton and McKay, 1966; and McKeown and others, 1976).

Formation	Member or unit	Rock type
Timber Mountain Tuff	Ammonia Tanks Member	Welded tuff
	Rainier Mesa Member	Welded tuff
Paintbrush Tuff		Vitric to zeolitized bedded tuff
	Tiva Canyon Member	Welded tuff
	Topopah Spring Member	Welded tuff
Stockade Wash Tuff		Nonwelded tuff
Belted Range Tuff	Grouse Canyon Member	Welded tuff
Tunnel beds		Vitric, argillized, or zeolitized bedded, and nonwelded tuff
Tuff of Crater Flat		Welded tuff
Tuff of Redrock Valley		Welded tuff
Alluvium		Conglomerate

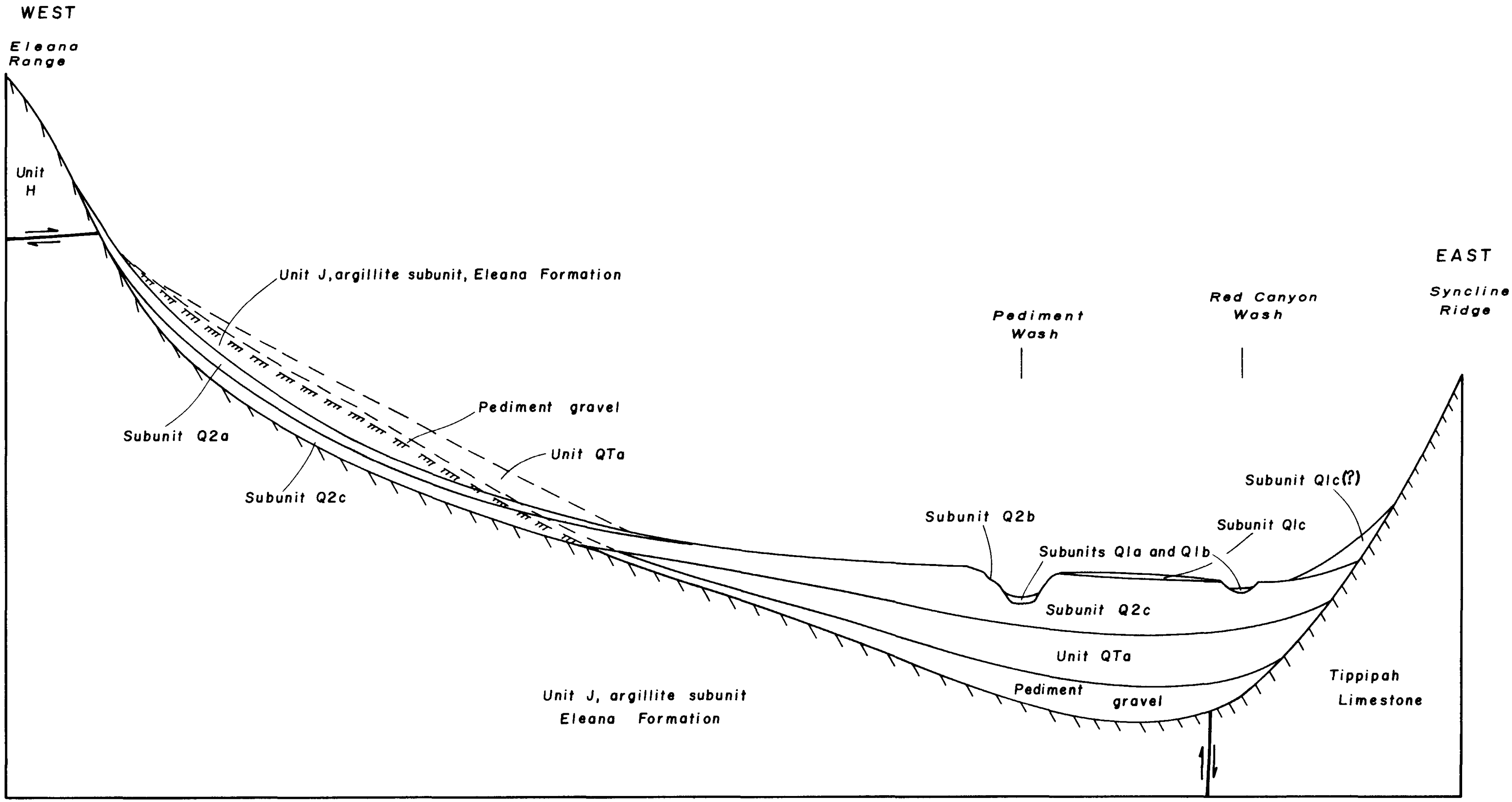


Figure 6.--Schematic cross section of Quaternary deposits between the Eleana Range and Syncline Ridge. Dashed lines show pediment gravel and unit QTa projected from ridge just north of cross section plane. Weathered zone is not shown; present east of Syncline Ridge only. Not to scale; length of cross section about 3.5 km.

The alluvial units overlying the weathered zone or the pediment gravel were mapped on the basis of differences in their drainage, desert pavements, soils, caliche, topographic expression, topographic relationships, depositional environments, and lithology. The alluvial units are divided into three units in ascending order--units QTa, Q2, and Q1. These units are separated by regional unconformities. Units QTa, Q2, and Q1 have been recognized throughout the NTS area and in the Lathrop Wells area southwest of NTS.

Units QTa, Q2, and Q1 differ in the Syncline Ridge area in their lithology and in their depositional environment. The ratio of volcanic rocks to Paleozoic sedimentary rocks changes from 1:1 to 2-4:1 to greater than 4:1 for units QTa, Q2, and Q1, respectively. These ratios are approximate and are a general characteristic that reflect drainage development in the Eleana Range and in the volcanic rocks west of the Eleana Range. Local sources can greatly affect the ratios, but the ratios are characteristic for the area as a whole. Depositional environments inferred from outcrops also reflect drainage development in the Syncline Ridge area. In unit QTa the predominance of debris flows is indicated by poor sorting, large boulders, and poorly developed bedding throughout the unit. In unit Q2, waterlain deposits are equal or slightly greater in volume than debris flows and are indicated by moderate to good sorting, few boulders more than 0.5 m in diameter, and well-developed bedding. In unit Q1, waterlain deposits predominate in volume over debris flows. The change from predominantly debris flows in unit QTa to predominantly waterlain deposits in Q2 and Q1 is a reflection of the development of drainage and lessening of slopes supplying those deposits through time. The change may also reflect climatic changes through time.

Weathered Zone

The Eleana Formation in the UE1L drill hole has a weathered zone 58 m thick beneath 61 m of older and middle fan deposits. The weathered zone is pale red to pale reddish brown and contains abundant clay. This weathered zone was also penetrated in the UE1a drill hole at the east edge of the Syncline Ridge area. The weathered zone represents a period during which the climate was much more humid than the present, and during which the Syncline Ridge area and Yucca Flat were tectonically and geomorphically stable. Any tectonic or geomorphic instability would have caused destruction of the weathered zone.

The weathered horizon has been found only east of Syncline Ridge in drill holes and by geophysical surveys. The lack of weathering in the Eleana Formation beneath the pediment gravel west of Syncline Ridge indicates that the pediment gravel is probably younger than the weathered horizon. Preservation of the weathered zone implies burial of the zone shortly after formation. Burial of the weathered zone would seem to require eastward tilting of the Syncline Ridge area because the deep basin east of the Syncline Ridge area would have caused erosion. Stripping of the Eleana Formation west of Syncline Ridge to form a pediment does not conflict with eastward tilting and burial of the weathered horizon.

Pediment Gravel

A pediment gravel that contains only fragments of Eleana quartzite, conglomerite, and sparse limestone is exposed between Syncline Ridge and the Eleana Range. The pediment and its gravel are exposed west of Pediment Wash between Red Canyon and Gap Wash and west of the Mid Valley road south of Gap Wash. Probable equivalents of the pediment gravel were penetrated in drill holes east of the pediment exposures.

The pediment gravel contains one-third or less sand and smaller sized particles. The larger fragments range from pebbles to boulders with most fragments less than 0.25 m in diameter and a maximum diameter of 1 m. Sand and smaller sized grains are angular; larger fragments are angular to subangular. Most of the larger fragments are flat prisms with the maximum dimension from 2 to 5 times the smallest dimension. No volcanic fragments were found in more than 50 m^2 of the walls of a trench cut through the pediment gravel or in sand-sized material from the trench walls. All of the fragments in the pediment gravel were apparently derived from unit H or the lower subunit of unit J of the Eleana Formation that forms the Eleana Range at the west edge of the pediment.

Exposures of the pediment gravel are covered by a flat, very dense desert pavement with brownish-black to black, shiny desert varnish. Scattered cobbles and boulders of volcanic rocks from the overlying unit, QTa, are imbedded in the pavement. Beneath the desert pavement is a compound soil formed by a vesicular A horizon overlying an argillic B horizon.

The A horizon is pale brown to light brownish gray and from 10 to 30 cm in thickness. The A horizon contains mostly silt-and clay-sized particles with small amounts of very fine grained sand sizes. The upper 5 to 10 cm is vesicular and usually contains less carbonate than the lower nonvesicular material. The A horizon contains less than one-third pebbles and cobbles in some locations and often contains no fragments larger than sand size where its thickness is greater than 20 cm.

The A horizon is believed to be eolian because:

1. Carbonate content of the A horizon is high where it should be leached. Caliche always underlies the A horizon and indicates a source other than the A horizon.

2. The mineralogy of the A horizon is virtually constant on alluvium that differs greatly in composition and age. Montmorillonite and clinoptilolite in the A horizon are present on quartzitic or argillitic alluvium as well as alluvium containing volcanic rocks. Similarly, montmorillonite and clinoptilolite are present in the A horizon on the pediment gravel, QTa alluvium, and all Q2 surfaces at several greatly differing elevations.

3. The presence of an argillic B horizon beneath a relatively unleached A horizon or the A horizon lying directly on caliche where the B horizon has been stripped also suggests an eolian A horizon.

The B horizon has been stripped from most areas and is present only on a few of the widest ridges that are flat rather than visibly convex. The B horizon is reddish brown, argillic and may contain silica cement or occasionally thin plates of opal or chalcedony. Except where disturbance of the soil is obvious, the B horizon contains no fragments larger than sand size.

The soil is underlain by a Stage IV (Gile and others, 1966) pedogenic caliche that cements the entire thickness of the pediment gravel. The caliche sequence in the trench cut through the pediment gravel, in descending order, is: dense, hard, laminated Stage IV caliche (1 cm) containing very few sand grains; dense, hard Stage IV caliche (2 to 4 m)

cementing larger fragments and separating sand grains grading into soft, porous State III caliche (1 to 2 m) that contains scattered hard nodules and fills all pore spaces in the gravel in the underlying weathered Eleana and in fractures in the Eleana.
The uppermost laminated caliche identifies the pediment gravel on slopes where it is overlain by unit QTa and outcrops of the pediment gravel are poorly exposed.

The pediment gravel is approximately 5 m thick where the pediment is exposed. East of the pediment exposures, probable equivalents of the pediment gravel are 25 to 50 m thick in drill holes north of Gap Wash. These equivalents, which contain only Eleana fragments, probably were deposited at the foot of the pediment slope. The lack of volcanic fragments in the pediment gravel and their presence immediately above the pediment gravel as boulders up to 10 m in diameter indicate that the pediment was cut before drainage onto the pediment was developed beyond the crest of the Eleana Range and after volcanic rocks on the east side of the range had been removed by erosion.

The pediment is confined to the area between the Eleana Range and Syncline Ridge that is drained by Gap Wash. A former drainage divide marks the northern edge of the pediment. The drainage divide is just south of the present-day Red Canyon and its former drainage to the east that lies north of Syncline Ridge.

Unit QTa

Unit QTa forms rounded hills and east-west ridges dissected by deep subparallel drainages. Drainage slopes and ridge slopes are smooth and moderate to steep. The ridges are smooth, parallel to drainages, and have accordant crests over relatively large areas. The thickness of the deposits ranges from about 15 m near the Eleana Range to 20 m in the UE17b drill hole.

Fragments in unit QTa have ratios of volcanic rocks to Paleozoic sedimentary rocks of 1:1 or slightly higher. Silt- and clay-size fragments are common throughout the unit; together with sand, the smaller grain sizes form 20 to 50 percent of these deposits. Larger fragments are as much as 10 m in diameter; 1- to 2-m diameters are common throughout the deposit. The largest boulders are at the base of the unit. Larger fragments have weathering rinds that are only a few millimeters thick. Caliche is more than 1 m thick and appears to be Stage IV. However, poor exposures and lack of a soil horizon in many areas make a pedogenic origin of the caliche uncertain. Bedding is absent to poorly developed in most exposures.

A very dense pavement is developed on wide ridge crests similar to that on the pediment gravel. The only differences are a higher percentage of fragments with a diameter greater than 0.25 m and more fragments with nearly equal dimensions in the pavement on unit QTa. Desert varnish is generally black with a shiny appearance. The soil beneath the pavement is the same as on the pediment gravel.

The sedimentary characteristics of unit QTa indicate that debris flows were the predominant mode of deposition. Although debris flows might indicate some climatic differences from the present, the presence of caliche and lack of weathering rinds indicate that the climate was semiarid. Steep slopes in the drainage basins supplying the fans of unit QTa and high runoff were probably the major causes of the debris flows.

Lack of erosion on the pediment gravel indicates that unit QTa was deposited shortly after the pediment gravel was deposited. The length of time between deposition of these two deposits is uncertain, but caliche in the pediment gravel and the different lithologies indicate that the pediment gravel and unit QTa are separate depositional units.

Unit Q2

Unit Q2 contains three subunits: subunit Q2c, fan deposits at lower elevations; subunit Q2b, terrace remnants; and subunit Q2a, fan deposits at higher elevations. These subunits have similar desert pavements and soils that differ from those of units QTa and Q1. Other characteristics differentiate the subunits.

Subunit Q2c is the oldest and most extensive subunit. Along the flanks of the Eleana Range and Syncline Ridge, subunit Q2c is a few meters thick and is at a lower elevation than unit QTa. Between Pediment Wash and Red Canyon Wash, east of Syncline Ridge and around the edges of the Syncline Ridge area, subunit Q2c is as much as 50 m thick and overlies unit QTa. Surfaces on subunit Q2c are characteristically flat to very slightly convex along the slope. Drainage patterns are dendritic to subparallel, spaced 150 to 250 m apart, and have steep sides. The drainages are developed headward with a flat bottom near the mouth, V-shaped progressing headward and a shallow concave profile covered by a desert pavement near the head. Most of the present drainages are in drainages abandoned before the pavement on subunit Q2c was developed.

Fragments in subunit Q2c have ratios of volcanic rocks to Paleozoic sedimentary rocks of 2:1 to 4:1. Local sources lower these ratios for short distances from the sources. Fragments are subangular to subrounded. Sand-size fragments commonly make up one-third of subunit Q2c and may form scattered lenses less than a meter thick. Clay-size material is conspicuously less abundant than in unit QTa. Fragment diameters greater than 1 m are rare even near source areas and most fragments are less than 0.5 m in diameter. The thickness of subunit Q2c is less than 5 m near the Eleana Range and in valleys cut into unit QTa and Paleozoic rocks. In the UE17a drill hole the subunit thickness is 22 m. The maximum thickness in the Syncline Ridge area is probably less than 60 m.

The desert pavement on subunit Q2c is very dense and smooth. The pavement contains few fragments with a diameter greater than 0.2 m and none greater than 0.5 m. Larger fragments are boulders from Q1 or Q2a imbedded in the pavement. Desert varnish on the pavement ranges from dark brown to black and is usually dull. The soil on subunit Q2c is a compound soil. The A horizon is the same as the A horizon on the pediment gravel and unit QTa except that it may be 50 cm thick on unit Q2c. The B horizon is reddish orange brown to orangish brown, argillic to cambic and contains little or no visible silica. Thickness of the B horizon varies from 10 to 50 cm. Fragments larger than sand size are usually absent in either the A or B horizons where the combined thickness is more than 20 cm. Caliche in subunit Q2c is Stage III to Stage IV and approximately 1 m thick.

Bedding in subunit Q2c is moderately to well developed. Waterlain deposits are equal to or slightly greater in volume than debris flow deposits. The presence of caliche, bedding, and the depositional environment indicate a climate similar to the present.

Subunit Q2b is present only as scattered terrace remnants on points along the major drainages west of Syncline Ridge. These remnants are a few meters wide, a few tens of meters long, and are 2 to 3 m below Q2c surfaces. Subunit Q2b in Jackass Flats typically has less than 1 m of fill on the terrace. Exposures are poor in the Syncline Ridge area, but fill on the terraces is unlikely to be much more than 1 m.

Desert pavement and soils on subunit Q2b are the same as on subunit Q2c. The pavement and soils are continuous from Q2c deposits down a smooth slope and onto Q2b deposits. The major difference between subunits Q2b and Q2c is the lesser development of caliche in Q2b. Caliche in Q2b is Stage II to Stage III and is commonly less than 0.5 m thick.

Subunit Q2a is present only in major drainages at higher elevations west of Pediment Wash and overlies subunit Q2c. Subunit Q2a is similar in appearance to subunit Q2c, but differs slightly in some characteristics. Q2a has a pavement noticeably less dense than on Q2c. The pavement on Q2a contains scattered boulders from 1 to 1 1/2 m in diameter. The surface on Q2a is not as smooth as on Q2c and the profile along the slope is slightly convex. Only the vesicular A horizon has been seen on subunit Q2a, but a poorly developed cambic B horizon may be present. Caliche in Q2a has not been seen. The thickness of Q2a is less than 5 m.

Subunit Q2a is significant in that its longitudinal profile crosses the profile of unit QTa at both the upper and lower ends of the Q2a profile. This double crossing of profiles indicates tectonic activity, probably in the form of tilting of the Syncline Ridge area.

Seep Deposits

Thick plates of caliche are present on top of Q2 pavements in and near the mouth of Red Canyon Wash. Two deposits of caliche plates lie on subunit Q2b and two lie on subunit Q2c.

Caliche plates are 3 to 8 cm thick and 15 to 20 cm across. The caliche is nearly pure and contains only a few sand grains. The plates are usually dense, but porous zones can be found. Both surfaces of the plates can be very irregular with relief as much as a centimeter. The irregular surface texture may be caused by dissolution, but some surfaces have textures suggesting algal growths. Concentric growths in porous zones also suggest algae. Some caliche plates contain ovoid structures 1 to 4 mm in diameter that may be gastropods or ostracods.

An elevation higher than Q1 wash deposits and the lack of alluvial material in these caliche deposits indicates that the caliche is older than Q1 deposits. The location of the caliche plates, their stratigraphic position and the textures seen in the plates suggest that the plates represent remnants of seeps at the mouth of Red Canyon Wash active between deposition of Q2 and Q1 deposits.

Unit Q1

Unit Q1 is divided into three subunits: subunit Q1c, fan deposits overlying unit Q2 and small fans at the mouth of Syncline Ridge drainages; subunit Q2b, inactive wash deposits; and subunit Q2c, active wash deposits. Subunit Q1c is relatively smooth but subunits Q1b and Q1a typically have a bar and swale topography with a relief of 0.5 to 1 m. Subunit Q1c probably is present in Gap Wash, but is recognizable only where it overlies Q2 deposits or in small fans bordering Syncline Ridge. Subunits Q1b and Q1a are present only in washes.

