GEOLOGY OF THE DEVILS HOLE AREA, NEVADA

By W.J. Carr

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CONVERSION FACTORS AND ABBREVIATIONS

For those readers who prefer to use metric (International System) rather than inch-pound units, conversion factors for the terms used in this report are listed below:

Inch-pound unit	Multiply by	To obtain metric unit
foot (ft)	0.305	meter (m)
mile (mi)	1.609	kilometer (km)
degree Fahrenheit (°F)	0.56(°F-32)	degree Celcius (°C)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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ABSTRACT

Detailed and reconnaissance mapping of the Devils Hole area has improved definition of the local geologic structure within a regional carbonate aquifer near its primary discharge points--the springs of Ash Meadows. Several formerly unmapped calcite veins, and other young calcite-lined paleo-spring feeder zones were found, as well as a number of previously unknown small collapse areas in the limestone. Although the predominant structural grain of the area is oriented northwest, the importance of the very subordinant northeast-striking faults and fractures is underscored by their association with Devils Hole itself, with most of the collapse depressions, and with many of the calcite veins in "lake beds" and alluvium. Probable channeling of ground-water flow may occur along one important northeast-striking fault zone. The persistent tendency for opening or pulling apart of the northeast-striking faults and fractures, possibly together with some carbonate-rock solution, has proproduced a very transmissive and complex carbonate aquifer. These openings may have been facilitated by underlying low-angle faults that separate brittle carbonate rocks from underlying, less-competent clastic rocks.

INTRODUCTION

This study of an area of Paleozoic carbonate-rock ridges adjacent to a major ground-water discharge area in southwestern Nevada (fig. 1) was done to document and increase understanding of the local geologic structure and geohydrology. The work consisted of geologic mapping at several levels of detail in an area of about 3 square miles centered around Devils Hole--a 50-foot-deep window to the water table less than 1 mile up gradient from springs of the Ash Meadows ground-water-basin discharge area. The mapping was done in late 1985 and early 1986 by the author for the U.S. Geological Survey. This report presents the results of that work, and includes three partly overlapping geologic maps (figs. 2, 3, and 4) of the area at different scales, as well as a preliminary interpretation of some aspects of the structural setting and its possible influence on rates and paths of ground-water flow. The work is part of a larger research study of ground water and paleoclimate of the southern Great Basin being conducted by the U.S. Geological Survey.

The author is grateful to Isaac Winograd for support and encouragement in this work. Alan Riggs and Raymond Hoffman of the Geological Survey provided useful information from their diving expeditions at Devils Hole. The National Park Service provided access to Devils Hole itself for this research. Winograd and K.A. Sargent provided helpful reviews.

REGIONAL GEOLOGIC SETTING

The study area (fig. 1) is located at the western edge of an unnamed series of ridges and hills of Paleozoic rocks in the Amargosa Desert of southwestern Nevada. This report uses the informal name, Amargosa ridges, for these hills, as well as the names Devils Hole ridge for the ridge extending north-northwest from Devils Hole, and Point of Rocks ridge for the ridge extending north-northwest from Point of Rocks springs. All but the northwesternmost and southeastern parts of this group of ridges expose the Cambrian Bonanza King Formation--a thick (about 5,000 feet) unit composed almost entirely of carbonate rocks. The Amargosa ridges are abutted in Ash Meadows and Amargosa Flat by thick, mostly fine-grained sediments of Tertiary and Quaternary age. The Bonanza King Formation is at the base of a regional hydrogeologic unit termed the "lower carbonate aquifer" (Winograd and Thordarson, 1975).

Immediately to the west and northwest of the Amargosa ridges is a roughly linear belt of springs (fig. 1) that collectively make up the principal discharge area of the Ash Meadows ground water basin (Winograd and Thordarson, 1975)--a large region extending more than 50 miles to the northeast of Ash Meadows. Thus, the general flow path for ground water is westward or southwestward through the study area to discharge points in Ash Meadows. The belt of springs probably is controlled mainly by a steep interface between the Paleozoic carbonate rocks and relatively impermeable basin-filling sedimentary and tuffaceous rocks of Ash Meadows. (Winograd and Thordarson, 1975, p. C81-C82). The contact, partly coincident with a steep west-facing gravity gradient (Healey and others, 1980; D.A. Ponce and K.S. Kirchoff-Stein, U.S. Geological Survey, written commun., 1986), is probably the location of an important high-angle, north-to-northwest-striking fault zone.

The Devils Hole-Point of Rocks ridges trend northwest, approximately parallel to the postulated fault zones in Ash Meadows, including possible extensions of the Stewart Valley Fault Zone (fig. 1) (Burchfiel and others, 1982). Several anticlinal axes with a northwesterly trend also parallel the Amargosa ridges (fig. 2; Burchfiel and others, 1982). The north-west structural grain of the study area is strikingly at variance with that of the Specter Range area a few miles to the north (fig. 1), where the predominant structural trend in a large area is northeasterly. Carr (1984) has called this major northeast-striking system of faults and folds the Spotted Range-Mine Mountain structural zone. This zone, which is seismically active (Rogers and others, 1983) and contains several Quaternary fault scarps, may continue across the Amargosa Desert into the southern end of the Funeral Mountains, passing just northwest of the study area.

STRATIGRAPHY

Bonanza King Formation

Bedrock of the study area consists entirely of the Banded Mountain Member of the Bonanza King Formation of Middle and Late Cambrian age (Barnes and Palmer, 1961). Approximately 1,500 feet of the member are exposed in the mapped area, and at least 500 more feet are exposed to the northwest and southeast, where, respectively, the upper contact with the Upper Cambrian Dunderberg Shale Member of the Nopah Formation (Barnes and Christiansen, 1967), and the lower contact with the Papoose Lake Member of the Bonanza King Formation are exposed. Denny and Drewes (1965), who mapped the Ash Meadows quadrangle (fig. 1), divided the Bonanza King into upper and lower parts, but placed the contact within the Papoose Lake Member, as presently used. Denny and Drewes (1965) did not map the Dunderberg Shale Member of the Nopah Formation. Burchfiel, Hamill, and Wilhelms (1982), who mapped an area southeast of Ash Meadows, locally divided the Bonanza King into its members but not in the area adjacent to the mapping reported here.

