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Geology and Hydrogeology of the Proposed Nuclear Waste Repository at Yucca Mountain, Nevada and the Surrounding Area

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Day 1, INTRODUCTION: In late 1987 Congress issued an amendment to the Nuclear Waste Policy Act of 1982 which directed the characterization of Yucca Mountain, Nevada as the only remaining potential site for the Nation's first underground high-level radioactive waste repository. The evaluation of a potential underground repository is guided and regulated by policy established by the Department of Energy (DOE), Nuclear Regulatory Commission (NRC), Environmental Protection Agency (EPA), Department of Transportation (DOT), and the U.S. Congress. The Yucca Mountain Project is the responsibility of the DOE. The purpose of this field trip is to introduce the present state of geologic and hydrologic knowledge concerning this site.

The potential high-level radioactive waste site at Yucca Mountain is approximately 160 km by road northwest of Las Vegas, Nevada, in an arid desert region. The location of Yucca Mountain, the surface site of the proposed underground repository, and other maps are shown on Figure 1. The potential repository is beneath land controlled by three Federal agencies, principally the Bureau of Land Management, but also by the DOE (Nevada Test Site) and the U.S. Air Force (Nellis Air Force Range). Yucca Mountain stratigraphy includes a sequence of ash-flow tuff, with minor bedded tuff and volcaniclastic sediments. The stratigraphic section for Yucca Mountain and the region are shown on Table 1. The proposed repository horizon is in densely welded silicic ash-flow tuff of the lower Topopah Spring Member of the Paintbrush Tuff (Tertiary). The repository is designed to be in the unsaturated zone approximately 400 to 300 m below the land surface and has a planned area of approximately 6.5 km^2. The water table is approximately 300 to 200 m below the repository horizon.

Important geologic and hydrologic topics of concern for site characterization are 1) tectonics of the site, including the rates of recent faulting and the geometry of extensional faulting; 2) recurrence rates, location, volume, and nature of Pliocene and Quaternary basaltic volcanism as close as 8 km to the potential site; and 3) hydrologic processes occurring and expected to occur in the unsaturated and saturated zone at Yucca Mountain. The geologic and hydrologic processes of concern will be projected and modeled for the next 10,000 years based on the Quaternary geologic record (2.0 Ma). Many other geologic and hydrologic investigations are planned during site characterization over the next six years.

Stop 1, TIMBER MOUNTAIN CALDERA, F.M. Byers, Jr.[2], W.J. Carr[6], and P. Orkild[5].

The Timber Mountain-Oasis Valley caldera complex (fig. 1), the central and largest volcanic feature of the Miocene SW Nevada volcanic field (Byers et al., 1976a; Christiansen et al., 1977), consists of a thick sequence of volcanic rocks that has several major cycles of ash-flow tuff and lava of calcalkaline and peralkaline compositions (Broxton et al., 1989; Sawyer and Sargent, 1989). Tuff and lava cycles, which extend from about 16 to 9 Ma (Marvin et al., 1970), were erupted, not only from Timber Mountain caldera, but also from the contiguous Silent Canyon and Crater Flat-Prospector Pass caldera complexes (Carr, W.J. et al., 1986). A younger ash-flow tuff and lava sequence, also included in the volcanic field, was erupted from the Black Mountain and Stonewall Mountain calderas northwest of Timber Mountain (Noble et al., 1984). A review of volcanological investigations in the southwest Nevada volcanic field during the past 30 years is given in Byers et al. (1989).

A stop will be made to view the Timber Mountain caldera part of the complex at an overlook outside the caldera on the edge of Pahute Mesa (fig. 1). The Timber Mountain-Oasis Valley caldera complex is about 40 km in diameter (fig. 1). The caldera and its central resurgent dome are elongate northwestward. Topographically expressed caldera structures are related to the eruptions of the Timber Mountain Tuff, which consists of two widespread members, the Rainier Mesa (11.6 Ma) and the Ammonia Tanks (11.3 Ma).

Two major subsidences of the Timber Mountain caldera occurred: the first resulted from eruption of more than 1,250 km^3 of the Rainier Mesa Member; the second from about 1,000 km^3 of the Ammonia Tanks Member. The Rainier Mesa collapse was the larger of the two; the Ammonia Tanks caldera is mostly nested within the central part of the complex. During eruption of both Members there was some collapse of the Oasis Valley western segment of the complex (Byers et al., 1976b).

The resurgent dome of the caldera, about 15 km in diameter, is composed of more than 900 m of magmatically uplifted Ammonia Tanks, radially and longitudinally faulted (Carr and Quinlivan, 1968). The caldera moat contains caldera fill debris, reworked tuff, rhyolite lava, and Thirsty Canyon Tuff from the Black Mountain caldera, about 30 km to the northwest, and younger basalt (2.8 Ma).

Rim Of Pahute Mesa: This stop provides a view of the eastern part of the Timber Mountain caldera and the exposure of the base of the Rainier Mesa Member of the Timber Mountain Tuff. About 4 km to the south, cuestas of Ammonia Tanks Member dip into the caldera, and the Stockade Wash Tuff and the Grouse Canyon Member of the Belted Range Tuff form much of the wall of the caldera and the valley floor between this viewpoint and the edge of the caldera (Byers et al., 1976a). On the skyline, about 30 km to the south, the rhyolite of Shoshone Mountain (about 9 Ma) overlies the southeastern caldera rim. Rainier Mesa is on the left (east), capped by the Rainier Mesa Member; resistant cap rocks below the mesa are the Rainier Mesa of the Timber Mountain tuff and the Tiva Canyon Member of the Paintbrush Tuff. Several faults in that area drop the section down toward the caldera.

A vitric bedded tuff, exposed in the adjacent roadcut, is overlain unconformably by about 3 cm of ash-fall and pyroclastic surge deposits of the Rainier Mesa Member. The Paintbrush Tuff is absent here and the Rainier Mesa Member thickens northward, and thereby indicates that the edge of Pahute Mesa was topographically high at the time of eruption of the Paintbrush and Timber Mountain Tuffs.

Just to the northwest of this viewpoint is the limit of another major volcano-tectonic feature (fig. 1), the Silent Canyon caldera (Orkild et al., 1968; 1969), which is largely beneath Pahute Mesa and is not topographically expressed. Although it is essentially hidden by younger tuff, it is well defined gravimetrically and by numerous drill holes. The major outflow tuff sheet from the Silent Canyon caldera is the Grouse Canyon Member of the Belted Range Tuff. Peralkaline tuff and lava associated with the Silent Canyon caldera intertongue with calcalkaline tuff and lava, such as the bedded tuff exposed in the adjacent roadcut (tuffs of Area 20; Table 1). Airfall and nonwelded tuff of the Crater Flat Tuff (Carr, W.J. et al., 1986) also occur in the Pahute Mesa area (Warren, 1983).

Stop 2, G-TUNNEL, Rainier Mesa, Nevada Test Site, E.L. Hardin[1].

G-tunnel is a long entry adit and a complex of drifts driven into the side of Rainier Mesa at about 2,034 m elevation. The tuff sequence comprises predominantly rhyolitic air-fall and welded/nonwelded ash-flow tuff and volcanoclastic beds that have been tilted gently and overlain discordantly by the Rainier Mesa Member of the Timber Mountain Tuff. Suitability of the nonwelded units for excavation by mechanical and other means was a principal factor in the selection of the mesa for nuclear testing. Five underground nuclear tests were conducted in G-tunnel during the 1960s under the auspices of Sandia National Laboratories. These test drifts are now sealed and isolated from the frequented openings.

The ride into G-tunnel ends at the bottom of an incline that leads upward in the section into the welded Grouse Canyon Member of the Belted Range Tuff. The densely welded portion of this unit, about 13 m thick, is similar to the Topopah Spring Member at Yucca Mountain, in physical, thermal, and mechanical characteristics. Near the bottom of the unit are two distinct vitrophyres and a rubble zone 1.0 to 1.3 m thick. Several near-vertical normal faults trend in the direction of structural dip and can be traced from the Demonstration Drift in the welded Grouse Canyon to the parallel drifts below, in the nonwelded Tunnel Bed #5. Another interesting feature is a perched water reservoir created by a fault that downdropped the moderately fractured welded unit against underlying nonwelded beds. A small seep can be observed in the roof, about halfway up the long access incline. Perched water has not been detected at Yucca Mountain and is expected to be less common because the elevation is more than 610 m lower and the mean annual precipitation (~16 cm/yr) is less than half that at Rainier Mesa (35 cm/yr).

Since 1979, the G-tunnel underground facility (GTUF) has been used by Sandia National Laboratories (SNL) for Project-sponsored prototype field-scale testing. Experiments have evaluated the mechanical and thermomechanical rock mass response, including a heated block experiment, borehole heater tests, and a mine-by experiment. SNL has used the GTUF for refining equipment and instrumentation, including cutting slots in welded tuff using a chain saw, and high-pressure flatjack development and tests. Prototype experiments including a thermal stress and rock mass response tests, are in progress.

In addition, other laboratories participating in the Project have used the GTUF for proof-of-concept or prototype testing, such as the crosshole VHF EM tomography experiment performed by Lawrence Livermore National Laboratory. The GTUF has been the location of a prototype testing program, whereby test methods specifically planned for the Yucca Mountain Exploratory Shaft Facility have been implemented. These prototype tests have included the following (some may still be underway): dry drilling and coring with dust hazard evaluation, hydrologic drillhole instrumentation, blast effects on instrumentation, intact fracture sampling methods, tracer diffusion test, high-pressure flatjack testing, engineered barrier (near-field) design testing, crosshole hydraulic and pneumatic flow testing, and photogrammetric mapping technology. Additional information on the latter two tests is provided below.

Prototype Underground Geologic Mapping At G-Tunnel, M. H. McKeown[7], G. M. Fairer[5], S. C. Beason[7].

The U.S. Geological Survey (USGS) and the U.S. Bureau of Reclamation (USBR) are developing equipment and techniques for geologic mapping of exposures in the proposed Exploratory Shaft Facility (ESF) and associated drifts at Yucca Mountain. Prototype geologic mapping in G-tunnel is one of the pre-excavation tests of plans, equipment, and techniques that will be used in drift mapping; other prototype tests are planned for shaft mapping. For both kinds of mapping, a computerized analytical plotter will be used to provide complete and accurate data. Information for use on the plotter will be obtained from a) close-range stereoscopic photographs, b) measurements and descriptions of features along detailed line surveys, and c) on-site observations by geologists. Maps and data-sets will be used to understand hydrologic characteristics of the unsaturated zone in which the proposed repository will be located.

During prototype testing, stereoscopic photographs were taken of washed-down surfaces in a selected segment of G-tunnel to provide film positives for close-range photogrammetric geologic mapping. Detailed line surveys were completed and additional geologic notes were recorded as necessary. Geologic mapping from combined data shows discontinuities such as faults, fractures, and breccia zones, as well as lithology and stratigraphy.