Sand- and pebble-size fragments are more abundant in Q1 subunits than in Q2 subunits, usually making up 50 to 75 percent of the deposits. Clay-size material is rare. Boulders are less than 0.5 m in diameter; larger boulders are reworked from older alluvium. Boulder trains and patches are a distinctive characteristic of Q1 deposits.

Pavements and varnish have not formed on Q1 deposits. Soils on Q1 are poorly developed. Soils have been found only in sand-size material in subunit Q1c and consist of a few centimeters that are leached of carbonate. Caliche is Stage I and consists of thin films on the bottoms of pebbles. Small fans at the foot of drainages from Syncline Ridge are thoroughly cemented by calcrete that forms a crust several centimeters thick.

Absolute Age of Quaternary Deposits

Definite ages of the Quaternary deposits in the Syncline Ridge area are not known because few absolute ages have been determined, and because interpretation is ambiguous for the few age dates in the Quaternary at NTS. Two samples of caliche in the pediment gravel were dated by the uranium disequilibrium-series method. These samples were taken from a trench (fig. 7) cut through a narrow ridge standing 15 to 25 m above valleys containing Q2c and Q2a deposits. Soft nodular Stage IV caliche at the base of the pediment gravel was dated as 128,000$\pm$ 20,000 years old (B. J. Szabo, written commun., 1977). The layer of soft caliche parallels the contact between the pediment gravel and the Eleana Formation that dips 12° into the ridge. Thinly laminated, dense, Stage IV caliche from the top of the caliche in the pediment gravel was dated as >5,000 years old. This laminated caliche dips toward the valley.

These age dates imply that the valleys were cut after 128,000 years and before 5,000 years ago. The age of the Q2 deposits in the valleys are, therefore, less than 128,000 years old. The Bishop ash (informal), 700,000 years old, was found in three locations around southwestern NTS in an eolian sand near the base of Q2 deposits. Fan deposits overlying the eolian sand have the same characteristics as Q2 deposits in the Syncline Ridge area. Although the Bishop ash in Q2 deposits may seem to be in conflict with the 128,000-year age of caliche in the pediment gravel, the conflict may be explained by:

1. The ash is not the Bishop ash. This explanation appears to be unlikely because of correlation and because of a lack of younger sources for the NTS area.

2. The caliche was deposited later than the Q2 deposits in the adjacent valleys. The lack of solution and redeposition features in the caliche and the dip away from the adjacent valleys of the 128,000-year-old caliche seem to eliminate this possibility.

3. The Q2 deposits in the valleys of the Syncline Ridge area are younger than both the Bishop ash and the caliche. This explanation is the most probable because certain characteristics of the Q2 deposits indicate that these deposits span a long period of time. The correlation of Q2 subunits between Yucca Flat and southwestern NTS is based almost entirely on surface features. The Q2 surface has an angular relationship to the Bishop ash. At some locations the pavements, soils and caliche clearly cut across bedding in Q2 alluvial deposits.

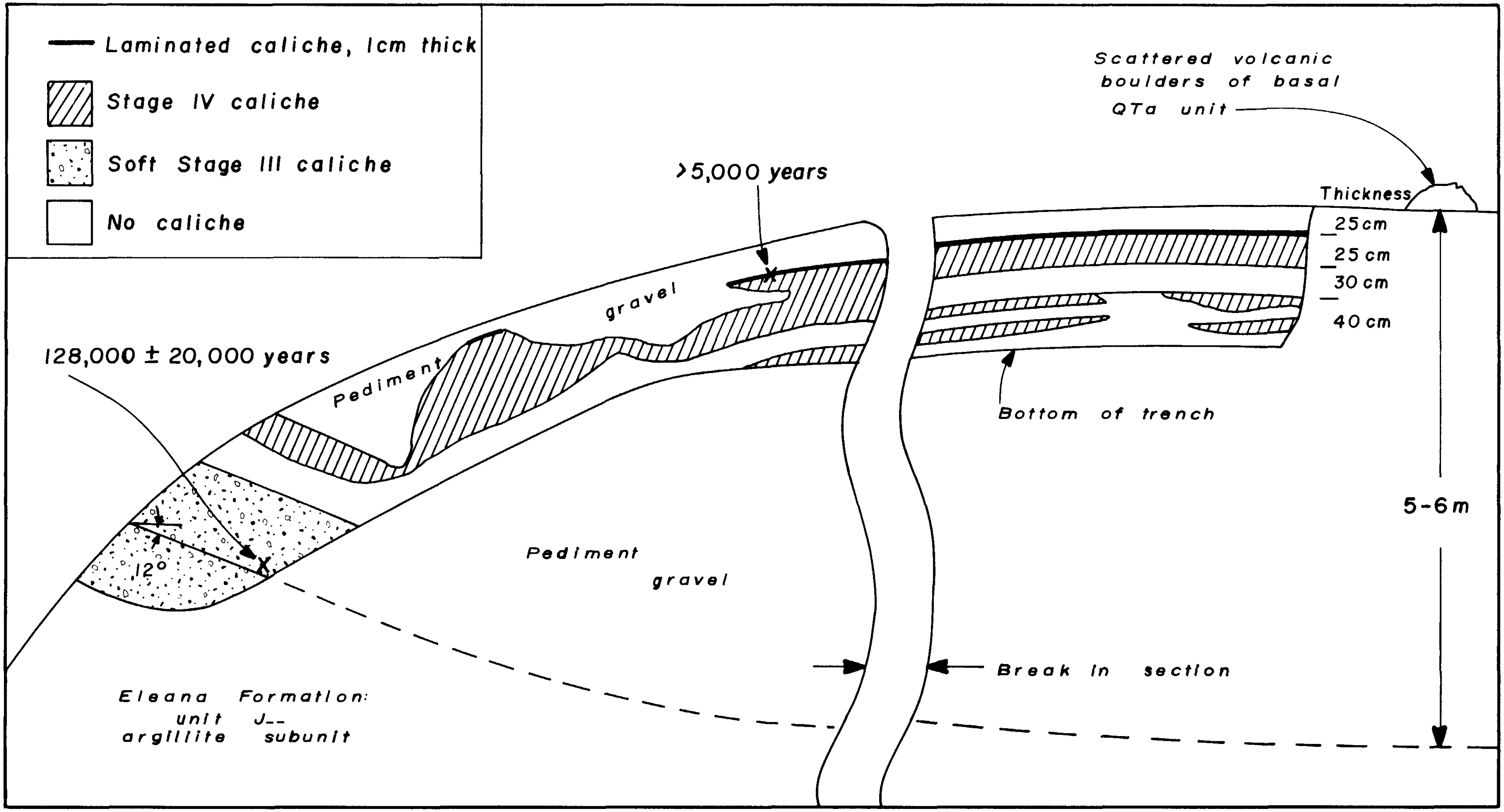


Figure 7.--Schematic cross section of trench cut through pediment gravel showing location of samples collected for age dating of caliche. Length of trench is about 25 m. [Modified from A. T. Fernald, written commun., 1977]

The almost complete smoothing of Q2 drainages and, in some areas, obliteration of the typical conical shape of alluvial fans suggests that the surface on the Q2 deposits was formed over a long period of nondeposition. These features all suggest that the valleys in the Syncline Ridge area could have been formed after the deposition of the caliche and the Bishop ash.

The lack of soil development, resumption of alluvial fan deposition, and deep erosion of the Q2 deposits is almost conclusive evidence that the Q1 deposits are Holocene. The boundary between the Pleistocene and Holocene has been placed at about 11,000 to 12,000 years ago. Van Devender and Spaulding (1979) present plant fossil evidence that indicates the desert vegetation did not appear until 8,000 years ago. Alluvial fans and deep erosion would seem more consistent with desert vegetation than the juniper-piñon forests that were present before 8,000 years ago.

The age of Q1a deposits in Red Canyon are known from tree-ring dates of a juniper. The juniper is growing on a Q1b terrace about 0.8 m above the Q1a deposits in the present wash. Erosion of the Q1a wash, probably during a single storm, exposed 70-year-old large roots. This exposure is clearly recorded as being 50 years ago in the 120-year record in a core of the trunk. The erosion of the Q1a wash is consistent with observations throughout the Southwest of erosion that began about 1840.

STRUCTURE

The Syncline Ridge area is bounded by Mesozoic, Tertiary, and Quaternary faults and fault zones. The area is divided into three blocks by Mesozoic lateral faults (fig. 2). Deformation within the Syncline Ridge area is mostly Mesozoic, but Tertiary and Quaternary faults are present at the edges of the block. Any of these deformations may affect the suitability of the area for a repository site.

Regional Setting

The Syncline Ridge area is located at the west edge of Yucca Flat between the Timber Mountain caldera and the fault blocks of Yucca Flat (fig. 8). The area lies at the west edge of the NTS seismic zone. Carr (1974) has inferred an offset of the Walker Lane shear zone near the Syncline Ridge area. Late Tertiary or Quaternary volcanism is present in Yucca Flat east of Syncline Ridge and in areas around NTS in the form of basalt intercalated with the alluvium. These structural features were active between 17 and about 11 m.y. ago, but the block faulting that formed Yucca Flat began less than 11 m.y. ago and perhaps less than 6 m.y. ago. Some faults such as the Yucca Fault are still active. Although not all basalts in the NTS area have been dated, the available age dates indicate that most basalts intercalated with alluvium are probably less than 5 m.y. old.

Paleozoic Deformation

During early Late Devonian time, a shallow trough began forming east of the Antler orogenic highland (fig. 4, Modified from Poole, 1974). East-directed horizontal forces during the remainder of Devonian and nearly all of Mississippian time caused deepening of the Antler

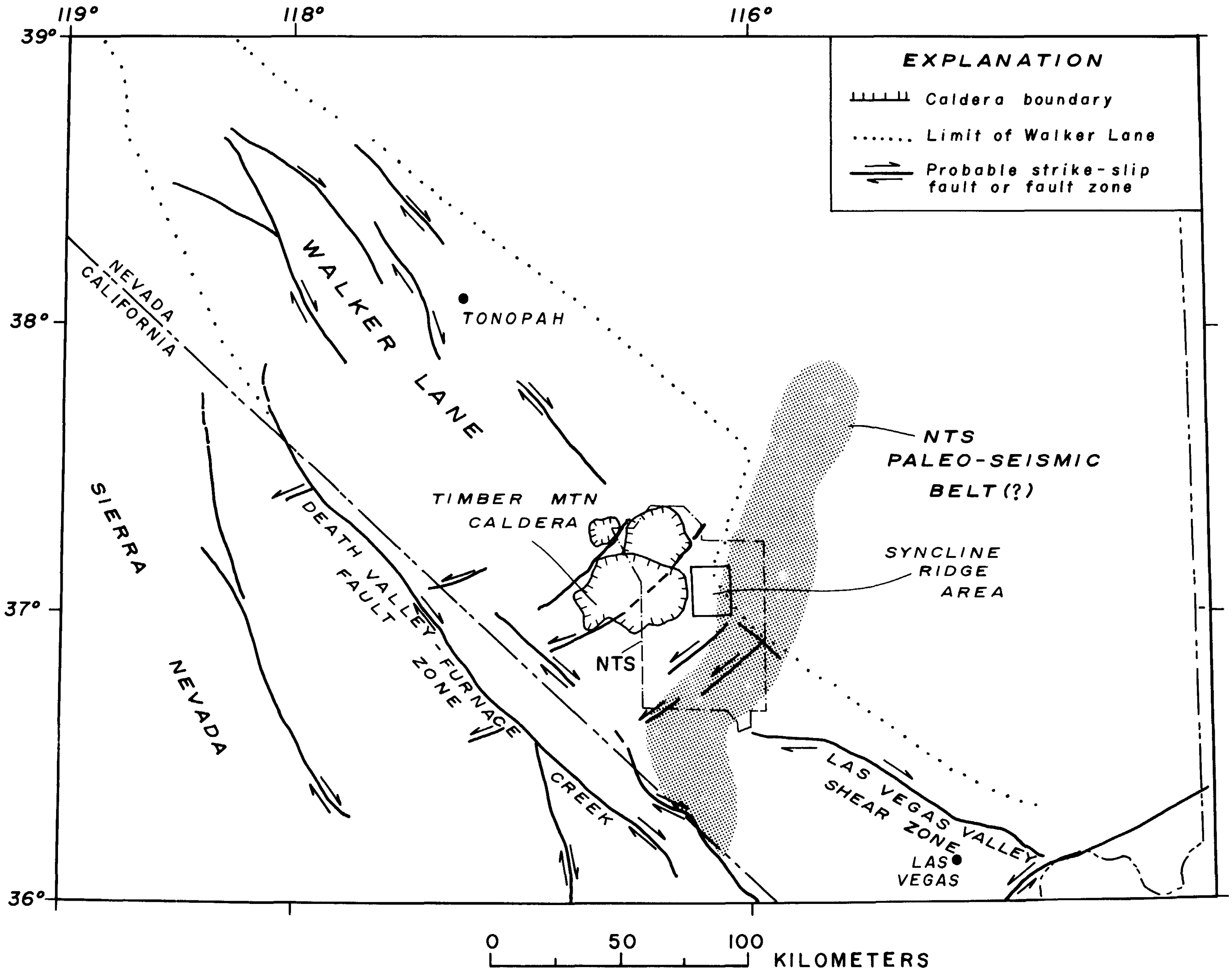


Figure 8.--Map of southern Nevada and part of California showing some major structural features near the Syncline Ridge area.

depositional trough in which the Eleana Formation and other stratigraphic units were deposited. The Antler orogenic highland was the source for the Eleana sediments. These highlands yielded mostly quartz and chert ranging from clay- to boulder-size fragments that were rapidly deposited in the foreland basin. The NTS outcrops of the Eleana are near the axis of the Late Mississippian trough which was east of Devonian and Early Mississippian axes.

Deformation during the Paleozoic Era in the depositional trough probably consisted of only large-scale folding and faulting at the basin margins. The effects of this deformation are not noticeable within the Syncline Ridge area. The tensional origin and later deformation of the quartz veins in the argillite of the Eleana Formation indicate that they may have been formed during the Paleozoic or earliest Mesozoic time. Their tensional origin may be diagenetic or it may have been caused by epeirogenic uplift. Deposition of the Tippipah Limestone indicates relative quiescence of the Syncline Ridge area during Pennsylvanian and Permian(?) time.

Mesozoic Deformation

During the Mesozoic Era the Great Basin and adjacent areas were deformed by compressional tectonics that began before or during Jurassic time (Carr, 1974). Regional structural features include the Walker Lane and Las Vegas Valley shear zones and structural bends in these zones that influenced the Tertiary faulting. In the Syncline Ridge area, the Mesozoic deformation produced folding, thrust faults, lateral faults, and high-angle normal and reverse faults. Metamorphism accompanying this deformation altered mudstones and claystones to argillite, sandstones to quartzite, and recrystallized the limestones. On a smaller scale, argillite in the Eleana Formation was thoroughly sheared and quartzites and limestones were highly fractured.

The Mesozoic structures appear simple at the surface, but geophysical surveys and data from drill holes indicate that alluvium and the Tippipah Limestone of Syncline Ridge conceal complex structures in the southern, central, and part of the northern blocks. The complexity and variation in structures of each structural block are caused by (1) contemporaneous folding, high-angle faulting and thrust faulting, (2) different strengths of quartzite or limestone and argillite, and (3) stress discontinuities at the lateral faults separating the three structural blocks.

The direction of the principal stress causing the Mesozoic deformation in the Syncline Ridge area was about N. 80° W. normal to the N. 10° E. trend of major folds and high-angle faults. Lateral faults and thrust faults are consistent with this direction. Folds and faults are bent by drag or by local stresses with an orientation different than the N. 80° W. regional compression. The faults and folds resulting from this Mesozoic deformation limit the size of structural blocks in which the argillite subunit will have continuity acceptable for a repository site.

Folds

Two N. 10° E. major folds are present in the Syncline Ridge area: the Eleana Range anticline and the Syncline Ridge syncline (fig. 3). The anticline is approximated in the south and central blocks by the crest of the Eleana Range. In these blocks, the anticline is asymmetric with steeper dips on the west side. In the northern block, attitudes in the lower subunit of unit J indicate that the anticline probably lies beneath the thrust plate that forms the Eleana Range. The lateral fault through Grouse Canyon probably terminates the anticline at the north end.

At the surface in the Tippipah Limestone, the Syncline Ridge appears to be simple with an axial fault in the south and central blocks. Seismic, electrical, and gravity data indicate that the syncline is still present beneath the Tippipah Limestone, but the deeper structure is complicated by horsts that parallel the syncline. The synclinal axis disappears beneath a fault in the northern block. Overturned beds on the upthrown, east side of the fault indicate that the fault is probably a thrust fault.

Small-scale folds have trends either perpendicular to, or at small angles to, the north-northeast trend of major structures. These small folds have a low height to width ratio. No folds were seen in the UE17e core because of the thick-bedded, homogeneous character of the argillite. Abrupt changes in dip in the core may indicate folding as well as faulting.

Thrust Faults

Only local thrust faults are present in the Syncline Ridge area. Regional thrust faults, such as the Mine Mountain and CP thrust plates, are present outside the structural boundaries of the Syncline Ridge area. Two thrust plates are present in the Eleana Range and two are present beneath Syncline Ridge (fig. 9). In the Eleana Range, units G, H, and I are thrust over unit J. Remnants of a second thrust plate of the Tippipah Limestone lie partly on the first thrust plate and partly on unit J just north of the Pahute Mesa road. Correlation of electric logs from the UE1L, UE16d, and UE16f drill holes indicates a double repetition of sections of the quartzite subunit and the Tippipah Limestone. These repetitions and lack of the lower part of the Tippipah Limestone immediately above the Eleana Formation at several locations around Syncline Ridge demonstrate that much, if not all, of Syncline Ridge is a thrust plate. Data from drill holes indicate that two thrust faults underlie the central block. Geophysical surveys indicate that these thrust faults are folded and faulted. The surveys and attitudes along the axial fault of Syncline Ridge indicate that the axial fault probably is one of the thrust faults (fig. 9). These thrust plates probably have displacements of only a few kilometers.

Complete exposure of the thrust fault between unit J and the Tippipah Limestone in the Eleana Range demonstrates why some local thrust faults may not have been recognized previously in poorer exposures. Rock that appears disturbed is only 5 to 7 m thick on either side of the fault between the argillite subunit and the overlying Tippipah Limestone. The fault breccia is dense, well cemented, and probably would not be recognized as a fault in a poorer exposure. Thrust faults in similar rocks in drill holes, recognized by repetition of correlated sections, have a similar thickness.

