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Structure of Pre-Cenozoic Rocks in the Vicinity of Yucca Mountain, Nye County, Nevada— A Potential Nuclear-Waste Disposal Site

U.S. GEOLOGICAL SURVEY BULLETIN 1647

Prepared in cooperation with the U.S. Department of Energy

Structure of Pre-Cenozoic Rocks in the Vicinity of Yucca Mountain, Nye County, Nevada— A Potential Nuclear-Waste Disposal Site

By G. D. ROBINSON

Prepared in cooperation with the U.S. Department of Energy

Preliminary interpretation of the structure of largely covered Proterozoic and Paleozoic rocks that underlie a potential nuclear-waste disposal site

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Structure of Pre-Cenozoic Rocks in the Vicinity of Yucca Mountain, Nye County, Nevada— A Potential Nuclear-Waste Disposal Site

By G. D. Robinson

Abstract

A potential nuclear-waste disposal site is being evaluated at Yucca Mountain, southern Nye County, Nevada. The site is within Tertiary volcanic rocks, and much of the surrounding region is underlain by such rocks. The volcanic rocks are as much as 3,000 m thick north and west of the site but thin to as little as 1,200 m under the site and apparently continue thinning southward beneath Quaternary cover. Regional ground-water flow is generally to the south, toward discharge areas in the southern Amargosa Desert. Hydrologic studies have indicated that effluents leaking from a repository in unsaturated volcanic rocks may drain downward and find pathways in older rocks beneath the volcanic rocks; therefore, it is important to know the lithology and structure of those rocks. This report is a preliminary interpretation of the gross distribution and present structure of the largely buried prevolcanic rocks in the study area of about 2,200 km^2 surrounding the site, viewed in an irregularly shaped regional setting of about 6,700 km^2.

The regional stratigraphic section begins with upper Proterozoic and Lower Cambrian clastic strata more than 1,800 m thick that are overlain conformably by Middle Cambrian through Upper Devonian dominantly carbonate strata as much as 5,000 m thick, Mississippian clastic strata as much as 2,400 m thick, and Pennsylvanian and lower Permian carbonate strata more than 1,100 m thick. Geophysical evidence suggests that large plutonic or metamorphic rock masses probably do not exist beneath Yucca Mountain at depths relevant to site selection.

Structural patterns indicate that the prevolcanic rocks are deformed into an essentially intact asymmetric synclinorial basin about 80 km broad, with Yucca Mountain in the southwest sector. The basin is flanked by uplifted upper Proterozoic clastic rocks and cored by Pennsylvanian and Permian carbonate rocks. The west and south limbs, where exposed, are steep to overturned; dips of exposed strata elsewhere are generally moderate to low. Buried subordinate folds beneath and around Yucca Mountain are interpreted to be concentric, open, moderately dipping, 8-24 km broad, and gently plunging north to northeast. Regional evidence suggests that one or more thrust faults break the Proterozoic-Paleozoic section beneath and (or) south of Yucca Mountain, but it (they) cannot be located or characterized with available information. Large strike-slip faults, though common in southern Nevada, are not recognized within the synclinorium. Because the synclinorium seems intact, it probably has not experienced mega-scale thrust- or strike-slip faulting. Many extensional dip-slip faults have broadened the synclinorium.

Viewed hydrologically, the two sequences of clastic strata (upper Proterozoic, Lower Cambrian, and Mississippian) are regional aquitards, the two sequences of carbonate strata (Middle Cambrian to Upper Devonian and Pennsylvanian and Lower Permian), regional aquifers. How and where these aquitards and aquifers intersect in the southward-thinning volcanic section and southward-thickening valley fill are key questions. Most of the site is probably underlain by Paleozoic rocks that have water-bearing properties, as low-dipping Silurian carbonate rocks have been penetrated in a deep drill hole in the center of the study area; the northern part of the site, however may be underlain by aquitard Mississippian clastic strata, as a positive magnetic anomaly there is evidently produced by magnetic minerals known locally only in those rocks. Much of the Yucca Mountain region is probably underlain by the lower Paleozoic aquifer, but Proterozoic aquitard rocks dominate the southern border and beyond.

INTRODUCTION

A potential nuclear-waste disposal site is being evaluated at Yucca Mountain, southern Nye County, Nevada (fig. 1). The repository would be in the unsaturated zone, wholly within Tertiary volcanic rocks which underlie much of the region. The volcanic rocks are estimated to be as much as 4,500 m thick north of Yucca Mountain but are believed to thin abruptly under the mountain and probably to continue thinning southward beneath Quaternary cover in the Amargosa Desert, as suggested by gravity (Snyder and Carr, 1982) and aeromagnetic (Kane and Bracken, 1983) data. Regional-ground water flow is generally to the south, toward discharge areas in the southeastern Amargosa Desert (Winograd and Thordarson, 1975). Hydrologic studies indicate that effluents leaking from a repository in the unsaturated volcanic rocks could drain downward into the ground-water flow system and find pathways in the older rocks; consequently, it is important to know the lithology and structure of the rocks beneath the volcanic rocks, especially south of the site.

Direct information on the rocks beneath the volcanic sequence, based on outcrops near the site, is meager (pl. 1,

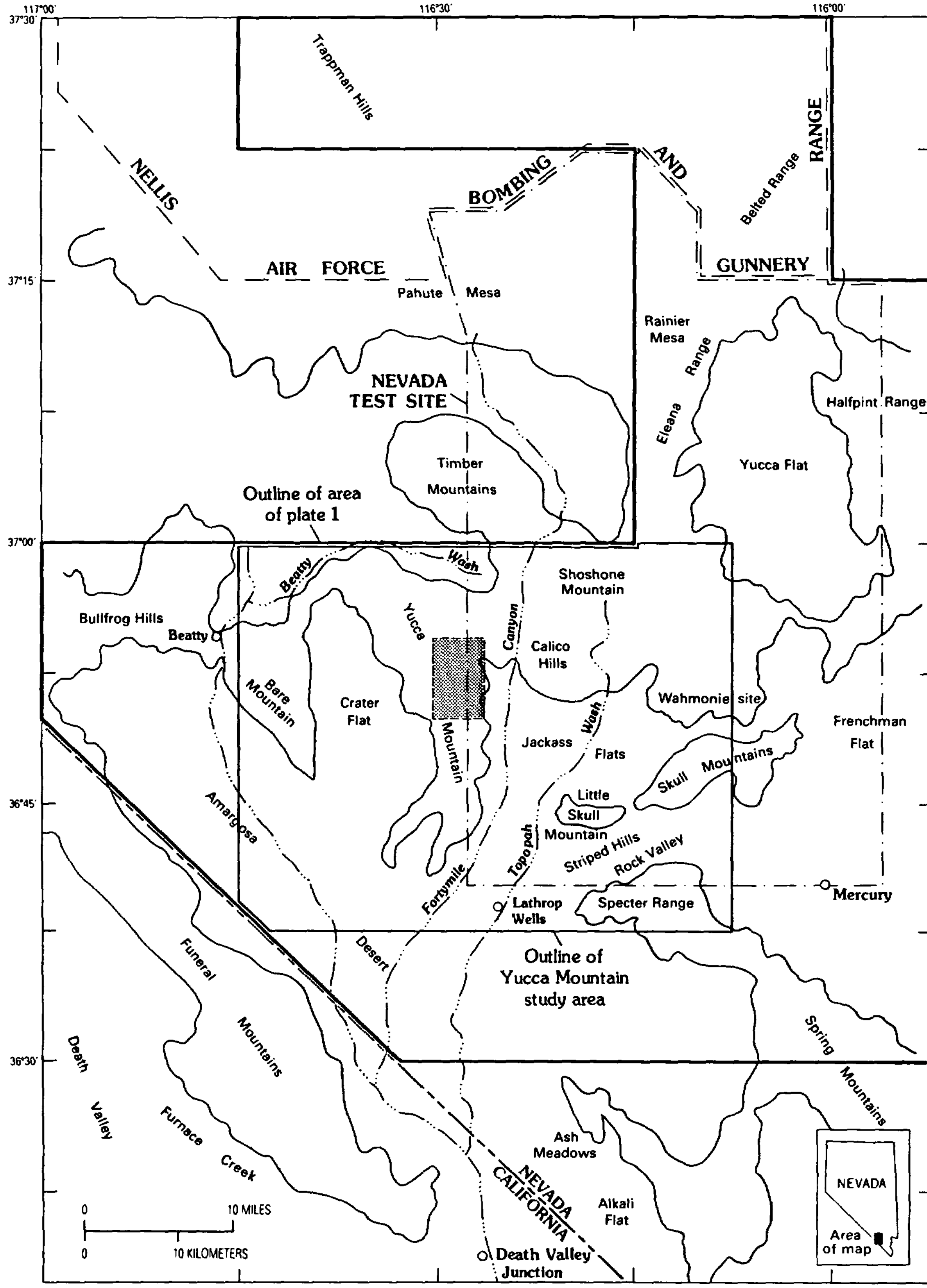

FIGURE 1.—Index map of Yucca Mountain region, Nevada and California, showing the proposed nuclear-waste disposal site (shaded), the Yucca Mountain study area, and area of plate 1.

map *A*). The nearest extensive exposure of such rocks is at Bare Mountain, 16 km west of the site. Small exposures of older rocks are present in the Calico Hills, 8 km to the east, and another area of large exposures is in the ranges that flank Rock Valley, 24 km and more to the southeast; to the north the volcanic cover is thick and continuous for many kilometers. Direct subsurface information consists of a single drill hole near the southeast corner of the site (pl. 1). Therefore, the problem must be approached mainly by extrapolating from and interpolating between outcrops of pre-Cenozoic rocks, aided by geophysical data. Yucca Mountain lies within the Cordilleran fold-and-thrust belt, so analogy with appropriate parts of the fold belt would appear to be a valuable tool in this study. Only the most general analogy with other segments of the Cordillera is feasible, however, and reliance is placed mainly on evidence within southern Nevada.

This report concentrates on the pre-Cenozoic rocks and their present structure in a rectangular area of about 2,200 km^2 that includes the main exposure of pre-Cenozoic rocks in the vicinity of the site, designated the Yucca Mountain study area (fig. 1), although the hydrologic system of concern extends much farther south. The study area is viewed in the context of an irregularly shaped region (pl. 1, map *A*) of about 6,700 km^2. Map data were compiled at a 1:48,000 scale but are presented here at a much smaller scale to emphasize the general nature of the conclusions. Most of the regional geologic aspects and the tectonic processes are left for future consideration. This report is a first approximation intended to focus future work.

Previous Work

Surface geology in the study area is fairly well known, largely because Yucca Mountain is partly within the Nevada Test Site (NTS). The entire NTS has been mapped geologically at a 1:24,000 scale, and the surrounding area has also been mapped, mostly at smaller scales (fig. 2). Direct subsurface information on prevolcanic rocks beneath the site is limited to drill hole UE25 p#1 (hereafter p1) near the southeast corner (pl. 1), completed in May 1983. Study of the cores and records is in progress: lithological, Michael D. Carr (written commun., 1983); geophysical, Douglas C. Muller (written commun., 1983); paleontological, Anita G. Harris (written commun., 1983). (Another drill hole (Maldonado and others, 1979) in prevolcanic rocks in the Calico Hills east of Yucca Mountain (fig. 1) begins and ends in Mississippian rocks, so it does not add to subsurface information.)

Bare Mountain has been recently reexamined by Michael D. Carr and Susan A. Monsen (written commun., 1983), and Monsen (1982) has completed intensive study of the structural evolution and metamorphic petrology of northwestern Bare Mountain. Barnes and others (1963a) and Carr (1974) have prepared syntheses at a 1:48,000 scale of the nine 7.5-minute quadrangles centered on the Yucca Flat quadrangle. A semitechnical summary of the NTS region has been compiled by Sinnock (1982). A host of publications on the Cordilleran fold belt, too numerous to list here, has also been consulted; a few are cited in the text.

Considerable geophysical work has been conducted in the region, mostly in relation to weapon testing and nuclear-waste management. Especially useful for this report have been aeromagnetic studies by Hazelwood and others (1963), Zietz and others (1977), and Bath and Jahren (1984); gravity studies by Healey and Miller (1971), Ponce (1981), Snyder and Oliver (1981), and Snyder and Carr (1982); and a seismic refraction study by Hoffman and Mooney (1983). Seismic reflection studies (L. W. Pankratz and H. D. Ackerman, written commun., 1982) have not proved useful with respect to subvolcanic relations. Hydrologic information has been derived from Winograd and Thordarson (1975), Winograd and Doty (1980), and Waddell (1982).