The Banded Mountain Member consists almost entirely of limestone and subordinate dolomite (description of map units for figures 2 and 3), the proportions of which vary both vertically and laterally, mainly as a result of alteration. The only clastic materials of any consequence in the member are siltstone, fine-grained sandstone, and minor shale in the lowest part (unit a, figs. 2 and 3). Some silty material is found in the carbonate beds at a few places higher in the member, especially in unit c. The silt tends to color some carbonate beds pale yellowish-brown. Subdivision of the member into map units a through f is somewhat arbitrary, and is not necessarily recognizable in the surrounding region, although unit a, with its noticeable clastic material, is a widespread zone (Barnes and others, 1962). Map units a, b, and c in this report appear to correspond approximately to all but the upper 200 feet of unit 1 as described by Barnes and others (1962, fig. 127.2) in the Yucca Flat area 50 miles to the north. The upper 200 feet of their unit 1 may be equivalent to unit d in this report. If this is correct, Barnes and others' unit 2 would be roughly equivalent to units e and f in this report, but unit c would be significantly thinner than in the Yucca Flat area. For the present study, a section of the Bonanza King Formation in the Specter Range, 4 miles northeast of Lathrop Wells (fig. 1), was examined; that section was found to be considerably different from that exposed 15 miles to the south near Devils Hole. This may result from a major thrust fault --the Specter Range thrust--that passes between the two areas.

A distinctive marker bed (fig. 4), extremely useful in mapping small structures, was found in the upper part of unit c. It consists of cuspate structure in a limestone bed 8 to 18 inches thick. It was given the informal field name of the "curly limestone bed", and was recognized, not only throughout the Devils Hole study area, but also in the ridges 1 mile or so to the east. It was not found, however, in a cursory examination of the Banded Mountain Member 8 miles southeast of Devils Hole. The bed may be a stromatolitic, or algal limestone.

Devils Hole, and all but 1 of 10 collapse depressions in carbonate rock found in this study are present in unit c of the Banded Mountain Member, suggesting some lithostratigraphic control for dissolution of the carbonate rock. Detailed work would be needed to determine the role, if any, of carbonate composition in the development of these cavities. The depressions are described in more detail in a later section.

"Lake Beds"

Fine-grained, poorly indurated clastic and calcareous sediments are present below an elevation of about 2,400 feet in Ash Meadows and Amargosa Flat. Most of these beds were deposited in shallow lakes, ponds and playas (Hay and others, 1986). Although their general distribution near the southwestern edge of Devils Hole ridge is shown on figure 3, these deposits were not mapped in detail. Their stratigraphy is described by Hay and others (1986), Swadley (1983), Denny and Drewes (1965), Naff (1973), and R.E. Pexton (1984). All but one spring (at Point of Rocks) issues from these sediments. One small area of poorly indurated sandstone (unit QTs; fig. 3) (perhaps a shoreline facies of the "lake beds") was mapped about 2,200 feet west-northwest of Devils Hole.

Colluvium and Alluvium

Alluvial units, which overlie the "lake beds", were divided into only two units in this mapping (fig. 2): colluvium and alluvium (QTa) of Pleistocene and Pliocene (?) age, and alluvium (Ql), largely of Holocene age. These units are described by Swadley (1983) and Hoover, Swadley and Gordon (1981). The older beds (QTa) contain numerous spring-related deposits, including calcite veins, to elevations as high as 2,460 feet (fig. 3) north of Devils Hole. Reworked fragments of calcite veins are locally present in Ql deposits along the present washes. No veins were observed in Ql deposits.

Calcium Carbonate Deposits Related to Groundwater

Deposits of calcium carbonate as pervasive cement (tufa) in or on alluvium, laminated veins or coatings, and circular "eyes" or ojos occur at many locations in the region, especially in the area around Devils Hole. The Quaternary deposits, of calcium carbonate, particularly the laminated veins of Pleistocene age, are being studied in detail as clues to the Quaternary paleohydrology and climate of the region (Winograd and Doty, 1980; Winograd and others, 1985; Winograd and Szabo, 1986). For this report I mapped (figs. 2, 3, and 4) all young (Pliocene-Pleistocene) veins and other calcium carbonate spring-related deposits found in the Devils Hole area to establish possible structural influences on their location. Although layered carbonate veins are common in the bedrock along many of the faults, those above an elevation of 2,540 feet invariably are yellowish, relatively coarse grained, and appear largely recrystallized. Many of the northwest-striking faults contain wide, coarsely crystalline, irregular veins; the best examples are at higher elevations on the ridge northeast of Devils Hole, outside the mapped area. These older veins commonly show several stages of brecciation. One example, in the mapped area, is in a northwest-striking fault on Point of Rocks ridge 0.5 miles east of Devils Hole (fig. 2). At that location, a gray limestone zone in unit b of the Bonanza King Formation coincides with the downward limit of the vein in the fault; the fault continues on the hillside below the gray limestone but contains no vein material. Viewed from a distance, and on aerial photos, it appears that the gray limestone, though nearly parallel to stratification, actually crosscuts the bedding at a very small angle and consists of a slightly lighter or bleached zone about 25 feet thick. Both the bedding and the lighter gray limestone zone are displaced about

20 feet vertically. The calcite vein in the fault contains Paleozoic bedrock clasts and appears to have undergone brecciation and recementation. Close examination of the lighter gray limestone showed that, in addition to being slightly lighter in color compared with rocks above and below, it contains scattered small (1/4-in. to 2-in.-wide) white calcite "eyes" and "squiggles". The lighter zone may represent an exhumed planar alluvium-bedrock contact, or a former water table; if the latter, it has been displaced by faulting and tilted slightly to the north or northwest. Where exposed, it ranges from about 2,500 to 2,610 feet in elevation. The fact that the vein does not continue below the possible former water table could be coincidental, but it is also possible that the older veins are not directly related to the presence of spring or ground water, but originated by downward movement of calcium carbonate from the land surface or by leaching of the host country rock and redeposition of the carbonate above the water table.