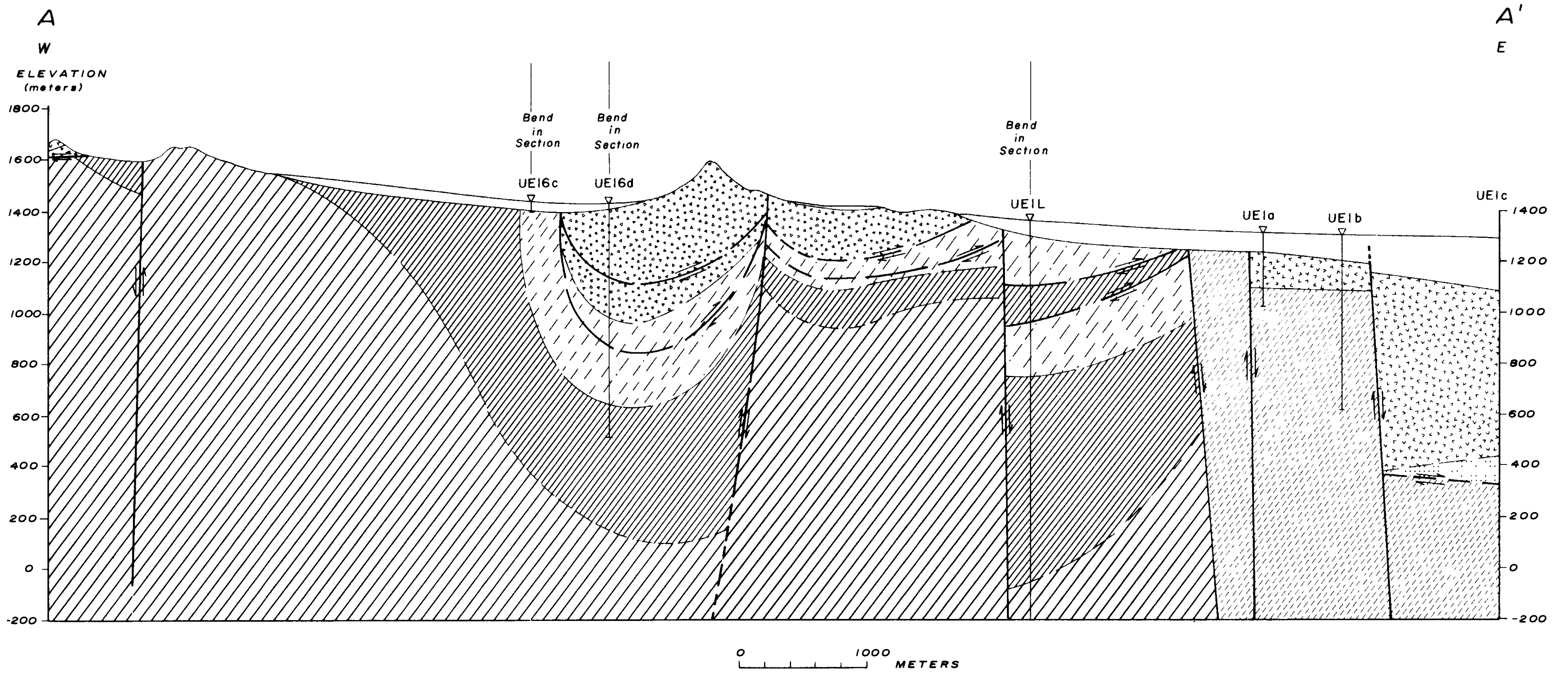


Figure 9.--Cross section through central block of Syncline Ridge area. (See fig. 3 for explanation of symbols.)

Thrust faults have not been seen and cannot be inferred in the argillite subunit. Small bedding plane faults are present, but the plastic nature of the argillite makes it too weak to transmit the stress needed for thrust faults of any size. Horizontal stresses apparently were relieved by pervasive shearing, small folds, and possibly flowage.

Lateral Faults

The Syncline Ridge area is divided by lateral faults into the southern, central, and northern blocks. Other lateral faults form the northern, southern, and probably the southwestern boundary of the Syncline Ridge area (figs. 2, 3). These lateral faults are part of a mosaic of lateral faults that may be related to an offset of the Walker Lane postulated by Carr (1974). This mosaic of lateral faults is obscured by volcanic rocks and alluvium and by Tertiary faults.

The southeast- to east-trending lateral faults bend southward at their eastern ends and are offset by, or terminate against, a south-southeast-trending fault zone. This fault zone displaces Tertiary volcanic rocks and probably the lower part of the Quaternary alluvium. The fault zone apparently offsets all Mesozoic faults intersecting it in the Syncline Ridge area and is probably the northern extension of Carr's (1974) Yucca-Frenchman flexure. These facts indicate that the south-southeast-trending fault east of the Syncline Ridge area is a Mesozoic lateral fault rejuvenated by vertical displacements during Tertiary and probably Quaternary time.

The lateral faults separating the three blocks within the Syncline Ridge area have right-lateral displacements of 200 to 1,000 m. The Grouse Canyon lateral fault has a similar direction of movement. Vertical displacement on these lateral faults in Mesozoic time was probably less than 200 m. In the few exposures available, the lateral faults are less than 20 m wide. Minor branching of these faults is apparent in the Eleana Range and can be inferred from Tertiary faults along the lateral faults. Relationships between the lateral faults, the syncline, the axial fault, and the thrust plate forming Syncline Ridge can only be explained by contemporaneity of all of these structures.

Numerous small-scale lateral faults with east or southeast trends were found by detailed mapping of the Tippipah Limestone in the central block. These lateral faults have lateral displacements less than 10 m and vertical displacements of less than a meter. The width of the faults is less than 1 m and usually less than 10 cm. Similar faults have been seen in the Eleana Formation and elsewhere in the Tippipah Limestone.

High-Angle Faults

Major high-angle normal and reverse faults with steep dips parallel the major N. 10° E. fold trends. Like the folds, these high-angle faults bend near lateral faults between the three blocks and at the Syncline Ridge structural boundaries. Only high-angle faults exposed at the surface and major faults determined from geophysical data are shown on figure 3. Other high-angle faults can be inferred from drill-hole data, but these faults are believed to have displacements of less than 100 m.

Only one high-angle fault in the Eleana Range and the axial fault of Syncline Ridge are visible at the surface. These faults are in upper plates of thrust faults, but they might begin in the lower plate. Displacements on nearly all the high-angle faults are probably 100 to 200 m, but the fault at the east edge of Syncline Ridge in the central block has a vertical displacement of more than 500 m. This displacement is based on the amount of the argillite subunit missing in an electrical sounding about 500 m west of the UE1L drill hole which penetrated 812 m of the argillite subunit. Consistent with the compressional tectonics that formed these faults, the high-angle faults apparently disturb only a thin zone of rock. Fault traces indicate that most of these faults are near vertical. Normal or reverse movement cannot always be determined because of the uniformity of the rocks they displace.

Tertiary and Quaternary Deformation

Tertiary deformation within or adjacent to the Syncline Ridge area includes the Timber Mountain caldera, Basin and Range normal faults, and rejuvenation of some Mesozoic faults by normal displacement. Quaternary deformation includes normal faults, rejuvenation of Mesozoic faults and basalt extrusion centers. This deformation was the result of regional extension along a N. 50° W. axis (Carr, 1974).

Basin and Range faults form the western boundary of the Syncline Ridge area. These arcuate normal faults (figs. 2, 3) roughly parallel major faults that scallop the caldera walls. Displacements on the western boundary faults are down toward the caldera. The last tectonic activity of the Timber Mountain caldera was pre-Thirsty Canyon Tuff, or more than 6 m.y. ago (Christiansen and others, 1977). Postcaldera movement on these faults needs further investigation; no Quaternary faulting has been noted.

Basin and Range normal faults have north-northwest to north-northeast trends around the periphery of the Syncline Ridge area. These faults form part of the boundary of the Syncline Ridge area, with the exception of the southern block, or lie just outside the boundaries. In the southern block, numerous normal faults with a northerly trend are present in the volcanic rocks. Some of these faults may be rejuvenated Mesozoic faults, but the close spacing of the faults indicates that some are probably Tertiary in age. The youngest faults are post-Rainier Mesa Member, or less than 11 m.y. old.

On the north and east boundaries of the Syncline Ridge area, normal faults and rejuvenated Mesozoic faults have northerly trends. These faults displace Tertiary volcanic rocks. The few faults that displace the alluvial surface are north of Red Canyon (fig. 3). The displacements are seen in Q2 or QTa alluvium.

A few small outcrops of Tertiary volcanic rocks are present within the area underlain by the argillite subunit between Syncline Ridge and the Eleana Range. These outcrops are north of Red Canyon and thus, no evidence of Tertiary faults has been found south of Red Canyon. No displacements of alluvium have been found in the central and northern blocks in the area south of Red Canyon. The lack of post-Mesozoic faults in the area underlain by the argillite subunit may be caused by the failure of this thick, highly plastic rock to transmit stress.

Tertiary and Quaternary rejuvenation of Mesozoic faults can be documented at several locations in the Syncline Ridge area. Elsewhere, rejuvenation is inferred from fault trends in directions typical of Mesozoic faults, but not Tertiary faults or from extrapolation of faults of probable Mesozoic age in Paleozoic rocks. The most obvious rejuvenations are the northern and southern boundaries of the area and the northern boundary fault of the graben between Syncline Ridge and Mine Mountain.

On the northern boundary a right-lateral Mesozoic fault has been rejuvenated along several faults east of the Eleana Range. This fault has no Tertiary or younger displacement in the Eleana Range or west of the range. Thick alluvium in the UE17c drill hole beneath the Rainier Mesa Member indicates that a fault scarp may have been present along the northern boundary before the Rainier Mesa Member was deposited. Fault scarps were not seen in this fault zone, probably because the zone parallels the present drainage. At the surface, north-trending Basin and Range faults paralleling the east front of the Eleana Range displace Q2 and QTa alluvium north of the rejuvenated fault.

Probable lateral faults have been rejuvenated on the southern boundary of the Syncline Ridge area. In the graben between Mine Mountain and Syncline Ridge some of the north-northeast to northeast faults forming the sides of the graben are probably extensions and rejuvenations of Mesozoic high-angle faults. These faults displace Q1 and Q2 alluvium. These faults terminate abruptly against the extension of the lateral fault separating the southern and central blocks (D. L. Healey, written commun., 1978).

Basalt has been found intercalated with alluvium in the UE1f, UE1h, and UE1j drill holes. No ages have yet been determined for these basalts, but age dates from other basalts in alluvial areas around NTS indicate that most of these basalts are less than 5 m.y. old.

POSTVOLCANIC GEOLOGIC HISTORY

A framework of the geologic history of the Syncline Ridge area is provided by the data from numerous drill holes, from geophysical surveys throughout Yucca Flat, and by deep erosion in the Syncline Ridge area (table 2). The geologic history of the Syncline Ridge area was much like that of the rest of Yucca Flat during deposition of the Tertiary volcanic rocks. After deposition of the last major volcanic unit, the Ammonia Tanks Member of the Timber Mountain Tuff, the geologic history indicates that the Syncline Ridge area was more stable and less deformed than other areas of Yucca Flat.

Yucca Flat contains three major north-south structural elements: an eastern basin, a central horst, and a western basin. The two basins coalesce in the southern quarter of Yucca Flat. The western basin and the central horst are offset to the east at the latitude of the northern boundary of the Syncline Ridge area. The geologic history of these structural elements differs from that of Syncline Ridge but their history provides some inferences on the events in the Syncline Ridge area.

The postvolcanic history of the Syncline Ridge area can be divided into four periods (table 2). The last three periods begin with tilting because tilting probably initiated most, or all, of the events that followed during that period. The events in each period are listed as though they were discrete and finite, but in reality most of these events

Table 2.--Geomorphic and structural events of the Syncline Ridge area and Yucca Flat

Period and event	Location of evidence	Age
Period I.		
1. Soil formation	Eastern basin, UE6e	Pliocene
2. Faulting	Eastern basin	Do.
3. Deposition of ash-fall tuff and alluvium;	Eastern basin	Do.
Erosion	Western basin and central horst	
4. Faulting	Eastern and western basins	Do.
5. Erosion	Syncline Ridge area, and Eleana Range; central horst(?)	Pliocene(?) and Pleistocene(?)
6. Formation of weathered zone	On Eleana Formation, east of Syncline Ridge	Pleistocene(?)
Period II.		
1. Eastward tilting	Syncline Ridge area	Pleistocene
2. Pedimentation and burial of weathered zone	do.	Do.
3. Deposition of pediment gravel	West of Syncline Ridge	Do.
Drainage development	Through Eleana Range	Do.
4. Soil formation on pediment gravel	West of Syncline Ridge	Pleistocene
5. Deposition of QTa	Yucca Flat	Pleistocene (>700,000 yrs)
6. Faulting(?)	Western basin	Do.
7. Soil formation on QTa	Yucca Flat	Do.
Period III.		
1. Eastward tilting; faulting	Syncline Ridge area; western basin	Do.
2. Dissection of QTa	Syncline Ridge area	Do.
3. Deposition of Q2c	do.	Pleistocene (<128,000 yrs)
4. Eastward tilting or faulting(?)	do.	Pleistocene
5. Erosion; deposition of Q2b	do.	Do.
6. Soil formation on Q2c and Q2b	do.	Do.
7. Eastward tilting(?)	do.	Do.
8. Deposition of Q2a	do.	Do.
9. Soil formation on Q2 deposits	do.	Do.
Period IV.		
1. Eastward tilting; faulting	Syncline Ridge area; western basin	Holocene(?)
2. Erosion	Syncline Ridge area	Holocene
3. Deposition of Q1c	do.	Do.
4. Erosion	do.	Do.
5. Deposition of Q1b	do.	Do.
6. Erosion	do.	Do. (<140 yrs)
7. Deposition of Q1a	do.	Do. (<140 yrs)

were probably continuous. The purpose of the list is to show the sequence of the periods during their major influence on the Syncline Ridge area.

The first period is incompletely known because evidence at the surface has been removed by erosion and only drill-hole data are available. This period may have extended from the deposition of the Ammonia Tanks Member, 11 m.y. ago, into the Pleistocene. Deep soil formation is the oldest postvolcanic event recorded beneath Yucca Flat. About 1 m of soil lies on the Ammonia Tanks Member in the UE6e drill hole in the eastern basin (Fernald and others, 1975). This thick soil indicates(1) a long period of weathering after deposition of the volcanics,(2) lack of erosion in the drill-hole area prior to faulting and burial of the soil, and(3) faulting shortly after soil formation. Downdropping of part or all of the eastern basin occurred shortly after the soil formation. The timing of faulting in the eastern basin is indicated not only by preservation of the soil but also by preservation of the Ammonia Tanks Member and thick sections of the Rainier Mesa Member in much of the eastern basin.

Shortly after formation of the eastern basin by faulting, ash-fall tuffs related to the Ammonia Tanks Member were deposited in Yucca Flat. Erosion west of the eastern basin during deposition of the ash-fall tuffs is indicated by interbedding of alluvium with the tuff and absence of the Timber Mountain Tuff in most of the western part of Yucca Flat. Some faulting, either during or shortly after deposition of the ash-fall tuff, is indicated by local remnants of the Rainier Mesa Member in the western basin.

Deepening of the eastern and western basins by faulting is indicated by preservation of the ash-fall tuff in the eastern basin and preservation of volcanic rocks older than the Timber Mountain Tuff in the western basin. Following the deepening of the basins, erosion stripped volcanic rocks from most of the Syncline Ridge and the Eleana Range. The boundary between the Tertiary and Quaternary periods may be within or at the end of this period of erosion. The sequence of events following stripping of the volcanic rocks is complete enough to indicate that these events could have all occurred during the Quaternary.

After stripping of the volcanic rocks from the Syncline Ridge area, a period of deep weathering occurred. This deep weathering is preserved in the form of 58 m of a weathered zone that is heavily iron-stained and contains abundant soft clay in the Eleana Formation in the UE1L drill hole. The same zone is also present at the east edge of the Syncline Ridge area in the UE1a drill hole. Geophysical surveys suggest that the weathered zone underlies alluvium in much of the Syncline Ridge area east of Syncline Ridge. The weathered zone indicates a period of structural and erosional stability. The thickness of the zone, the iron-staining, and the soft clay indicate a period of greater precipitation than the present.

The second period of events begins with eastward tilting of the Syncline Ridge. Only tilting, rather than uplift, can account for burial of the weathered zone east of Syncline Ridge and its erosion west of Syncline Ridge. The process of pedimentation west of Syncline Ridge, along with erosion in the Eleana Range supplied the alluvium that buried the weathered zone. Pedimentation occurred between Syncline Ridge and the Eleana Range from Red Canyon south to the volcanic rocks south of Gap Wash. The presence of volcanic rocks just north of Red Canyon indicates that Red Canyon probably had not cut through the Eleana Range at this time. The lack of volcanics in the pediment gravel also indicates that Gap Wash and smaller drainages were not developed through the Eleana Range at this time.

After deposition of the pediment gravel, a possible period of soil formation is indicated by a pedogenic(?) caliche in the pediment gravel, but this caliche might have been deposited at the beginning of period III. Large boulders from 1 to 10 m in diameter in the base of QTa deposits indicate development of drainage through the Eleana Range. Presence of the Bishop ash near the base of Q2 deposits in Jackass Flat indicates that QTa deposits are more than 700,000 years old. Preservation of the weathered zone, formation of the pediment, deposition of the pediment gravel, and apparent conformability of the pediment, pediment gravel, and QTa deposits indicates that very little deformation took place in the Syncline Ridge area and in the western basin during the second period. A thick, poorly exposed, pedogenic(?) caliche in QTa deposits indicates a period of soil formation prior to the tilting and faulting that began the third period.

Eastward tilting of the Syncline Ridge area at the beginning of the third period is indicated by deep dissection of the QTa deposits and by Q2 profiles that cross the pediment and QTa profiles near the Eleana Range and at lower elevations near Pediment and Red Canyon Washes. Erosion or faulting of the western basin followed by erosion would have caused only a single crossing of profiles. Some faulting in the western basin may have accompanied the tilting to accommodate the debris eroded from the QTa deposits.

During dissection of the QTa deposits, caliche may have been deposited in the pediment gravel when dissection reached the Eleana Formation. This caliche could have been deposited by underflow into the pediment gravel on top of the relatively impermeable argillite of the Eleana. Similar underflow is present today in the bottom of Red Canyon for at least a kilometer east of the Eleana Range. Deposition of the caliche in the pediment gravel would have stopped after dissection reached below the pediment gravel. An apparently undisturbed sample of caliche in the pediment gravel gave an age of $128,000 \pm 20,000$ years. This age indicates that most, if not all, the Q2 deposits in the Syncline Ridge area are younger than 128,000 years.

After dissection of QTa and the Eleana Formation deposits, as deep as 25 m between Pediment Wash and the Eleana Range, Q2c was deposited in the Syncline Ridge area. The erosion that followed deposition of Q2c may have been caused by eastward tilting of the Syncline Ridge or by faulting in the western basin of Yucca Flat. Divergence of Q2c and Q2b surfaces downstream from the upper part of Pediment Wash to Gap Wash at the west side of Syncline Ridge seem too large to be accounted for by erosion alone. Major soil development took place on Q2 deposits following deposition of Q2b. Some soil development prior to Q2b deposits is indicated by a greater development of caliche in Q2c than in Q2b. That major development of the soil took place after deposition of Q2b is indicated by the similar soils on Q2c and Q2b and on the slope between these two surfaces.

Tilting or faulting may have preceded deposition of Q2a, but Q2a is too thin and has too limited an extent to determine whether its profile crosses Q2b or Q2c twice. The Q2a deposits are present only between Pediment Wash and the Eleana Range. These deposits are found only in larger drainages dissecting QTa and the Eleana Formation. The deposition of Q2a after soil development began on Q2b and Q2c is established by the poorer pavement on Q2a and the general lack of caliche in Q2a. An age older than Q1 is established by the topographic location of Q2a above Q1 and by similarity of soils on Q2a, b, and c.

The fourth period began with faulting in the western basin of Yucca Flat. This faulting included some faults north of Red Canyon that displace Q2 deposits but not Q1 deposits. Erosion of Q2 deposits of 10 to 15 m along Red Canyon, Red Canyon Wash, Pediment Wash, and Gap Wash seems too large to be accounted for by climate only. Convergence of Q1 and Q2 surfaces from Pediment Wash upstream and downstream indicates that eastward tilting probably accompanied the faulting. Three cycles of erosion and deposition occurred after deposition of Q2 deposits. The youngest erosion and deposition are less than 50 years old in Red Canyon. The presence of only incipiently developed soils and caliche, lack of desert pavement, or varnish and bar and swale topography indicate that all the Q1 deposits are probably Holocene or less than 10,000-12,000 years old.