Method of Study

The Yucca Mountain study area (fig. 1) was selected as the primary area for investigation because it embraces all substantial outcrops of pre-Cenozoic rocks near the proposed disposal site. Encompassing fifteen 7.5-minute quadrangles and about 2,200 km^2, the study area also embraces much of the Alkali Flat-Furnace Creek Ranch ground-water system draining Yucca Mountain (Waddell, 1982, pl. 1). A more appropriate study area would extend farther south to include ground-water discharge areas in Alkali Flat in southeastern Amargosa Desert, but surface and subsurface information south of Lathrop Wells is minimal. To provide more outcrop control than offered by the scant exposures in the study area, a regional setting, designated the Yucca Mountain region, was chosen (fig. 1; pl. 1). This region includes all the detailed mapping in the NTS and a fringe area of varying width depending on the presence of outcrops of pre-Cenozoic rocks.

A literature search failed to disclose better exposed analogs to the rocks of the study area along strike but suggested that the Yucca Flat area to the northeast, with its many exposures of pre-Tertiary rocks and its scores of drill holes that reach them under cover, would be useful for comparison. The search further suggested that pre-Tertiary rocks of the study area are likely to be deformed into folds of breadth and amplitude measurable in kilometers; to be broken by thrust faults, commonly west dipping and a few thousand meters to many kilometers apart in plan view; and to have behaved generally in a more ductile rather than brittle fashion in view of their rearward position in the fold belt.

Published geologic maps in the region were spot checked by Michael D. Carr and me. As many aspects of the published structural interpretations on Bare Mountain (Cornwall and Klienhampl, 1961) seemed debatable, the mountain was remapped (Michael D. Carr and Susan A. Monsen, unpub. map, 1983). A simplistic geologic map of the pre-Cenozoic rocks of the Yucca Mountain region was constructed (pl. 1, map *B*), on the base provided (pl. 1, map *A*), using the remapped data of Bare Mountain. Ignoring Cenozoic rocks, outcrops were connected in as simple a way as possible, consonant with the structural generalities suggested by the literature and influenced by the available drill-hole, gravity, aeromagnetic and seismic refraction data. The resulting map emphasizes folds; faults are interpreted only where unavoidable.

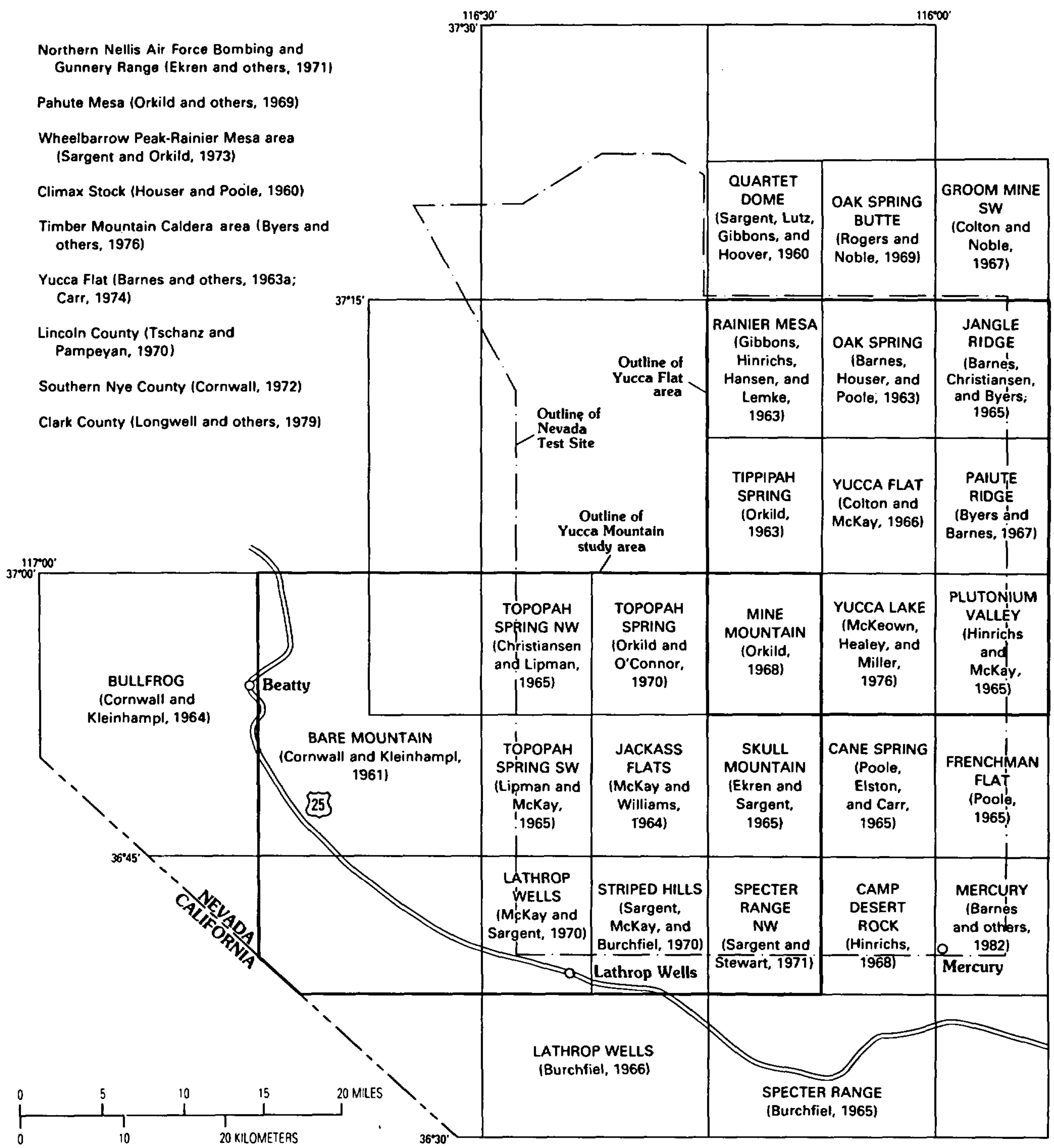

FIGURE 2.—Index map and listing of published geologic maps referred to in this report and used to construct the geologic maps on plate 1. Small rectangles, 7½-minute quadrangles; large rectangles, 15-minute quadrangles. Maps other than quadrangles listed.

Acknowledgments

Gary L. Dixon provided the impetus for the project of which this report is the first published product. Desiree Stuart-Alexander persuaded me to join the project. My debt to Michael D. Carr and Susan A. Monsen is evidenced by numerous references throughout the text. David B. Snyder prepared a Cenozoic isopach map of the study area on which figure 7B is largely based. Nancy W. Howard, of Lawrence Livermore National Laboratory, and D. L. Healey provided computer printouts of drill-hole data as of July 1983. Walter D. Mooney supplied unpublished results of a seismic refraction survey. Michael D. Carr, John H. Stewart, James C. Yount, David B. Snyder, and Desiree Stuart-Alexander provided helpful reviews. The report was prepared in cooperation with the Nevada Nuclear Waste Storage Investigations Project of the Department of Energy.

REGIONAL STRATIGRAPHY AND STRUCTURE OF PRE-CENOZOIC ROCKS

Pre-Cenozoic rocks that crop out in the Yucca Mountain region have a composite thickness on the order of 10 km (table 1). Except for a few small plutons, Mesozoic rocks are absent. Stratigraphic units were generalized into systems and their thicknesses rounded to the nearest 500 m (extreme right-hand column, table 1). These thicknesses and the measured attitudes were used to produce map *B* on plate 1. Pre-Proterozoic (that is, lower Precambrian or Archean) rocks are reportedly exposed in two small areas on the perimeter of the region, but their age of formation is in question. In the Trappman Hills, 55 km northwest of Yucca Flat (fig. 1), Ekren and others (1971) assigned an early Precambrian age to gneissic quartz monzonite and biotite schist; however, a recent K-Ar age (McKee, 1983) on muscovite of only 14.0 ± 0.5 m.y., clearly a reset age, leaves the depositional age of the rocks unknown. In the Bullfrog Hills, about 10 km west of Beatty (fig. 1), Cornwall and Kleinhampl (1964) assigned early Precambrian age to quartz-mica-feldspar gneiss and quartz-biotite-muscovite schist; the age of these rocks is also put in question by a K-Ar determination on muscovite of 11.2 ± 1.1 m.y. (McKee, 1983).

A synclinorial basin, about 80 km broad, is recognized between Bare Mountain on the west and Halfpint Range on the northeast. The basin is asymmetric, dips being steep to overturned on the west and south limb, and moderate to low where exposed elsewhere. The basin is flanked by uplifted upper Proterozoic clastic rocks and cored by Pennsylvanian and Permian carbonate rocks. Exposed subordinate folds within the basin are 8-24 km broad, concentric, open, dip moderately, strike within 30° of north, and plunge gently northward. As the study area is in the southwest sector of the synclinorium, the axes of buried subordinate folds probably strike and plunge northeasterly, and buried subordinate folds are probably similar to exposed folds in other respects.

The basin is terminated on the southwest by enigmatic structures beneath the Amargosa Desert; on the southeast, by the Rock Valley fault zone, south of which folds consistently strike northeasterly; and on the northeast, by a major northeast-trending thrust system, here named the Tippipah thrust zone. On the east, beyond the limits of the geologic map (pl. 1 map *B*) the synclinorium passes into a series of generally north-trending folds broken by widely spaced west-dipping thrusts and more closely spaced steep north- trending faults (see Tschanz and Pampeyan, 1970, pls. 2 and 3; Longwell and others, 1979, pls. 1 and 5). Relations on the northwest are obscured by thick and continuous masses of volcanic rock, beneath which the synclinorium may be truncated by continuation of the Tippipah thrust zone.

If plate 1, map *B*, has some degree of plausibility, it leads to some thoughts about faults. If the structural synclinorium is as intact as it seems, there is no reason to assume large displacements within it by thrust- or strike-slip faulting. Yet, for many years, the Mine Mountain and C P thrusts, exposed mainly in the Mine Mountain and Yucca Lake 7.5-minute quadrangles (fig 2), respectively, have been regarded as major regional structures, or as parts of a single great structure. Cross sections drawn in those and adjoining quadrangles (see, for example, Colton and McKay, 1966; Orkild, 1968; McKeown and others, 1976; or, on a smaller scale, Barnes and others, 1963a, pl. A-6; Carr, 1974; Winograd and Thordarson, 1975, pl. 2) show shallow thrust surfaces that are horizontal or dip gently westward, less commonly eastward, to the edge of each map (and inferentially indefinitely beyond); Snyder and Carr (1982, figs. 2, 3) infer that the C P thrust extends southwestward to the Amargosa Desert. Few of the above interpretations, limited as most of them are to maps and cross sections without text, attempt to measure horizontal displacement; Barnes and others (1963a, p. 142) stated "the resulting maximum movement along the thrusts is unknown but must be at least 5 or 10 miles."

But evidence of regional continuity is tenuous at best, and more restrained interpretations can be entertained. For example, as shown on plate 1, map *B*, the thrusts may be local slides into subordinate synclines of the synclinorium. On the maps cited above, and others, these thrusts are shown displaced into the subsurface by young normal faults, but examination of the maps involved shows no compelling evidence of such displacement—the thrust faults could as easily be interpreted as being displaced upward, and the upper plates regarded as little larger than the areas of aggregate outcrop. I do not necessarily embrace this position but propose it for consideration.