Six instruments developed for mapping include 1) stereogrammetric camera mount, 2) strike-rail goniometer, 3) right-angle prism goniometer, 4) laser goniometer, 5) prism beam splitter, and 6) geogyroscope. These new techniques and instruments were developed to increase underground mapping accuracy and precision.

Cross-hole Pneumatic And Hydraulic Prototype Test, R. C. Trautz[5].

Cross-hole pneumatic and hydraulic tests, commonly referred to as interference tests in the petroleum industry, evaluate formation properties such as permeability and storativity, determine location of structural features such as faults and no-flow and recharge boundaries, and determine if reservoirs or fractured aquifers exhibit permeability anisotropy (Earlougher, 1977; Hsieh and Neuman, 1985; and Hsieh et al., 1985). Cross-hole testing is a methodology requiring at least one active (producing or injecting) well and at least one observation well. Gas or water is injected into or produced from an isolated test interval within a drill hole and formation response to fluid-pressure change is monitored in nearby observation holes. Test results, namely active and observation well fluid pressures, temperatures and injection or production flow rates, are used to calculate permeability. Analysis of test results depends upon flow domain boundary conditions, the type of fluid injected into the formation (water or gas), the formation saturation state, and the type of test conducted (e.g., steady state, transient, or instantaneous injection). The primary objective of the pneumatic and hydraulic cross-hole prototype test is to develop and/or refine field equipment (hardware), software, quality assurance technical procedures, and determine optimum testing configuration.

Stop 3, CLIMAX STOCK AND THE HIGH-LEVEL SPENT FUEL TEST, W.T. Hughes[8] and S.R. Mattson[1].

The Cretaceous (93 Ma) Climax quartz monzonite and granodiorite intrudes Paleozoic and Precambrian sedimentary strata (Maldonado, 1977) at the northern end of Yucca Flat. The granodiorite is light gray to greenish medium gray, equigranular; and averages 28 percent quartz, 16 percent potassium feldspar, 45 percent plagioclase, and 9 percent biotite. The quartz monzonite is light to medium gray and is highly porphyritic with respect to potassium feldspar (5 percent) and quartz (10 percent); it has an average modal analysis of ;28 percent quartz, 25 percent potassium feldspar, 40 percent plagioclase, and 6 percent biotite (Houser and Poole, 1961; Maldonado, 1977).

The Climax stock is part of the Oak Spring Mining District which produced mainly tungsten. Surface.workings visible from the Climax headframe are part of the mining district that began operating in 1937. Because of conflicts with the nuclear testing program, the Atomic Energy Commission bought out the mining interests in the 1960s. Mineralization and hydrothermal alteration comprise clay minerals, feldspars, quartz, epidote, pyrite, scheelite, and chalcopyrite. This mineralized area will be one of many considered in evaluating the potential of Yucca Mountain to contain economic resources (See Stop 13b).

Spent Fuel Test - Climax: The Climax stock was the host rock for two nuclear weapons tests, Hard Hat and Piledriver, in the 1960s. From 1980 to 1983, as part of the Spent Fuel Test at Climax (SFT-C), spent fuel from a commercial nuclear reactor was emplaced in drifts mined from the previously developed Piledriver shaft. The SFT-C work was operated by DOE under the technical direction of Lawrence Livermore National Laboratory. The main objectives of the SFT-C were to demonstrate and evaluate safe and reliable waste packaging, transport, and storage of nuclear spent fuel in a geologic media, and the ability to retrieve spent fuel canisters. In addition, the test provided information on the suitability of crystalline rock a repository host medium. The tests were conducted at the 427 m level, in quartz monzonite.

By 1980 the central emplacement drift and two parallel heater drifts had been constructed. For maximum stability they were perpendicular to the main joint set (N30E) and parallel to another joint set (N60W). Instrumentation emplaced in the heater drifts evaluated the effects of mining and heating of the central drift.

Eleven spent fuel canisters were emplaced in the central drift. At both ends of this drift, three heaters were alternated with the spent fuel canisters. The heat and radiation effects produced by spent fuel were compared to the effects of heat alone on the rock. Heaters were emplaced in the drifts on either side of the central drift to simulate, for the middle of the central drift, the interior environment of a large repository grid containing 8,000 canisters. Predictive models based on a 15.2 m (50 ft) square cell were compared to measurements made in the middle portion of the central drift.

Extensive testing included thermal load heater tests, natural cool down of the granitic rocks after waste removal, post-test sampling of the granitic rocks for detecting heat or radiation effects, geomechanical tests, and stress/strain instrumentation (e.g., Isherwood et al., 1982; Patrick et al., 1983; Montan and Bracken, 1984). The maximum canister temperature recorded was 145°C, and a peak rock temperature recorded was 85°C, both within 3-4° of modeling predictions. When installed, the canisters provided approximately 1,500 watts of thermal power and generated 650 watts of thermal power when removed. Studies of the rocks detected no changes in strength or deformability, and no increases in the number of micro-cracks in the rocks Thermal expansion elevated the central drift floor 3 mm, close to predicted values.

Underground: The stainless steel spent fuel canisters were transported to the SFT-C site by surface transport vehicle, then lowered down the spent fuel access hole into the cylindrical shielding cask on the underground rail car. The remotely operated rail car weighs 130,000 lbs, of which 80,000 lbs is due to the shielding cask. The rail car transported each canister along the drift and lowered it into one of eleven steel-lined boreholes, then covered the hole with a 5,000 lb concrete floor plug. An unshielded fuel assembly would deliver a lethal dose in less than one minute, but with the cement floor plug in place the radiation levels were less than background (approximately 0.02 millirem/hour) from the granitic rocks.

The water table at this location is 145 m below the drift. Water observed in the shaft results from condensation and/or surface infiltration. At one time, one of two parallel shear zones toward the end of the main emplacement drift produced about a gallon of water per day which was pumped out because of instrumentation corrosion problems. Clay alteration is evident in the lower shear zone that did not seep water. Displacements of a few hundredths of a millimeter were observed across the shear zone during the experiments.

Stop 4, SEDAN CRATER, H.L. McKague[9].

Both high explosive and nuclear cratering experiments were conducted principally during the period 1960 to 1970, as part of a program designed to assess the peaceful uses of thermonuclear devices. Several experiments of both types were conducted in alluvium and in bedrock in Frenchman Flat, Yucca Flat, and Pahute Mesa, the largest of which was the Sedan experiment in Yucca Flat.

The Sedan crater was formed on July 6, 1962, by a thermonuclear explosion (70% fusion, 30% fission) having a yield equivalent to 100 kt of TNT at a depth of 193.5 m. The seismic energy released was 2.45×10^{18} ergs, equivalent to an earthquake magnitude of 4.8. The maximum depth of the crater was 98.5 m; the average radius was 185.3 m. The crater volume was about 5×10^6 m^3. The crater lip is 5.5 to 29 m above pre-shot levels. Ejecta were found as far as 1,770 m from ground zero. Observed overturning of the alluvium strata in the lower part of the lip is similar to that at the Teapot-Ess nuclear created crater, about 0.8 km south of here (Shoemaker, 1960). Winograd (1980) proposed consideration of radioactive waste disposal in unsaturated alluvial deposits of the Great Basin. He discussed waste burial in Sedan crater as an example of the potential use of the unsaturated zone for waste isolation. This paper was one of several factors that influenced the DOE decision, in the early 1980s, to consider exploration studies to include sites in the unsaturated zone, such as Yucca Mountain, Nevada.

Day 2, Stop 5, DETACHMENT FAULTING AND MINERALIZATION AT BULLFROG MOUNTAIN, BULLFROG HILLS AREA, Florian Maldonado[5].

The Bullfrog Hills, a structurally extended terrane, contains two detachment faults overlain by a complex system of listric and planar rotational normal faults (Ransome et al., 1910, Maldonado, 1985a, 1988, and Maldonado and Hausback, in press). The detachment faults separate three groups of rocks. The lower detachment fault separates metamorphosed upper Proterozoic rocks from overlying lower and middle Paleozoic clastic and carbonate rocks. The Paleozoic rocks are brecciated, commonly not metamorphosed, and the stratigraphic section is incomplete and highly attenuated. The upper detachment fault separates these Paleozoic rocks from overlying Miocene volcanic, volcaniclastic, and sedimentary rocks. The Miocene and Paleozoic rocks are allochthonous relative to the underlying metamorphic rocks and will be referred to as upper and lower plates, respectively.

Upper plate rocks form most surface exposures and dip moderately to steeply into the upper detachment fault, or, where the lower plate has been tectonically removed, into the lower detachment fault. Upper plate rocks are broken, tilted, and repeated in blocks bounded by normal faults that terminate against, or flatten and merge into the upper detachment fault. Normal faults in the upper plate are listric faults that form imbricate, oval, and horseshoe map patterns and planar rotational faults that form imbricate map patterns. These upper-plate faults have extended the upper plate more than 100 percent and possibly more than 275 percent locally. The dip direction of the normal faults (predominantly west) and the repetition and dip direction (predominantly east) of the Miocene rocks indicate that extension, at least of the upper plate, was west-northwest and occurred between about 8 and 10 Ma and not younger than about 7.5 Ma as previously indicated (Maldonado, 1985a, 1988). This constraint on extension is based on the age of the youngest deformed unit, a latite lava flow dated at 10 Ma (Maldonado and Hausback, in press) and the oldest undeformed unit, a basalt lava flow dated at 8 Ma (Maldonado, in press).

The stop at Bullfrog Mountain shows a partial section of the Miocene succession underlain by the upper detachment fault. The mountain, a rotated block, contains essentially conformable hydrothermally altered strata dipping about 40° to 60° into the upper detachment fault. The block forms an oval map pattern, bounded on the west and below by the upper detachment fault and on the east by a normal fault which separates the Bullfrog Mountain block from the block eastward by about 3,000 m of apparent stratigraphic separation. This fault is interpreted to merge into or be truncated by the upper detachment fault. The lower plate, below the upper detachment fault, is comprised of slivers of brecciated Paleozoic rocks. Below the Paleozoic rocks the lower detachment fault separates Paleozoic rocks from Proterozoic metamorphic rocks. However, on the southwest edge of Bullfrog Mountain, Paleozoic rocks have been tectonically eliminated, placing Miocene rocks on metamorphic rocks. The metamorphic rocks are penetratively foliated and lineated and consist of mylonitic quartzofeldspathic gneiss, biotite schist, marble, and amphibolite dikes of amphibolite facies (Carr and Monsen, 1988). These rocks have been correlated with the late Proterozoic Johnnie (?) Formation (B.W. Troxel, oral commun., 1986).

Gold mineralization at Bullfrog Mountain is in a quartz vein complex in the Miocene succession; it has been referred to as the "Original Bullfrog Vein" (Ransome et al., 1910). This complex, truncated by the upper detachment fault, is intensely brecciated, and contains disseminated gold along with fragments of the Eleana Formation, quartz latite lava flow(?), and the Lithic (?) Ridge Tuff. Gold along faults at other localities in the upper plate suggests that some gold mineralization and hydrothermal alteration are probably coeval with extension.