ENGINEERING GEOLOGY

Engineering properties of argillite are summarized in this report to demonstrate the relationship of geology to these properties. These properties are not intended to provide data for engineering studies; such studies will be reported on by the other organizations. Separate studies of engineering properties of the argillite are being made by Sandia National Laboratories, Inc., Lawrence Livermore Laboratory, and other organizations.

A. R. Lappin of Sandia National Laboratories provided the original data for the physical properites, geochemical properties, mineralogy, and chemistry sections. Paul D. Blackmon of the U.S. Geological Survey also contributed X-ray diffraction data for the mineralogy section. Thermal properties were obtained from J. H. Sass (written commun., 1978). A. R. Lappin of Sandia National Laboratories contributed data on thermal properties at elevated temperatures. M. P. Chornack of Fenix & Scisson, Inc., assisted in the fracture analysis study.

Argillite Distribution

Schlumberger vertical electric soundings were made in the Syncline Ridge area to determine the distribution of the argillite subunit. The isopach map (fig. 10) is derived from these electrical soundings. The 70 ohm-m and lower resistivity used to define the argillite subunit may not coincide exactly with the stratigraphic boundaries, but the map provides an approximation of the shape and thickness of the argillite subunit. Contours in the central and southern structural blocks are not shown because of sparse data and rapid variations in thickness.

The northern structural block might contain subsurface structures that could cause significant variations in thickness from those shown on the isopach map. Such variations seem unlikely when the density of data and the relatively uniform variation in thickness in the northern block are compared with these data in the central and southern blocks. The telluric map (fig. 11) has a broad, low resistivity area in the same area as the isopach map. This similarity indicates a continuity and thickness of argillite in the northern

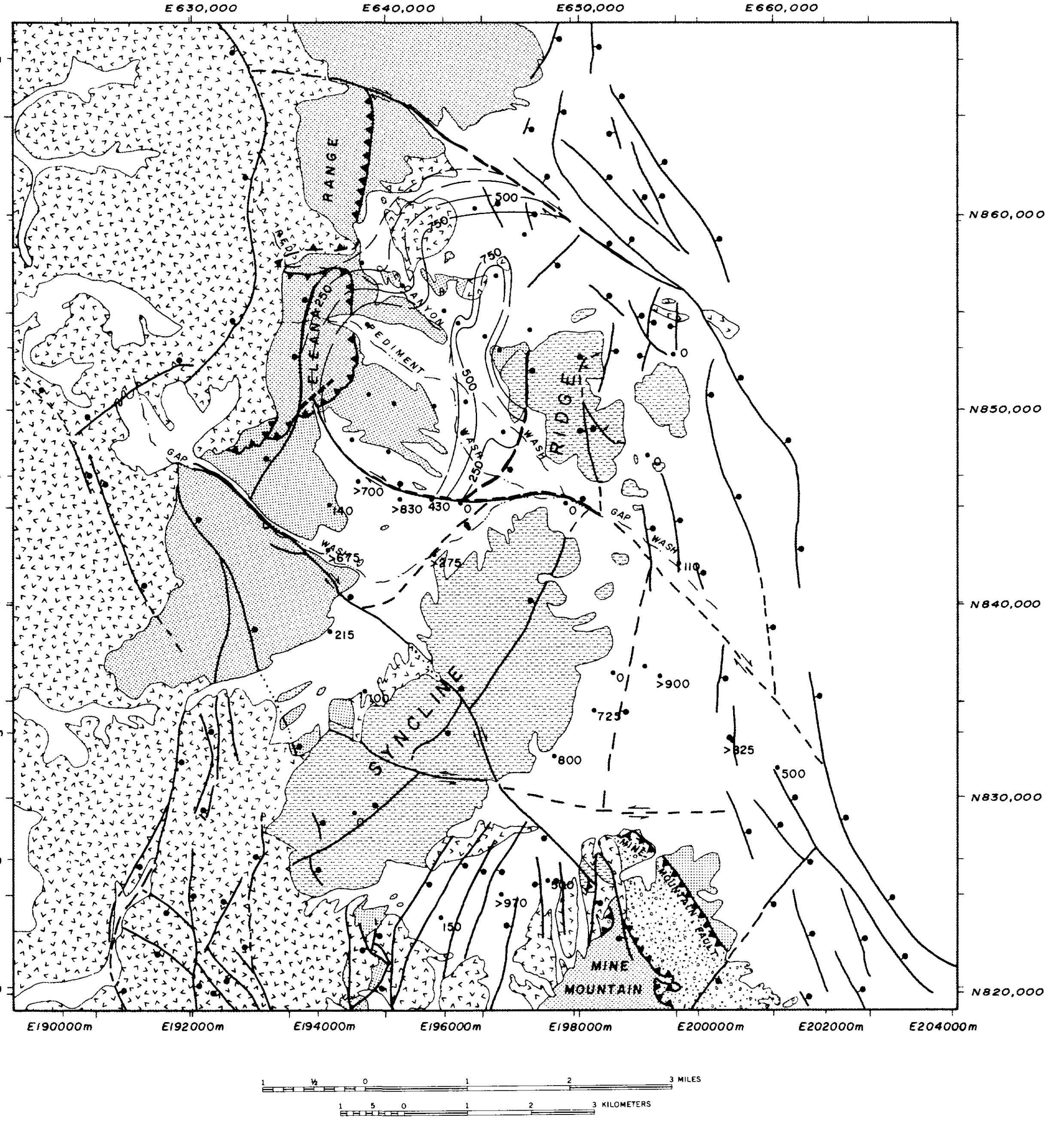


Figure 10.--Isopach map of argillite subunit. Contour interval, 250 m. Map derived from geoelectrical sections computed from Schlumberger vertical electrical soundings (VES). Argillite subunit of unit J, Eleana Formation, is defined as continuous geoelectrical section with a resistivity of less than 70 ohm-m. (See fig. 2 for explanation of other symbols.)

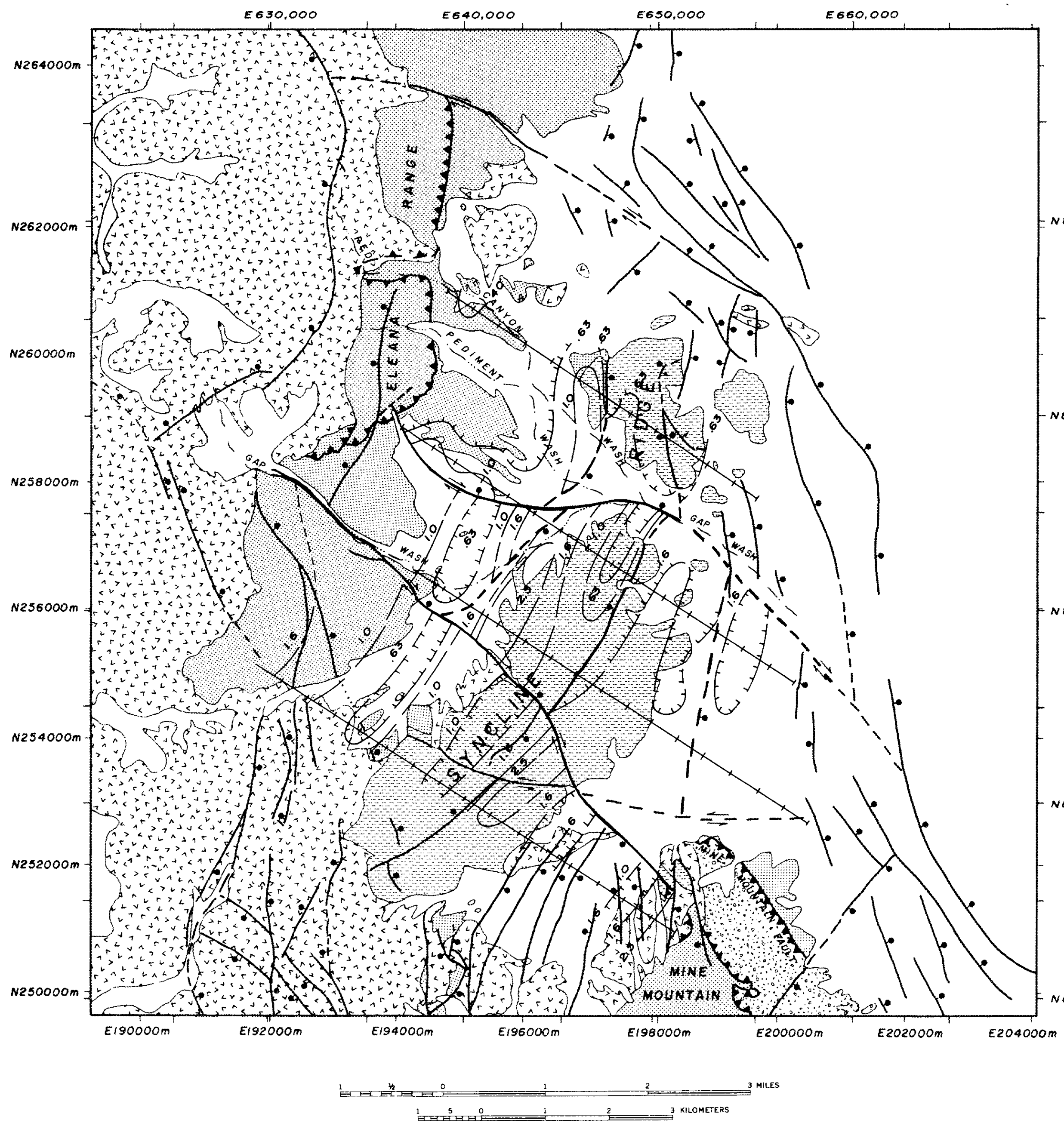


Figure 11.--Telluric map of Syncline Ridge area. Contour interval on equal logarithmic intervals of relative voltage. (See fig. 2 for explanation of other symbols.)

structural block similar to that shown on the isopach map. Anomalies may not coincide for the two maps near boundaries separating greatly differing resistivities because of the difference in the two techniques and the volume of rock "seen" by each method. Both maps do show the same general features; highly variable thicknesses of argillite in the southern and central blocks and a thick, continuous body of argillite in the western part of the northern block.

The Bouguer gravity anomaly map (fig. 12) has a pattern similar to the isopach and telluric maps. Although density data from drill-hole geophysical logs do not indicate a significant density contrast between the Eleana Formation and the Tippipah Limestone (W. F. Hanna and others, written commun., 1978), the similarity of the gravity anomaly map and the telluric map in the central block indicates that a density contrast large enough to reflect structure probably does exist. The gravity map also reflects the narrowing of the argillite isopach contours near Red Canyon. The data are not complete enough to interpret this narrowing, but it may reflect a fold rather than a fault in the argillite. A detailed gravity survey that includes the narrowing has not yet been interpreted.

Low-Quartz Argillite

The incompetency of low-quartz argillite can affect the location and construction of a repository site. Prediction of low-quartz argillite is dependent on its origin and its areal and vertical distribution. Data from the UE17e core suggest that the low-quartz argillite is stratigraphically controlled. Distribution of the low-quartz argillite varies between the UE17e and UE1L drill holes and a drill hole in the Calico Hills. The variation in distribution suggests that the low-quartz argillite may be formed by shearing accompanied by chemical changes within specific stratigraphic intervals. Spacing and thickness of low-quartz argillite in the UE17e core and velocity data from this drill hole and the UE1L drill hole indicate that the argillite subunit contains several intervals that contain little or no low-quartz argillite and are thick enough for a repository site. The data are not conclusive, but they indicate that low-quartz argillite may be predictable. Complete avoidance of low-quartz argillite over a large area is unlikely because of deformation of the argillite subunit. Thickness of low-quartz argillite where its frequency is low is probably less than 1 m.

Origin of Low-Quartz Argillite

The argillite subunit in the UE17e core can be divided into five intervals containing more than 20 percent, and four intervals containing less than 10 percent low-quartz argillite (table 3). This difference is statistically significant[2]. The uniformity of the argillite subunit and the thickness of the intervals alternately containing abundant and scarce low-

---

[2]The number of samples is low, but the differences are significant at the 95-percent confidence level. Lack of a significant difference may not be equally true because of the small number of samples. The small number makes a B error (indication of the lack of a significant difference when a real difference exists) more likely. Lack of a significant difference in a small number of samples may only mean that the data are insufficient, not that a difference is lacking.

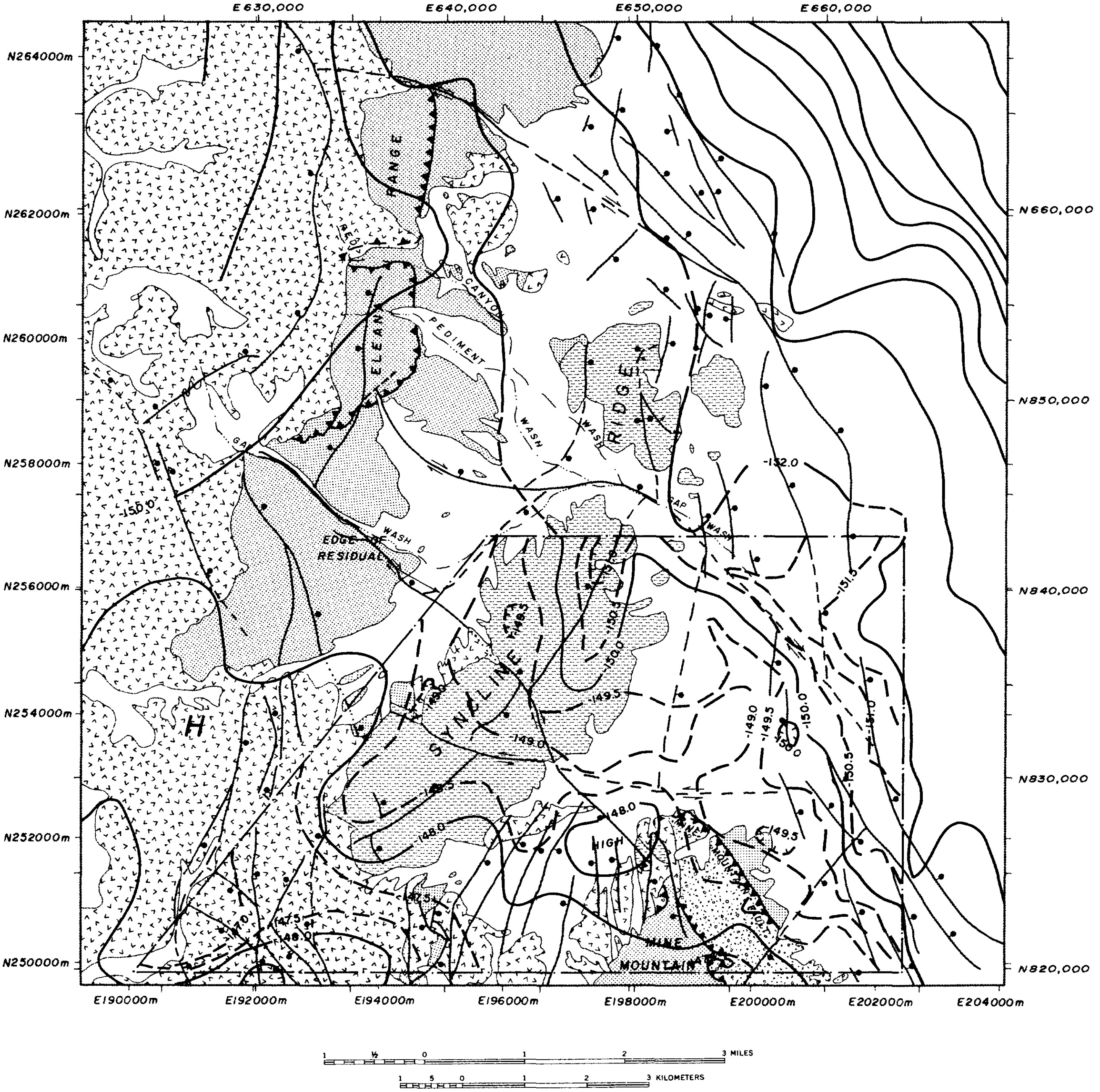


Figure 12.--Bouguer gravity anomaly map. Contour interval: 1/2 mgal (trapezohedral) and 2 mgal. (See fig. 2 for explanation of other symbols.)

Table 3.--Abundance, thickness, and spacing of low-quartz argillite and quartz veins in the UE17e drill hole

Depth interval (m)	73.5-259.1	259.1-294.1	294.1-422.1	422.1-580.0	580.0-642.2	642.2-707.7	707.7-747.1	747.1-873.9	873.9-914.4	Total of all depth intervals containing >20 percent low-quartz argillite	Total of all depth intervals containing <10 percent low-quartz argillite	Total	Significant difference[1]
Interval thickness (m)	185.6	35.0	128.0	157.9	62.2	65.5	39.4	126.8	40.5	455.7	385.3	840.9	
Number of low-quartz argillite zones	117.0	3.0	56.0	23.0	26.0	7.0	23.0	21.0	23.0	245.0	54.0	299.0	Yes
Total thickness of low-quartz argillite zones (m)	76.8	0.9	32.3	8.5	21.0	2.4	9.4	12.5	10.4	150.0	24.4	174.4	Yes
Percent of low-quartz argillite	41.4	2.7	25.2	5.4	33.8	3.7	24.0	9.9	25.6	33.0	6.3	20.7	Yes
Average spacing, low-quartz argillite zones (m)	1.6	11.7	2.3	6.9	2.4	10.9	1.7	6.0	1.8	1.9	7.1	2.8	Yes
Average thickness, low-quartz argillite zones (m)	0.7	0.3	0.6	0.4	0.8	0.4	0.4	0.6	0.5	0.6	0.5	0.6	No
Number of quartz veins	177.0	31.0	170.0	136.0	64.0	31.0	45.0	148.0	72.0	528.0	348.0	874.0	No
Number of quartz veins bordered by low-quartz argillite	70.0	3.0	59.0	23.0	20.0	2.0	24.0	21.0	47.0	220.0	49.0	269.0	Yes
Percent of quartz veins bordered by low-quartz argillite	39.5	9.6	34.7	16.9	31.2	6.4	53.3	14.2	65.3	41.7	14.1	30.8	Yes
Total thickness of quartz veins (mm)	258.0	35.0	457.0	239.0	100.0	59.0	90.0	263.0	115.0	1,020.0	596.0	1,616.0	No
Total thickness of quartz veins bordered by low-quartz argillite (mm)	115.0	3.0	141.0	33.0	44.0	2.0	44.0	42.0	79.0	423.0	80.0	503.0	Yes
$\frac{\text{Quartz veins (mm)}}{\text{Depth interval (m)}} \times 10^3$	12.9	9.3	33.2	14.1	14.9	8.4	21.3	19.3	26.4	20.8	14.4	17.9	No
$\frac{\text{Quartz veins bordered by low-quartz argillite (mm)}}{\text{Low-quartz argillite (m)}}$	1.63	3.33	4.37	3.88	2.10	0.83	4.68	3.36	7.60	2.82	3.28	2.89	No
Average thickness of quartz veins (mm)	1.5	1.1	2.7	1.8	1.6	1.9	2.0	1.8	1.6	1.9	1.7	1.8	No
Average spacing of quartz veins (m)	1.05	1.13	0.75	1.16	0.97	2.11	0.88	0.86	0.56	0.86	1.11	0.96	No

[1]At 95-percent confidence limits between intervals containing more than 20 percent and those containing less than 10 percent low-quartz argillite.

quartz argillite indicate that the low-quartz argillite is probably stratigraphically controlled. The formation of alternating intervals of abundant and scarce low-quartz argillite is visualized as follows:

1. Differences in either source or depositional environment alternately deposited intervals that contained greater or lesser amounts of quartz or clay minerals.