Conversely, the zone of thrusts shown at the north edge of plate 1, map *B*, clearly shown by Gibbons and others (1963), by Sargent and Orkild (1973, section BB'), and recognized by Carr (1974, fig. 2) and by Barnes and others (1963a, fig. A-5), has not been given due consideration. The westernmost fault of the zone cuts out at least the entire Cambrian, and considerable displacement is evident on the

Table 1. Pre-Cenozoic stratigraphic and hydrogeologic units, Yucca Mountain region, Nevada.
[Modified from Winograd and Thordarson (1975); ? = series boundary uncertain]

System	Series	Stratigraphic unit	Major lithology	Maximum thickness (meters[1])	Hydrogeologic unit	Age and main lithology used in this report (thickness in meters)
Cretaceous to Permian		Granitic stocks	Granodiorite and quartz monzonite in stocks, dikes, and sills		(A minor aquitard)	Cenozoic and Mesozoic granitic plutons
Permian and Pennsylvanian		Tippipah Limestone	Limestone	1,100	Upper carbonate aquifer	Permian and Pennsylvanian carbonate rocks >1,000
Mississippian and Devonian		Eleana Formation	Argillite, quartzite, conglomerate, limestone	2,400	Upper clastic aquitard	Mississippian argillite >2,500
Devonian	Upper	Devils Gate Limestone	Limestone, dolomite, minor quartzite	>420	Lower carbonate aquifer	Devonian carbonate rocks 1,000
	?					
	Middle	Nevada Formation[2]	Dolomite	>460		
Devonian and Silurian		Undifferentiated	Dolomite	430		
Ordovician	Upper	Ely Springs Dolomite	Dolomite	95		
	Middle	Eureka Quartzite	Quartzite, minor limestone	105		
	?	Pogonip Group: Antelope Valley Limestone	Limestone and silty limestone	460		Silurian and Ordovician carbonate rocks 1,000
	Lower	Pogonip Group: Ninemile Formation	Claystone and limestone interbedded	105		
		Pogonip Group: Goodwin Limestone	Limestone	>275		
Cambrian	Upper	Nopah Formation Smoky Member	Dolomite, limestone	325		
		Halfpint Member	Limestone, dolomite, silty limestone	220		
		Dunderberg Shale Member	Shale, minor limestone	70		
	Middle	Bonanza King Formation Banded Mountain Member	Limestone, dolomite, minor siltstone	745		Cambrian carbonate rocks 3,000
		Papoose Lake Member	Limestone, dolomite, minor siltstone	660		
		Carrara Formation	Siltstone, limestone, interbedded. Upper half mainly limestone; lower half mainly siltstone	320		
	Lower			290	Lower clastic aquitard	
		Zabriskie Quartzite	Quartzite	70		
		Wood Canyon Formation	Quartzite, siltstone, shale, minor dolomite	665		Proterozoic quartzite >2,000
Precambrian		Stirling Quartzite	Quartzite, siltstone	1,040		
		Johnnie Formation	Quartzite, sandstone siltstone, minor limestone and dolomite	>975		

[1]Thicknesses given by Winograd and Thordarson in feet, converted to meters.
[2]Nevada Formation of Johnson and Hibbard (1957).

other strands. The zone has not been named. Only the easternmost fault of this zone, the only strand that places younger rocks over older, has been given any significance by Barnes and others (1963a, "Eleana plate," fig. A-6) or by Carr (1974, fig. 7). The entire zone is absent from figure 1 of Stewart and others (1966), which purports to show all the major thrust faults in the region, and from the State geologic map (Stewart and Carlson, 1978). For this study, I call it the Tippipah thrust zone—not to be confused with the steep Tippinip fault, which apparently offsets it in the Oak Spring quadrangle (Barnes and others, 1963b).

Plate 1, map *B*, shows only one short strike-slip fault, east of Lathrop Wells, within the synclinorium. Because such faults have been emphasized by Carr (1974), some discussion is in order. On a gross scale, strike-slip faults having displacements on the order of tens of kilometers unequivocally exist in the southwestern Great Basin. The Yucca Mountain study area is within the broad Walker Lane belt of northwest-striking right-lateral faults (see, for example, Carr, 1974, fig. 1). Northwest of the study area, major strands of the belt are a few tens of kilometers apart, so one or two strands might be expected to cross the study area. Further, conjugate northeast-striking left-lateral faults are to be expected in this region of westward crustal extension; one such may be the Cane Springs fault in the southeastern NTS (labelled CS) on Carr's (1974) figure 1, and another a few kilometers northwest (labelled MM for Mine Mountain). The existence of this crisscross pattern is supported by detailed mapping of numerous small faults that fall into one or the other of these categories (Carr, 1974, p. 9). At the scale of the geologic maps (pl. 1), only two faults of northeast trend, that east of Lathrop Wells, noted above, and the Mine Mountain of Carr, are large enough to demand recognition within the synclinorium, and offset of the Mine Mountain fault can be rationalized as dip slip. As with thrust faults, there may be strike-slip faults of significant offset (thousands of meters) within the synclinorium, but the present method of study does not elicit them.

STRUCTURE OF PRE-CENOZOIC ROCKS OF THE YUCCA FLAT AREA

Structures of pre-Cenozoic rocks in the Yucca Flat area are here discussed in some detail to make the area more useful for comparison with the Yucca Mountain study area.

The Yucca Flat area is especially advantageous for comparative purposes because its geology has been synthesized at a 1:48,000 scale by Barnes and others (1963a) and by Carr (1974, especially figs. 2 and 7). Both of these reports recognize folds but emphasize faults, especially thrust faults. The tectonic map of Barnes and others (1963a; hereafter simply Barnes) is reproduced in reduced form as figure 3; Carr's (1974) tectonic map is reproduced in reduced form as figure 4*A*.

Barnes divided the area into an eastern block ("1" on fig. 3) and a western block ("2," "3," and "4" on fig. 3). The eastern block is composed mainly of Proterozoic (=upper Precambrian) and lower Paleozoic rocks, in which major folds trend northwest and are disrupted by younger-over-older thrusts of small displacement and by young high-angle faults whose dominant trend is north-northwest. The entire block is interpreted to be a single thrust plate of unspecified dip and sense of displacement. The western block is composed mainly of upper Paleozoic rocks but includes sizable areas of lower Paleozoic rocks in the southern part; major folds, having axes 3 to 5 km apart, trend northeast. The folds of the western block are broken into three plates by thrust faults, the upper plates of which seem to have moved relatively eastward (the individual plates are not identified in cross section). The folds are also cut by many high-angle faults of varied trend.

Carr (1974), in studying the orientation of the regional stress field, accepts the geologic map of Barnes but offers a different interpretation of the structure of the subvolcanic rocks (his fig. 7). The main underlying structure of the area is visualized as that of a single great thrust sheet, mainly of lower Paleozoic carbonate rocks, that has been folded on an axis that trends north-northeast, and then eroded so that the lower plate, consisting mainly of upper Paleozoic clastic rocks, appears as a window and subcrops beneath Cenozoic cover, in the north-central and southwestern parts of the Yucca Flat area. Carr does not actually join the west-dipping and east-dipping traces at the north end of his figure 7, but leaves a 6-km-long gap, as shown by query on figure 4*A*. Further, he does not specify this interpretation in his text and states (p. 8) that "the underlying Paleozoic rocks consist mainly of the lower plates of major thrust faults" (plural) and, a few lines later, refers to "the carbonate rocks of the upper plates of the Mesozoic thrust faults" (again plural). (Carr (written commun., 1983) has informed me, however, that I read his intent correctly.) He recognizes the presence of large north-northwest-trending folds in the upper plate, and north-northeast-trending folds in the window (lower plate).

The direction of thrusting is not specified by Carr but a "schematic" section (his fig. 8) shows the main (C P) thrust, which is broken by steep faults, as having moved relatively eastward in one faulted segment and relatively westward in an adjoining segment. In addition, he recognizes a few large strike-slip faults in the southern part of the area, of unspecified relation to thrusting but presumably younger, and shows all the steep faults that Barnes shows.

To serve as a useful analog, Yucca Flat is best described with the same broad-brush approach applied to the Yucca Mountain study area. The resulting simplistic interpretation of the structure of the Yucca Flat area (pl. 1, map *B*) emphasizes folds and contrasts with the interpretations of Barnes (fig. 3) and Carr (fig. 4*A*).

The thickness and configuration of the Cenozoic rocks, which cover about 90 percent of the Yucca Flat area, help to reveal buried structure. A crude isopach map of the mainly volcanic Cenozoic cover is presented in figure 5*A*, translated from D. L. Healey's map of the depth to the buried sub-Cenozoic surface (fig. B-7 in Hazelwood and others, 1963), which is based on many drill holes. Note that the gravity anomaly map (fig. 6*A*) closely resembles the Cenozoic isopach map (fig. 5*A*); consequently, gravity data have been used to produce a crude isopach map (fig. 5*B*) of the Yucca Mountain study area, which lacks deep drill holes except for p1.

The Yucca Flat isopachs show that the Cenozoic cover is generally thinner than 600 m between outcrops of pre-Tertiary rocks; it is substantially thicker than 600 m only beneath the eastern margin of Yucca Flat, where it approaches 1,500 m, and at the west edge of the area, where it is even thicker, toward the main eruptive centers. A minor strip of thick cover below western Yucca Flat is separated by a long narrow ridge from the main mass of volcanic rocks under eastern Yucca Flat. The isopachs show a north trend that conforms poorly to the attitudes of the pre-Tertiary rocks but matches the trend of young steep faults, which are numerous. Here, it appears that the distribution and thickness of preserved masses of volcanic rocks have been determined as much by postdepositional structural events as by the landforms upon which the volcanic rocks were deposited, which in turn must have been influenced by the underlying structure. This point is made here to balance a later argument that Cenozoic isopachs are helpful in determining the structural pattern of folds in the pre-Cenozoic rocks of the Yucca Mountain study area.

To return to structural comparison, the Yucca Flat area of plate 1, map *B*, is different from figures 3 and 4*A* but not as different as casual inspection might suggest. Thus, plate 1, map *B*, displays essentially the same major fold axes as figure 3 in the northeast and west-central sectors and in addition

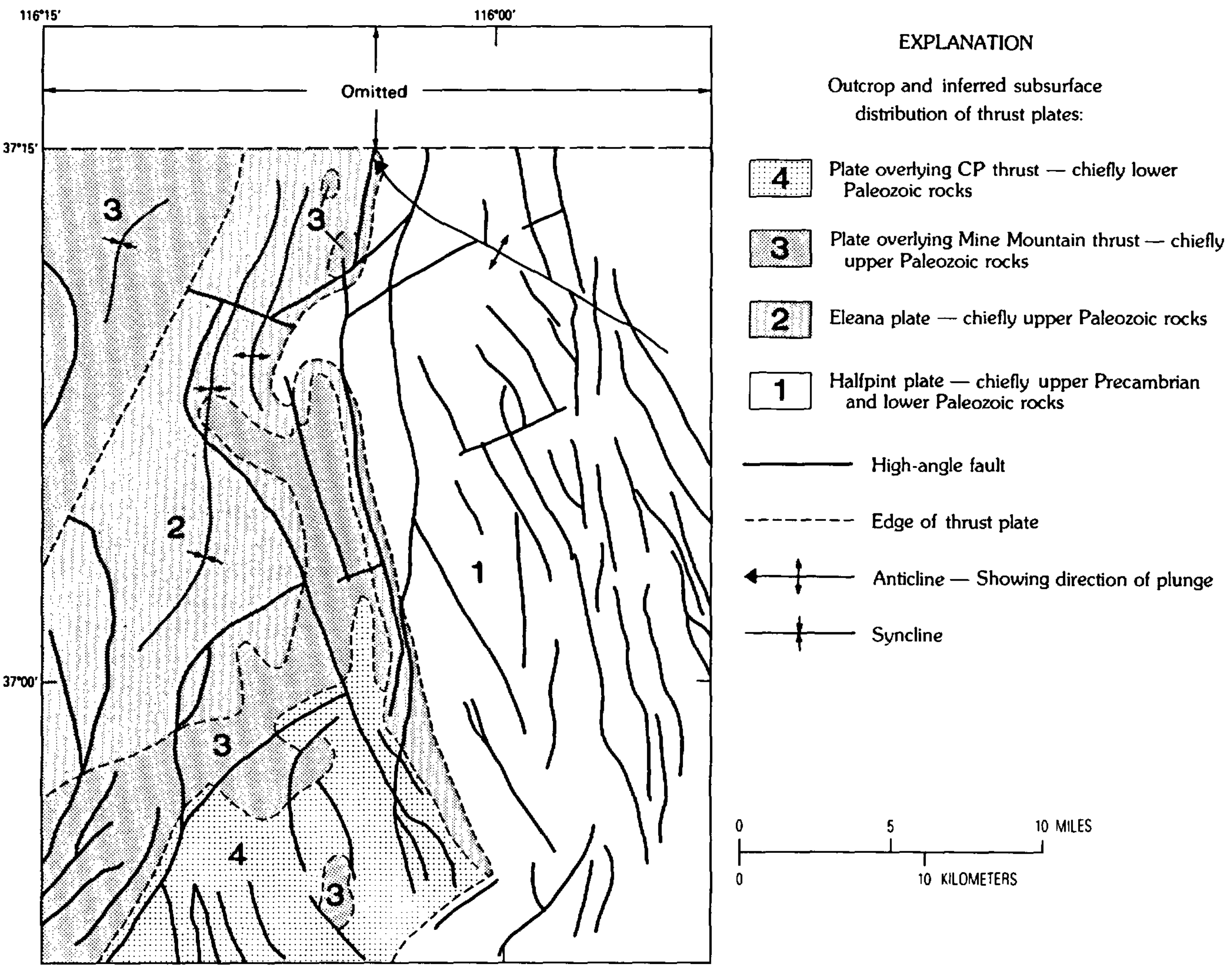

FIGURE 3.—Preliminary tectonic map of Yucca Flat area by Barnes and others (1963a, fig. A-6), emphasizing faults (reduced from 1:48,000 scale).