Stop 6, NORTHERN BARE MOUNTAIN, FLUORSPAR CANYON, Yucca Mountain Project Staff.

Bare Mountain exposes a faulted, folded, generally northward dipping section of upper Proterozoic and Paleozoic miogeoclinal sedimentary rocks (fig. 1 and fig. 3; Carr and Monsen, 1988). Bare Mountain is bordered on the east by Crater Flat, filled with as much as 3.5 km of Cenozoic volcanic and sedimentary rocks (Ackermann et al., 1988), on the southwest by the northern Amargosa Desert, a broad alluvial valley filled by less than 1 km of Cenozoic deposits (Healey and Miller, 1972), and to the north by a complexly faulted terrane of middle Miocene volcanic and sedimentary rocks (Carr and Monsen, 1988).

The Fluorspar Canyon fault forms the saddle on the south flank of Beatty Mountain (middle Miocene rocks) and is near the northwest flank of Bare Mountain (upper Proterozoic and Cambrian metasedimentary rocks) (Monsen, 1983). The fault has been interpreted by Carr and Monsen (1988) as part of a regional, low-angle normal fault system that propagated to the surface during the late Miocene. The regional low-angle normal fault system extends from the Bullfrog Mountain area (Stop 5) eastward to the head of Fluorspar Canyon. Whether the Fluorspar Canyon fault continues to the east remains a question (Carr and Monsen, 1988). Additional studies of the structural setting of this area will occur as site characterization of Yucca Mountain continues.

Stop 7, STEVES PASS, CRATER FLAT OVERLOOK, Yucca Mountain Project Staff.

The eastern flank of Bare Mountain and the western flank of Yucca Mountain are visible from this location. Based on gravimetric and magnetic data, Crater Flat has been interpreted as an asymmetric graben extending southward into the Amargosa Desert (Synder and Carr, 1984). The conspicuous surface expression of this graben is confined to Crater Flat (Carr and Monsen, 1988). The structure of Crater Flat and western Yucca Mountain has been variously interpreted to be either the result of movement along faults of the Crater Flat-Prospector Pass caldera (Carr, W.J. et al., 1986) or as part of a listric and normal fault pattern that soles into low-angle normal faults

(Scott, 1986, 1988; Scott and Rosenbaum, 1986).

To the east, Yucca Mountain is a remnant of a volcanic plateau that was subsequently dissected by erosion along numerous steeply westward-dipping faults (See Stop 13a for discussion). Westward, Bare Mountain is bounded by the north-south trending Bare Mountain fault, which has been active during the Quaternary (Reheis, 1988). In many locations, the Bare Mountain fault dips steeply eastward and has components of dip-slip and right-lateral strike slip (Reheis, 1988; Carr and Monsen, 1988). The gold producing Sterling Mine is on the eastern flank of Bare Mountain, at or near the intersection of two thrust faults (Tingley, 1984; DOE, 1988; see Stop 13b) that displace miogeoclinal Paleozoic strata. The volcanic centers of Little Cones, Red Cone, Black Cone, and northernmost cone are visible from south to north, respectively, forming part of a northwestern trend of basaltic volcanism (See Stops 10 and 13b).

Stop 8, SPRING DEPOSITS OF THE NORTHERN AMARGOSA DESERT, W C Swadley[5].

Marl and limestone exposures along U.S. 95, near the north end of the Amargosa Desert, are part of a widespread group of similar deposits over much of the Amargosa Desert basin. These outcrops are the northernmost of a discontinuous band of marl, siltstone, and limestone exposures that extend about 60 km southeastward. They have been attributed to deposition in a Pliocene-Pleistocene lake, informally called Lake Amargosa (Swadley and Carr, 1987). However, the deposits are more likely the result of deposition in discontinuous marshes and small ponds fed by carbonate-rich springs similar to springs at Ash Meadows in the southern part of the basin (Hay et al., 1986). The deposits are thus analogous to the spring and marsh deposits of Las Vegas Valley (Quade, 1986).

The spring deposits crop out north of U.S. 95 approximately 19 km northwest of the town of Amargosa Valley (formerly Lathrop Wells). Most of the exposure consists of pale-yellowish-gray to light-greenish-gray marl that weathers white to very light gray. It is sandy, locally tuffaceous, thin bedded to massive, and weathers to low rounded mounds. Several prospect pits offer good exposures. The marl contains vertebrate remains (including fragments of mammoth teeth), gastropods, plant stems, and diatoms. Downslope from the conspicuous white marl exposures, an exposure of light-gray, hard, fine-grained, crystalline, Pliocene or Pleistocene, limestone that weathers yellowish gray. The limestone forms low ledges that are partly covered by alluvium and windblown sand. No spring vents have been recognized in the deposits. The exposures are surrounded and partly covered by late Holocene alluvial deposits derived from the nearby hill slopes and the stratigraphic relation of the spring deposits to the underlying bedrock is unknown. A sink hole-like opening in coarse fan alluvium 0.3 km northwest of the outcrop appears to be fault related, but no connection between this feature and a possible fault controlling the location of the spring deposits has been established.

Spring deposits north of U.S. 95 are similar in lithology and occurrence to more extensive claystone and carbonate deposits of the Amargosa Flat and Ash Meadows areas. These two areas were studied by Hay et al. (1986) who described deposits of calcareous claystone, chalky to crystalline limestone, and sandy, silty, and tuffaceous mudstone. Based on detailed field relations and chemical and X-ray diffraction clay mineral analyses, they concluded the sediments are a mixture of playa deposits and marsh and pond deposits. Carbonate minerals and various Mg-clays constitute much of the deposits precipitated from ground water supplied by fault controlled springs. The ponds and marshes were fresh to slightly saline. Radiometrically determines ages of volcanic-ash interbeds range from 3.2 to 2.4 Ma.

Correlation of deposits north of U.S. 95 with those analyzed by Hay et al. (1986) at Amargosa Flat is based on similarities in lithology and the presence of similar deposits exposed discontinuously in the area between these two exposures. In the southern part of the Lathrop Wells quadrangle (Swadley, 1983), spring-related deposits are well exposed and are continuous with those of the Amargosa Flat area. Correlation has been extended northwestward through the Big Dune quadrangle (Swadley and Carr, 1987), but it is somewhat less certain because of increasingly larger gaps between exposures.

Age of the northern deposits is indicated by the presence of vertebrate remains (*Mammuthus* sp.) that C.A. Repenning (U.S. Geological Survey, written commun., 1982) considers to be less than 2 Ma. This age is younger than the radiometric ages reported by Hay et al. (1986) and suggests that spring-related deposition sites may have occurred at various times over much of the Amargosa basin during the late Pliocene and Quaternary. Similar spring deposits are currently forming in the Ash Meadows area, where several large springs discharge carbonate-rich ground water.

Stop 9, TYPE SECTION OF THE CRATER FLAT TUFF, W.J. Carr[6] and F.M. Byers Jr.[2].

The main stratigraphic and lithologic units (fig. 2) from the base of the exposure upward are (1) vitric ash fall tuff, containing a thick boulder fluvial and/or debris-flow deposit; (2) Bullfrog Member of the Crater Flat Tuff; (3) vitric nonwelded to partially welded unit of the Bullfrog resting in a scour or pocket on the main Bullfrog; (4) a coarse breccia of welded Bullfrog clasts; and (5) the Prow Pass Member of the Crater Flat Tuff. The lowest member, the Tram, is not present here. This is the only section where the Crater Flat Tuff is essentially unaltered.

The lowest exposed volcanic unit comprises several hundred feet of very light gray bedded ash, and reworked tuff. Some of the tuff contains conspicuous biotite and hornblende and may be related to a group of dacitic to rhyolitic lavas that mostly underlie the Crater Flat Tuff in the Crater Flat region (Carr, W.J. et al., 1986). One such lava, a quartz latite, in this general stratigraphic position, is exposed 9 km northwestward (unit Tql, fig. 2: after Swadley and Carr, 1987).

In the upper part of the vitric bedded tuff unit is a resistant, pale yellowish-green lens of crudely bedded coarse to massive bouldery gravel about 30 m thick. The clasts are rounded, as much as 2 m in diameter and apparently consist of only three rock types: porphyritic and non-porphyritic densely welded tuff of the Grouse Canyon Member of the Belted Range Tuff; and welded tuff of the Tram Member of the Crater Flat Tuff. The tuff matrix contains small pumice fragments, especially in the lower part. The closest Grouse

Canyon exposures are more than 50 km northward; no Grouse Canyon is present in the deep drill holes at Yucca Mountain, 20 km northward. To account for transport of such large boulders over a long distance, Carr, W.J. et al. (1986) suggested the deposit was a catastrophic debris flow. However, the rounded clasts, the locally pumiceous matrix, and the crude bedding may indicate a fluvial origin.

The Crater Flat Tuff is well exposed in the canyon about 0.8 km east of the vitric tuff described above. It consists of three compositionally similar ash-flow tuff members characterized by subequal modal plagioclase, sanidine, and quartz, with minor biotite, hornblende, and rare clinopyroxene (Byers et al., 1976b; Carr, W.J. et al., 1986). Quartz is strongly resorbed in the Bullfrog and Prow Pass Members. At this locality the Tram Member is not present.

The Bullfrog Member has a prominent dark vitrophyre about 5 m thick near the base, where welding increases abruptly upward. The member is moderately welded and devitrified in much of this section and is about 150 m thick. The average of four K-Ar age determinations of the Bullfrog, obtained from biotite and sanidine, is 13.5 Ma.

Two unusual units are present near the head of the canyon, where the top of the Bullfrog is well exposed. A lens of gray, mostly vitric nonwelded ash-flow tuff of Bullfrog composition is in a large scour or pocket directly on top of the welded devitrified Bullfrog. This unit resembles a thickened nonwelded vitric top that is occasionally found preserved as a thick cap on a normally zoned ash-flow. Here the unit is unusually thick and has a sharp lower contact. In equally sharp contact above the gray vitric tuff is a lens of purplish-gray monolithologic breccia that is exposed laterally for nearly 2 km (fig. 2). The breccia blocks consist entirely of welded Bullfrog. The blocks are unlike any other Bullfrog exposed in the area. Carr (1988) suggested the breccia slid into this position, perhaps caused by tectonic movements accompanying nearby caldera collapse.

Above the breccia is a thin bedded tuff overlain by about 50 m of orange-brown and cavernous-weathering Prow Pass Member of the Crater Flat

Tuff. The Prow Pass at this location is a simple cooling unit that is nonwelded to partially welded. It has fewer mafic phenocrysts than the Bullfrog and contains minor orthopyroxene and rare to sparse biotite and hornblende. The Topopah Spring and Tiva Canyon Members of the Paintbrush Tuff are on the ridge above the Prow Pass.

On the basis of topography, structure, geophysics, and other evidence (fig. 2; Carr, W.J. et al., 1986), the source of the Crater Flat Tuff was the Crater Flat-Prospector Pass caldera complex, the southern edge of which is about 3 km north of this locality. Other workers (e.g., Scott, 1988) interpret the basin under Crater Flat as a basin-range graben underlain by a detachment fault. Two drill holes in central Crater Flat show that the structural depression is mostly older than the Paintbrush Tuff (Carr, 1988), but the holes are not deep enough to resolve the structural genesis of Crater Flat.