2. Quartz veins were formed prior to the deformation that produced the present incompetence of the low-quartz argillite.

3. Regional deformation and probably the accompanying low-grade metamorphism produced or enhanced the differences in competence between the high-quartz and low-quartz argillite. The spacing and frequency of the low-quartz layers in alternating intervals of abundant and scarce low-quartz argillite are difficult to reconcile with a purely mechanical origin of the low-quartz argillite. The relatively uniform thickness of the low-quartz argillite layers (fig. 13) is also inconsistent with a purely mechanical origin.

The report on UE17e (Hodson and Hoover, 1979) postulated a genetic relationship between quartz veins in the argillite and the low-quartz argillite zones. Further study of the quartz veins and the low-quartz argillite indicates that the relationship is spatial with no genetic significance. Significant differences in the number, percent, and total thickness of quartz veins bordered or enclosed by low-quartz argillite (table 3) can be explained by formation of low-quartz argillite in the same interval as previously-formed quartz veins. Quartz veins with approximately equal thickness and spacing would have a number, percent, or thickness enclosed by low-quartz argillite directly proportional to the amount of low-quartz argillite formed at a later time in the same volume of rock.

If the quartz veins were related to the low-quartz argillite, the thickness or spacing of quartz veins should vary with the abundance of low-quartz argillite. These significant differences are lacking (table 3). A single parameter lacking a significant difference might be attributed to the low number of samples. This lack in several genetically-related parameters, especially when spatially-related parameters have a significant difference in the same samples, makes the low number of samples an unlikely cause for the lack of significant differences.

The differences in physical appearance of low-quartz and high-quartz argillite are reflected by the neutron and velocity logs in the UE17e drill hole (figs. 14, 15). The criteria (figs. 14, 15) used to define intervals containing either abundant or scarce amounts of low-quartz argillite were arbitrarily selected. The minimum interval used in the graph was 6.1 m to minimize drill-hole roughness effects on the velocity intervals of 3.05 m. The velocity log was used to define intervals containing less than 10 percent low-quartz argillite because it was more definitive than the neutron log.

Only one interval containing less than 10 percent low-quartz argillite had a velocity lower than 3,500 m/s (fig. 15). Intervals not meeting the criteria of either abundant or scarce low-quartz argillite have velocities greater than 3,500 m/s and low-quartz argillite contents as high as 24 percent. These velocities may be high because thickness or spacing of the low-quartz argillite layers is such that they do not affect the velocity.

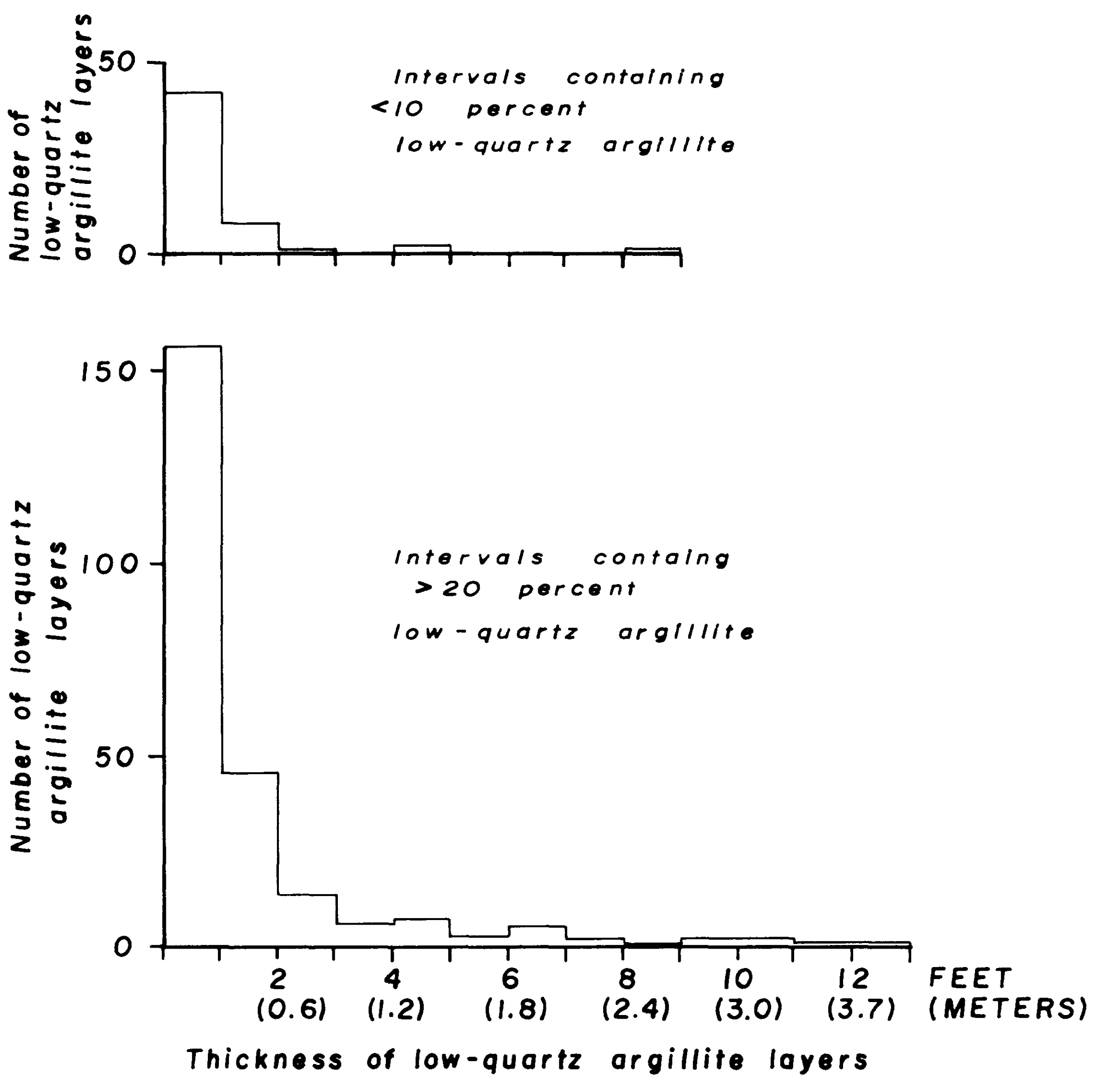


Figure 13.--Frequency of thickness of low-quartz argillite layers in the UE17e drill hole.

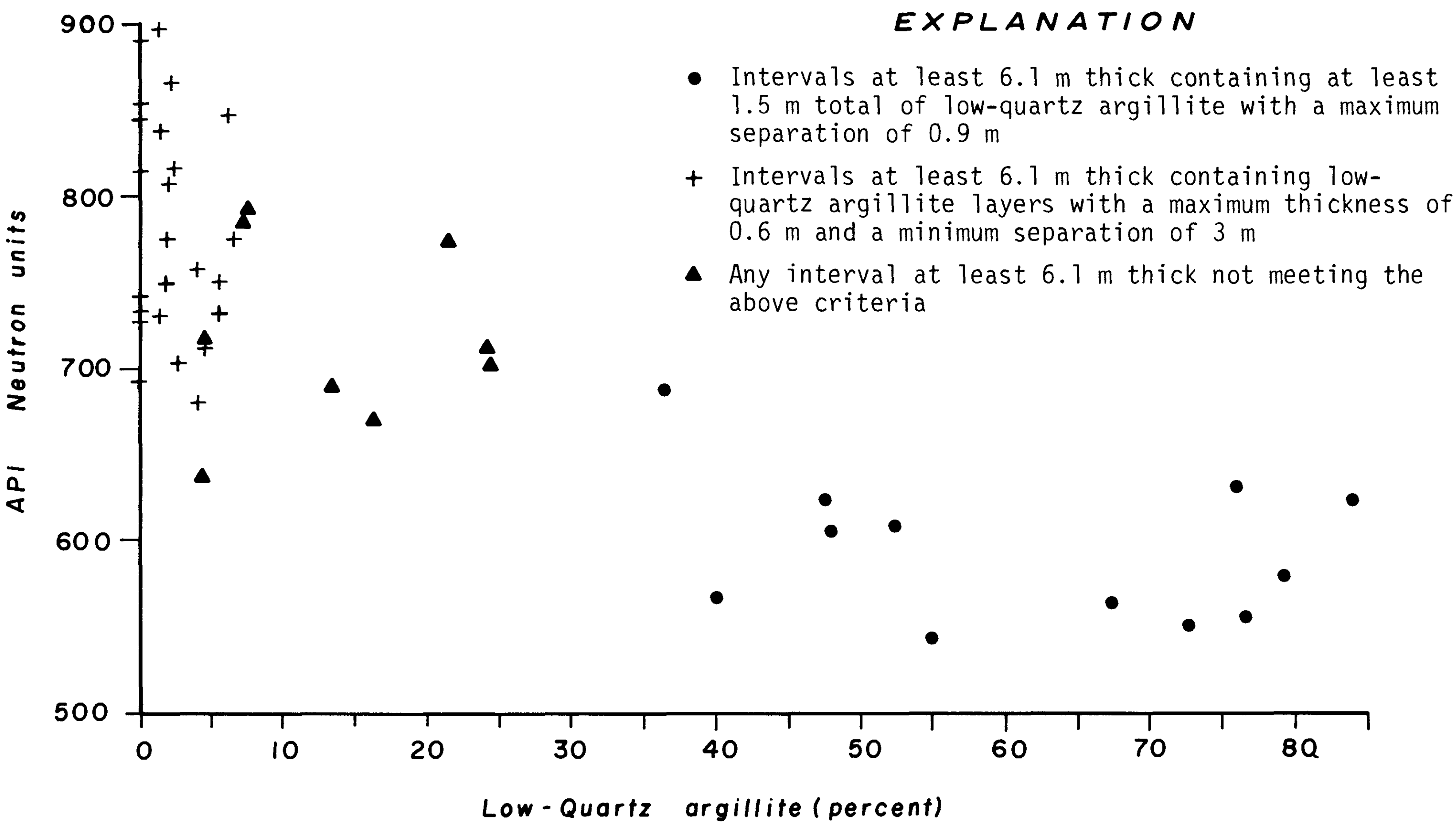


Figure 14.--Graph of low-quartz argillite content versus API neutron units in the argillite subunit, unit J, Eleana Formation, UE17e drill hole.

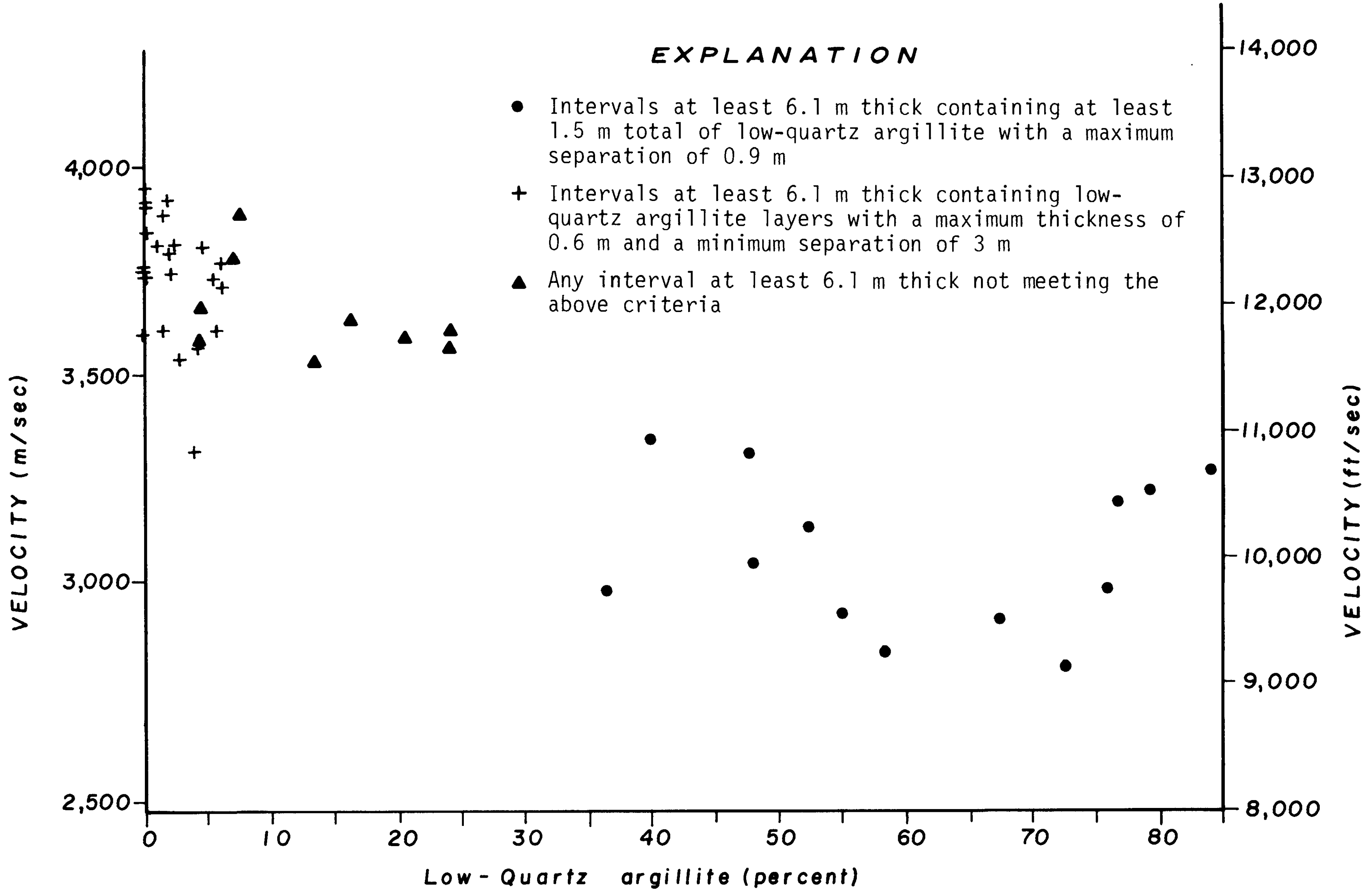


Figure 15.--Graph of low-quartz argillite content versus compressional velocities, argillite subunit, unit J, Eleana Formation, UE17e drill hole.

Using the 3,500 m/s velocity as a criterion, about 45 percent of the argillite subunit in the UE17e drill hole can be inferred to contain abundant low-quartz argillite. This amount is closely comparable to 54 percent of the core that contains more than 20 percent low-quartz argillite. The 3,500 m/s velocity was used in the UE1L drill hole to define intervals of abundant and scarce low-quartz argillite. The amount of argillite with velocities less than 3,500 m/s is about half as much in UE1L as it is in UE17e (fig. 16). The number of intervals of abundant low-quartz argillite thicker than 15.2 m is fewer in UE1L than in UE17e (fig. 17). Conversely, the number of intervals of scarce low-quartz argillite thicker than 15.2 m is greater in UE1L than in UE17e (fig. 17).

These differences in the amount of low-quartz argillite and the thickness of intervals with abundant or scarce low-quartz argillite are emphasized further by a drill hole in the Calico Hills. No low-quartz argillite was found in 416 m of core. The differences in low-quartz argillite content in the UE17e, UE1L, and Calico Hills drill holes imply a cause that differs areally. However, lithologic similarity of thin beds within the argillite subunit, such as the quartzite near the middle or the fragmental limestone at its base, implies that, at any given time of deposition, lithologies in the argillite subunit are uniform over large areas. This implication may apply to the original composition of the low-quartz argillite layers. If it does apply, then the origin of the low-quartz argillite layers must be either mechanical or metamorphic. Similar mineralogy in samples from the UE17e, UE1L, and Calico Hills drill holes indicate a similar level of metamorphism. Although the structural location of these drill holes varies in detail, implying possible differences in mechanical deformation, these differences are not readily apparent in cores.

The argument for stratigraphic control of location and a mechanical origin of the low-quartz argillite is inconclusive, but evidence for a purely mechanical origin is lacking. Lack of correlation between quantitative parameters of the quartz veins and low-quartz argillite in contrast to correlation of their spatial parameters indicates that they are not genetically related and that they formed at different times. Formation of the quartz veins in tensional openings is unlikely after formation of the incompetent low-quartz argillite because the low-quartz argillite is too weak to support the openings in which the quartz veins formed.

The vertical variation of low-quartz argillite abundance in the UE17e drill hole implies a stratigraphic control of the location of low-quartz argillite. The thin low-quartz argillite zones and their relatively uniform thickness are not indicative of a purely mechanical origin. Areal variation in the amount of low-quartz argillite could imply either a stratigraphic or mechanical control of the low-quartz argillite.

Differences between the high-quartz and low-quartz argillite, such as sedimentation characteristics, quantitative mineralogy, chemistry, and stratigraphic correlation with geophysical logs, may provide the best evidence for stratigraphic control or its lack. The uniformity, fine-grained character, and regional deformation of the argillite may make discrimination of evidence for a stratigraphic or mechanical origin difficult.

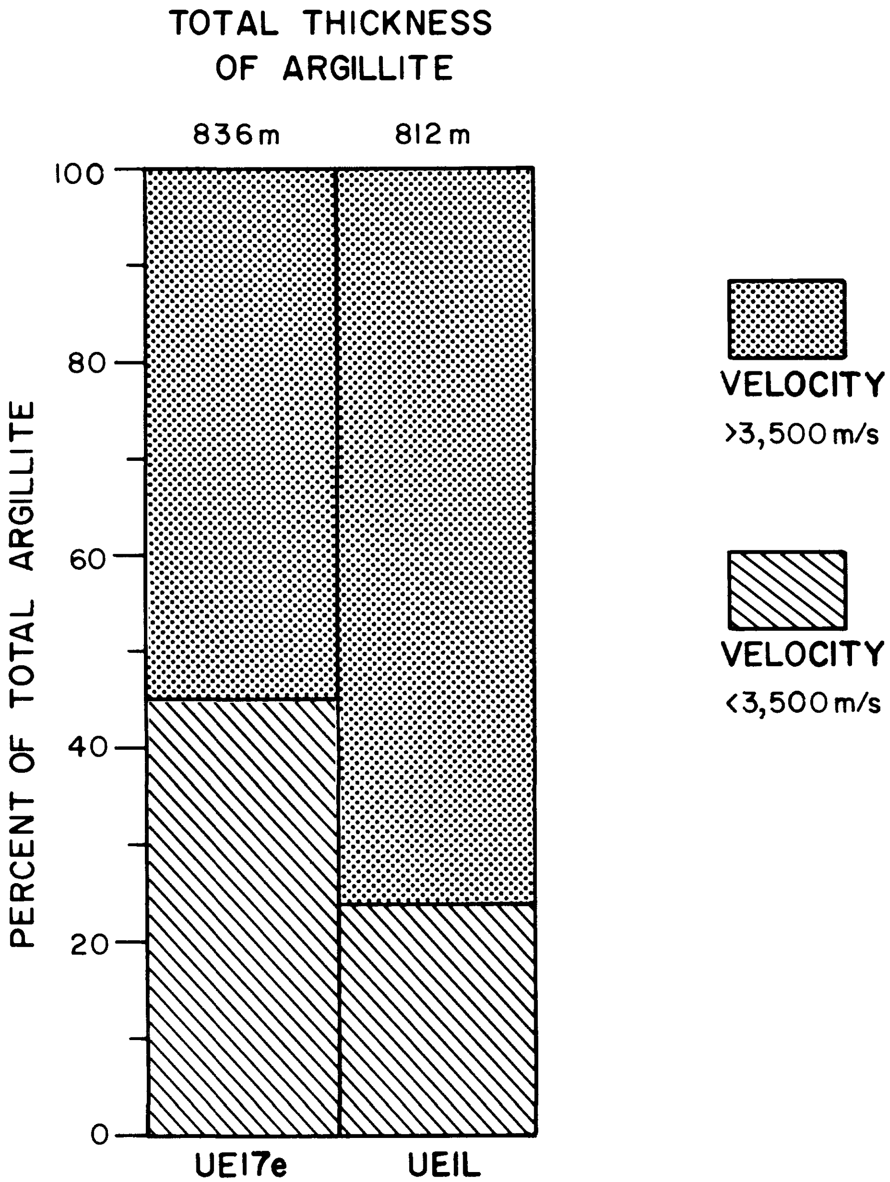


Figure 16.--Amount of argillite subunit, unit J, Eleana Formation, with velocities less than 3,500 m/s (abundant low-quartz argillite) and greater than 3,500 m/s (scarce low-quartz argillite) in the UE17e and UE1L drill holes.