recognizes a major north-trending syncline in the south-central sector. This leads to a fanlike distribution of fold axes, which are spaced similarly in both interpretations—a few kilometers apart in the western half, a single large anticline in

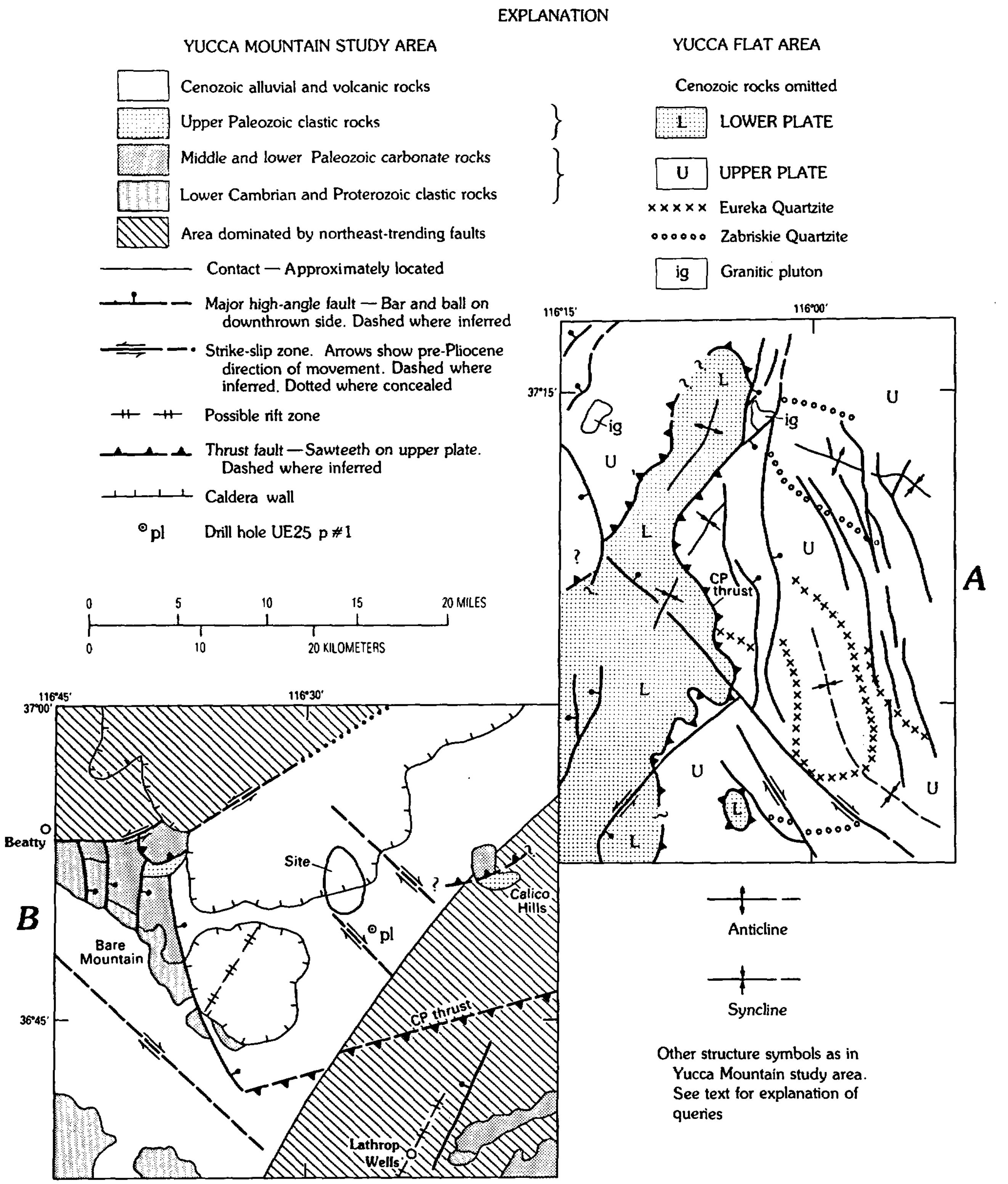

FIGURE 4.—Geologic-tectonic maps emphasizing faults. *A*, Yucca Flat area by Carr (1974) (modified slightly and reduced from 1:48,000 scale); *B*, Yucca Mountain study area by Snyder and Carr (1982, figs. 3 and 4 combined, modified slightly, and reduced about one-half).

the eastern half. The overall northerly trend and plunge of folds, noted by Barnes, are even more apparent if the numerous steep faults are omitted.

The upper plate of the C P thrust, plate 4 on figure 3, has similar limits to those of the fault surrounding the C P Hills on plate 1, map *B*, except to the south. The Eleana plate, plate 2 of figure 3, corresponds to the Mississippian rocks thrust on older Paleozoic rocks in the most easterly strand of the Tippipah thrust zone of plate 1, map *B*, and that part of Barnes' plate 3 in the northwest corner of the area corresponds to the rest of the Tippipah zone.

Similarly, the simplistic interpretation is not as different from Carr's (fig. 4*A*) as it may appear; the main difference is in the treatment of thrusts. Two other distinct differences, however, do occur. Two sets of strike-slip faults are shown on figure 4*A* that are not recognized by me or Barnes. Also, Carr, though not recognizing a large syncline in the south-central part of Yucca Flat, portrays a north-northeast-trending elliptical synclinal basin in the center of the southeastern sector. This structure, deeply buried, is based on stratigraphic assignments from several deep drill holes. The simplistic interpretation of plate 1, map *B*, does not show this

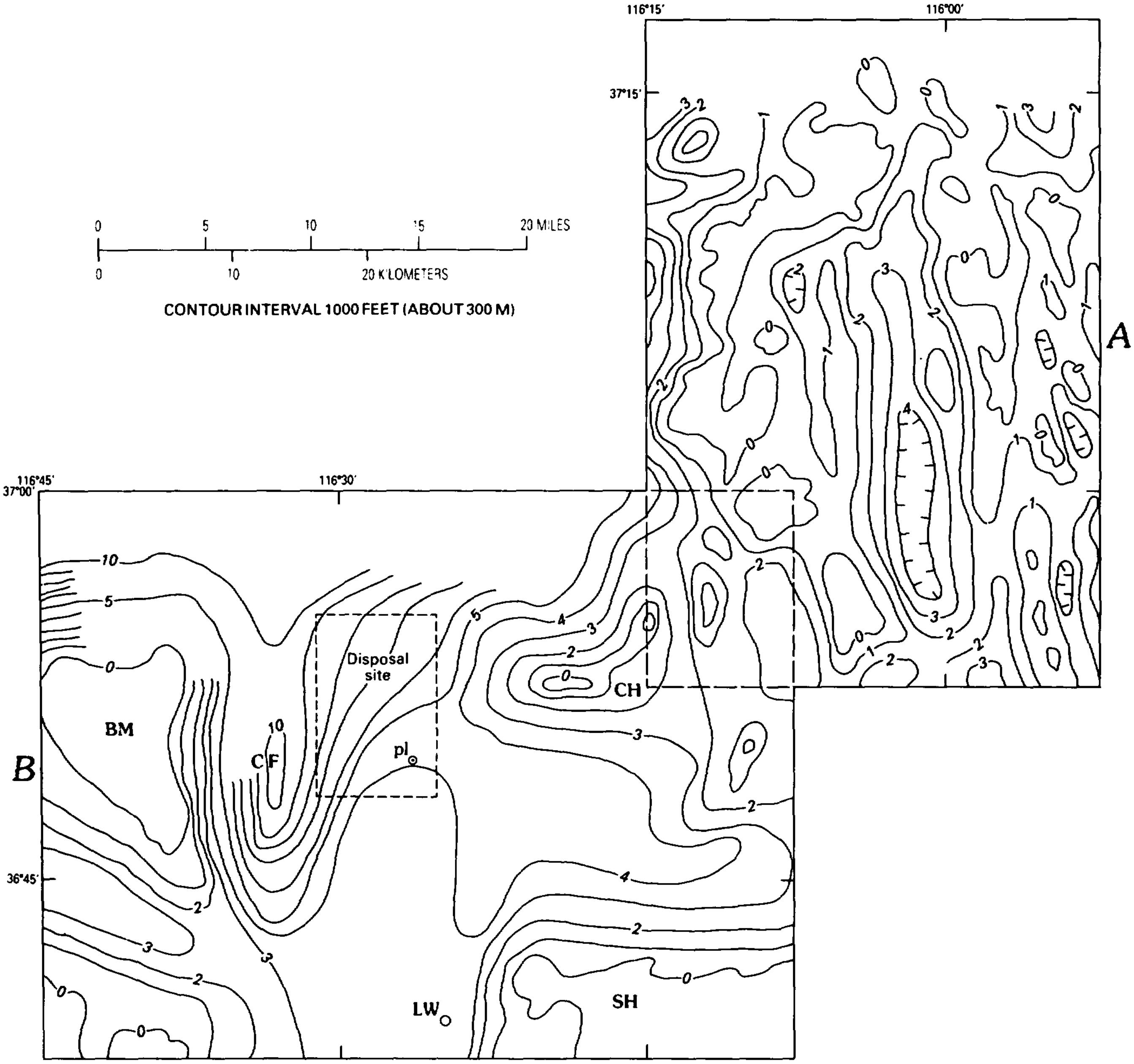

FIGURE 5.—Isopach map of Cenozoic rocks. *A*, Yucca Flat area; from 1:24,000 quadrangle maps by D. L. Healey (in Hazelwood and others, 1963.) *B*, Yucca Mountain study area; modified from 1:48,000 map by D. B. Snyder (1983, unpublished map) to improve fit with aeromagnetic data where Cenozoic cover is thick. BM, Bare Mountain; CH, Calico Hills; SH, Striped Hills; CF, Crater Flat; LW, Lathrop Wells. p1, drill hole UE25 p#1.

structure because I ignore all geologic age assignments from drill holes in the Yucca Flat area, although I accept depth determinations to the subvolcanic surface.

Ignoring age assignments from drill holes leads to other interpretative differences, too, and requires explanation. In the Yucca Flat area, some 170 holes have been drilled into pre-Cenozoic rocks. Systemic and (or) formational age assignments, however, have been made for only a fraction of the total number of holes, and many of them are questionable because with rare exceptions drilling stopped after only a few meters of deeply weathered pre-Cenozoic rocks were penetrated. Cores or cuttings from only a few holes have yielded diagnostic fossils.