Stop 10, LATHROP WELLS VOLCANIC CENTER, Bruce M. Crowe[3], F. Perry[10], S. Wells[10], L. McFadden[10], C. Harrington[3], D. Champion[11], B. Turrin[11].

The Lathrop Wells volcanic center, the youngest of a group of five small volume Quaternary basaltic centers in and adjacent to Crater Flat (fig. 3), is 20 km south of the Yucca Mountain exploration block. It is an asymmetric (elongate NW-SE) scoria cone flanked eastward, north and south by blocky aa lava flows.

The age of the Lathrop Wells center has proven problematic. An original age estimate of 270 ka (DOE, 1986) was based on K-Ar age determinations from the lava flows and from a bomb from the summit of the main cone. This age appeared inconsistent with the degree of preservation of the main scoria cone and some of the lava flow units. It was originally assumed the center formed during a single pulse of magmatic activity (monogenetic volcanic center). Lava flow age determinations were believed to indicate the age and duration of volcanic activity; however, subsequent detailed work shows this is incorrect.

The volcanic center has been newly mapped at a scale of 1:4,000 (Crowe et al., 1988). There are at least two to as many as four episodes of eruptive activity from spatially separate vents and fissure systems. Local soils with partial horizon development between eruptive units and the differing degrees of geomorphic preservation of the deposits require a lengthy eruptive history. Analysis and comparison of geomorphic and pedologic properties of the Lathrop Wells scoria cone with those of the Cima volcanic field (Wells et al., 1988) indicate the Lathrop Wells cone is most similar to the youngest cone of the Cima field, which is about 15 ka, based on various direct and indirect dating techniques. Features indicative of a Late Pleistocene or Holocene age of the final eruptions of the Lathrop Wells volcanic center include 1) cone slopes near the angle of repose (29°), 2) the absence of development of a cone-slope apron at the base of the cone, 3) paucity of rilling and mass wasting features on cone slopes, and 4) poor horizon development of soils on the tephra. The major uncertainty in calibrating the age of the final scoria eruptions of the scoria cone are the rates of erosional degradation and soil formation in an area of high eolian flux. Rock varnish studies show lava flow surfaces contain heavy mineral components derived from volcanic ash in the upper varnish sequence. The position and presence of minerals is consistent with introduction from a young scoria-fall eruptive event (Harrington, 1988).

Studies of the direction of remanant magnetism of volcanic units of the Lathrop Wells center show two distinct field directions. The north and northeast lava flows have a field direction that differs from the older fissure system that is inferred as the source of the southwest lava flows. A currently unresolved inconsistency is the pole position for bombs from the main scoria cone rim. This preliminary field direction appears to match that of the older fissure system. There are several possibilities for these data: 1) the preliminary field direction for bombs from the cone rim is incorrect, a possibility that will be clarified with additional data; 2) field directions of the cone rim and older fissure units are identical, but they represent separate eruptive events; and 3) the measured field direction from the cone rim is the same event as the older fissure system, a matter that requires a complex cone growth history.

Sixteen new K-Ar age determinations and re-evaluation of existing K-Ar data indicate the lava flows are younger by at least a factor of two than the reported age of 0.27 Ma. Weighted averages of 34 K-Ar age determinations from the lavas that correspond to the two distinct magnetic field directions yield 0.133 ± 0.010 Ma for the younger flow unit and 0.115 ± 0.012 Ma for the older flow unit. The ages are inverted from the observed stratigraphic relations, but are identical at the 95% confidence level. Based on analysis of the reported analytical precision, differences in ages between the two lava flow units is less than or equal to approximately 0.030 Ma. K-Ar ages are consistent with the uranium trend chronology and stratigraphy of the surficial alluvial units in the Yucca Mountain region (Swadley et al., 1984); however, geomorphic preservation of the younger flow unit and the topographic position of the younger flows compared to modern alluvial surfaces are permissive with a significantly younger age than indicated by K-Ar. The K-Ar ages of the lava flows of the Lathrop Wells center will be compared with studies of other isotopic systems: U-Th disequilibrium measurements using solid source mass spectrometry, $^{4}He/^{3}He$ surface exposure ages, thermal luminescence, and $^{40}Ar/^{39}Ar$ measurements.

A new finding from the study of the Lathrop Wells volcanic center is the complex eruptive history and long duration for activity at this small volume center, these observations are supported by preliminary studies of two other Quaternary centers (Little Black Peak and Hidden cones) 47 km northwest of Yucca Mountain. All the centers exhibit the following features: 1) multiple eruptions from closely spaced volcanic vents, 2) intermittent eruptive activity over time spans exceeding 10^5 yrs, 3) decreased magma volume and increase in the ratio of scoria/lava of successive eruptions. Preliminary studies of other Quaternary volcanic centers in the Yucca Mountain region, in the Lunar Crater, and Cima volcanic fields indicate that small-volume centers commonly exhibit the same patterns of eruptive activity. Polycyclic volcanic eruptions may be a common characteristic of basaltic centers of the southern Great Basin.

These observations imply several significant implications. First, petrologic studies of small volume basaltic centers are generally incomplete. Samples are normally collected and analyzed only for lava flows, because these rocks tend to be less vesicular and less altered; hence, the complete range of magma compositions in the centers is unstudied. Second, repeated basalt magma eruption from adjacent vents requires structural control of subsurface magma feeder pathways; this suggests the initial magma pulse may create a preferential subsurface pathway for later pulses. Third, the long duration and complex eruptive history of the volcanic centers must be considered in assessing potential volcanic hazards to the proposed Yucca Mountain repository.

Day 3, **Stop 11, GEOLOGIC FEATURES AT FRAN RIDGE,** R.W. Spengler[5] and W.R. Page[5].

Natural and man-made exposures at Fran Ridge provide opportunities to study in detail lithologic and structural characteristics of the Paintbrush Tuff, particularly the Topopah Spring Member, near the eastern margin of a 230 km^2 area, referred to as the area of site specific geologic investigations (fig. 3). Fran Ridge is one of several north-trending east-tilted ridges typical of the Yucca Mountain area (fig. 3). Jackass Flats and Midway Valley are east and west of the ridge, respectively. Busted Butte is the conspicuous outcrop directly southward.

STRATIGRAPHY: The Paintbrush Tuff comprises the Topopah Spring, Pah Canyon, Yucca Mountain, and Tiva Canyon Members, in ascending order (Byers et al., 1976b). The Topopah Spring Member reaches a maximum thickness of about 350 m, beneath the northern half of the proposed repository site (Spengler and Fox, in press). At Fran Ridge, the member is about 250 m thick, based on interpolation between boreholes. At this stop, only 30 m of the upper part of the member is exposed. Southward, along the northern flank of Busted Butte, a nearly complete section of the cliff-forming Topopah Spring and Tiva Canyon Members, separated by a slope-forming interval of bedded tuff, can be seen. At Fran Ridge this bedded tuff sequence is about 14 m thick and is dominantly composed of ash-fall material.

Almost all the rock within the Topopah Spring Member is moderately to densely welded, except for zones a few meters thick near the top and base, which are nonwelded to partially welded. In ascending order, the member includes three distinctive and mappable depositional units within the site area: lithic-poor rhyolite, lithic-rich rhyolite, and quartz latite caprock (Spengler et al., 1987). The rhyolite units are phenocryst poor and distinguishable on the basis of type, size, and abundance of lithic clasts. Within the site area, the lithic-poor rhyolite is the thickest depositional unit and can be divided into five mappable zones. Except for a basal vitric zone, mappable zones are primarily differentiated on the basis of relative abundance of lithophysal cavities and include, in ascending order, the lower nonlithophysal, lower lithophysal, middle nonlithophysal, and upper lithophysal zones. Lithophysal cavities, generally 1-3 cm in diameter, formed during early stages of ash-flow tuff crystallization. The cavities increase the bulk porosity of the rock and, in the proposed repository area, may influence the thermal response, stability, and hydrologic characteristics of the rock mass.

Rock exposed at the drill collar of a horizontal hole UE25-H1, continuously cored in a westerly direction, is the middle nonlithophysal zone and contains few lithophysae (Norris et al., 1986). The proposed repository would be excavated in rock lower in the section, but which has similar physical and structural characteristics.

Above the drill pad, lithophysae increase progressively. At Fran Ridge, the lithophysae-rich rock, about 11 m thick, is referred to as the upper lithophysal zone. Volumetric estimates of lithophysal cavities, derived from coreholes along a north-south section through the proposed repository, suggest that most rock within the upper lithophysal zone consistently contains between 20 percent and 30 percent lithophysal cavities.

Up slope, the uppermost depositional unit, a quartz latite caprock forms a conspicuous bench; it typically contains abundant phenocrysts (5 percent near the base to about 15 percent near the top).

STRUCTURAL CHARACTERISTICS, Faults: The western flank of Fran Ridge is cut by the Paintbrush Canyon-Fran Ridge fault zone, one of the longest Quaternary fault zones in the site area. The Paintbrush Canyon fault merges with the

Fran Ridge fault along the western edge of Fran Ridge, and may extend northward to the southern boundary of the Timber Mountain caldera and southward to the Stagecoach Road fault, directly south of Busted Butte (fig. 3). If the Paintbrush Canyon-Fran Ridge fault zone connects with the Stagecoach Road fault, their combined length would exceed 30 km. The Paintbrush Canyon fault displaces Miocene strata almost 400 m at the northern end of Fran Ridge. West dipping strata have been mapped between the Paintbrush Canyon and Fran Ridge fault planes (Scott and Bonk, 1984). Detailed mapping elsewhere in the area suggests that west-dipping strata are common within major north-trending fault zones (Scott and Bonk, 1984). The conspicuous fault "busting" the center of Busted Butte probably is a splay of the Paintbrush Canyon fault.

Fractures: Surface studies of hydraulically cleared outcrops, between 200 and 300 m^2 in size, reveal two-dimensional patterns of complexly anastomosing, steeply dipping fractures in welded units of the Tiva Canyon and Topopah Spring Members (Barton and Larsen, 1985). A hydraulically cleared outcrop, at the southern end of Fran Ridge, displays a two-dimensional fracture system in the middle nonlithophysal zone of the Topopah Spring Member (Barton and Hsieh, 1989). Fractures over 2 m in length are preferentially oriented north-northwest and dip westward. This information and the abundance of moderately dipping fractures in core from the 120 m horizontal core hole UE25-H1 (Norris et al., 1986), suggest that the attitude of the fracture system in the middle nonlithophysal zone at Fran Ridge coincides with the attitude of mapped faults in the immediate vicinity (Scott and Bonk, 1984).