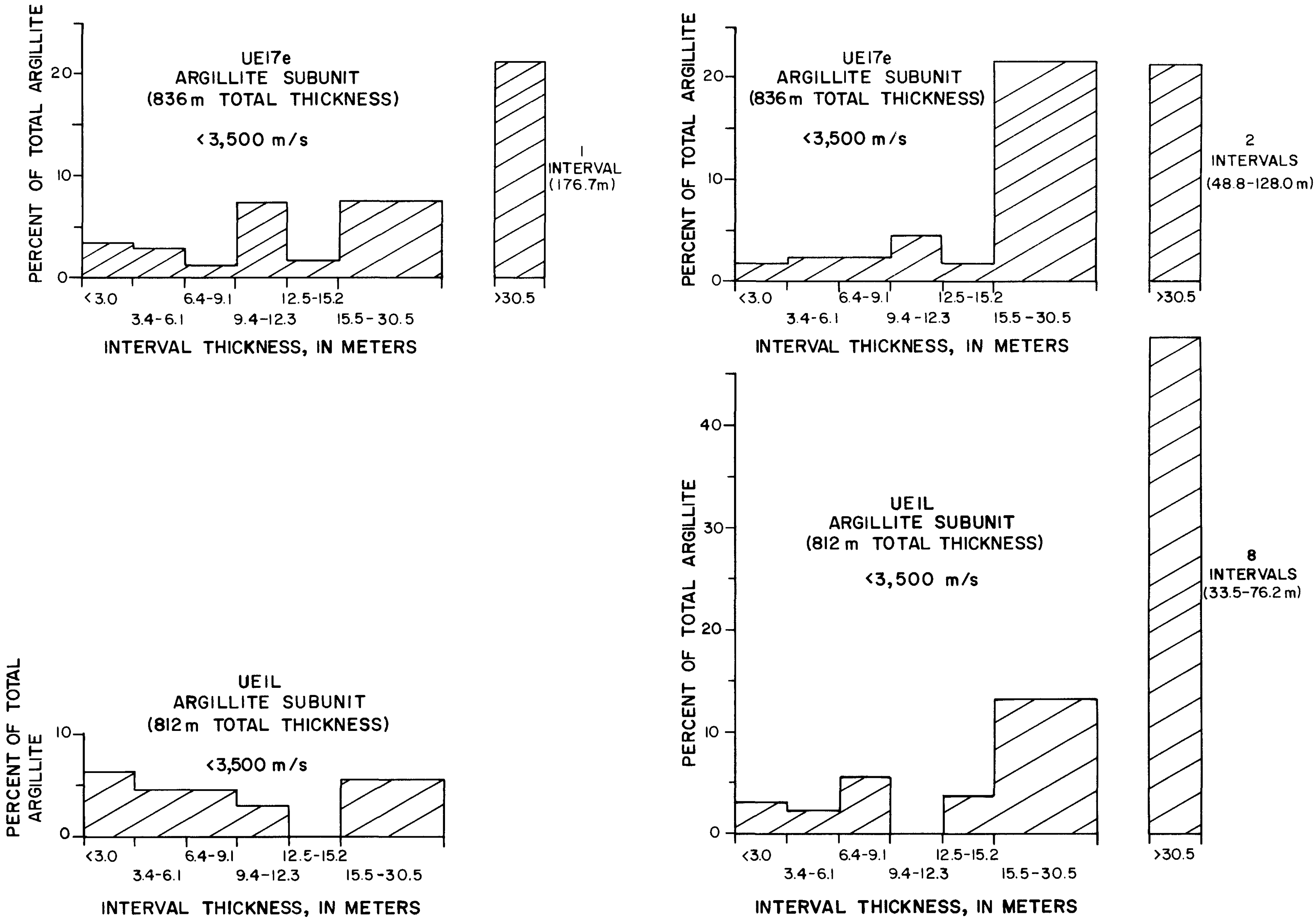


Figure 17.--Frequency of thickness of argillite with velocities less than 3,500 m/s (abundant low-quartz argillite) and greater than 3,500 m/s (scarce low-quartz argillite) in the UE17e and UE17L drill holes.

Competency

Caving and large washouts in unit J of the Eleana Formation in some drill holes make the competency of the argillite subunit questionable. Physical properties of core samples are a measure of the competency of the rock itself, but the effect of discontinuities on competency cannot be measured until construction provides access for in situ measurements. Until such construction, drill hole and core parameters can provide an approximation of competency. Core index and hole gauge were studied and fracture analyses were made to determine relative competency of the argillite subunit.

These studies indicate that the argillite has a low competency caused by the thorough fracturing. Competency is greater below weathered rock, but more than 50 percent of the rocks below the weathered rock is incompetent. Washouts and caving in drill holes may be partly caused by the low competency of the argillite, but a major cause may be drilling procedures.

Core Index

A total of 1,652.47 m of core was taken from 34 drill holes in the Syncline Ridge area (table 4) of which 88 percent was recovered. Only core taken from unit J of the Eleana Formation was used in the CI (core index) study. A CI was calculated for each cored interval to determine the rock competency.

The CI is a measure of rock competency. It is a dimensionless number from 0 to 100, 50 being the dividing point between competency (0-50) and incompetency (51-100) (J. R. Ege and M. J. Cunningham, unpub. data, 1975). Incompetency in the rock is generally due to jointing, faulting, and low compressive strength. The CI is calculated by the following formula:

$$CI = \frac{\text{core lost (m)} + \text{core broken (m)} + 1/10 \text{ number of fractures}}{\text{drilled interval (m)}} \times 100$$

Lost core is defined as core that was not recovered from the drilled interval. Broken core is defined as a length of recovered core fragmented into pieces less than 10 cm in length. Fractures are defined as the number of tectonic fractures in the core, excluding the fractures in the broken core intervals. All tectonic fractures will limit the size of intact core pieces greater than 10 cm in length. Healed fractures within core pieces greater than 10 cm are not counted as fractures. The total number of fractures is divided by 10, thereby relating the standard length of unfractured core to 10 cm, the upper limit of broken core.

Histograms of core indices in unit J of the Eleana Formation from the Syncline Ridge area are shown on figure 18. Histogram A represents the CI for the total 1,652.47 m of core of which 28 percent of the rock is classified as competent (0-50) and 72 percent as incompetent (51-100).

The core was divided into two categories, weathered rock, histogram B, and unweathered rock, histogram C. Histogram B represents 579.88 m or 35 percent of the total core used in the study. Histogram B indicates that only 4 percent of the weathered rock is competent. The greater amount of incompetent rock is caused by the weathering and near-surface stress relief. A thrust fault near the Tippipah-Eleana contact may be an additional cause of the incompetency of the rock.

Table 4.--Drill holes used in core index study

[Leaders (---) indicate core taken below weathered zones]

Drill hole	Total depth (meters)	Depth of weathering (meters)	Type of drill hole Selected core	Continuous core
		Exploratory		
UE1m	156.76	138.41		X
UE16b	110.03	110.03+	X	
UE16c	43.89	43.89+	X	
UE16d	914.4	---	X	
UE16f	451.0	---	X	
UE17a	370.2	---	X	
UE17b	78.18	---	X	
UE17c	178.49	---	X	
UE17e	914.4	18.29		X
UE17f	30.33	30.33+		X
UE17g	31.7	16.06		X
		Eleana Heating Experiment		
SI-1	24.38	16.58		X
SI-2	28.19	16.55		X
SI-3	24.38	16.34		X
SI-4	28.19	17.22		X
SI-6	24.38	16.34		X
SI-7	25.15	17.04		X
SI-8	23.62	15.64		X
SI-8A	18.29	15.88		X
SI-9	24.38	17.53		X
SI-10	25.76	16.31		X
SI-11	25.15	16.52		X
SI-11A	18.29	16.98		X
SI-12	23.62	18.29		X
SI-13	25.76	17.28		X
SI-14	24.38	16.34		X
SI-15	23.62	16.98		X
SI-16	25.76	16.58		X
TH-1	24.38	17.28		X
TH-2	24.48	17.65		X
TH-3	24.38	15.39		X
TH-4	24.38	15.59		X
TH-5	24.38	15.35		X

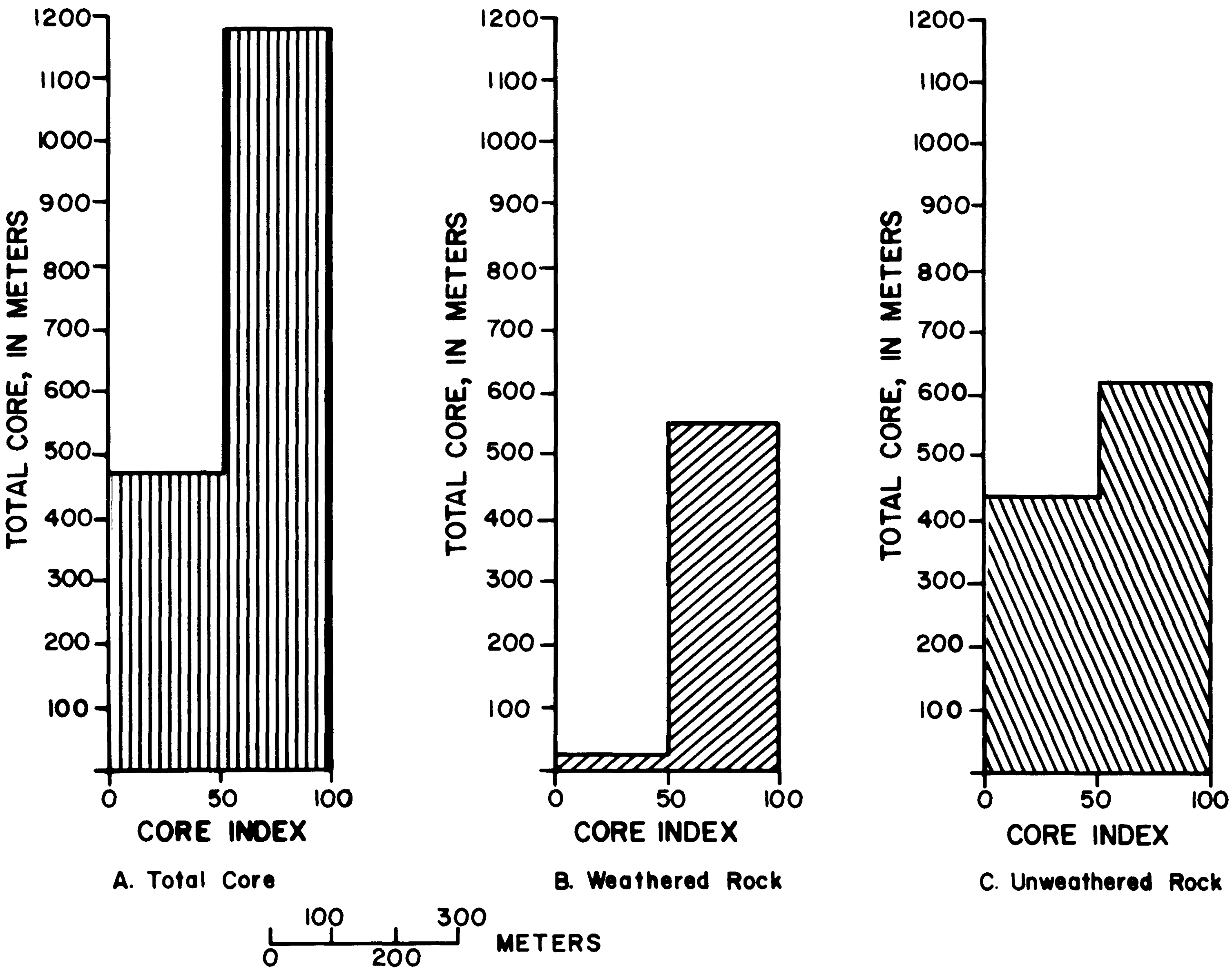


Figure 18.--Histograms of core indices, unit J of the Eleana Formation.

Histogram C represents 1,072.59 m or 65 percent of the total core. Histogram C indicates that 41 percent of the unweathered rock is competent and 59 percent is incompetent. Although rock competency is greater below the zone of weathering as shown by CI histogram C, more than 50 percent of the rock is incompetent. Any excavation in the upper part of unit J will probably require more than normal support.

Drill-Hole Gauge

Some of the drill holes in the Syncline Ridge area had numerous washouts in the upper part of unit J of the Eleana Formation. Some washout areas caved and required heavy (barite) mud to stabilize the drill holes. These washouts are a possible indication of incompetent rock.

To determine whether incompetency of the argillite was the cause of the washouts, caliper logs were classified into six out-of-gauge categories: 1 to 0 inch less-than-gauge and 0 to 1, 1 to 2, 2 to 4, 4 to 8 and greater than 8 inches out-of-gauge. Electric logs from the same holes as the caliper logs were used to classify argillite intervals as less than 30 ohm-m and quartzite intervals as greater than 50 ohm-m. The 30 to 50 ohm-m resistance was not used because interpretation of its rock type is ambiguous. This category includes less than 5 percent of the logs. The same interval is included twice in some drill holes because some intervals were reamed from 22.22 cm to 31.12 cm in different drilling fluids.

The caliper log categories and the electric log categories were combined to provide a comparison of washouts in argillite and quartzite. For all holes, fluids, and hole diameters, the histogram of out-of-gauge hole (fig. 19) indicates that argillite and quartzite are roughly comparable in rock competency. The argillite differs only in the 2- to 4-inch out-of-gauge category. In general the histogram shows that washouts do <u>not</u> indicate that the argillite is an incompetent rock.

A comparison of out-of-gauge histograms in different drilling fluids (fig. 20) indicates that hole stability was not greatly improved nor washouts reduced substantially by a change in drilling fluids. The differences between argillite and quartzite are the largest in holes drilled with water, as might be expected. The lack of improvement in holes drilled with bentonite mud and barite mud indicate that washouts in argillite may have causes other than rock competency. Most washouts in the Eleana Formation are probably caused by drilling procedures. Therefore, washouts in drill holes in argillite should not be used as a measure of competency unless drilling procedures are known to be uniform.

Fracture Analysis

The fracture data from the Eleana heating experiment and UE17e drill holes were combined for the Syncline Ridge fracture analysis. Dip of the fractures per 10° dip interval was recorded for all core. Rosette diagrams (fig. 21) show 10° dip intervals from 0° to 90° The number of fractures in each 10° interval is shown by the length of the ray in each interval. The horizontal bar across the top of the rosette diagram indicates the fracture frequency. Only tectonic fractures, as opposed to mechanical fractures due to drilling and (or) handling,

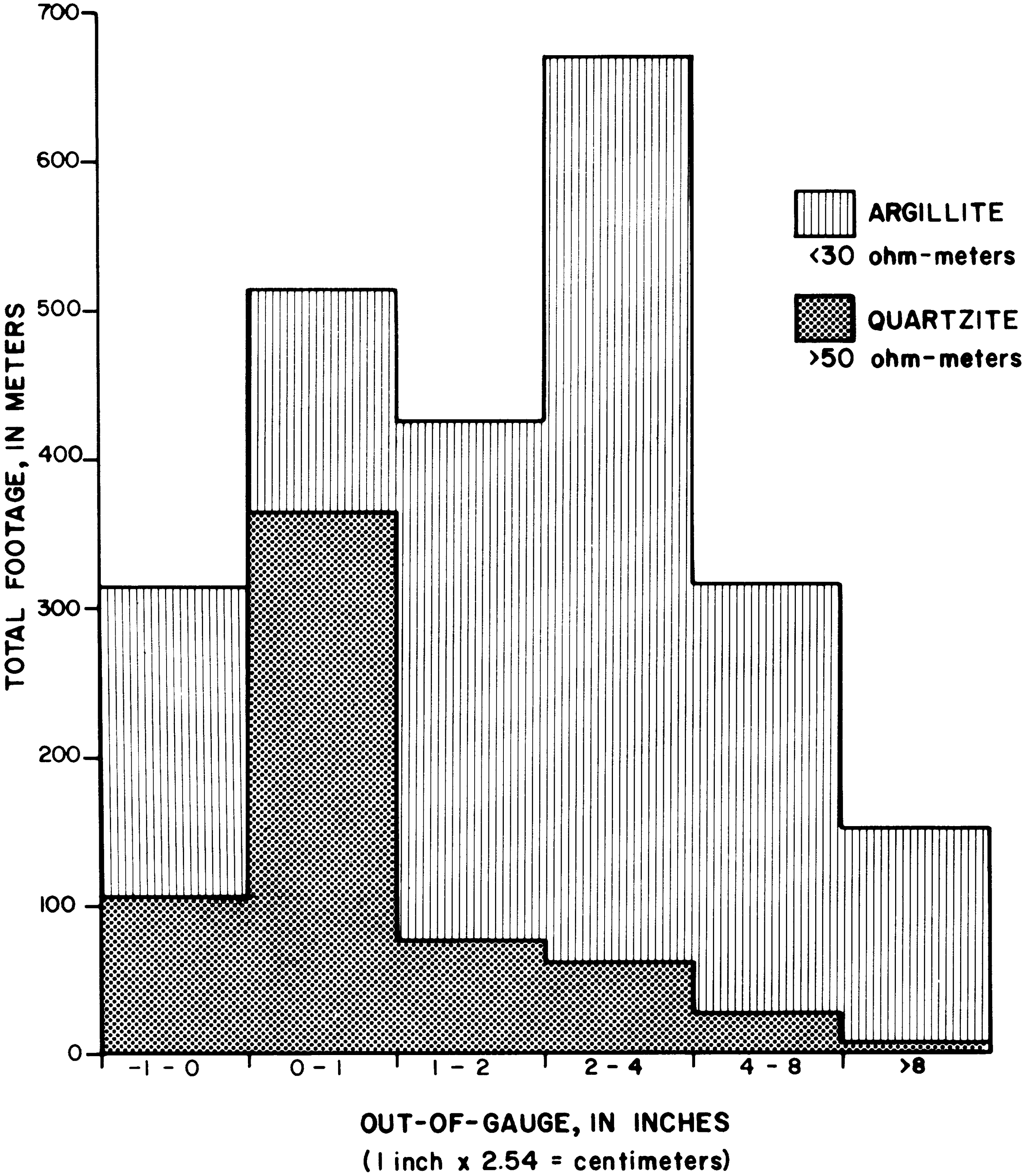


Figure 19.--Histograms of out-of-gauge hole in argillite and quartzite in unit J, Eleana Formation.