STRUCTURE OF PRE-CENOZOIC ROCKS OF THE YUCCA MOUNTAIN STUDY AREA

Previous Interpretations

The only published interpretation of the structure of the Yucca Mountain study area is that of Snyder and Carr (1982,

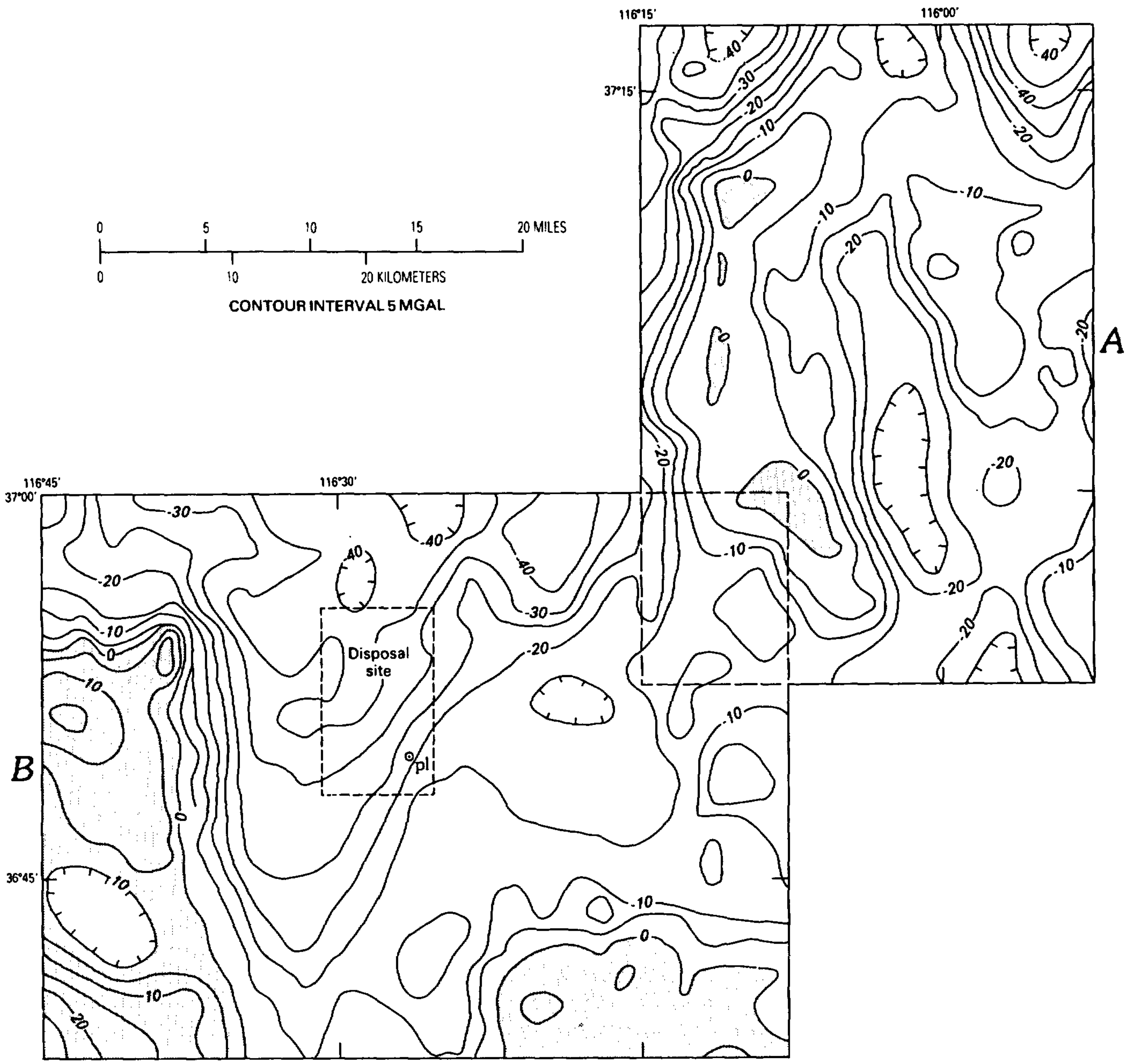

FIGURE 6.—Isostatic residual gravity anomaly map (from R. W. Saltus, unpub. data, 1981). Positive areas shaded; negative ("basin") areas hachured. *A*, Yucca Flat area; *B*, Yucca Mountain study area; p1, drill hole UE25 p#1.

figs. 3 and 4; fig. 4*B*, this paper). Various faults are shown, as well as the outlines of caldera walls, but no folds. Snyder and Carr extrapolate from previous work in the Yucca Flat area (Carr, 1974), extending the southeast-dipping limb of the folded C P thrust across the study area to the major east-frontal fault of Bare Mountain. They do not, however, similarly extend the northwest-dipping limb. The north-dipping thrust plate of lower and middle Paleozoic carbonate rocks shown at the northeast corner of Bare Mountain might be regarded as part of the northwest limb, or an outlier of it. If so, the disposal site and its environs overlie a great prevolcanic window of lower plate "upper Paleozoic clastic rocks" (that is, Eleana Formation), and are so shown on an unpublished diagram by W. J. Carr (written commun., 1982). (The lower and middle Paleozoic carbonate rocks thrust over upper Paleozoic clastic rocks in the Calico Hills, shown near the east-central edge of figure 4*B*, presumably are parts of the upper and lower plates, respectively, but are omitted on Snyder and Carr's fig. 4, thus the queries in fig. 4*B*.)

Drill hole p1 (added to Carr's map) did not encounter Mississippian clastic rocks beneath the volcanic cover; rather, it met Silurian carbonate rocks (A. G. Harris, written commun., 1983). This single datum by no means invalidates the folded thrust hypothesis for the study area—the 1,000 m or more of section represented by the difference between Silurian and Mississippian could, for example, be accounted for by subsidiary thrusting, by post-thrust normal faulting, or by continuation of the steeply dipping section exposed on Bare Mountain—but neither does it aid that hypothesis.

Structure sections across the study area by Sinnock (1982, fig. 20) show broad concentric folds in the prevolcanic rocks. Sinnock stated (p. 40) that "stratigraphic dips of 20° and greater suggest a ubiquitous folded character of the miogeosynclinal strata."

Sub-Cenozoic Surface: Depth and Configuration

Thickness and configuration of the Cenozoic cover, and depth and configuration of the sub-Cenozoic surface, are important in themselves and as clues to underlying structure. Further, the relation of the cover to buried structures has important hydrologic implications. The depth to the sub-Cenozoic surface in the Yucca Mountain study area is known only in drill hole p1; therefore, geophysical methods must be used to estimate the depth elsewhere. Seismic reflection has not proved helpful here, owing to absorption of reflected energy by the thick volcanic cover (L. W. Pankratz and H. Ackermann, written commun., 1983). Seismic refraction offers promise, but only unreversed profiles are yet available (Hoffman and Mooney, 1983). Consequently, gravity measurements, combined with density determinations, have been the principal source of data. Figure 6*B* is a gravity anomaly map generalized from unpublished data by R. W. Saltus (written commun., 1981); Snyder and Carr (1982, fig. 7) offer a closely similar map, using slightly different density contrast.

David Snyder used the gravity anomaly map and three-dimensional gravity modeling to generate a Cenozoic isopach map (unpub. map, 1983) at a scale of 1:48,000, which was modified by me (figure 5*B*) to improve fit with aeromagnetic data (Kane and Bracken, 1983) where the Cenozoic cover is thick and the interpretation of gravity data correspondingly difficult. Figure 5*B* shows that the thickest volcanic cover extends southward under Crater Flat from nested calderas north of the study area; maximum thickness under Crater Flat may reach 3 km. Thickness of volcanic rocks under the north part of the site may reach or exceed 2.5 km; profiles produced by seismic refraction (Hoffman and Mooney, 1983) suggest a thickness of this magnitude. The Cenozoic cover decreases in thickness southeastward across the site to around 1,200 m (confirmed by drill hole p1, in which the base of the volcanic rocks was reached at a depth of 1,244 m; D. C. Muller and M. D. Carr, written commun., 1983). Between Paleozoic outcrops in the Calico Hills and Striped Hills, the maximum thickness of Cenozoic rocks, which include southward-increasing volumes of alluvial deposits, seems somewhat greater than 1,200 m, apparently increasing gradually southward between the Striped Hills and southern Amargosa Desert. However, according to gravity studies by Healey and Miller (1971), the combined alluvial and volcanic cover in the southern Amargosa Desert, south of Lathrop Wells, is thinner than suggested by figure 7*B*, probably ranging from 600 to 1,000 m in maximum thickness.

The proportions of Quaternary continental deposits and Tertiary volcanic rocks that together constitute the Cenozoic cover can be directly determined in Yucca Flat with the aid of abundant drill hole data and likewise at the proposed repository site for the same reason, but only indirectly (by geophysical methods) elsewhere in the study area. Snyder and Carr's profiles (1982, p. 21-23) show a significant thickness of alluvial fill only in Jackass Flats and adjoining Fortymile Canyon (fig. 1), southeast of the site, where the maximum thickness is less than 300 m. Healey and Miller (1971) lump the two components throughout. Aeromagnetic maps suggest that the volcanic rocks pinch out about at the latitude of Lathrop Wells and therefore that alluvial deposits constitute most or all of the cover in the Amargosa Desert. This seems evident at the coarse high-altitude scale of the State aeromagnetic map (1:500,000, Zietz and others, 1977), of which the relevant part is presented here, enlarged, as figure 7 and apparently confirmed by low-altitude surveys (Greenhaus and Zablocki, 1982, fig. 4; Kane and Bracken, 1983). The close spacing of contours and the paired round and elliptical strong positive and negative anomalies are characteristic of those produced by known bodies of volcanic rock. Such bodies are scarce or absent in the southeast quarter of the Yucca Flat area and along the southern border of the Yucca Mountain study area.

The southward thinning of the volcanic rocks has been placed in question by recent north-south unreversed seismic refraction measurements (Walter Mooney, written commun., 1984). Preliminary profiles suggest that some highly magnetized volcanic rocks may indeed thin as proposed but that an underlying thick sequence of less magnetized volcanic rocks may continue southward far beyond Lathrop Wells. However, I tentatively accept radical southward thinning of the entire volcanic section. Eventually, the matter should be resolved by completion of the refraction studies and acquisition of additional geophysical and drilling information.

The configuration of the buried surface of the pre-Cenozoic rocks offers clues to the buried structure, but they must be dealt with cautiously, for that surface represents paleotopography modified by Cenozoic structural events. The detailed surface mapping available indicates that such events, large enough to make a difference at the scale of this report, are mainly steep[1] north-trending primarily dip-slip

[1]In this report the term "steep" is used for all principally dip-slip faults having dips of 50° or more, whether of normal, reverse, or unknown sense of displacement. Although large young faults are drawn with solid lines on published cross sections of this region (and most others), the dips of many are actually uncertain or unknown, yet become the basis for genetic inference. To avoid such involvement at this stage, I use the noncommittal term "steep," with the tacit acknowledgment that the large high-angle dip-slip faults in the study area, nearly all of which strike within 30° of north, are probably extensional and thus normal.