Vertical variations of fracture density in core samples have been estimated by calculating fracture densities for a unit volume of 1 m^3 (Scott et al., 1983). Most fractures occur in the moderately to densely welded section of the Topopah Spring Spring Member, where 28 to 42 fractures per m^3 were estimated in core holes USW G-4 and USW GU-3/G-3, within or near the proposed repository area (Spengler and Chornack, 1984; Scott and Castellanos, 1984). Fracture density in nonwelded to partially welded zones below the Topopah Spring rarely exceeds 4 fractures per m^3.

Within the upper part of the Topopah Spring Member, most fracture surfaces are uncoated or partially coated with silica; calcite is locally abundant. In the lower Topopah Spring Member, zeolites and minor amounts of manganese oxides partially coat fractures. Coatings of zeolites and manganese and/or iron oxide minerals are prevalent along fracture surfaces in the underlying tuffaceous beds of Calico Hills and the Crater Flat Tuff. Below the Crater Flat Tuff, most fractures are filled with calcite, clay, and zeolite minerals. Fracture fillings, as much as 1 to 5 mm thick, rarely cover the entire fracture surface in core samples of units within the Paintbrush Tuff. However, in stratigraphic units below the Topopah Spring, fillings appear to have completely resealed many (20 percent to 80 percent) of the fractures (Spengler and Chornack, 1984).

Stop 12, CREST OF YUCCA MOUNTAIN, THE POST-ERUPTION HISTORY OF YUCCA MOUNTAIN, D.T. Vaniman[2].

The history of alteration and of possible past variations in fluid flux, transport directions, and transport mechanisms is partially recorded in the post-eruption mineralogic and petrologic features of tuff at Yucca Mountain. The petrologic record above the water table indicates no major alteration of the candidate host rock since ~11.5 Ma. Some fracture minerals (e.g., calcite and clays) at relatively shallow depths indicate a small amount of ongoing transport and deposition, in at least the uppermost part of the tuff sequence.

The major alteration observed in the unsaturated tuff below the potential repository horizon is zeolitization of glasses within 80 to 200 m above the present water table (the bottom of the vitric zone in fig. 4). This zeolitization occurred before 11.6 Ma, based on the pre-Timber Mountain age of tectonic tilting recorded by geopetal features of tuff that formed toward the end of major zeolitization. The last major alteration below the water table occurred at 11 Ma (based on K-Ar illite determinations; Aronson and Bish, 1987) when a hydrothermal system developed during waning stages of volcanism in the nearby Timber Mountain caldera.

Exceptions to these predominantly middle- to late-Miocene alteration ages appear to be few. Relatively young calcite (perhaps 26 to 310 ka) occurs in fractures 34 to 330 m deep in or near the exploration block at Yucca Mountain (uranium-series ages by Szabo and Kyser, 1985). Other fracture mineral ages are poorly constrained.

The stratified layers of devitrified (mostly quartz plus feldspar) and nonwelded (mostly glass or zeolite) tuff beneath the proposed host rock are the major coarse-scale mineralogic variability at Yucca Mountain (fig. 4). Clinoptilolite is the most abundant zeolite. There are subordinate amounts of mordenite. As noted above, the highest zone of pervasive zeolitization is about 80 to 200 m above the present water table. This is also the elevation above which porous glass (in nonwelded and unaltered glassy tuff) is preserved. This glass would be mostly dissolved or altered if it were beneath the water table. Paleo-lake shorelines (and/or paleo-marshes, see Stop 8) in the Amargosa Valley support a past rise in water table of about 80 m beneath Yucca Mountain (W. Dudley, written commun., 1988). The top of the pervasive zeolitized zone II in Figure 4 may be close to the maximum sustained rise in paleo-water table beneath Yucca Mountain.

Stop 13a, OVERVIEW OF STRATIGRAPHY, STRUCTURE, AND TECTONICS FROM THE CREST OF YUCCA MOUNTAIN, R.W. Spengler[5] and K.F. Fox, Jr.[5].

Yucca Mountain reaches an elevation of 1,800 m, at the Prow, directly north of us. The mountain is bordered on the west, south, and east by the broad intermontane alluvial basins of Crater Flat, Amargosa Desert, and Jackass Flats, respectively, and they range from 800 to 1,200 m in altitude.

The crest of Yucca Mountain is near the western edge of the proposed repository block (fig. 3). Bedrock within the proposed repository area, as well as, in the surrounding site specific geologic investigations area (fig. 3) consists of Miocene tuff and lavas that in places exceeds 2.5 km in thickness. An unsaturated lithologic sequence of welded ash-flow tuff underlain by nonwelded zeolitic ash-flow and bedded tuff dominates the more than 500 m of rock above the static water level. These unsaturated rocks may provide natural barriers to radionuclide migration.

STRATIGRAPHY: Sedimentary strata exposed outside the area of site specific geologic investigations comprise late Proterozoic and Paleozoic (600 to 300 Ma) limestone, dolomite, shale, argillite, and quartzite (Waddell et al., 1984). The most extensive exposure of a nearly complete north-dipping sequence of Paleozoic rocks flanks Crater Flat directly westward at Bare Mountain; outcrops of Paleozoic rock also occur to the east at the Calico Hills, and about 10 km to the southeast at Striped Hills.

Drill hole UE-25p#1, west of Fran Ridge, and about 3 km southeast of Stop 13, provides the only direct subsurface information about the distribution of Paleozoic rocks beneath the the site area. At this locality, dolomite was encountered at depths from 1,240 m to 1,807 m (Carr, M.D. et al., 1986).

Miocene Volcanic Rocks: Most of the tuff and lava underlying Yucca Mountain erupted between 14 and 11 Ma (Byers et al., 1976b) from sources associated with the Timber Mountain-Oasis Valley caldera complex, immediately north (fig. 1 and 3) of the site specific geologic investigation area. Chocolate Mountain, the high peak to the north, consists of caprock lithology of the Tiva Canyon Member of the Paintbrush Tuff and is within the Claim Canyon cauldron segment of the caldera complex. The volcanic rocks are 1.25 km thick at the western edge of Fran Ridge (Carr, M.D. et al., 1986). They thicken to at least 1.8 km beneath Stop 13 and to the north (Spengler et al., 1981; Scott and Castellanos, 1984). The rocks are probably as much as 3.2 km thick beneath central Crater Flat (Snyder and Carr, 1984; Ackermann et al., 1988; and Hoffman and Mooney, 1984). The volcanic section thins significantly southward, toward the Amargosa Desert (Carr, M.D. et al., 1986).

The sequence of rocks underlying Yucca Mountain mostly comprises rhyolitic ash-flow tuff intercalated with thin beds of volcaniclastic rock. The ash-flow tuff consist of an alternating sequence of nonwelded to densely welded rock.

Major stratigraphic units are continuous across most of the site area. As observed at Fran Ridge (Stop 11), rocks in the upper half of the section (the Paintbrush Tuff) are mostly densely welded. Rocks in the lower part of the volcanic section (Lithic Ridge Tuff; Tram, Bullfrog, and Prow Pass Members of the Crater Flat Tuff; and tuffaceous beds of Calico hills) are typically porous partially welded tuff, that have been pervasively altered to clay and zeolite.

The tuffaceous beds of Calico Hills and the upper part of the Prow Pass Member are more than half of the 100 to 300 m interval between the proposed level of the proposed repository drifts and the static water level (Waddell et al., 1984). Both units contain abundant zeolites that may influence rock permeability and sorptive capacity. Therefore, they may be an important natural barrier to the migration of some radionuclides (Broxton et al., 1987). This interval appears to form a continuous blanket of zeolite-rich rock beneath the northeastern half of the proposed repository site. However, the tuffaceous beds of Calico Hills are mostly vitric tuff beneath the southwestern half of the proposed repository site, whereas, rhyolite lava occurs to the northeast of the proposed repository.

STRUCTURE, Faults between the Paleozoic and Miocene Sections: Low-angle extensional faults that partly separate the Paleozoic and Miocene rocks are recognized at two localities within 20 km of this stop: at the northern end of Bare Mountain (Carr and Monsen, 1988) and in the central Calico Hills (Simonds and Scott, 1987).

At Calico Hills, discontinuously exposed low-angle faults have been mapped in the Paleozoic sequence, in the Miocene sequence, and between the two sections (Maldonado, 1985). These exposed faults appear to be part of an anastomosing network of interconnected low-angle extensional features that coincide crudely with the contact between Paleozoic and Miocene sequences (Simonds and Scott, 1987). A fault between the Paleozoic and Miocene sections has also been inferred within the site area in drill hole UE-25p#1 (Carr, M.D. et al., 1986). However, the attitude of this fault is uncertain.

Faults in the Miocene Volcanic Section: Volcanic strata at Yucca Mountain area series of fault-bounded blocks 1 to 4 km wide. The central block of Yucca Mountain, which includes the proposed repository area, is tilted 5° to 10° eastward. Like many structural blocks at Yucca Mountain, the central block is elongate north-south and bounded by westward dipping high-angle faults (Scott and Bonk, 1984). Structural complexities increase to the south and east of the central block, where faults tend to increase in abundance and amount of displacement. Major faults offset strata (100 to 200 m) vertically; however, Solitario and Paintbrush Canyon faults segments displace strata more than 400 m (Carr, 1984; fig. 3). The dip of strata increases as much as 20° south and east of the proposed repository (Scott and Bonk, 1984; Scott and Rosenbaum, 1986).

Faults along the western edges of major blocks form highly brecciated zones as wide as 500 m. In addition to overturned blocks that are several hundreds of meters in size, these fault zones commonly enclose west-dipping strata, as mapped along the Paintbrush Canyon-Fran Ridge and Solitario fault zones (Scott and Bonk, 1984). The western parts of blocks are relatively intact; however, internally, blocks grade eastward to broken zones characterized by abundant subparallel, west-side-down, west-dipping faults (Scott and Bonk, 1984; Spengler and Fox, in press). Individual faults in the broken zones displace strata only a few meters; however, a characteristic feature of these zones is that the dip of strata between the faults progressively steepens eastward toward the extreme eastern edges of broken zones (Scott and Bonk, 1984).

Paleomagnetic studies, in conjunction with field mapping, indicate the southern end of Yucca Mountain has been rotated about 30° clockwise, relative to the northern about 25 km away (Scott and Rosenbaum, 1986). North to south, broken zones appear to increase in width at the expense of intact parts of blocks, possibly indicating that deeper structural levels are exposed toward the southern part of Yucca Mountain.

Broken zones are absent in areas north of the proposed repository, where a change in structural style occurs. In this area, all rock units dip 5° southeastward and several faults, coincident with northwest-trending drainages, show evidence of strike-slip movement. Lateral displacement along these faults is uncertain, but is probably minor as inferred from little or no apparent offset of upper stratigraphic units.

Geometry of structures in the Miocene Volcanic rocks: Tectonic models to explain the near-surface geometry of Yucca Mountain structures include the basic modes of extension in extensional terranes outlined by Wernicke and Burchfiel (1982). These modes are 1) extension by rotational planar normal faulting (Carr, M.D. et al., 1986), 2) imbricate listric (concave upward) normal faulting with reverse drag (Scott et al., 1983), 3) listric normal fault bounding a series of planar fault blocks (Scott and Bonk, 1984).