COLLAPSE DEPRESSIONS

Twelve depressions, in or near the carbonate bedrock, including Devils Hole itself, have been found in the mapped area (fig. 2). Four of these--Devils Hole, localities A and E (fig. 4), and a hole and depressions in alluvium (I, fig. 2)--were known before the current mapping. All but three (I, J, and K, fig. 2) of the depressions occur within 600 feet of Devils Hole. Other holes, such as one outside the mapped area, about 1.8 miles north-northeast of Devils Hole (fig. 1), occur in the calcareous "lake beds" and appear to be the result of percolation and piping, possibly to underlying open fractures in the Paleozoic carbonate rocks.

The depressions in carbonate rock range from holes or shallow depressions 1 foot or so in diameter, to Devils Hole, which is an opening approximately 75 feet by 25 feet in plan view and 50 feet deep above the water table. Devils Hole is the only such feature in the Ash Meadows area whose subsurface extent is even partially known. According to Alan C. Riggs (U.S. Geological Survey, written commun., 1985; 1986), Devils Hole extends to more than 300 feet below the water table, and a network of passages extends at least 300 feet to the northeast, including an uncollapsed subterranean opening above the water table called "Brown's room" (fig. 4). The average width of the passageways is about 6 feet. The passageways and room walls seem to be largely controlled by fault planes. Riggs (U.S. Geological Survey, written commun., 1985) reports that, near the north-eastern end of "Brown's room", a chimney extends about 50 feet above the water table, which is at an altitude of about 2,360 feet. Surface elevation above this point is estimated to be about 2,425 feet (figs. 3 and 4), so that the room probably comes to within about 10 or 15 feet of the ground surface, yet no sign of surface collapse is present. An important northwest-striking, northeast-dipping fault zone with as much as 100 feet of throw is present at the surface near this location (fig. 4), as well as a small northeast-striking fault.

Evidence of surface collapse and direct connection of accompanying fractures with the water table was found at two localities, one near Devils Hole (D, fig. 4), and the other on top of Point of Rocks ridge southeast of Devils Hole (K, fig. 2) at an elevation of about 2,940 feet or nearly 600 feet above the regional water table. At both places, the openings are irregular fractures in limestone, open from 1 to 2 inches to as much as 10 inches, and are accompanied by small elongate shallow depressions in the bedrock. At both localities, the trend of openings and depressions is to the northeast. The fractures tend to be curved, and many do not follow adjacent old fractures; the exposed surfaces have no deposits of calcium carbonate. In the winter and early spring of 1985-86, the openings at these two localities were damp, exuded warm moist air, and supported a growth of bright-green moss. When reexamined in June, the openings were dry and the moss was dormant. According to E.P. Weeks (U.S. Geological Survey, oral commun., 1986), this situation is expected because of the temperature differential in winter between the warm (32°C) ground water, air, and rocks in the subsurface and cooler air above ground. The temperature differential would cause convection through the openings and condensation of moisture at the surface. In warmer months, the temperature differential would not exist and little or no upward airflow would occur.

Moisture emanation was not found at any of the other mapped openings; however, three openings (A and E, fig. 4, and I, fig. 2) are sizable and obviously extend to considerable but unknown depth. Site A is a hole about 3 feet across that has been partially exposed by a prospect trench. At site E, two fenced-off openings about 1.5 and 3 feet across extend through thin alluvium into the bedrock; this opening extends at least to the water table, 120 feet below land surface (I.J. Winograd, U.S. Geological Survey, oral commun., 1986) At site I, (fig. 2) a hole about 3 feet across extends to unknown depth in moderately cemented alluvium. The opening has probably connected with the bedrock at times. The fact that none of these openings appears moist in cool weather, like the two described above, suggests that they do not communicate effectively with the water table; they may be temporarily sealed by alluvium and rock debris.

The isolated depression at site J (fig. 2), about 1 mile north-northeast of Devils Hole, is similar to those near Devils Hole, but is considerably higher, at an elevation of about 2,575 feet, or more than 200 feet above the water table. It may be significant that the depression at J lies near, but not on, a possible northeastward projection of the fault zone in Burro Trail Canyon; however, no such structure is known to connect the two areas, which are about 0.75 miles apart, and slight curving or offset of a northeast projection of the structure would be required to intersect site J.

Although an attempt was made to locate all collapse features in the area mapped, it is very likely some small ones have been overlooked. Any large features, such as the one at site E (fig. 4), generally are obvious on the aerial photographs used for the mapping.

STRUCTURE

As mentioned earlier in this report, the ridges around Devils Hole are near a junction between major northeast-northwest-striking structural zones, but the predominant features of the Amargosa ridges are northwest-trending faults and folds. Low-angle faults also are present, and strike-slip fault zones may be present nearby. To the casual observer, the ridges appear relatively simple structurally, but as is commonly the case, closer study has revealed complex structure.

Folds

Several folds of northwest axial strike have been mapped in the region. Burchfiel, Hamill, and Wilhelms (1982) mapped a northwest-trending fold they called the Ash Meadows anticline in an area southeast of Devils Hole. In unpublished mapping R.H. Moench, R.L. Christiansen, and M. W. Reynolds (data on file at U.S. Geological Survey, Denver, Colorado) mapped a similar structure that they called the Pahrump Hills anticline. Figures 2 and 2A show a northwest-trending anticlinal axis in the northwestern part of Point of Rocks ridge. The southern end of Devils Hole ridge is interpreted to be the upfaulted western limb of that anticline (fig. 2A). If this is correct, the opposing limbs of the fold are steep (more than 45°) at the southwestern edge of Devils Hole ridge and northeastern edge of Point of Rocks ridge. Results of mapping by Denny and Drewes (1965) and the present study suggest that the entire Amargosa ridge system is a folded anticline containing a series of lesser anticlines and synclines that plunge gently to the northwest. One important anticlinal axis lies on Point of Rocks ridge east of Devils Hole. Some of the steepening of the dips on the limbs of the anticline noted above may be a result of rotation along the major northwest-striking faults.