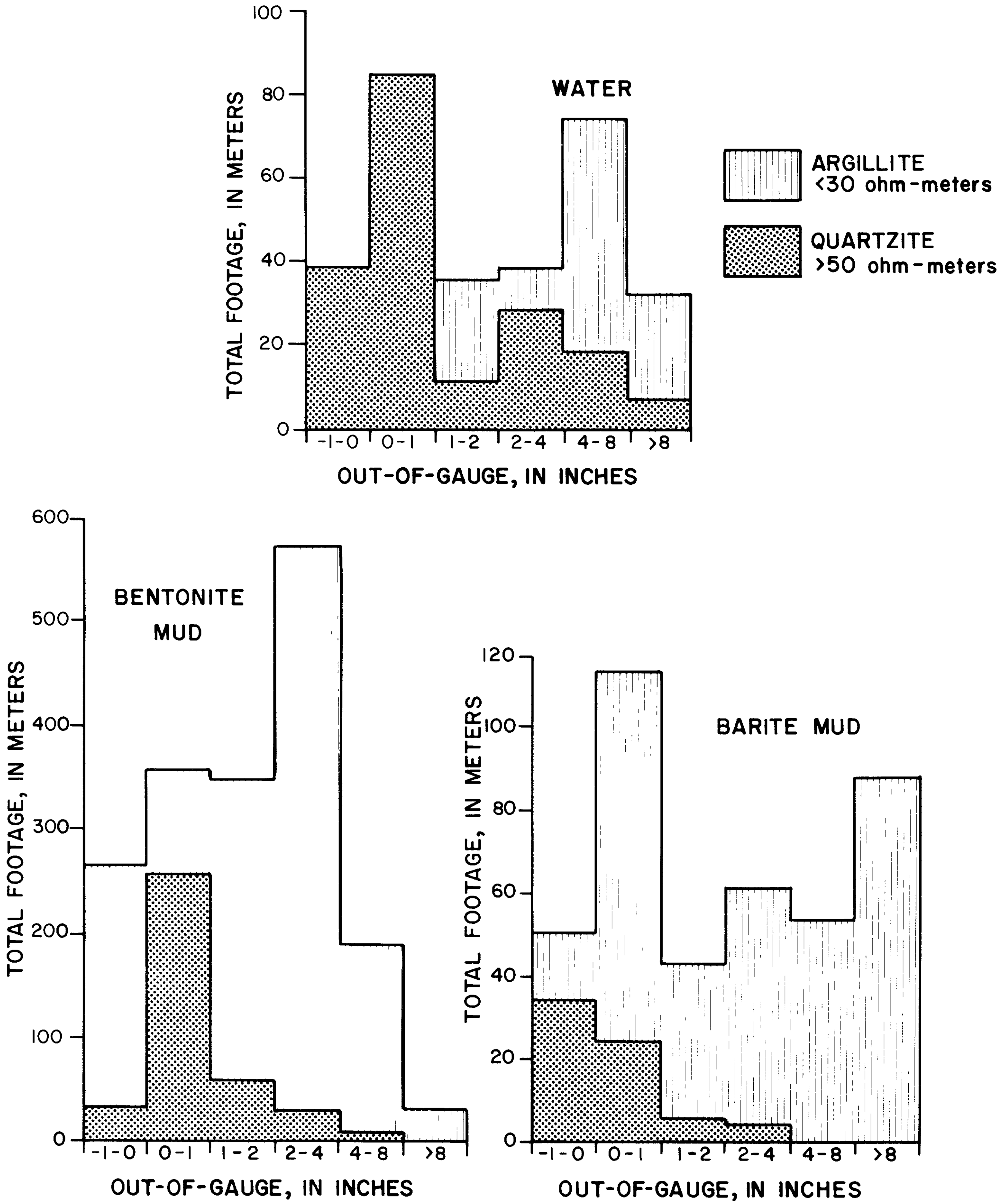


Figure 20.--Histograms of out-of-gauge hole by type of drilling fluid in argillite and quartzite in unit J, Eleana Formation.

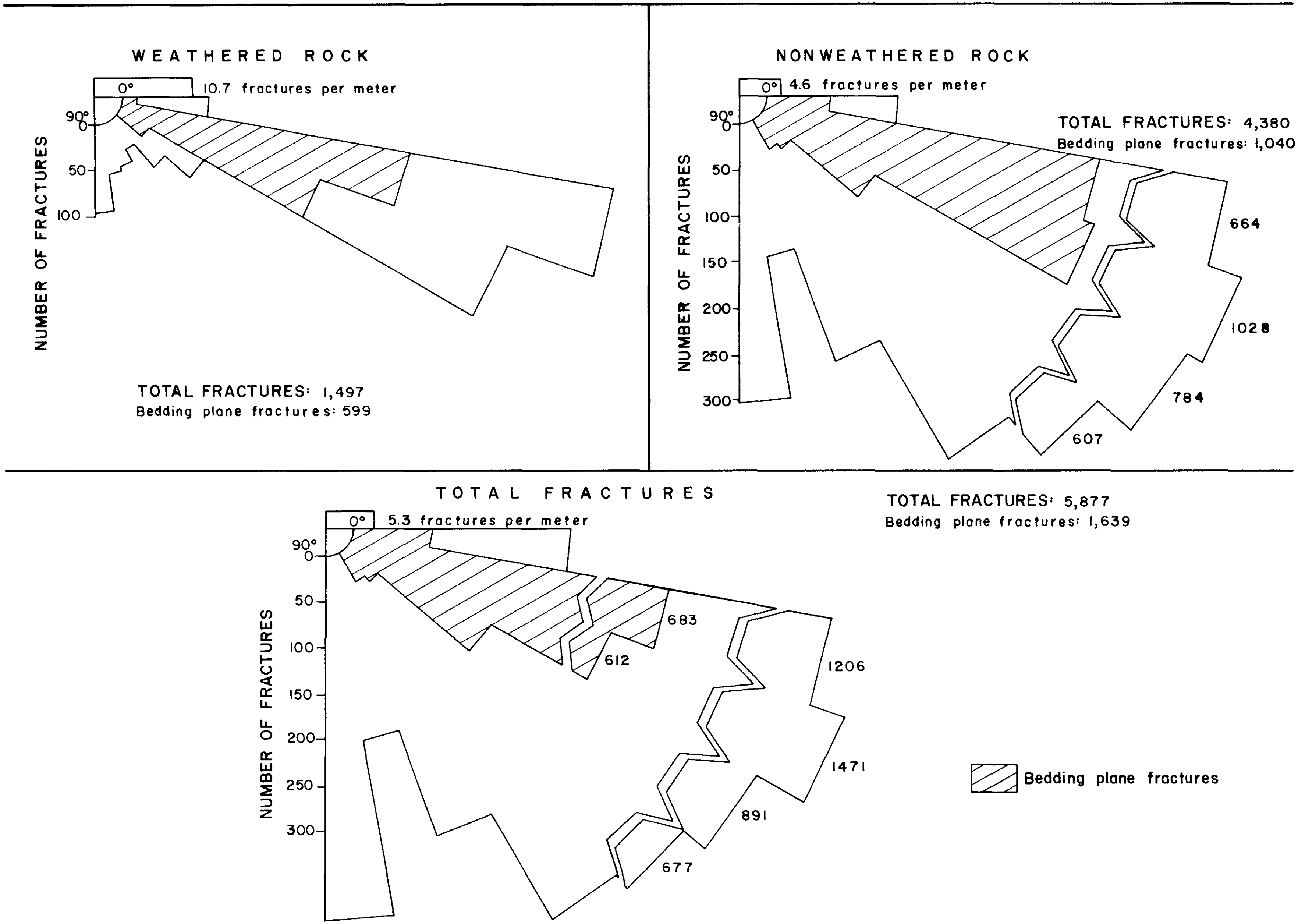


Figure 21.--Fractures per 10°-dip interval, total fractures, and fractures in weathered and unweathered rock, unit J, Eleana Formation, in the UE17e and Eleana heating experiment drill holes. Broken rays and accompanying numbers indicate extent and total number of fractures in ray.

were classified as "open" or "closed." "Open" fractures are those fracture surfaces which are exposed in the core box.

The average fracture frequency for the combined Eleana heating experiment and UE17e drill holes is 5.3 fractures per meter (fig. 21). The weathered rock has a fracture frequency of 10.7 fractures per meter; nonweathered rock 4.6 fractures per meter.

The weathered zone extends to a depth of approximately 18.29 m. The argillite has a fracture frequency of 9.1 fractures per meter to a depth of 77.72 m. The higher fracture frequency in both cases is due to weathering and (or) near-surface stress relief. A thrust fault near the Tippipah-Eleana contact may be an additional cause for the higher fracture frequency.

The fracture data indicate that the majority of fractures are essentially parallel to bedding. The range of dips (0° to 60°) of bedding-plane fractures is large because of the thick stratigraphic interval that has been deformed.

Separation of fractures into "open" and "closed" categories in both weathered and nonweathered rock indicates that open fractures are more numerous (fig. 22). Open fractures were not completely healed and reopened during drilling and handling.

Fracture filling can affect the coefficient of friction along fractures. Fillings of clay and clay with iron staining can reduce friction along fractures; quartz and calcite can increase friction. The rosette diagrams for various fillings in open and closed fractures (fig. 23) do not clearly suggest any significant effect on the rock competency. Fractures filled by clay with iron staining are absent below 18.3 m, the approximate depth of weathering. Clay-, quartz-, and calcite-filled fractures decrease with depth. Clean and polished fractures and clean fractures increase with depth.

The CI study indicated that more than 50 percent of the nonweathered rock is incompetent and that competency does not increase with depth. The fracture frequency indicates that the incompetency is probably due to fractures. Fractures will probably be a major factor in design of excavations in the argillite.

Mineralogy

The mineralogy of the argillite from Syncline Ridge was determined by X-ray diffraction analysis of 60 samples (table 5). Previous studies of the Eleana Formation indicate that argillite in the Eleana Formation in the NTS area has been heated to temperatures of 150° to 200°C by regional metamorphism (F. G. Poole, oral commun., 1976). These temperatures are based on colors of conodonts and ratios of organic compounds. The pyrophyllite found in most of the samples indicates a temperature of 300°C or higher, according to A. R. Lappin (oral commun., 1977). The different temperatures determined by these methods may be caused by metastable formation of pyrophyllite or by different sample locations having undergone different temperatures.

The argillite has been separated into two types: high-quartz and low-quartz by visual observation and X-ray diffraction. The quartz content of 15 samples of argillite was determined by X-ray diffraction using standard samples to calibrate quartz content to diffraction peaks. Eleven high-quartz argillite samples ranged from 24 to 37 percent quartz; four low-quartz argillite samples ranged from 15 to 24 percent quartz. The only difference between high- and low-quartz argillite is the quartz content; differences in other minerals are not apparent.

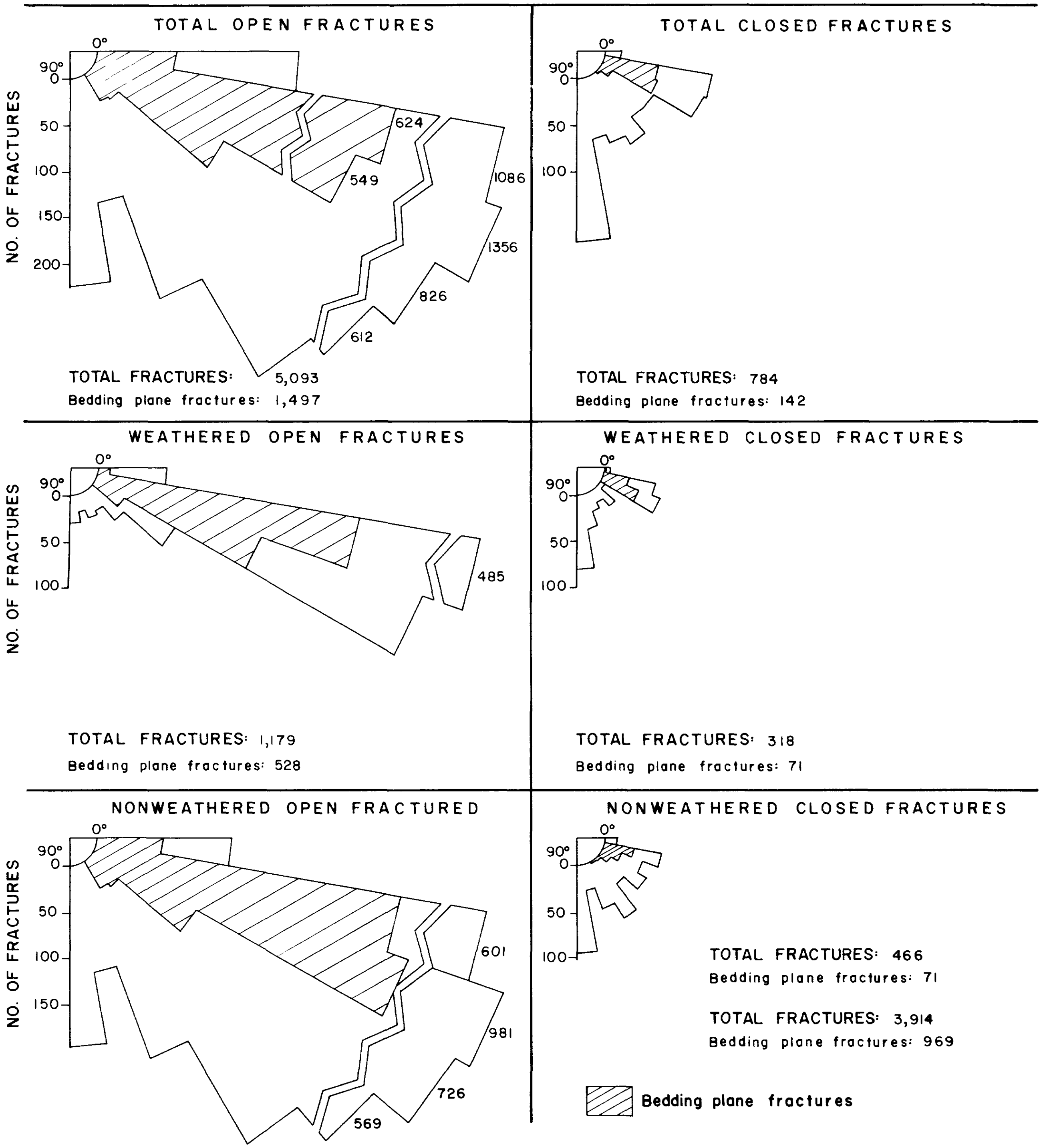


Figure 22.--Fractures per 10^{0}-dip interval, total open and closed fractures, and open and closed fractures in weathered and nonweathered rock, unit J, Eleana Formation, in the UE17e and Eleana heating experiment drill holes. Broken rays and accompanying numbers indicate extent and total number of fractures in ray.

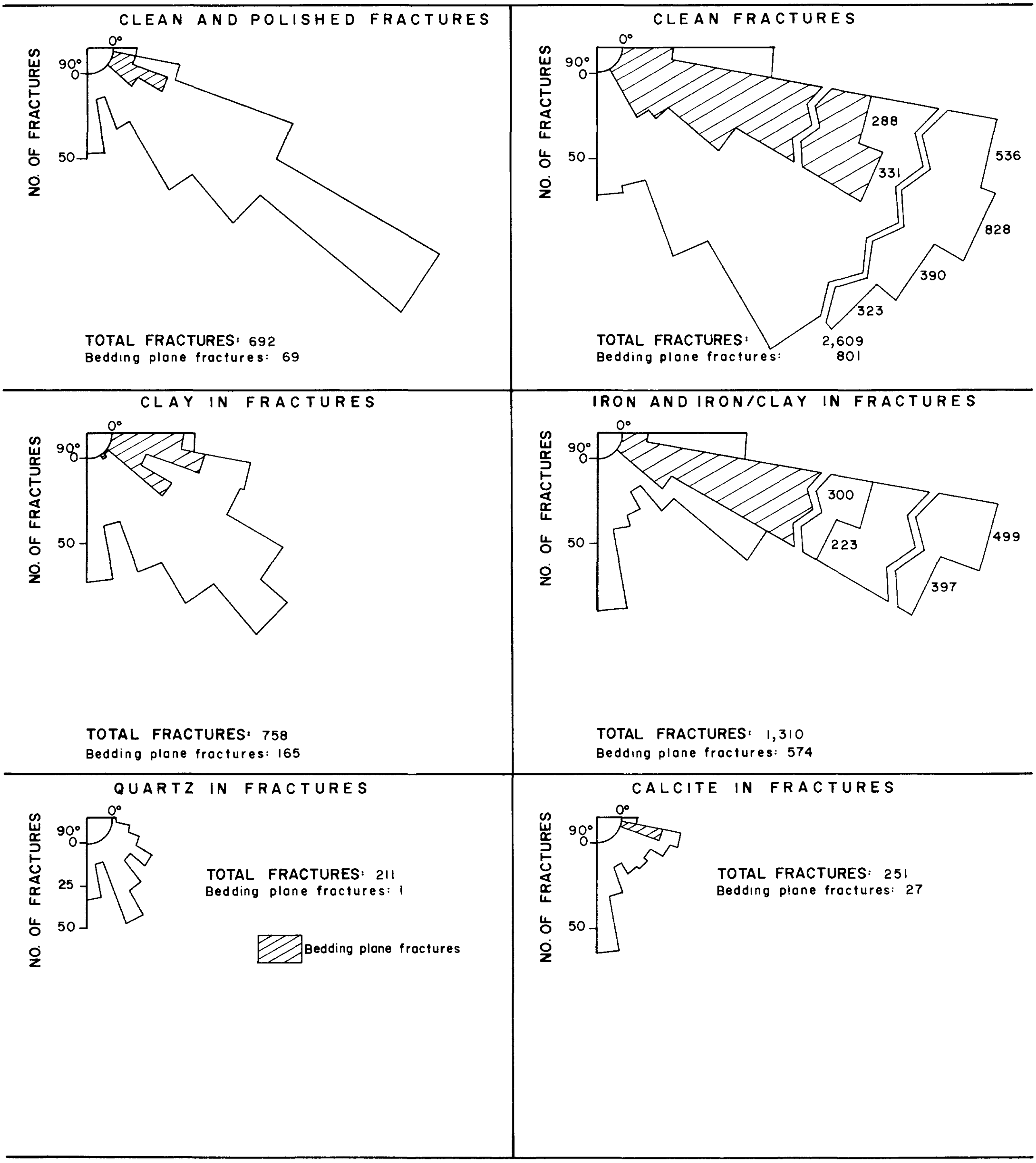


Figure 23.--Fractures in 10°-dip intervals for unfilled fractures and various fracture fillings, unit J, Eleana Formation, in the UE17e and Eleana heating experiment drill holes. Broken rays and accompanying numbers indicate extent and total number of fractures in ray.

Table 5.--Mineralogy of the argillite from unit J of the Eleana Formation in the Syncline Ridge area

Constituents	Samples containing constituent (percent)
Illite	100
Kaolinite	100
Siderite	98
Quartz	100
Ankerite	80
Pyrophyllite	72
Microcline	55
Chlorite	30
Sodic plagioclase	20
Calcite	13
Pyrite	less than 10

Chemical and Selected Trace Element Analysis

The bulk chemical analyses for eight samples have been compiled for the argillite (table 6). Analysis for selected trace elements have been compiled in table 7. No significant difference in major or trace elements is apparent between high-quartz and low-quartz argillite.