Cross sections, constructed by Scott and Bonk (1984) show major block-bounding fault zones as two subparallel, curvilinear fault planes enclosing west-dipping strata that are similar to western Colorado Plateau structures described by Hamblin (1965); however, the numerous west-side-down faults within broken zones have been interpreted (Scott and Bonk, 1984) as more steeply dipping planar features that terminate against the major curvilinear block-bounding structures.

Many structural elements of the extensional fault model described by Hamblin (1965) and the clay model experiments by Cloos (1968) on the development of "down-to-basin" faults in the Gulf coast region appear remarkably similar to structural elements currently recognized in the volcanic section at Yucca Mountain. In general, these similarities include 1) evidence of reverse drag flexures and subparallel west-dipping curvilinear block-bounding fault planes; 2) abundant west-dipping subparallel faults with progressive eastward increase in strata rotation, presumably to accommodate eastward increase in the reverse drag flexure; 3) increase in the abundance of west-dipping subparallel faults at deeper structural levels, and 4) appearance of a horst and graben pattern, possibly indicating the western edge of each reverse drag flexure.

These similarities support the hypothesis that major high-angle block-bounding faults and broken zones at Yucca Mountain form listric geometries at depth (Scott, 1986; Spengler and Fox, in press).

TECTONICS: At the previously described localities (Stops 6 and 7) where Late Proterozoic and Paleozoic rocks are exposed, and presumably below Yucca Mountain, the basement rocks consist of imbricated thrust sheets, stacked during one or more episodes of Mesozoic thrust faulting. These rocks were buried in late Oligocene and early Miocene intermontane basins by thick deposits of siltstone, claystone, fresh-water limestone, tuff, and conglomerate, and finally buried by the silicic ash-flows and intercalated bedded tuff, directly beneath us. This sequence and the underlying basement rock were faulted during a catastrophic episode of crustal extension that culminated during or shortly after eruption of 14 to 11 Ma tuff and 10 Ma basalt flows, which locally cap the tuff. Study of the geomorphic evolution of the Amargosa River (which flows southward through the Amargosa Desert south of our vantage point) and Fortymile Wash (east of Yucca Mountain) suggests that the distribution and structural geometry of geologic formations, at Yucca Mountain and its immediate vicinity and perhaps even much of the landscape, were established in approximately their present form by about that time (Huber, 1987).

Many of the faults that formed during middle and the late Miocene have also been active in the Pleistocene and even the Holocene. These faults include the north-trending Windy Wash, Fatigue Wash, and Solitario Canyon faults to the west, the Bow Ridge and Paintbrush Canyon faults to the east, and the northeast-trending Stagecoach Road fault to the southeast (fig. 3).

The Windy Wash fault, 4 km west, is marked by a west-facing scarp that locally reaches 4 m in height (Swadley et al., 1984). The fault exhibits, through progressive offset of surficial deposits, at least seven episodes of movement during the Quaternary, including four within the last 0.3 Ma (Whitney et al., 1986). The most recent movement displaced a 3.5 to 6.5 ka silt deposit less than 10 cm (Whitney et al., 1986).

The Solitario Canyon fault, flanking the west side of Yucca Mountain at Stop 13, and the Bow Ridge fault (Stop 16) on the east side of Yucca Mountain are of special interest, because trenches expose fissure-filled calcium carbonate and silica veins deposited in the fault zone. The vein in the Solitario Canyon fault zone is a wedge-shaped body, thinly layered to laminated, tapering downward from a thickness of about 2 m near the surface, to about 1 m at a depth of 2 m. At the Bow Ridge fault, steeply dipping, upwardly bifurcating veins are filled by carbonate-silica deposits, as are low-angle veins which intersect them. The vein material is conspicuously laminated parallel to vein walls, indicating repeated opening and filling of the fissures (Taylor and Huckins, 1986).

One or more episodes of ground breakage and fault dilation is also recorded along segments of the Windy Wash (Fault M of Swadley et al., 1984), Solitario Canyon, and Bow Ridge faults by a fissure within the fault zone that is filled with uncemented, reworked black volcanic ash. The ash is chemically and petrographically similar to the basaltic ashes erupted approximately 1.2 Ma at the cones in Crater Flat (Vaniman et al., 1982), and also to the much younger basaltic ash at Lathrop Wells center that apparently formed in several eruptive stages during the late Pleistocene and Holocene (Crowe et al., 1988).

The north-trending Quaternary faults at Yucca Mountain have been postulated to be listric normal faults that flatten at depth and merge with a detachment fault, forming the contact between the volcanic and volcaniclastic strata of Yucca Mountain and subjacent Paleozoic rocks, or possibly with other detachment faults within the basement rock (Scott, 1986). As yet, the Quaternary movement on the detachment fault(s), which is implied by this hypothesis, has been neither demonstrated nor refuted.

Stop 13b, BASALTIC VOLCANISM, Bruce M. Crowe[3].

Pliocene and Quaternary basaltic volcanic rocks are exposed west of Yucca Mountain, in Crater Flat. Vaniman et al. (1982) divided these rocks into three episodes including 1) 3.7 Ma basalt cropping out in the southeast side of Crater Flat, 2) a series of four 1.2 Ma volcanic centers extending across Crater Flat, and 3) the Lathrop Wells volcanic center described previously (Stop 10).

The 3.7 Ma basalt of Crater Flat occur as deeply dissected scoria cones and associated lava flows (fig. 3) and as more extensive lava flows with no recognized scoria vents (southeast Crater Flat). The deposits retain no original scoria cone slopes; they are preserved only where onlapped by lava flows or where feeder dikes have preserved the erosional resistance of the deposits. Dike trends are radial and concentric adjacent to original scoria vents. Away from vents, dikes trend north-northeast, parallel to faults in Yucca Mountain. Erosion highly modified lava flows and modified all topography created by flow fronts and primary flow features. Aeromagnetic data are interpreted to indicate that the 3.7 Ma lavas are not continuous in subsurface; they probably formed at and adjacent to surface scoria cones, similar to other the Quaternary basalt centers. Basalt flows, dated 3.7 Ma and encountered at shallow depth in drill hole VH-1 just north of the outcrop area of the 3.7 Ma basalt, are moderately porphyritic; total phenocryst content ranges from 12 to 20 modal percent. Olivine (Fo_{80-75}) is the major phenocryst phase with lesser amounts of plagioclase (An_{82-68}), clinopyroxene and iron-titanium oxides (Vaniman et al., 1982). Phlogopite is present in the groundmass of basalt and as a vein-fill in dike rocks. All measured 3.7 Ma basalt outcrops have reversed magnetic polarity.

The 1.2 Ma basalts include, northeast to southwest, northernmost cone (not visible from Yucca Mountain), Black Cone, Red Cone, and Little Cones. Each center comprises a partially dissected main scoria cone, several satellite scoria cones, and multiple aa flows. K-Ar ages for the centers average about 1.2 Ma (Vaniman et al., 1982). However, preliminary field studies of Little Cones, Red Cone, and Black Cone centers indicate that each center exhibits multiple time-separate volcanic events. Their eruptive history is probably similar to the polycyclic patterns of the Lathrop Wells volcanic center (Stop 10).

Wells et al. (1988) described scoria cone geomorphology of Crater Flat and noted the cones have geomorphic features comparable to Cima volcanic field cones, dated at about 1 Ma. Red Cone and Black Cone have summit craters filled with coarse spatter that mantles the inward dipping crater walls. Aa flow fronts from the centers are well preserved; erosion has completely modified primary flow surface topography. The northernmost center is significantly more erosionally incised than the other centers. Scoria deposits are only locally preserved and alluvial deposits have onlapped the lava flow fronts. Basalts of the 1.2 Ma eruptive event are aphyric to sparsely porphyritic; olivine is the main phenocryst mineral (Fo_{77-62}) and plagioclase is a microphenocryst mineral (An_{70} and greater) (Vaniman et al., 1982). All measured basalt outcrops have reversed magnetic polarity.

MINERAL AND ENERGY RESOURCES OF THE YUCCA MOUNTAIN REGION, S.R. Mattson[1].

Mineral and energy resources will be assessed to evaluate the potential for inadvertent human intrusion or interference with functioning of a high-level nuclear waste repository. The possible occurrence of natural resources that could attract human activity (i.e., mining or drilling) now or in the foreseeable future must be evaluated during site characterization to determine if human activity could lead to a loss in waste isolation. A key feature for resource evaluation is comparison of the surrounding area with the site to determine if the Yucca Mountain site would have a real or perceived mineral resource potential.

Mineral Resources: There are over 182 drillholes and 23 trenches within 10 km of the site. Numerous mapping projects have covered the area, and the portion on BLM land has been open for exploration until recently. During these activities no mineral resources, except zeolites, of possible industrial potential, have been identified. The abundant zeolites at Yucca Mountain are not considered economically important now or in the future. Trillions of tons of zeolites occur in playa lakes and volcaniclastic sediments that would likely be mined before bedrock sources became economically important (DOE, 1988). Continuing mineral resource evaluation includes geochemical analyses for elements for which no analyses currently exist (e.g., Hg) and for elements for which only limited data are available (e.g., Au) (DOE, 1988). For example, 106 analyses are available for gold that exhibit concentrations at, near, or below crustal average (0.004 ppm) with a single reported exception of 0.06 ($\pm$ 15 percent) ppm gold from drillhole USW G-2 (515 m deep) (Mattson, 1988). More than 200 additional analyses performed for land withdrawal should be available from the Nevada Bureau of Mines and Geology by the time of this field trip.

Joint mining (Sterling Mine and Mother Lode property) is operating in the area, approximately 13 km and greater from the site, on the eastern flank and interior of Bare Mountain, in a host of thrusted Paleozoic siltstone and dolomites. Open-pit/underground gold mines, heap-leach pad, and a tailings pile are visible from the top of Yucca Mountain. In 1980, the Sterling Mine was estimated to have produced 500,000 tons, with an average grade of 0.25

oz/t gold (Bonham, 1984) and unreported reserves; the new Mother Lode property has sulfide reserves of 1.6 million tons of 0.049 oz/t Au and 3.3 million tons of 0.057 oz/t Au (Lockard, written commun., 1989). The Bond Gold Bullfrog and Montgomery-Shoshone deposits, 3.3 km west of Beatty, Nevada with reserves of 17.4 million tons of 0.103 oz/t Au and 0.240 oz/t Ag (Jorgensen et al., 1989a, 1989b), began operations in late 1988. These deposits are in highly altered ash-flow units of the same age as those in the Yucca Mountain area. Additional deposits may exist in the Bare Mountain Paleozoic rocks or at depth in the Paleozoic rocks in the region beneath the sedimentary cover and volcanics. Paleozoic rocks underlie the Yucca Mountain site but are probably deeper than 3.0 km.