Further mapping of the entire Amargosa ridges area is necessary to complete understanding of the folds and faults in the area.

High-angle faults

The area is cut by a pervasive set of northwest-striking faults that dip generally northeastward in the western part of the area and southwestward in the ridges to the east. The faults generally dip antithetically to the bedding, at angles of 65° or more (figs. 2 and 2a). Strike of most of the faults is roughly parallel to the strike of the bedding. Only a few fault dips were measurable, but the few dips measured, in combination with fault traces over topography, indicate that the average fault dip is about 70°; the steeper fault planes tend to be in areas of lower stratal dips, which, in the Devils Hole area, average about 40° to the southwest. Throw on the northwest-striking faults is typically 50 to 100 feet, but a few faults have as much as 200 feet of offset (fig. 2A).

A few northeast-striking faults occur in the area. With one notable exception, these are small faults with generally less than 5 feet of offset. The best example is the main fault exposed in Devils Hole (fig. 4), which strikes N 40° to 50° E, dips 80° to 85° to the southeast, and has a stratigraphic displacement of only about 2 feet down to the northwest, which makes it a high-angle reverse fault. Numerous other small faults with a northeast-strike were mapped (fig. 4) near Devils Hole by tracing marker beds. Nearly all of these have less than 2 feet of vertical offset, and most are also down to the northwest but are normal faults. Most of the smaller collapse depressions near Devils Hole are controlled by these northeast-striking faults and fractures.

The only major zone of northeast-striking faults in the area is exposed at the head of Burro Trail Canyon, 0.4 mile northwest of Devils

Hole (figs. 2 and 3). This zone of faults strikes about N 55° E and has a cumulative displacement of more than 100 feet down to the northwest (fig. 3). Fault relations are not clear to the southwest and northeast in areas mostly covered by alluvium. Burro Trail Canyon, however, is a prominent topographic feature that aligns with the faults, which cross Devils Hole ridge at a relatively low saddle. Northeast of the saddle, the Burro Trail canyon fault system probably terminates or is offset on several of the large northwest-striking faults. The occurrence of a few northeast-striking faults near the collapse feature at site J (fig. 2), and the collapse itself, however, suggest the possibility that the northeast-striking fault zone may extend that far. To the southwest, down Burro Trail Canyon, relations also are obscure. A few prominent northwest-striking faults appear to connect across the canyon, but this may be fortuitous. Alignment of the canyon with the fault zone, and the cluster of calcite veins and ojos near its mouth (fig. 3), suggest that the Burro Trail Canyon fault system continues southwestward. The association of springs, spring deposits, and sinkholes with northeast-striking structures is discussed further in the following section.

Another fault with a northeast strike is present at the northern edge of the studied area; its southern end is shown near the top of figure 2, and its general location is indicated by a line of dots on figure 1. Strike of the fault is about N 20° E, and it too crosses a ridge at a relatively low saddle. This fault is of interest for two reasons: it offsets alluvial unit QTa (of probable Pleistocene age in this area), and, on the north, at the foot of the ridge, it contains youthful-appearing (uncrystallized) laminated calcite veins, some of which are associated with a low, inactive spring mound. At the same location, on the trend of the fault, is a hole in the "lake beds", mentioned earlier and ascribed to piping.

Another fault that cuts Pleistocene alluvium was mapped (fig. 2) at the foot of Point of Rocks ridge 0.8 mile southeast of Devils Hole. This small fault strikes northerly and dips 75° to the west. It contains a prominent laminated calcite vein that does not continue above an elevation of about 2,460 feet.

Low angle faults

Faults parallel or nearly parallel to bedding commonly are difficult to detect and map, and it is possible some have been overlooked in the study area. An important fault of this type was mapped on Point of Rocks ridge, where, for most of its length, it forms a slightly discordant contact between map units a and b of the Banded Mountain Member of the Bonanza King Formation. The fault dips northeastward 10° to 25°. In the main northwest-trending canyon that splits the ridge, the low-angle fault appears to be cut off or dropped below the level of exposure by one of the larger northwest-striking faults. Other northwest-striking faults, however, on the western spur of Point of Rocks ridge, are present only in the upper plate of the low-angle fault and do not offset it. During the study period, these features could not be mapped or studied in detail, but several observations are of interest: (1) The zone of separation and low-angle movement occurred within unit a, the only exposed part of the section containing shale and other clastic material; (2) the upper plate (mostly unit b) is highly fractured and brecciated; (3) some of the faults in the upper plate intersect but do not offset the low-angle fault; (4) the high-angle faults do not flatten or curve to join the low-angle fault but terminate abruptly downward, and (5) the low-angle structure is exposed along the crest of the anticline described earlier (fig. 2), although the dip of the low-angle fault is opposite to that of the western limb of the anticline. According to K. A. Sargent (U.S. Geological Survey, written commun., 1986), characteristics 1-4 above are similar to features he observed in Paleozoic rocks of the Specter Range (fig. 1).