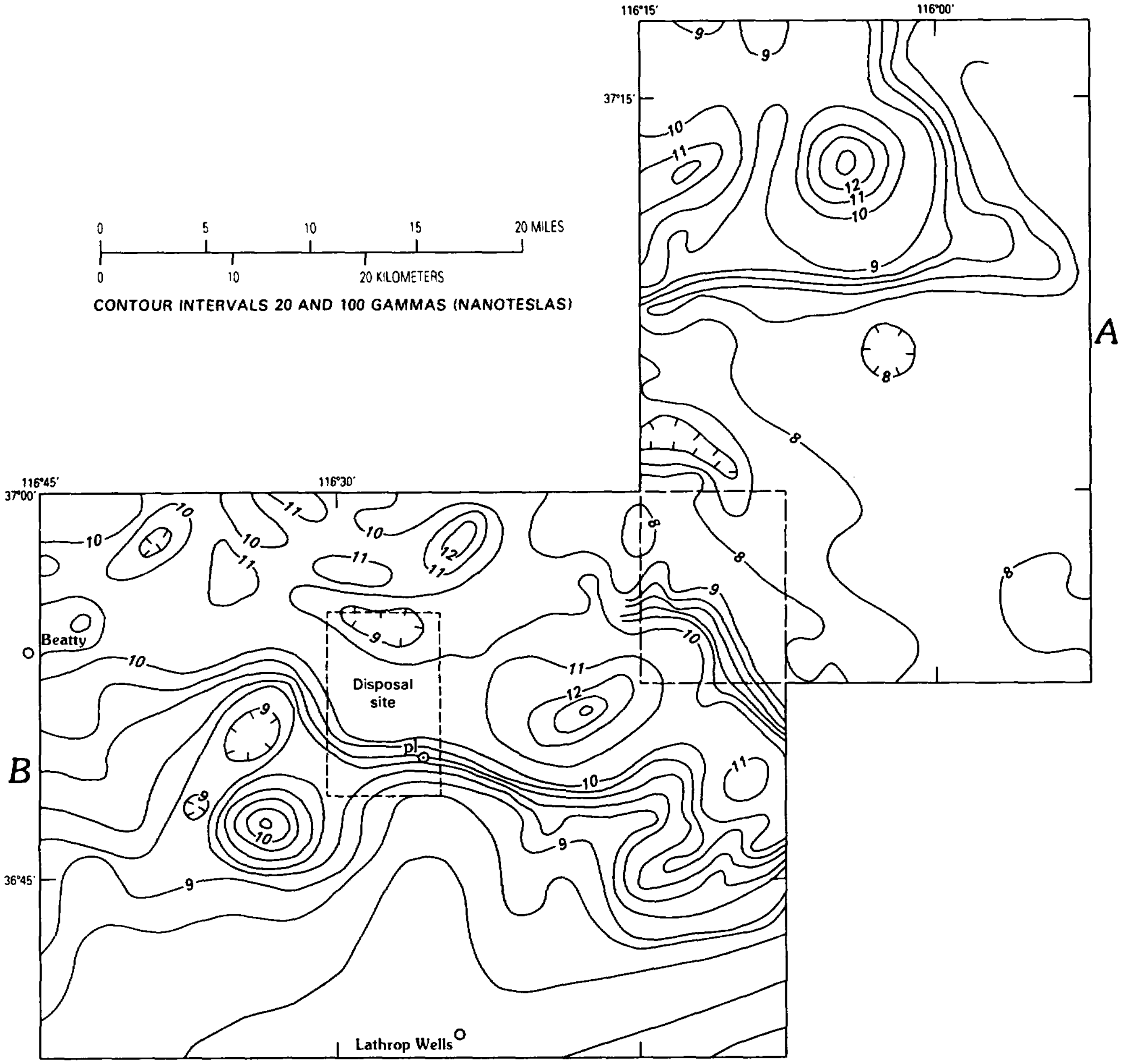

FIGURE 7.—Aeromagnetic map. Total intensity magnetic field in gammas relative to an arbitrary datum. Areas of lower intensity hachured. Earth's main magnetic field removed. From Zeitz and others (1977), flown at 8,000-ft (2.4 km) elevation, half-mile (0.8 km) spacing. *A*, Yucca Flat area; *B*, Yucca Mountain study area; p1, drill hole UE25 p#1.

fault displacements of extensional type. In the Yucca Flat area such fault movements, generally resulting in offsets measurable in hundreds of meters and closely spaced, had much influence on the shape of the subvolcanic surface. In the Yucca Mountain study area, by contrast, Cenozoic faults are more widely spaced (an important element in selection of a repository site) and were probably less influential in shaping the buried surface. A major exception is the immense fault, of probable Cenozoic age, at the east front of Bare Mountain, which has an apparent vertical offset of more than 4,500 m (Snyder and Carr, 1982, fig. 10) and drastically changed the older surface. Other evident but less drastic modifying influences were the domal uplifts of Tertiary age that formed the Calico Hills (Orkild and O'Connor, 1970; Snyder and Oliver, 1981) and that were associated with emplacement of granodiorite near Wahmonie (fig. 1) (Ekren and Sargent, 1965; Ponce, 1981).

Figure *5B* can serve as a crude topographic or landform map of the buried surface by reversing the contours, but keeping in mind that the resolution of gravity modeling declines with depth. So viewed, it suggests that slopes on the present outcrops descend with similar declivity beneath the volcanic rocks to a broad surface of low relief. Figure 8 shows this more vividly, if not very realistically. If topography is a guide, that surface is likely underlain by broad low-dipping structures. It may be further ventured that those structures involve carbonate rocks, by analogy with Yucca Flat: There, high areas on the sub-Cenozoic surface are mostly underlain by thick clastic rocks, Precambrian or Mississippian, and low areas by carbonate rocks.

Structure of Exposed Pre-Cenozoic Rocks

Prevolcanic rocks are exposed around the periphery of the Yucca Mountain study area (pl. 1, map *A*). The exposures are almost as extensive as those in the Yucca Flat area but are not as well placed for eliciting overall structure—the outcrops in the southwest corner and in most of the southeast corner are separated by major faults from the synclinorium and involved in unrelated structures (see pl. 1, map *B*); about 90 percent of the remaining outcrops are in a single area, Bare Mountain. Because Bare Mountain is on the west side of the study area, it provides some basis for interpolation from Yucca Flat.

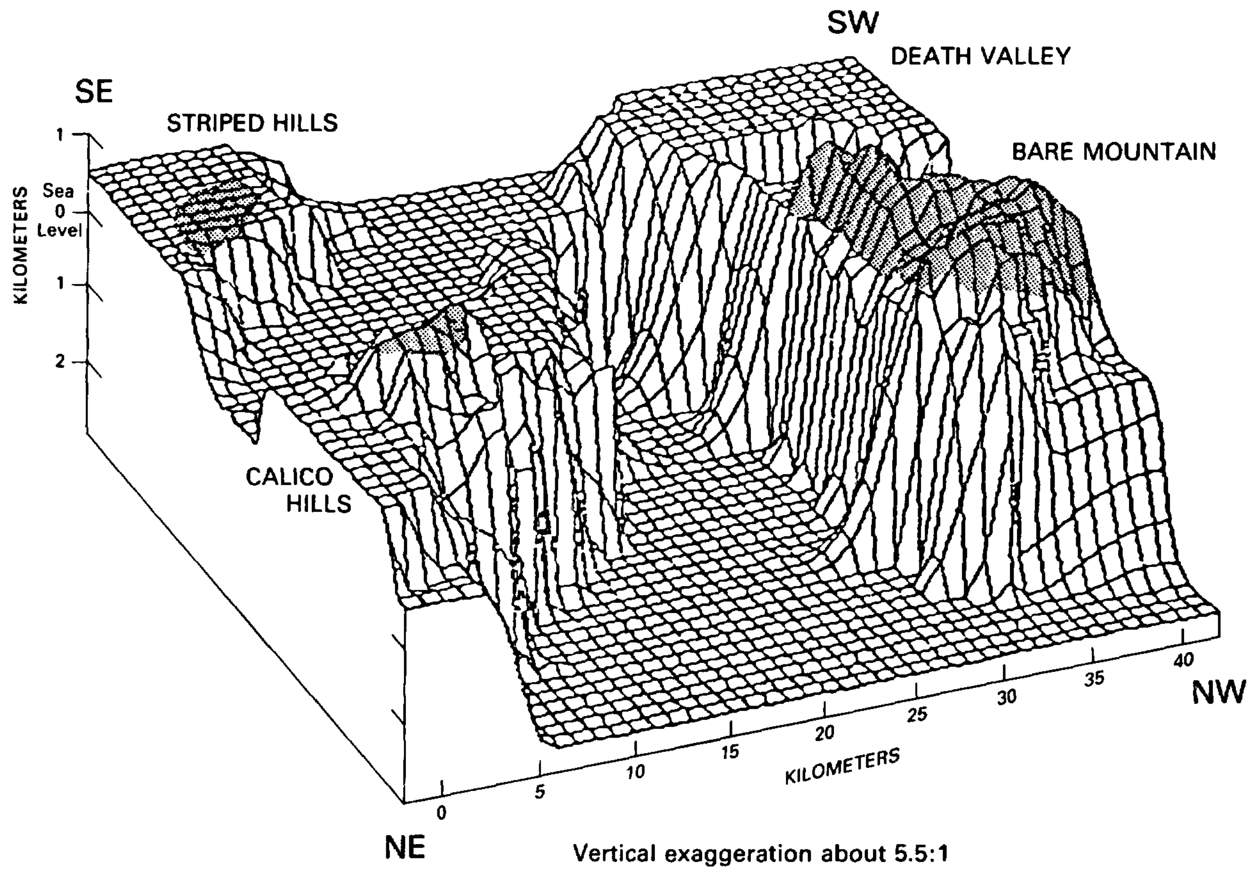

FIGURE 8.—Mesh perspective of the sub-Cenozoic surface of the Yucca Mountain area. View from the northeast. Based on three-dimensional gravity model. Stippling indicates outcrops of pre-Cenozoic rocks at Bare Mountain, Striped Hills, and Calico Hills. Flatness of lower surfaces (below 2.4 km) exaggerated owing to lack of resolution of the modeling method. (From Snyder and Carr, 1982, fig. 13.)

Bare Mountain

Almost the full range of Proterozoic and Paleozoic rocks that crop out in the Yucca Flat area also crop out on Bare Mountain (table 1). Viewed simplistically, these rocks at the north end of the mountain are folded into a broad northeast-trending steeply plunging syncline cored by Mississippian rocks; a slide block of Ordovician and Devonian rocks lies on the synclinal core. Near the north end of the mountain a nearly horizontal klippe of Cambrian rocks lies on Mississippian rocks. The south end of the mountain, underlain largely by Proterozoic rocks, seems anticlinal overall but has obscure trend and plunge. Large masses of Proterozoic and Cambrian strata, interpreted as slide blocks, complicate the relations there, as does an east-dipping thrust fault that carries Proterozoic rocks over Cambrian.

This simple interpretation little resembles that of Cornwall and Kleinhampl (1961), who reported that the area experienced "folding, probably in the middle or late Paleozoic" that "imparted a northerly dip," followed "probably in the Mesozoic," by "intense deformation that was characterized by repeated southwestward thrusting, locally to the point of imbrication, and by related tear faults"; the thrust faults "are relatively low angle," and the tear faults strike north, dip 50°-70° east, and "have apparent right-lateral displacements." Further, "moderate thrusting and normal faulting in the middle or late Tertiary" are said to have resulted in southward thrusting of Tertiary volcanic rocks up and over Paleozoic rocks at the north end of the mountain.

Differing substantially with Cornwall and Kleinhampl, plate 1, map *B*, represents a distillation of recent reassessment (Michael D. Carr and Susan A. Monsen, unpub. map, 1983; Michael D. Carr, written commun., 1984). According to Carr, nearly all the contacts mapped by Cornwall and Kleinhampl as Mesozoic thrusts, including the supposed south-directed Tertiary thrust, are better regarded as low-angle normal faults of late Cenozoic age, shown simply as "slide blocks" on the figure. Unequivocal pre-Tertiary thrust faulting seems confined to the two small areas noted above, regarded by Carr as remnants of a single thrust sheet that is similar in style to the C P thrust and may occupy a similar structural niche. Further, Carr reported that the tear faults, regarded as complementary to the thrusts by the earlier workers, are much younger—several cut quartz latite dikes similar to one that has yielded a K- Ar age on biotite of about 13.9 m.y. (Carr and others, 1984, p. 15) and quite unrelated to pre-Tertiary thrusting. Carr's reassessment leads me, if not necessarily Carr, to recognize a radical reduction in the density and severity of thrusting as reported at Bare Mountain by Cornwall and Kleinhampl and supports the inference that thrusts are likely to be minor features beneath the volcanic rocks to the east. This conclusion is an expectable consequence of the rearward position of Bare Mountain, and the entire study area, in the Cordilleran fold belt.

Dominance of ductile over brittle behavior as a concomitant feature of a higher pressure-temperature environment is supported by the presence of marbleization at places in the Cambrian rocks (Carrara Formation) noted by Cornwall and Kleinhampl (1961), of bedding-parallel metamorphic fabric (S 1) in northwest Bare Mountain "ranging from penetrative schistosity in metapelites to spaced cleavage in metasandstones" (Monsen, 1982, p. 21), and of mesoscale (hand specimen to outcrop size) parallel folds that suggest regional metamorphism. However, the indication of regional metamorphism is weakened by the fact that metamorphic grade abruptly decreases southward, from lower amphibolite facies (staurolite, chloritoid, garnet) to the biotite zone of the greenschist facies within about 6 km (Monsen, 1982, p. 34 and fig. 10). Thus an alternative suggestion by Monsen (1982, p. 51) that "a localized thermal source such as a deep level pluton may have contributed to metamorphism."

Aeromagnetic studies also indicate a pluton beneath northern Bare Mountain (Kane and Bracken, 1983, p. 7). But Monsen concluded that "although metamorphism at Bare Mountain may in part be a localized event, the development of the metamorphic fabric and a broadly synchronous folding event suggests that metamorphism probably occurred within a more regionally extensive deformational regime," and she noted that the regionally metamorphosed Funeral Mountains (fig. 1), where "metamorphic fabrics are well developed and the metamorphic assemblages indicate relatively high temperature lower crustal conditions during metamorphism" (citing Labotka, 1980; and Giarmita and others, 1983), are nearby to the southwest but, it must be pointed out, probably across strike-slip faults of unknown but possibly great horizontal displacement.