Historical mine sites include the Silicon Mine (silica source from 1918-1929), in northwestern Yucca Mountain; the Thompson Mine, in northwestern Yucca Mountain; the Tip Top Mine, at Bare Mountain; the Telluride or Harvey Mine (all with less than 100 flasks of mercury production), at Bare Mountain; and fluorspar production at the Daisy Mine and other localities at Bare Mountain (DOE, 1988). The Daisy Mine was the largest fluorspar producer in Nevada (Smith et al., 1983). In addition to these historical mining sites, several exploratory pits and workings are known in Crater Flat, Frenchman Flat, and the Calico Hills, all with no known production. The Horn Silver Mine, more than 20 km to the northeast, produced gold in the 1920s to 1930s. Industrial minerals are mined south of Yucca Mountain, at the Lathrop Wells cinder cone (Stop 10), where volcanic cinders and pumice are mined for aggregate in foundation block and decorative cover in the Las Vegas area (DOE, 1988).

Geothermal Resources: Down-hole temperatures at Yucca Mountain (19 wells) vary from a low of 21°C (102 m) to a high of 65°C (1,006 m) (Garside and Schilling, 1979; Trexler et al., 1979; Benson and McKinley, 1985; Sass et al., 1988). Heat flow in the region around Yucca Mountain varies from 0.6 to 3.1 HFU (Heat Flow Units) (Sass et al., 1980; Sass and Lachenbruch, 1982). Heat flow determinations at Yucca Mountain consist of four values: 1.25, 1.1, 1.3 and 1.6 HFU (average 1.3 HFU) (Sass et al., 1980; Sass et al., 1988), and are demonstrably low compared to the Nevada average (2.0 HFU). Regional Geothermal resources are considered low-temperature (<90°C) and of limited economic use (DOE, 1988). Further down-hole temperature measurements, temperature gradient information, heat flow determinations, and geochemical work are planned during site characterization to 1) assess the presence of geothermal resource potential and 2) to assess the causes of local variations observed in heat flow determinations over short lateral distances.

Oil and Gas Resources: No known oil or gas fields are in the Death Valley region (Bedinger et al., 1984) or southern Nye County, despite the drilling of some 60 unsuccessful exploration holes (Brady, 1984a, 1984b). At Yucca Mountain the Paleozoic rocks are deeper than approximately 3.0 km below most of the repository area and have likely passed the thermal maturity to produce oil and gas (DOE, 1988). However, further evaluation is planned during site characterization because of the following: 1) In central Nevada the Railroad Valley field contains the largest producing well in the continental United States (4,000 barrels a day; Fritz, 1987) and wells have produced oil from ash-flow tuff in central Nevada (Garside et al., 1977), 2) Although most Paleozoic rocks in the Yucca Mountain region are known to be past the gas producing maturity as determined from Conodont Alteration Index (CAI) data (Harris et al., 1980), new CAI data from a drillhole (UE-25p#1) revealed a CAI of 3 (140° to 180°C) in the gas producing range (Carr, M.D. et al., 1986). The drillhole is 3 km from the candidate site and penetrated Silurian rocks at a depth of 1.2 km. It is planned to assess site oil and gas resource potential, including new maturation data; geochemistry and organic geochemistry data; and to assess possible source rocks, reservoir rocks, and structural traps and seals (DOE, 1988).

Stop 14, SATURATED AND UNSATURATED ZONE HYDROGEOLOGY: Characterization of Unsaturated-Zone Infiltration, Alan L. Flint[1,2].

Objectives of the unsaturated-zone infiltration studies at Yucca Mountain are 1) to determine the effective hydraulic conductivity, storage properties, and transport properties as a function of moisture content or potential, and 2) to determine the present and estimate the future spatial distribution of infiltration rates of surficial materials covering Yucca Mountain. Four activities are planned to collect the required data for these objectives: laboratory analysis of matrix hydrologic properties, evaluation of natural infiltration, characterization of hydrologic properties of surficial materials, and artificial infiltration studies.

Analysis of matrix hydrologic properties is designed to support unsaturated-zone infiltration studies and vertical boreholes studies. The objectives are 1) to characterize the flux-related matrix hydrologic properties of major unsaturated-zone hydrogeologic units through laboratory testing of geologic samples from near-surface boreholes and excavations, and from boreholes drilled in the exploratory shaft, and 2) to use statistical and geostatistical methods to calculate, with known uncertainties, the values of flux-related matrix hydrologic properties in the rock beneath Yucca Mountain. The geostatistical methods will consist of a three-dimensional multivariate analysis using a variety of kriging techniques (e.g., simple kriging, cokriging, disjunctive kriging, and universal kriging) to estimate hydrologic properties and state variables at specific points or blocks, depending on the specific needs of the finite element or finite difference flow models.

The calculation of natural infiltration is to characterize the upper flux boundary condition for Yucca Mountain under present climatic conditions in order to model flow through the thick unsaturated-zone beneath Yucca Mountain. Four major studies will determine boundary conditions. Neutron access holes studies will monitor natural infiltration in about 100 shallow bore holes. Studies using artificial-infiltration control plots will monitor natural infiltration in major surficial hydrogeologic units. These plots will be instrumented to automatically monitor water content and water potentials using a variety of instrumentation (e.g., tensiometers, psychrometers, time domain reflectometers, and heat-dissipation probes). Tritium profiling studies will determine flow velocities averaged over approximately the last 35 years by analyzing tritium produced by nuclear-weapons testing. Water budget studies will calculate net infiltration by mass balance methods, will use intensive meteorological measurements of energy balance components and direct measurements of evapotranspiration.

Methods designed to characterize the hydrologic properties of surficial materials include sampling, testing, and mapping; remote sensing; nuclear borehole geophysical logging; shallow surface seismic exploration; and geotomography studies. The main purpose of these tests is to help characterize the infiltration-related hydrologic properties of the surficial materials of Yucca Mountain. Surficial hydrogeologic units and geostatistical analysis will then be used to model infiltration processes on Yucca Mountain.

Artificial infiltration tests will be conducted on surficial materials covering Yucca Mountain to characterize near-surface water movement. Water fluxes, flow velocities and flow pathways will be characterized in the major hydrogeologic surficial units. The main purpose of these tests is to determine the upper flux boundary conditions for Yucca Mountain under present and simulated wetter climatic conditions. A series of different types of artificial infiltration studies is proposed; portable infiltrometer studies, ponding studies, and rainfall-simulation studies where each type of study increases in complexity and builds on the results of previous studies.

Site Vertical Boreholes - Unsaturated Zone Percolation, J. P. Rousseau[5].

Seventeen vertical boreholes will be drilled from the surface of Yucca Mountain through the repository block and into the underlying Calico Hills unit and will terminate at the water table. These boreholes will be used to test various hypothetical models of fluid flow in the unsaturated zone as presented by Montazer and Wilson (1984). Drilling will provide access to (1) define structure and stratigraphy of rocks penetrated; (2) characterize the spatial variability of the hydrologic and geologic properties associated with each geohydrologic unit; (3) recover core and drill-bit cuttings for laboratory measurement of hydrologic and physical properties of the rock matrix; (4) determine saturation of each geohydrologic unit as a function of depth; (5) perform in situ pneumatic and hydraulic tests to evaluate bulk permeability of the combined matrix and fracture system; (6) recover matrix pore-water and in situ gases for age dating and hydrochemical analysis; (7) measure and monitor in situ, the potential field in which unsaturated flow occurs; (8) visually observe and record the density and orientation of fractures with depth; (9) evaluate tracer travel times using gas-tracer tests; and (10) conduct geophysical logging.

An important component of the borehole drilling program is the in situ measurements of fluid flow potential. Each borehole will be permanently instrumented with sensors designed to measure and monitor the various components (liquid, gas, vapor) of the total-fluid potential field. In situ instrumentation and stemming provide a means of (1) evaluating the dynamic stability of each component of the total-fluid potential field, (2) measuring those components of the total-fluid potential field that incorporate the contributions of larger-scale heterogeneities and anisotropies of the conductive media than is possible from core analysis alone, (3) isolating discrete rock intervals to characterize potentials associated with abrupt physical changes in rock conductive properties (i.e., joints, faults, shear zones, and fractures versus matrix), features that may not be conducive to physical sampling and laboratory tests, (4) isolating and containing mobile pore gases and water vapor for subsequent sampling and hydrochemical analysis without excessive mixing and contamination in the borehole, (5) evaluating the effects of diurnal and seasonal variations in surface temperature and pressure with depth, and (6) tracking the downward propagation of recharge resulting from individual storms. This monitoring program will have an estimated duration of three to five years.

Gaseous Phase Flow And Transport Through Yucca Mountain, R. C. Trautz[5] and E. P. Weeks[5].

Because the proposed nuclear waste repository would be in the unsaturated zone, the potential exists for radionuclide release to the environment through air-filled voids, particularly fractures. Topographic and barometric effects are observed when wells UZ6 and UZ6S are open to the atmosphere. Three mechanisms for air and water vapor circulation through Yucca Mountain have been proposed by United States Geological Survey researchers: (1) air flow, due to density differences created by geothermal gradients in thick fractured units (Montazer and Wilson, 1984); (2) topographically induced air (Weeks, 1987); and (3) barometric pumping (Weeks, 1987). The topographic effect occurs when an area has substantial topographic relief, such as Yucca Mountain. The column of air extending from a fractured-rock outcrop on the side of the mountain to its crest will be colder, drier, and therefore more dense during cold weather than the column of air within the mountain between the crest and the outcrop elevation. The warmer, less dense, formation air will tend to rise to the crest of the mountain while cooler, denser air enters along the mountain flanks. The airflow reverses direction in summer, when atmospheric air is warmer than formation air. When air pressure in the mountain lags behind changing atmospheric pressure, the topographic effect is superimposed upon the barometric effect; therefore a pressure gradient forms that causes formation gas to flow. It is believed that such air flow will occur throughout the mountain. Gas-injection tests at several locations will characterize fracture permeability and storativity of the hydrologic units. These data may be used to model air flow throughout the mountain for both natural and repository conditions.

Regional And Local Flow Systems Near Yucca Mountain, Nevada, J. B. Czarnecki[5] and R. R. Luckey[5].

Yucca Mountain overlies a ground-water subbasin extending from about the edge of the Timber Mountain caldera (about 30 km from the design repository area) in the north, to a ground-water divide between Fortymile Wash and Ash Meadows in the east, to Eagle Mountain to the south, and to the Funeral Mountains and Greenwater Range to the west. Water may flow across subbasin boundaries, especially along the northern boundary. Water levels within the subbasin range from more than 1,100 m above sea level north of Yucca Mountain to about 600 m near the south end at Franklin Lake playa. Subbasin ground-water flow is generally north to south. Within this subbasin, water flows in alluvium, tuff, and carbonate rocks of Tertiary age and younger.

Sources of inflow to the subbasin are thought to be: under flow derived from recharge on Pahute and Rainier Mesas, under flow from the northwestern edge of the Amargosa Desert, periodic flooding along Fortymile Wash and the Amargosa River, and possibly precipitation on the Funeral Mountains and Greenwater Range. Minor recharge from precipitation is believed to occur elsewhere in the subbasin, including Yucca Mountain. Discharge occurs primarily as evapotranspiration at Franklin Lake playa, where depths to water are less than 3 m and upward hydraulic gradients are as much as 1.6. Evapotranspiration rates at the playa are estimated to range from 1 to 3 mm per day.