Physical Properties

The physical properties data of high-quartz argillite from core samples from the Syncline Ridge area have been compiled as histograms (fig. 24). The mean, median, and mode are shown for each property to provide an approximation of statistical analysis. Specific data for these properties are in the reports on UE17e and the Eleana heating experiment drill holes.

The bulk density for UE17e was obtained by two methods, drill-hole logs (fig. 25) and natural-state density measurements (fig. 24). The natural-state bulk density is slightly higher. The natural-state bulk density was obtained by the use of solid core and does not account for lower densities caused by fractures. The drill-hole density may not be fully corrected for variations in the borehole such as fractures, hole rugosity and (or) borehole fluids.

Geomechanical Properties

The geomechanical properties for the argillite in the Syncline Ridge area have been compiled as histograms (fig. 26). The mean, median, and mode are shown for each histogram.

The unconfined compressive strength, Young's modulus and Poisson's ratio show that there are two groups within the measurements. The lower group of values is the result of highly fractured core. The higher group of values was obtained from more competent rock. The low-quartz argillite histograms show that this rock is not as competent as the high-quartz argillite.

Thermal Properties

Temperature profiles from drill-hole data suggest fairly uniform temperature gradients in the Syncline Ridge area (J. H. Sass, written commun., 1978). The temperature in UE17e was approximately 38.5°C at a depth of 800 m. The UE1p and UE1m drill holes, in the Mine Mountain structural block, have a higher gradient. These higher gradients indicate that heat flow can vary from one structural block to another.

Fifty-six needlepoint thermal conductivities were measured both axially and radially to core samples from UE17e. At 25°C the axial measurements range from 4.5 to 8.6 mcal $cm^{-1} sec^{-1} {}^{\circ}C^{-1}$; radial measurements range from 3.7 to 8.2 mcal $cm^{-1}sec^{-1} {}^{\circ}C^{-1}$. At 25°C, the thermal conductivity range for salt is 12.75 to 17.2 mcal $cm^{-1}sec^{-1} {}^{\circ}C^{-1}$; for granite and granodiorite, 6.62 to 7.89 mcal $cm^{-1}sec^{-1} {}^{\circ}C^{-1}$ (Clark, 1966).

Thermal conductivities of argillite at temperatures from 25° to 500°C decreased approximately 40 percent (A. R. Lappin, written commun., 1978).

Table 6.--Bulk chemical analysis of eight samples of argillite

Constituents	Range (percent)	Mean
SiO_3	53.74-65.36	58.33
Al_2O_3	16.38-27.05	20.20
Fe_2O_3	0.44- 1.55	0.75
FeO	1.98- 7.50	4.92
MgO	1.44- 2.14	1.79
CaO	0.28- 1.16	0.70
Na_2O	0.73- 1.29	0.89
K_2O	1.08- 2.13	1.49
H_2O^+ and CO_2	7.11-10.35	8.49
H_2O^-	0.67- 1.10	0.90
TiO_2	0.73- 0.94	0.85
P_2O_5	0.12- 0.32	0.26
MnO	0.011-0.155	0.07
SrO	0.011-0.021	0.015

Table 7.--Selected trace element analysis on eight samples of argillite

Constituents	Range (ppm)	Mean (ppm)
Ag	>1	>1
Cd	0.10- 0.16	0.13
Cl	15.0 - 55.0	35.8
Co	30.0 - 44.0	35.3
Cr	124.0 -261.0	154.3
Cu	22.0 - 25.0	23.7
Mo	3.6 - 24.0	7.8
Pb	19.0 - 30.0	23.1
V	126.0 -260.0	176.5
Zn	75.0 -148.0	111.6

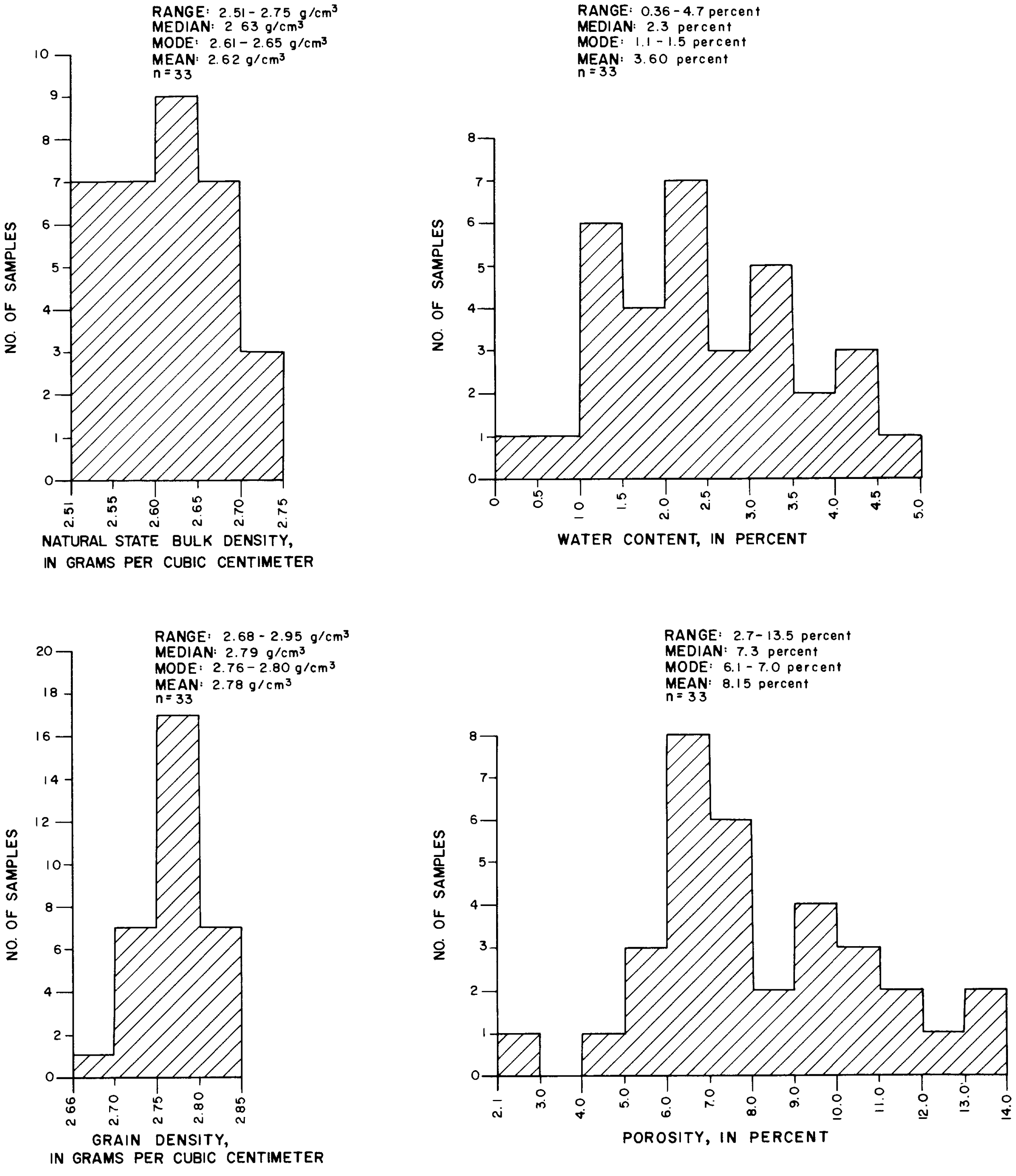


Figure 24.--Physical properties of high-quartz argillite from core samples taken in the Syncline Ridge area.

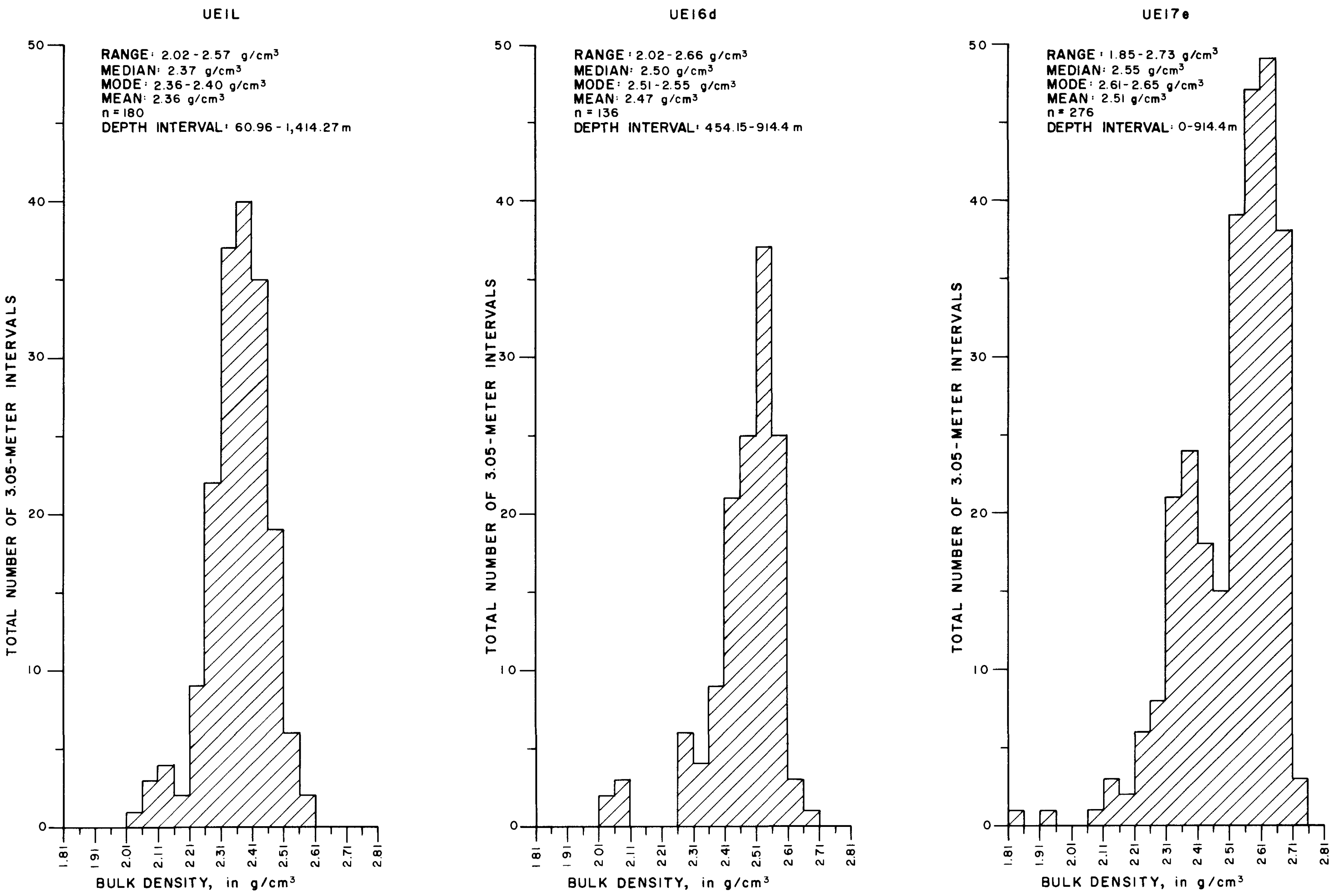


Figure 25.--Bulk density of quartzite and argillite subunits, unit J, Eleana Formation from drill-hole data for UE1L, UE16d, and UE17e.

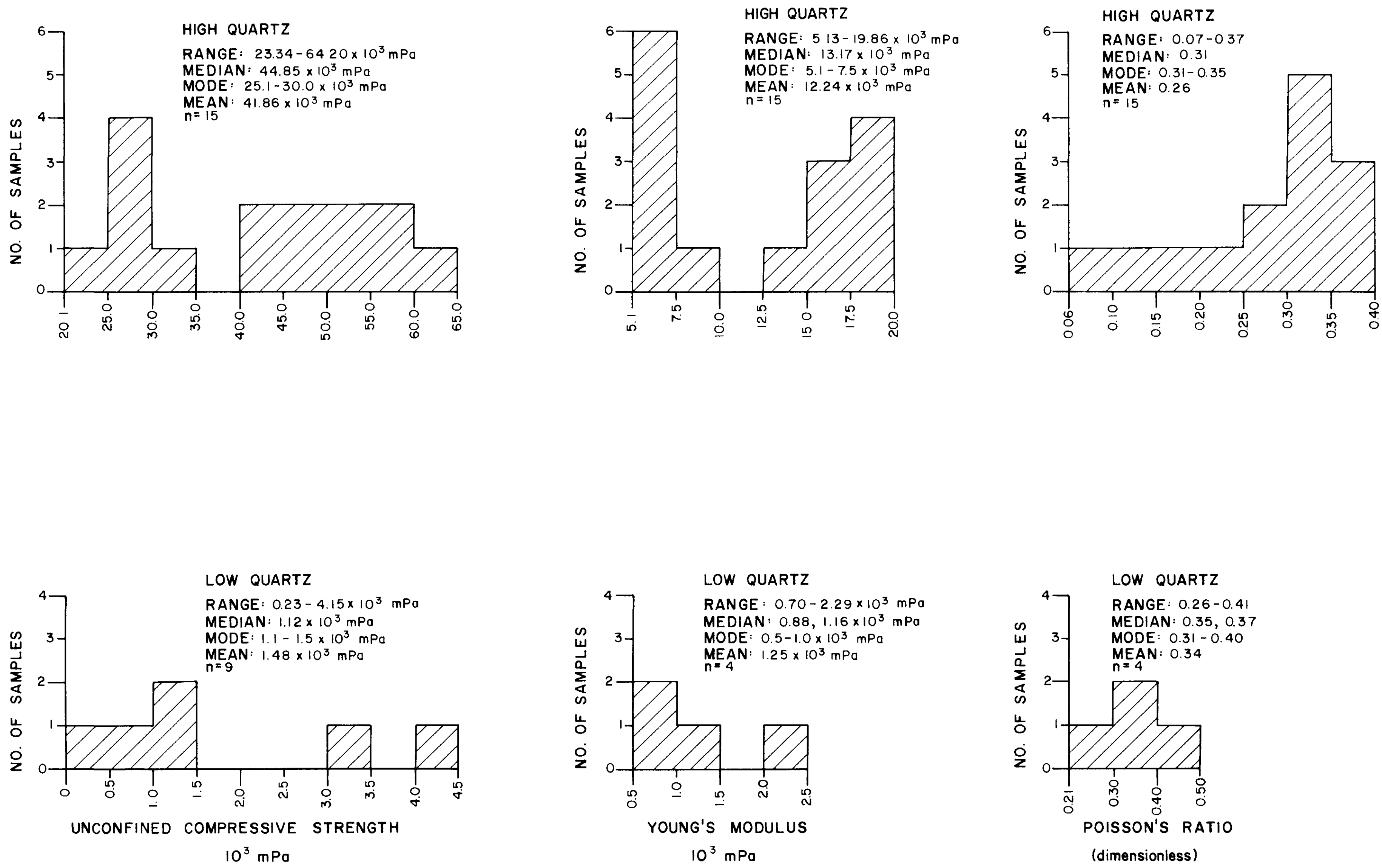


Figure 26.--Geomechanical properties of argillite in the Syncline Ridge area.

REFERENCES CITED

Ball, S. H., 1907, A geologic reconnaissance in southwestern Nevada and eastern California: U.S. Geological Survey Bulletin 308, 218 p.

Barnes, Harley, and Poole,F. G., 1968, Regional thrust-fault system in Nevada Test Site and vicinity, in Eckel, E. B., ed., Nevada Test Site: Geological Society of America Memoir 110, p. 233-238.

Carr, W. J., 1974, Summary of tectonic and structural evidence for stress orientation at the Nevada Test Site: U.S. Geological Survey Open-file Report 74-176, 53 p.

Christiansen, R. L., Lipman, P. W., Carr, W. J., Byers, F. M., Jr., Orkild, P. P., and Sargent, K. A., 1977, Timber Mountain-Oasis Valley caldera complex of southern Nevada: Geological Society of America Bulletin, v. 88, p. 943-959.

Clark, S. P., Jr., 1966, Handbook of physical constants: Geological Society of America Memoir 97, 587 p.

Colton, R. B., and McKay, E. J., 1966, Geologic map of the Yucca Flat quadrangle, Nye and Lincoln Counties, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-582, scale 1:24,000.

Ekren, E. B., Rogers, C. L.,Anderson, R. E., and Orkild, P. P., 1968, Age of Basin and Range faults in Nevada Test Site and Nellis Air Force Range, Nevada, in Eckel, E. B., ed., Nevada Test Site: Geological Society of America Memoir 110, p. 247-250.

Fernald, A. T., Byers, F. M., Jr., and Ohl, J. P., 1975, Lithologic logs and stratigraphic units of drill holes and mined shafts in Areas 1 and 6, Nevada Test Site: U.S. Geological Survey Report USGS-474-206, 62 p.

Fernald, A. T., Corchary, G. S., and Williams, W. P., 1968, Surficial geologic map of Yucca Flat, Nye and Lincoln Counties, Nevada: U.S. Geological Survey Miscellaneous Investigations Map I-550, scale 1:24,000.

Gary, Margaret, McAfee, Robert, Jr., and Wolf, C. L., eds., 1972, Glossary of geology: American Geologic Institute, New York, 805 p.

Gibbons, A. B., Hinrichs, E. N., Hansen, W. R., and Lemke, R. W., 1963, Geology of the Rainier Mesa quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-215, scale 1:24,000.

Gile, L. H., Petersen, F. F., and Grossman, R. B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, no. 5, p. 347-360.

Gordon, MacKenzie, Jr., and Poole, F. G., 1968, Mississippian-Pennsylvanian boundary in southwestern Nevada and southeastern California, in Eckel, E. B., ed., Nevada Test Site: Geological Society of America Memoir 110, p. 157-168.

Hodson, J. N., and Hoover, D. L., 1979, Geology of the UE17e drill hole, Area 17, Nevada Test Site: U.S. Geological Survey Report USGS-1543-2, 36 p.

Johnson, M. S., and Hibbard, D. E., 1957, Geology of the Atomic Energy Commission Nevada Proving Grounds area, Nevada: U.S. Geological Survey Bulletin 1021-K, p. 333-384.

Leopold, L. B., and Langbein, W. B., 1962, The concept of entropy in landscape evolution: U.S. Geological Survey Professional Paper 500-A, p. A1-A20.

McKeown, F. A., Healey, D. L., and Miller, C. H., 1976, Geologic map of the Yucca Lake quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1327, scale 1:24,000.

Orkild, P. P., 1963, Geologic map of the Tippipah Spring quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-213, scale 1:24,000.

Orkild, P. P., 1968, Geologic map of the Mine Mountain quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-746, scale 1:24,000.

Poole, F. G., 1974, Flysch deposits of the Antler foreland basin, western United States, in W. R. Dickinson, ed., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 58-82.

Poole, F. G., Houser, F. N., and Orkild, P. P., 1961, Eleana Formation of Nevada Test Site and vicinity, Nye County, Nevada, in Geological Survey Research, 1961: U.S. Geological Survey Professional Paper 424-D, p. D104-D111.

Van Devender, T. R., and Spaulding, W. G., 1979, Development of vegetation and climate in the southwestern United States: Science, v. 204, p. 701-710.

Winograd, I. J., and Thordarson, William, 1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712-C, 126 p.