A better exposed and more spectacular example of a similar structure has been mapped by Naff (1973) in an area about 2.5 miles southeast of Point of Rocks Springs (fig. 1). This is in the area of the Ash Meadows anticline (Burchfiel and others, 1982) mentioned earlier. The author briefly examined this area, and, although I do not agree with several of Naff's conclusions, I found his mapping to be a good representation of the structure. A low-angle fault is located near the stratigraphic contact between the lower Bonanza King Formation and underlying Middle and Lower Carrara Formation--a relatively incompetent unit that contains much thin-bedded limestone and some shale. Numerous faults and fractures, predominantly of northwest strike, are present in the upper plate of Bonanza King. As Naff (1973) contends, few of these high-angle faults offset the underlying low-angle fault; any such offsets are limited to a few feet at most. The difference in structural style between the two plates is striking, as the lower plate has few faults and consists of an asymmetric anticline whose exposed core is the Precambrian and Lower Cambrian Wood Canyon Formation. The southwestern flank of the anticline is very steep to overturned to the southwest. Naff (1973) concluded that the low-angle fault, which he called the Ash Meadows thrust fault, was folded along with the underlying anticline, but the amplitude of the fold in the lower plate is much greater than the gentle flexure of the low-angle fault. Therefore, the low-angle fault probably is a younger feature, unrelated to the folding of the rocks beneath it. It seems reasonable to conclude that the low-angle faulting was a result of slippage near the top of incompetent bedding in the Carrara Formation--possibly localized over the older anticlinal axis. Naff (1973) also felt that the faults in the upper plate are tear faults and that they curve and flatten to join the low-angle fault. Some of these faults do appear to be curved or listric, but many seen by the author intersect the low-angle fault at a relatively high angle and appear to be sheared off by it. Naff suggested that because of the apparent structural continuity and similarity of style in the upper plate between his area and the Devils Hole area, the low-angle faulting extends beneath Devils Hole as well.

As mentioned before, the upper plate of the low-angle fault on Point of Rocks ridge, southeast of Devils Hole, is highly fractured and brecciated. Other areas mapped in this study that display unusual brecciation include the southwesternmost bedrock area (unit d) 0.2 to 0.3 mile west-northwest of Devils Hole, and the two low ridges (also in unit d) on the southwestern flank of the main ridge north of the Ash Meadows-Crystal Road, 0.8 to 1.1 miles north-northeast of Devils Hole (fig. 2).

Winograd and Thordarson (1975, p. 73) also pointed out the contribution of low-angle or thrust faults in the breakup and fracturing of upper plates. They suggested that the high hydrologic transmissivity of the Specter Range area is partly a result of structure in the upper plate of the Specter Range thrust.

CHRONOLOGY OF TECTONIC EVENTS

Establishing the sequence and age of structural events is particularly difficult in the Devils Hole study area, largely because of the absence of all but the uppermost Tertiary deposits. The age of a series of poor exposures of Tertiary rocks (Denny and Drewes, 1965; Naff, 1973), that form a northwest-trending belt in Ash Meadows near the California state line, about 4 miles southwest of Devils Hole, is essentially unknown. These rocks, largely sedimentary with some tuffaceous beds, are folded into generally east-west trending anticlines and synclines with local dips of more than 60°. In one area examined in the study, the fold axes swing almost 90° from a north to west strike, after the fashion of drag folds. Naff (1973) felt these rocks are most likely late Tertiary in age. In the area mapped by Naff (1973) 2 miles southeast of Point of Rocks, he shows several small outcrops of Tertiary sedimentary rocks that onlap the Paleozoic rocks, but do not appear to be disturbed by the nearby low-angle fault, although this relation is not clear. The Tertiary beds strike east-northeast and dip about 30° to the south. A slide block of Bonanza King Formation that appears to rest on top of the low-angle fault mapped by Naff is, in turn, onlapped by the Tertiary rocks. From this evidence, and the fact that the exposed Tertiary rocks are unfaulted, it is reasonable to conclude that the low-angle faulting is older than the Tertiary sediments, and, from the folding relations described earlier, the main folding of the Paleozoic rocks predates the low-angle faulting. The age of the few Tertiary rocks exposed in the Ash Meadows area is, therefore, critical in dating the age of structural events in the region. These Tertiary rocks underlie the "lake beds" of latest Tertiary age, whose age (2 to 4 million years) is mostly Pliocene, on the basis of dated ash beds within them (Hay and others, 1986). The "lake beds" are displaced a few feet in several places, but show no major structural disturbance (R.E. Pexton, written commun., 1985; Denny and Drewes, 1965).

Deposits in the southeastern part of the Ash Meadows quadrangle, near Grapevine Spring, called fanglomerate by Denny and Drewes (1965) and assigned a probable age of late Pliocene or early Pleistocene, are similar to the Funeral Formation of the Furnace Creek area in California, whose age is about 4 million years based on a whole-rock basalt K-Ar date reported by McAllister (1973). Uranium-series ages obtained on calcite veins in the Funeral Formation in Furnace Creek Wash suggest the Funeral is more than 2.5 million years old (I. J. Winograd, U.S. Geological Survey, written commun., 1986). The fanglomerate at Grapevine Spring uncomformably overlies the Tertiary sedimentary rocks of the Ash Meadows area (Denny and Drewes, 1965). Denny and Drewes (1965) stated that the Tertiary sedimentary rocks of Ash Meadows closely resemble those of Oligocene (?) age in the southeastern corner of the Funeral Mountains (fig. 1). The latter rocks are tilted nearly as much as the adjacent Paleozoic rocks-40° to 60° in many places. The Tertiary rocks of Ash Meadows also resemble Tertiary rocks north of the Specter Range on the Nevada Test Site; these units, which include the rocks of Pavits Spring, whose age is roughly 15 million years (Carr and others, 1986, fig. 2), also are gently folded. These relations and rough correlations suggest that the folded Tertiary sedimentary rocks of Ash Meadows are not late Tertiary but probably are at least as old as middle Miocene. Such an age would agree well with what is known about Tertiary deformation in the Walker Lane belt of southwestern Nevada (Carr, 1984, p. 18-21).

Relations briefly discussed above lead the author to conclude that most of the structural displacements in the Devils Hole area occurred well before about 4 million years ago, but, until the age of the Tertiary rocks in Ash Meadows can be established, it is impossible to place any definitive age on the folding and faulting of the Paleozoic rocks.