Amargosa Desert

Information on the pre-Tertiary rocks in the Amargosa Desert in the southwest corner of the study area is from Cornwall (1972). The rocks are mainly quartzite but include minor amounts of other clastic types, and they are of Late Proterozoic age. Attitudes shown by Cornwall suggest that the rocks have been deformed into broad open folds that plunge gently to the northeast. Lithologically, they seem similar to the Proterozoic rocks on southern Bare Mountain, but it may not be appropriate to think of the bodies as structurally continuous, for they may be separated by one or more right-lateral strike-slip faults concealed beneath the alluvium of the desert and, if so, may initially have been deposited many kilometers apart.

Striped Hills and Specter Range NW Quadrangles

Information on structure of the pre-Cenozoic rocks in the southeast corner of the Yucca Mountain study area is from Burchfiel (1966), Sargent and others (1970), and Sargent and Stewart (1971). The dominant feature is the Rock Valley fault (pl. 1, map *B*), between the Striped Hills on the northwest and the Specter Range on the southeast. The Rock Valley fault is plainly a major feature, traceable for 50 km or more from an apparent western termination near Lathrop Wells to at least the south side of Frenchman Flat. Its nature, however, is problematical, for it is scantily exposed and owes its recognition mainly to topographic expression and to its evident position as a boundary between distinct structural domains. Sargent and others (1970) mapped it as a dotted straight line and indicated left-lateral slip, which suggests that it dips steeply, but they showed it as a thrust, dipping gently north, in cross section. Burchfiel (1966) mapped it as steep and dip slip, down to the south, but described it (p. 5) only as "a large northeast-striking fault of unknown displacement." Sargent and Stewart (1971) mapped the fault as a north-dipping thrust with left-lateral slip that dies out near the west edge of the Specter Range NW quadrangle, but they showed segments of fault along strike across the quadrangle, including a bit of southeast-dipping thrust in the center and a brief stretch at the east edge that shows Quaternary alluvium faulted, south side up. The straight course of the fault for many kilometers is sufficient evidence that it is not a low-dipping thrust. Burchfiel's description seems the best available without subsurface information.

North of Rock Valley, the Striped Hills and a discontinuous ridge of outcrops of pre-Cenozoic rocks to the east of the hills expose an east-striking sequence that becomes younger from south to north, from Proterozoic (Wood Canyon Formation) into Middle Devonian. In the Striped Hills, the beds are essentially vertical; to the east, dips are lower and northward. These exposures provide a convincing south limb of the regional synclinorial basin. At the west end of the Striped Hills, about 5 km northeast of Lathrop Wells, a steep north-northeast-trending fault is clearly indicated by offset outcrops. Burchfiel (1966) mapped it as left-lateral strike slip; Sargent and others (1970) mapped it as having oblique displacement, left-lateral strike slip, and west-side-down dip slip.

The prevolcanic rocks south of Rock Valley in the Specter Range constitute the same sequence but seem distinctly different structurally, owing to large folds that strike northeast and innumerable faults that also strike northeast, including a few thrust faults.

Skull Mountain Quadrangle

A tiny exposure of prevolcanic sedimentary rocks is present at the east central edge of the Yucca Mountain study area, about 6 km east-northeast of Jackass Flats (pl. 1, map *A*). It is a patch of clastic rocks less than 150 m long at the west margin of a small granodiorite pluton in the northeast quadrant of the Skull Mountain quadrangle (fig. 2; Ekren and Sargent, 1965). Ekren and Sargent described the exposure as "light green to tan quartzite, calcareous sandstone and conglomerate" and doubtfully assigned it to the Eleana Formation. The exposure and the pluton are in a horst that has been uplifted a kilometer or more (Ponce, 1981, figs. 19 and 21). The body might be a xenolith, rafted up from the Proterozoic section or from one of several Paleozoic formations that have minor clastic components; however, its lack of metamorphism favors roof pendant origin. On plate 1 the exposure has been treated as Mississippian in place.

Mine Mountain Quadrangle

The Mine Mountain quadrangle forms the northeast corner of the Yucca Mountain study area and the southwest corner of the Yucca Flat area (fig. 2). Mine Mountain, in the northeasternmost corner of the quadrangle, is capped by moderately to steeply dipping Devonian rocks. Extensive exposures of steeply dipping Mississippian rocks are present on the northwest flank of the mountain, and smaller exposures on the east flank (Orkild, 1963, 1968). The inverted stratigraphy and the near horizontality of many stretches of contact between the two Systems, despite dips of the strata, plainly indicate a low-angle fault relation, which is complicated by many steep younger faults. A large northeast-trending fault that nearly bisects the Mine Mountain quadrangle and bifurcates (pl. 1, map *B*) in the northwest corner of the adjoining Yucca Lake quadrangle (McKeown and others, 1976) separates the upper plate of the Mine Mountain low-angle fault—called a thrust by the preceding authors—from the Cambrian rocks of the upper plate of the C P thrust of the preceding authors. The close juxtaposition of the two allochthonous masses and the presence between them of a wedge of fault-bounded rocks of intermediate Ordovician age permit, but do not require, interpretation of the whole as essentially a single mass of limited extent and scale of displacement—a complex slide block into a subordinate synclinal basin—rather than a thrust fault. Less likely is the possibility that it is an outlier of the Tippipah thrust zone, which is a variant on the Carr (1974) concept illustrated on figure 4*A*. The slide block hypothesis is the simplest way to deal with these troublesome relations, but the degree to which it corresponds to actuality is unknown, as noted earlier. This hypothesis is not, however, entirely an artifact of the map compilation method but is favored by a somewhat circuitous paleotopographic argument. That the allochthonous masses are erosional remnants of a once-continuous thrust sheet would be more plausible if the syncline in which they sit was topographically low during the Permian to Miocene hiatus, but the opposite apparently was true—the synclinal clastic Mississippian rocks seem to have been topographically high during and before eruption of the volcanic rocks, as they are the most thinly covered and widely exposed pre-Cenozoic rocks of the area. Thus, it may be that the upper-plate carbonate rocks are preserved despite their paleotopographic position rather than because of it.

Some large outcrops of Devonian and Mississippian rocks are present near the center of the Mine Mountain quadrangle, and a small outcrop of Devonian rocks, at the west-central edge. The large central outcrops appear to be in initial stratigraphic sequence, Devonian rocks on the east striking nearly north and dipping moderately west under Mississippian rocks. These exposures are the basis for the truncated anticlinal nose shown in the south-central part of the Mine Mountain quadrangle on plate 1, map *B*. The small outcrop is interpreted as a slide block but may be the remnant of a thrust plate. The simplest way to map it is as an isolated mass, but it could be connected with the Mine Mountain block or plate to the northeast and (or) to the block or plate of Devonian rocks in the Calico Hills, equally nearby to the southwest.

Calico Hills

The final area of pre-Cenozoic exposures in the Yucca Mountain study area is in the Calico Hills, at the north-central edge of the Jackass Flats quadrangle (McKay and Williams, 1964) and the south-central edge of the Topopah Spring quadrangle (Orkild and O'Connor, 1970). Because the volcanic rocks flanking the Paleozoic rocks are domed and intensely altered, and the Paleozoic rocks too are bleached and recrystallized in places, the Calico Hills have received much attention as the possible locus of a shallow buried intrusive mass, which, if large and shallow enough, might have potential for nuclear-waste storage. Heat and effluents from a buried intrusive body would seem to be responsible for the metamorphism noted, but if an intrusion is present, drilling has shown that it must be deeper than about 800 m below the surface, and various geophysical studies, discussed by Snyder and Oliver (1981), combine to suggest that it is more than a kilometer deep, probably much more.

The Paleozoic rocks consist of a deeply eroded and internally faulted low-dipping slab of Devonian rocks, lying in fault contact on Mississippian rocks that strike generally northward and dip eastward at moderate to steep angles. The attitude of the Mississippian rocks here has guided the interpretation that a large, slightly appressed syncline cored by Mississippian rocks underlies the Calico Hills and the area to the south.

Folds in Pre-Cenozoic rocks

Plate 1, map *B*, shows a preliminary conception of the shape and scale of folds in the Yucca Mountain study area. The position of the area in the southwest sector of a synclinorial basin inevitably leads to the general conclusion that subordinate folds are likely to trend north to northeast, toward the center of the basin, and to plunge similarly. The folds are visualized as concentric because that is the normal pattern of exposed folds in the Yucca Mountain region and throughout the bulk of the Cordilleran fold belt; only the enigmatic metamorphic core complexes of late Cenozoic age (Crittenden and others, 1980) demonstrate plastically drawn-out folds having thickened axial areas and thinned limbs; somewhat paradoxically, all well-known examples are much nearer the leading edge of the fold belt (Coney, fig. 1, in Crittenden and others, 1980). It is, nevertheless, conceivable that the study area is underlain at no great depth by a core complex, and if so the shapes of folds may be very different from those in plate 1, map *B*. The matter is discussed further at the end of this section.

Visualizing the most likely wavelength, amplitude, and angle of plunge of specific subordinate folds is difficult. It is not, however, a matter of mere guesswork, for the folds recognized in the Yucca Flat area invite extrapolation, and direct aids and constraints to characterizing folds are offered by the outcrops at the borders of the Yucca Mountain study area and by information from drill hole p1. Given the known stratigraphy and attitudes in outcrops and in hole p1, the degrees of freedom in drawing large but subordinate folds are limited. For example, consider eliminating the syncline shown under much of the proposed site. The axis of that syncline then becomes the axis of a simple huge anticline in place of the two anticlines plus syncline now shown. An anticline that large is not itself unreasonable—it would be comparable to the Halfpint Ridge anticline in the Yucca Flat area—but it would ignore the magnetic data (Bath and Jahren, 1984), which has been interpreted to indicate the presence of "strongly magnetized Eleana Formation of Paleozoic (Mississippian) age beneath (the volcanics at) the northern edge of the Site." Magnetized Eleana might have been emplaced there by thrust faults, but more likely it is a continuation of magnetized Eleana exposed in the Calico Hills, for the two occurrences are connected by an east-trending anomaly (Bath and Jahren, 1984, fig. 2) which extends westward to underlie the locally metamorphosed Proterozoic and Paleozoic rocks of northwestern Bare Mountain noted previously (Monsen, 1982). The anomaly is shown, but not as clearly, on figure 7 of this report.

Modifications of Folds

The synclinorium and its subordinate folds have been modified by many structural events. These may conveniently be thought of as prevolcanic and postvolcanic. Before the volcanic rocks were deposited, the folds were broken by thrusts (some of which may have formed before folding ended and may themselves have been folded), by right-lateral strike-slip faults of the broad Walker Lane belt, by complementary faults of northeasterly strike and opposite sense of slip to the Walker Lane, and possibly by north-trending precursors of basin-and-range type faults. The probability is great that at least one thrust fault having displacement measurable in a few kilometers underlies the southern part of the Yucca Mountain study area. The hydrologic effects of a thrust fault are dependent partly on its scale and partly on the physical characteristics of the rocks at the thrust surface. Whatever the mechanical effects, they are likely to be confined to within a few meters or tens of meters of the thrust surface. Larger, but still local, effects may result from juxtaposition by discontinuous thrusts of rocks having very different water-bearing properties. Therefore, thrust faults in the Yucca Mountain region may be thought of as second-order phenomena in comparison with areally extensive folds, in the context of regional hydrology.

Only one steep prevolcanic fault appears on plate 1, map *B*, the northeasterly trending fault east of Lathrop Wells. One or more steep prevolcanic faults probably underlie the Amargosa Desert, but their locations and characteristics are unknown.

Postvolcanic events that have affected the buried pre-Tertiary rocks include various faults and at least two localized uplifts. Only the largest postvolcanic faults, in terms of length and offset, are shown on plate 1, map *B*, and these unrealistically, for they have been projected straight down thousands of meters into the pre-Cenozoic rocks, as though vertical, although correct account of the dips, if known, might lead to locations hundreds, in some instances thousands, of meters away. Theoretically, closely spaced steep faults, formed serially away from a common starting place, could produce apparent folds in homoclinal beds; or, conversely, folded beds could be "unfolded" by an appropriately timed series of closely spaced steep faults. This report assumes random timing of young faults and ignores such possible complexities.