HYDROGEOLOGIC INTERPRETATION

The Devils Hole area is highly transmissive hydrologically as evidenced by the large discharge of water from many springs in the Ash Meadows area (Winograd and Thordarson, 1975). Winograd and Pearson (1976) discussed an important carbon-14 anomaly in the age of water being discharged from the larger springs. Briefly, they found that water from all but one of the springs had a similar carbon-14 content (about 2.4-percent modern), whereas one of the largest springs, Crystal Pool (fig. 1) has a carbon-14 content almost 5 times larger (about 11.1-percent modern) than all the other spring waters analyzed. Their conclusion is that water discharging from Crystal Pool is following a preferred pathway from recharge areas many miles to the northeast. This pathway enables the water to move much more rapidly than water reaching other springs. Because Crystal Pool is centrally located within the discharge zone, it is likely that a natural pipeline or "megachannel" is located relatively near the discharge area. Furthermore, the flow direction is probably from the northeast (Winograd and Thordarson, 1975), a direction normal to the alignment of larger springs at the spring line, so that the ground water that discharges at Crystal Pool must pass through the Devils Hole area. The top of the regional lower clastic aquitard (Winograd and Thordarson, 1975) is about 3,500 feet[1] below the water table in the Devils Hole area.

Carr (1974) proposed a stress model for the region in which the minimum principal stress direction during the last 5 million years or so has been oriented about N 50° W so that faults or fractures with a

[1] The approximate thickness of the Papoose Lake Member (Barnes and others, 1962), plus about 500 feet of the lower part of the Banded Mountain Member, both of the Bonanza King Formation, and about 1,000 feet of the Carrara Formation.

northwest strike would be under compression, and faults with a northeast strike would tend to open. The openings of Devils Hole, and sinkhole fracture and fault relations in the surrounding area, strongly support Carr's model. The fresh-looking openings that breathe moist air in cooler months suggest that the proposed stresses are presently active.

Thus, faults and fractures with a northeast trend potentially are the most permeable in the carbonate aquifer. As described earlier, few large northeast-striking faults are present in the Devils Hole area, with one exception--the fault zone that aligns with Burro Trail Canyon (fig. 2). This fault zone strikes about N 60° E and, if projected southwestward, would pass through School Spring (figs. 2 and 3) and, with no change in strike, project directly to Crystal Pool. The distance between Crystal Pool and the fault-controlled saddle at the crest of Devils Hole ridge is 1.8 miles. School Spring is one of the highest springs, and its discharge is small; no carbon-14 analyses of its water are available. On the basis of gravity data, there is no indication of a possible extension of the fault zone southwestward to Crystal Pool, although work by D.A. Ponce and K.S. Kirchoff-Stein (U.S. Geological Survey, written commun., 1980) tightened the Bouguer gravity contours of Healy and others (1980) and increased the north-south-trending gradient (fig. 1) in the area around Crystal Pool. That spring is located near the middle of the gradient, approximately where a buried north-south fault may be present in the bedrock. Also, Crystal Pool is at the southern end of that north-south gradient; at the spring location, the gravity gradient makes a sharp bend to the west and northwest (fig. 1). It appears that Crystal Pool could be at or near the intersection of an important northeast-striking fault zone, mostly within the Paleozoic bedrock, with a major basin-bounding north-south fault, and with a north-west-striking structure paralleling or coinciding with a possible extension of the Stewart Valley fault zone (fig. 1).

Examination of figure 35 in the report of Winograd and Thordarson (1975) shows a definite relation between spring temperature and proximity to the lower carbonate aquifer; the springs closest to bedrock have, in general, the highest temperature. However, if one contours the temperature data in figure 35, it appears that both Crystal Pool and School Spring are anomalous--the contours must bulge southwestward to include these two springs. In fact, the temperature shown for School Spring (34.5°C) is 1.5°C higher than the water temperature in Devils Hole. All these factors suggest a highly permeable, northeast-striking zone in the Paleozoic rocks, probably a projection of the fault zone mapped at Burro Trail Canyon. Northeast-striking calcite veins (R. E. Pexton, 1984) in the Devils Hole region, the structure mapped at Devils Hole itself (fig. 4), and the other northeast-striking fault (fig. 1) noted, which contains laminated carbonate veins and has a spring mound on its trend, can be cited as additional evidence of the hydrologic significance of northeast-oriented structure.

If low-angle faults, such as the ones mapped by Naff (1973) and the ones mapped in this study (fig. 2), underlie the Devils Hole area, they could help not only to explain the highly brecciated and faulted areas, but also could facilitate opening of fractures and faults of northeast-strike by allowing pull-apart of the upper plate in the direction of minimum principal stress. In other words, tensional forces oriented northwest-southeast might be more effective in maintaining openings if frictional drag were decreased by low-angle faults riding on relatively incompetent clastic rocks.

The relatively rapid transmission of water discharging at Crystal Pool remains an unsolved problem, however. The discovery of a possible major structural channel in the aquifer striking northeast from the spring toward and through Devils Hole ridge (fig. 1) does not provide a complete solution, although the association is intriguing. It is not unreasonable to assume that the Burro Canyon fault zone extends at least halfway through the Amargosa ridges; however, in order to explain the carbon-14 anomaly at Crystal Pool, a longer highly permeable channelway seems required. Present data neither rules out nor confirms that such a longer pathway exists.

SUMMARY

This study of the Devils Hole area was undertaken to help document details of relationships between local geology, structure, and groundwater conditions. These relationships are important to better understanding of the movements of groundwater in the complex and extensive carbonate rock aquifer to points of surface discharge in nearby Ash Meadows.

Geologic mapping shows that Devils Hole and other nearby features related to groundwater, such as laminated calcite veins and collapse areas, occur not only within a relatively limited elevation range, but also within the same general stratigraphic intervals of the Banded Mountain Member of the Bonanza King Formation. Further work would be needed, however, to determine whether this apparent association is real and whether it could be related to relative solubilities of the carbonate rocks, or some other factor. Twelve collapse areas, all much smaller than Devils Hole, were identified in the mapping. Two of the smallest collapses have fracture openings that exhale warm moist air in the winter.

The Devils Hole area is located within a series of northwest-striking steep ridges of bedrock that are controlled by northwest-striking folds and faults in the Paleozoic rocks. Although this northwesterly-trending structural grain is the most prominent in the area, small faults and fractures of northeast strike are the most important hydrologically, and control the location of Devils Hole and many of the other collapse depressions and several Quaternary calcite veins. In addition, one mapped prominent fault zone of northeast strike may provide a channelway for groundwater movement southwestward to discharge at Crystal Pool in Ash Meadows.

A low-angle fault mapped within a slightly shaly part of the Bonanza King Formation on the ridge east of Devils Hole may play a role in

promoting permeable openings in the aquifer.

From general relationships in the area, it is concluded that most of the structural disturbances occurred well before about 4 million years ago, but establishing the age of undated older Tertiary rocks in and near Ash Meadows is critical to dating the periods of important structural activity. The openings at Devils Hole together with sinkhole, fracture and fault relations in the surrounding area are in accord with a general stress field model (Carr, 1974) for this part of the Great Basin in which the minimum principal stress direction during the last 5 million years or so has been oriented northwest-southeast; faults and fractures of northwest strike would tend to be closed, whereas those of northeast strike would tend to open. The youthful appearance of some of these features suggests that the proposed stresses are currently active.

Other geohydrologic interpretations made in this report include the structural setting of Crystal Pool, which is probably situated near the intersection of a highly permeable northeast-striking fault with major north and northwest-striking faults in the subsurface. Low-angle faults in the region, including one on the ridge east of Devils Hole, could increase permeability by aiding breakup of the upper plates and opening fractures and faults of northeast strike.

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APPENDIX I

DESCRIPTION OF MAP UNITS, FIGURES 2, 3 and 4

Q1 ALLUVIUM (QUATERNARY) - Unconsolidated bouldery deposits within active or youthful washes (0-10 ft.)

QTa COLLUVIUM AND ALLUVIUM (PLEISTOCENE AND PLIOCENE (?)) - Fans and debris flows, moderately consolidated, partially dissected, composed of bouldery gravel; younger material commonly has a varnished pavement. In places includes a thin cover of Holocene alluvium. Consists of units Q2 and QTa of Hoover, Swadley and Gordon (1981). (0 to 50 ft thick)

QTs SANDSTONE (PLEISTOCENE (?) AND PLIOCENE) - Fine-grained, light-colored, locally stratified, calcareous sand and silt, weakly cemented. Probably a strand deposit of lake or pond (0 to 20 ft thick)

QTl "LAKE BEDS" (PLEISTOCENE (?) AND PLIOCENE) - White to light tan or pale green, highly calcareous clay and silt, poorly bedded and consolidated. (0 to 100 ft thick)

BONANZA KING FORMATION, BANDED MOUNTAIN MEMBER, UNITS A THROUGH F (CAMBRIAN)

UNIT f Dolomite and dolomitic limestone, gray, indistinctly bedded to massive, with sugary, recrystallized appearance. Upper contact not exposed in map area; lower contact gradational. (More than 250 ft thick).

UNIT e Dolomite and some limestone near base, light and dark gray, banded, ledgy; contacts gradational. (About 200 ft thick).

UNIT d Limestone and subordinate dolomite, dark gray, massive to crudely bedded; lower contact abrupt. (About 200 ft thick).

UNIT c Limestone and limy dolomite, dark gray to very light gray, thick-to-medium-bedded, banded or striped appearance; some intervals yellowish-tan or pastel pink-weathering and silty. Lower half of unit tends to be thicker bedded, less banded and light-colored, and contains zones of brown-weathering chert in blobs and discontinuous thin layers, commonly associated with prominent striping of light and dark layers a few inches thick; convoluted or cuspate beds are common. A distinctive marker bed about 1 foot thick is present about 100 ft below top of unit; bed contains distinctive cuspate layers, probably stromatolitic. Upper contact abrupt, lower very gradational. (About 400 ft thick).

UNIT b Limestone, very dark gray to gray, mostly massive to thick-bedded, except in upper part, which contains some thin-to-medium-bedded gray-to light-gray limestone. (About 200 ft thick).

UNIT a Calcareous siltstone and sandstone, limestone and minor shale; siltstone and sandstone are light reddish to yellowish brown, limestone gray to light gray. Clastic beds are most prominent in lower part. Base of unit is base of Banded Mountain Member, but base is not exposed in mapped area. (More than 150 ft thick).