The dips of deformed pre-Cenozoic rocks have doubtless been lowered, raised, or even reversed in direction as a result of tilting of basin-and-range blocks. Postvolcanic low-angle normal faults should be less likely to affect deeply buried subvolcanic rocks, but such rocks near or at the surface would be equally affected, as around Bare Mountain where shallow-dipping normal faults variously involve Proterozoic through Devonian strata. Possibly there are buried low-angle normal faults that involve prevolcanic rocks elsewhere in the Yucca Mountain study area, but they have not been detected. If present, such low-angle extensional faults have merely broadened the synclinorium. If the motive were to reconstruct pre-Cenozoic conditions, these effects would have to be dealt with; concern here, however, is with existing structure so that present dips are sufficient, whatever their cumulative history.

The Paleozoic rocks have been domed, presumably by a concealed intrusion, in the Calico Hills and uplifted in a horst, probably also generated by subjacent intrusion, in the Skull Mountain quadrangle; other such disturbances may be concealed under the Cenozoic cover. Magnetic and gravity evidence, previously cited, combine to indicate that the known intrusions and any others are too deep, too small, or both, to be of significance to repository siting at Yucca Mountain.

Still another modification of the map pattern arises from large irregularities in the subvolcanic surface, itself tectonically induced in part. On plate 1, map *B*, contacts, whether depositional or structural, between Systems are drawn as though the subvolcanic surface were flat, but it is not. Large departures from horizontality, such as those below Crater Flat, affect the shapes of contacts in different ways depending on the geometric relations between the uneven surface and dipping beds. The patterns of the folds have not been adjusted to take any of these postfolding events into account.

The interpretation of plate 1, map *B*, is so simplistic that the figure is unaccompanied by cross sections, for the third dimension is easily visualized without them; however, a simplistic hydrogeologic cross section is shown in figure 9. An exception to simple visualization of the third dimension is the deep trough of Crater Flat. Carr (1982) thought that the alluvium and volcanic rocks of Crater Flat are underlain by a circular resurgent dome, about 11 km across but of unspecified depth, that has risen into a Tertiary caldera (Carr, 1982, fig. 3). The geologic and geophysical evidence that Carr cited for the concealed caldera is persuasive and is further supported by the recent seismic refraction survey (Hoffman and Mooney, 1983) between Bare Mountain and Little Skull Mountain (fig. 1), which indicates sharp and steep structural discordances on the east and west sides of Crater Flat that persist to depths of 4 km or more. But the evidence for a resurgent dome within the caldera is not convincing.

As Crater Flat contains a row of young basaltic cones that trends about N. 35° E. (considered a "possible rift zone" by Carr), I have shown a basalt feeder dike there (pl. 1, map *B*) but do not otherwise take into account the possibility that a large intrusive mass may underlie Crater Flat. If such a body is present, it is too deep to be of significance to repository selection or operation, as judged by evidence from one drill hole (USWVH-1), 762 m deep in central Crater Flat, and available geophysical data. In this connection, it is interesting that the seismic refraction profile mentioned above indicates a continuous "prominent reflector" at a depth of about 13 km, perhaps produced by the top of a Tertiary or Quaternary intrusion but more likely by the Precambrian crystalline basement.

Finally, the possibility that the Yucca Mountain study area is underlain by part of a metamorphic core complex must be considered, as the area is within the arcuate zone of core complexes that extends across eastern and south-central Nevada (Stewart, 1983, fig. 5) and is not far from the exposures of high-grade metamorphic rocks with anomalously young (Miocene) radiometric ages in the Bullfrog and Trappman Hills, mentioned earlier. Stewart (1983) and McKee (1983) concluded that the Bullfrog and Trappman Hills (fig. 1) represent core complexes; this conclusion seems premature, as the evidence consists solely of one K-Ar age on muscovite from each locality and is unsupported by other field evidence. Instead, Tertiary volcanism may be responsible for resetting the ages of initially much older, probably Precambrian, muscovite-bearing rocks.

The hypothesis nevertheless offers an intriguing direction for future research, and scattered occurrences of younger-over-older displacements on low-dipping faults offer supportive hints. The idea seems academic with respect to selection of a nuclear-waste repository at Yucca Mountain, as there seems to be no evidence in the available geophysical data of discontinuities within thousands of meters beneath Yucca Mountain that are suggestive of the infrastructure-décollement-suprastructure relations characteristic of core complexes.

SOME HYDROLOGIC ASPECTS

Much hydrologic investigation has been carried out in the region using previously available geologic information as background and framework (see summary by Waddell, 1982). For regional hydrologic purposes, the rocks of the study area are classed as either aquifers or aquitards (table 1; see Winograd and Thordarson, 1975, for details). Aquifers include, from oldest to youngest, the thick and extensive mainly carbonate rocks of Cambrian through Devonian age; the thinner and areally restricted carbonate rocks of Pennsylvanian and Permian age; several thin and areally restricted volcanic rock types; and valley fill. Aquitards include thick and extensive Proterozoic and Lower Cambrian clastic rocks; the less thick and extensive Mississippian clastic rocks; and most of the locally thick but areally restricted units of volcanic rocks. I mapped these hydrologic units in the Yucca Flat area by regrouping the units of Barnes and others (1963a, fig. A-4). I have extended Winograd and Thordarsons units into the Yucca Mountain study area (fig. 9). Yucca Mountain is in the center of the Alkali Flat-Furnace Creek Ranch ground-water basin, as defined by Waddell (1982). At the

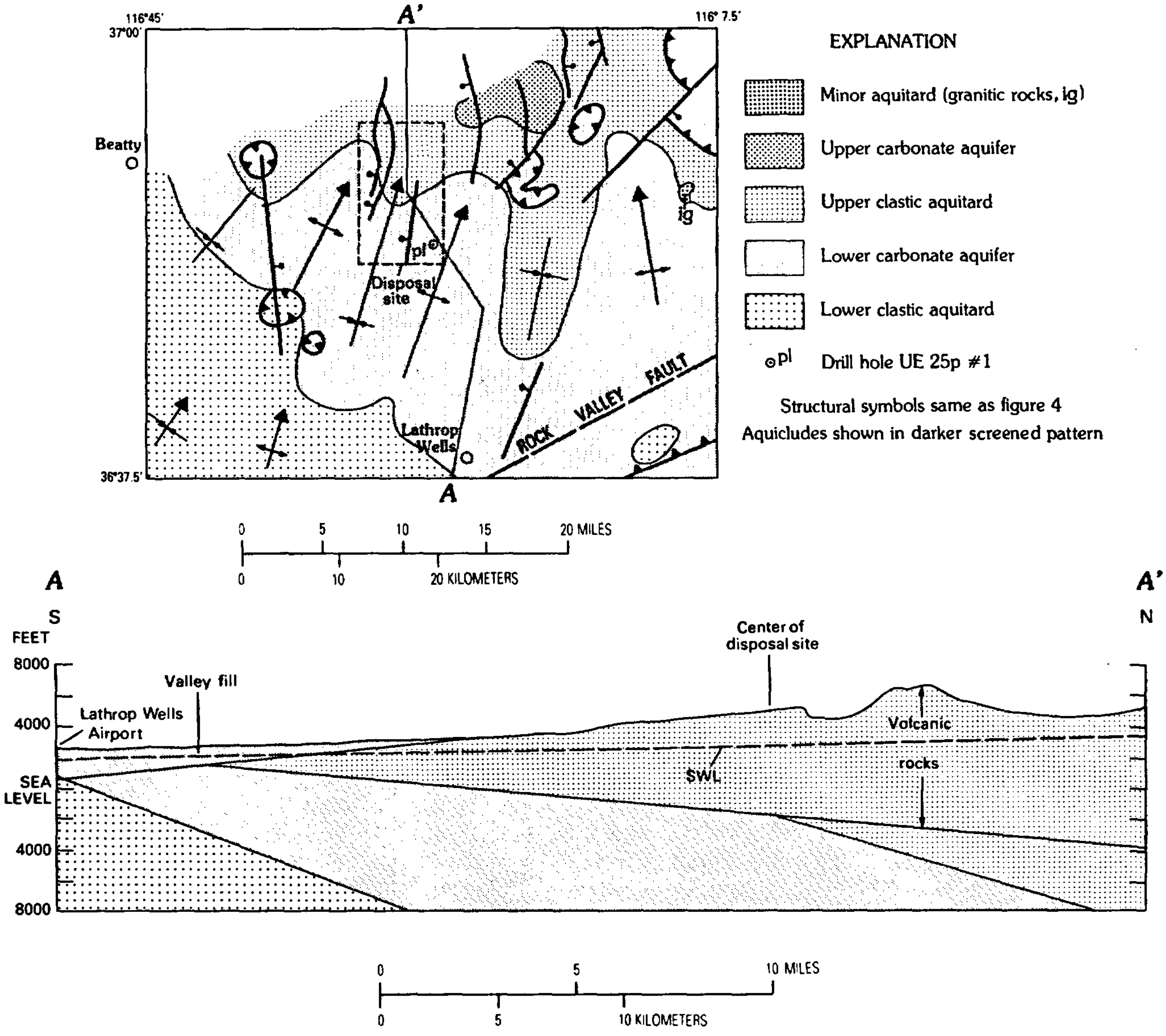

FIGURE 9.—Simplistic hydrogeologic map of Proterozoic and Paleozoic rocks and diagrammatic hydrogeologic cross section of the Yucca Mountain study area. Location of section is the same as A-A' of Waddell (1982, pl. 1) and the static water level (SWL) is also from Waddell's plate 1. On the basis of aeromagnetic maps, the cross section represents the volcanic rocks as thinning to zero near Lathrop Wells.

latitude of Yucca Mountain, the breadth of the basin is within the study area.

The potential repository being evaluated lies in unsaturated welded tuff. In practice (Winograd and Thordarson, 1975) the entire volcanic sequence at the site is regarded as aquitard because the bulk of it has essentially no grain porosity. The volcanic rocks, however, are riddled by tectonic and cooling fractures and are broken by many steep faults, some having wide breccia zones, leading to hydraulic connection with the underlying Paleozoic rocks. Principal transmission would be expected where the connection is made with the lower Paleozoic aquifer. Regional ground-water flow is southward, mainly through the lower Paleozoic aquifer to its buried contact with thick alluvium several kilometers north of Lathrop Wells; thereafter, flow is apparently largely in alluvium to discharge points in Alkali Flat, 30-40 km south of Lathrop Wells, "but the role of the Paleozoic and Precambrian rocks beneath the alluvium is unknown" (Waddell, 1982, p. 16). It should be noted that ground water from Yucca Flat does not travel the same general path or discharge in Alkali Flat; rather, diverted by the upper clastic aquitard, its course is farther east and it discharges in eastern Ash Meadows (fig. 1; Winograd and Thordarson, 1975).

Because ground water flows generally southward through the potential disposal site and the Yucca Mountain study area, the north-south relations of aquifers and aquitards is of special interest. This interest is served only in part by published north-south cross sections—that by Winograd and Thordarson (1975, pl. 1) is drawn through Yucca Flat and does not distinguish aquifers from aquitards in the subvolcanic rocks and that by Waddell (1982, pl. 1) traverses the site and study area, but it too fails to distinguish aquifers from aquitards in the prevolcanic rocks. Figure 9 includes a crude attempt to add that distinction. This improvement in detail, if correct, may be useful to future hydrologic investigations.

CONCLUSIONS

Understanding the pre-Cenozoic rocks and their structures in the Yucca Mountain study area, and particularly the region to the south, is important to the selection and successful functioning of a nuclear-waste disposal site. Thus, the study herein should be refined by better delineation of the effects of known faults on contacts between Systems, as well as the effects of irregularities in the subvolcanic surface on contact patterns. Knowledge of the fold pattern can be improved and significant thrust faults perhaps located by strategically placed drill holes, between the site and Lathrop Wells, deep enough to encounter the rocks of more than one pre-Cenozoic system. Such holes would help establish the true thickness of the volcanic rocks and also test the hypothesis that the study area is underlain at shallow depth by a metamorphic core complex.

Regionally, more detailed surface mapping is needed, supported by carefully planned drilling and geophysical studies. Geophysical work to the south should include seismic reflection studies, despite their ineffectiveness in and near the proposed repository, where the energy-absorbing volcanic rocks are thick. In the southern part of the Alkali Flat-Furnace Creek Ranch ground-water basin the volcanic rocks are thinner or absent, providing the opportunity for seismic reflection work to be effective.

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