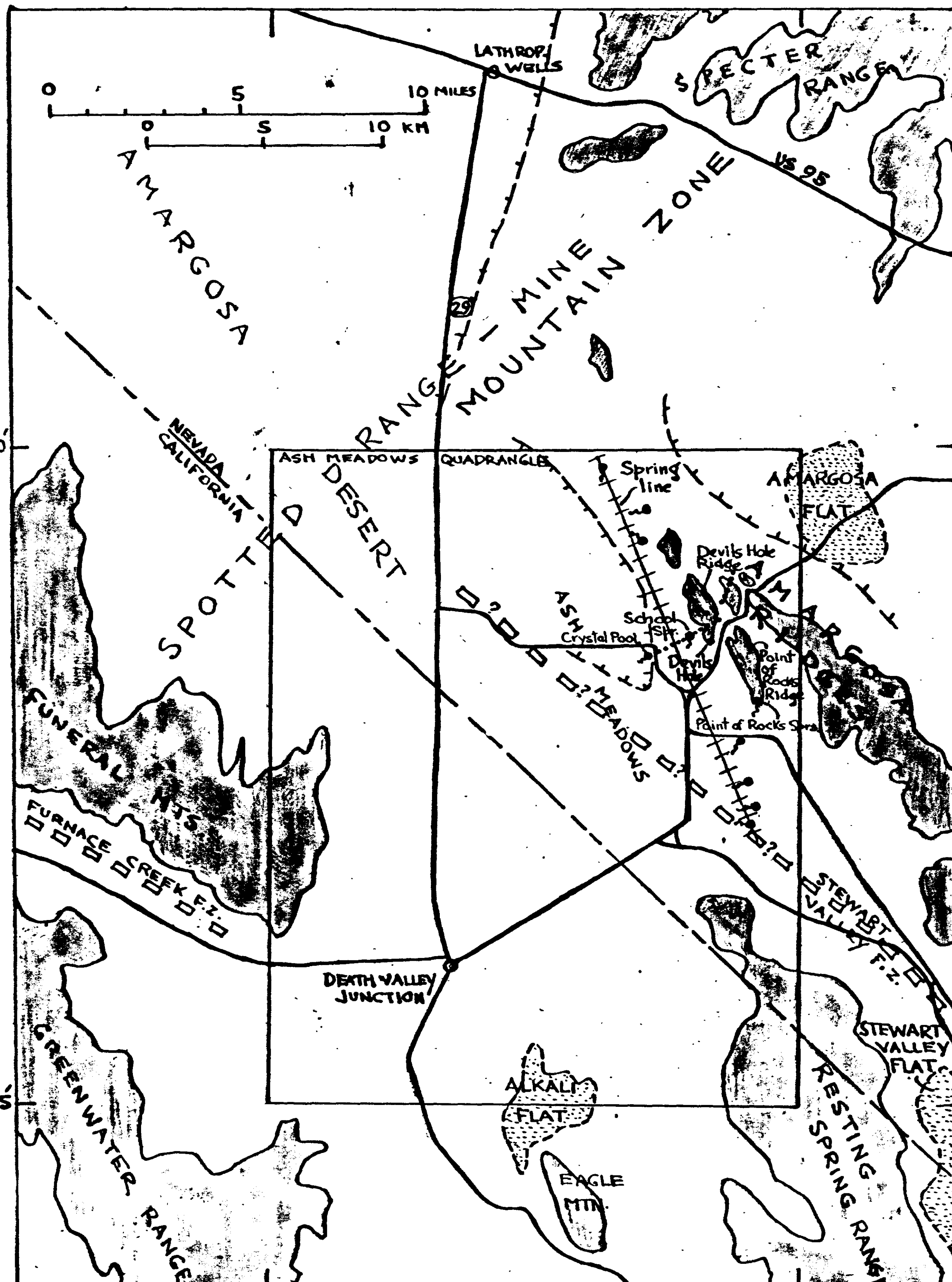

FIGURE 1 MAP OF REGION AROUND DEVILS HOLE Dashed lines with hachures show location of steep gravity gradients in Ash Meadows–Lathrop Wells area. Lines of dots in Devils Hole area represent northeast-striking structures mentioned in text. F.Z.- Fault zone.

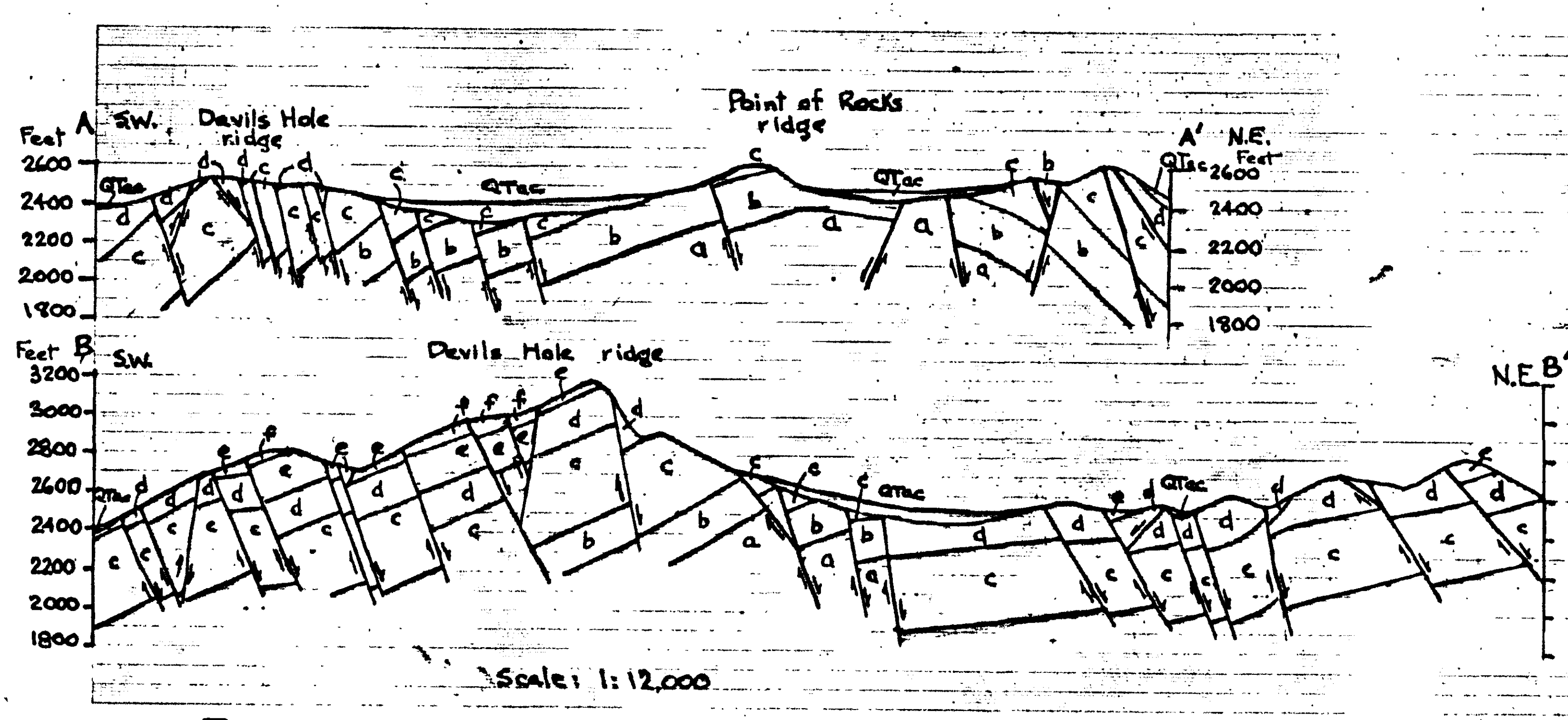

FIGURE 2A GEOLOGIC SECTIONS OF THE DEVILS HOLE AREA
Location of sections is shown on figure 2.