Earlier conceptual models of subbasin flow included spring discharge near Furnace Creek Ranch in Death Valley. A refined conceptual model now attributes this discharge to a separate, deeper flow system in carbonate rocks of Paleozoic age (Czarnecki, 1987). This model indicates that less water flows beneath Yucca Mountain; hence, ground-water travel times are longer than in previous conceptual models.

Hydraulic-head and temperature data from deep holes in the Amargosa Desert indicate an upward gradient and possible upward leakage from an underlying carbonate aquifer of Paleozoic age.

The local flow system at Yucca Mountain is arbitrarily defined as the flow system within about 5 km of the proposed designed repository. The local system includes a large hydraulic gradient to the north where the water-level altitude changes about 300 m in less than 3 km in the vicinity of Yucca Wash, and a small gradient to the south where water level altitude changes less than 0.3 m in 3 km. The local flow system also contains a substantial change in water levels near the Solitario Canyon Fault. The water level is about 35 m higher on the west side of the fault compared to that on the east side of Yucca Mountain.

In some areas of the local flow system, there is a pronounced upward gradient. At test well UE-25 p#1, completed in the underlying Paleozoic carbonates rocks, the water level is about 22 m above that in the overlying tuff. At test well USW H-3 on the crest of Yucca Mountain, the water level in the lower tuff is about 40 m higher than that in the upper tuff. Water levels are being continuously monitored in 28 test wells completed in the local flow system. These test wells are monitored to provide data for mapping the potentiometric surface, to determine any long-term water-level cycles or trends, to determine vertical and horizontal gradients, and to obtain data to estimate flow system hydraulic properties.

Water levels at Yucca Mountain are as much as 750 m below land surface. These depths present special problems for accurately measuring water levels. Measurements must be adjusted for borehole deviation from vertical, deformation due equipment weight, and down-hole temperature. Because of the extremely small hydraulic gradient south and east of Yucca Mountain, the measurements must be accurate to determine flow direction. To estimate hydraulic properties of the flow system using barometric fluctuations and earth tides, the water-level monitoring network must provide accurate water-level data without interruption for many months.

Future work in the subbasin includes expansion of water-level monitoring network in the Amargosa Desert and Fortymile Wash. This network will include data from mining company boreholes and two new boreholes in Crater Flat drilled specifically for this study. Additional work will be done to improve estimates of ground-water discharge by evapotranspiration.

Large hydraulic gradients at the north end of Yucca Mountain and at Solitario Canyon will be further characterized through additional drilling, hydraulic testing, and geophysical surveys. Flow and chemical transport in fractured tuff will be studied by conducting hydraulic and tracer tests within test wells UE-25 c#1, UE-25 c#2, and UE-25 c#3. Data from these test wells and geohydrologic characterization activities within the regional and local flow systems will be synthesized through refinement and development of numerical models of ground water flow.

Stop 15, SURFACE FACILITIES, R.C. Murray[1], A.C. Matthusen[1], S.R. Mattson[1].

Proposed surface facilities are currently planned to be in Midway Valley. Central surface facilities will include areas for receiving and repackaging waste shipments, site operations, and general logistical support. These facilities would occupy approximately 75 acres directly eastward of Exile Hill, on a gently sloping alluvial fan area. The period of operation of the surface facilities may vary, but it will probably be 50 yrs or longer. Geologic siting criteria leading to selection of this site include surface slope (grade of 2.6%), protection from flash flooding, location of structural features such as major faults, and proximity to rock outcrops that could be used for a waste emplacement ramp portal.

Drilling and outcrop information indicate that the surface facilities site is on an alluvium wedge, the thickness of which is zero at the margins of Exile Hill to 27 m at UE-25 RF-3 (approximately 500 m eastward), to approximately 50 m on the east side of the valley at UE-25 WT-5 (Scott and Bonk, 1984). The proposed site lies above the flood zone for a predicted 100-year flood, although the northern margin is in the 500-yr flood zone for Drill Hole Wash. Flood control measures are not anticipated to present major engineering difficulties or costly additions to facility design and construction.

The main siting and design concern is damage potential from seismic activity that could result in the release of radionuclides to the accessible environment. Preliminary studies indicate the annual probability of exceeding a peak ground acceleration of 0.4 g to be $\leq$ 0.0005. Such low probability results from relatively long return periods for events on local faults and resulting low rate of regional seismicity. The site overlies an imbricate normal fault zone proposed by Scott and Bonk (1984), a north-south trending belt of closely spaced, high-angle normal faults. The offset along individual faults in this zone may be minor, but cumulative vertical displacement across the zone is believed to be on the order of 100 m. Strata within the zone have been rotated up to dips of 50° in difference to the 5° to 15° dip in Exile Hill, as evidenced by drill hole and core measurements in Midway Valley. Planned trenching studies in the proposed site area will investigate surface-fault rupture hazards; these study results will help determine the final facility location.

Stop 16, TRENCH 14, E.M. Taylor[5], J.S. Stuckless[5], and S.S. Levy[2].

Geologic investigations at Yucca Mountain, Nevada, have exposed near vertical veins containing carbonate, opaline silica, sepiolite, and fine-grained sediments in a fault intersected by Trench 14 (fig. 5). Concern arose whether these deposits were precipitated from downward-percolating water, as in a soil environment, or from ascending spring waters.

Trench 14 exposes, east to west, (1) fractured bedrock, (2) a fault zone of discrete near-vertical veins in brecciated bedrock, and (3) colluvium adjacent to the bedrock beyond the main fault zone. The north wall exposes a nonwelded tuff, stratigraphically between the 11.3 Ma Rainier Mesa Member of the Timber Mountain Tuff and the 12.6 Ma Tiva Canyon Member of the Paintbrush Tuff. On the south wall, the nonwelded tuff is absent. The brecciated Tiva Canyon bedrock has been locally recemented by both secondary carbonate and silica, especially within the main fault. The fault zone, approximately 2.5 m wide on the north wall, is characterized by prominent banded carbonate and opaline silica veins and splays into a zone with five main veins, approximately 4 m wide on the south wall. The adjacent well-cemented colluvium is sandy, with a large component of angular rock fragments. Soil formed in the colluvium has a well-developed K horizon cemented by secondary carbonate and opaline silica. The colluvium and the vein fillings are unconformably overlain by a finer grained depositional unit composed of slopewash with eolian additions.

Secondary carbonate concentrated at the bedrock-colluvial contact decreases with distance from the fault zone in Trench 14. The near vertical bands exposed in the vein fillings were precipitated from calcium- and silica-enriched water moving along fractures. A basaltic ash is present in fractures in the veins. Carbonate in fault fillings and colluvium has a microcrystalline structure. The colluvial deposit is laterally persistent, the concentration of secondary carbonate decreases with depth, and there are discrete soil horizons. Clasts within the sediments have been jacked apart by the secondary carbonate. Sepiolite has been identified in vein fillings and colluvium. A few charophytes and chrysophyte cysts have been noted in sediment samples from Trench 14. No ostracodes have been found (R. M. Forester, USGS, written commun., 1985; J. P. Bradbury, USGS, oral commun., 1985).

The vein fillings and colluvium in Trench 14 contain opal-CT and opal-A (Vaniman et al., 1988). Preliminary $^{18}O/^{16}O$ data for the opaline silica (J.R. O'Neil, USGS, written commun., 1985) are similar to values reported for low-temperature quartz. These values are also consistent with precipitation at about 15°C from water isotopically similar to ground water at the Nevada

Test Site today (Claassen, 1985). Opal-C (typical of hydrothermal veins) has not been reported.

Trench 14 exposes at least three distinct silica deposits, in addition to the vein-filling, in which calcite is a minor constituent or locally absent. These deposits include (1) drusy quartz and chalcedony lining fractures and lithophysal cavities in the Tiva Canyon bedrock (2) silica cementation of fault breccia in the Tiva Canyon bedrock, and (3) chalcedony and (or) opaline silica in the nonwelded tuff. Preliminary $^{18}O/^{16}O$ data suggest the drusy quartz probably formed at somewhat higher temperatures than the opaline silica. Although breccia cement is predominantly silica, other secondary minerals, such as calcite and sepiolite, are locally abundant.

Restriction of in situ drusy quartz to the Tiva Canyon bedrock suggests quartz formation predates fault juxtapositioning of the Tiva Canyon bedrock against the nonwelded tuff exposed in the trench walls. The matrix of the brecciated tuff contains fragments of drusy quartz and silica cement, as well as undisturbed silica cement. This indicates that there have been multiple episodes of brecciation. Age relationships among episodes of brecciation, faulting, and silica deposition have not yet been established.

Field, chemical, mineralogical, biological, petrographic, and isotopic data are consistent with a pedogenic origin for the vein fillings (Taylor and Huckins, 1986); thus, the possibility of origin by ascending waters seems quite unlikely. Sepiolite, common in pedogenic deposits (Hay and Wiggins, 1980; Callen, 1984; Hay et al., 1986), also occurs in low-temperature spring-type and playa deposits in the Amargosa Desert (Khoury et al., 1982; Hay and Stoessell, 1984). Ostracodes are indigenous to all modern springs near the NTS, and they are ubiquitous in the fossil record of springs and other shallow ground-water deposits. Chrysophyte cysts and perhaps charophytes could be introduced as windblown debris. Other eolian material, such as volcanic ash, has washed into near-vertical cracks in the Trench 14 deposit, and biological materials are known to exist in eolian materials throughout the region. Conversely, because gyrogonites (of the charophytes) float and because chrysophytes are very abundant in modern springs, sparse fossils of each could be preserved near the margin of the body of water without other aquatic organisms. The choice between these two alternatives will have to be based on detailed sampling, but at present, existence of a standing body of cold water in the vicinity of Trench 14 seems less likely.

Vertically and horizontally laminated carbonate and opaline silica deposits are common in Quaternary sediments throughout the arid and semiarid parts of the southwestern United States. Carbonate leached from the surface and upper horizons of the soil by downward percolating meteoric water subsequently precipitates in lower soil horizons at a depth controlled by soil moisture and texture (McFadden and Tinsley, 1985). Because so little carbonate is in the parent material, carbonate precipitated in the vein filling must be derived almost exclusively from eolian additions (Gile et al., 1966, 1981; Bachman and Machette, 1977). A very small contribution to the carbonate may be derived from in situ leaching of the parent material and carbonate reprecipitation. Studies elsewhere in southern Nevada have shown that rainwater can transport eolian-derived carbonate to depths of more than 3 m (Lattman and Simonberg, 1971).

Stop 17, EXPLORATORY SHAFT, E.L. Hardin[1] and S.R. Mattson[1].

The Exploratory Shaft Facility (ESF), a statutory requirement of the Nuclear Waste Policy Act (NWPA) of 1982, as amended in 1987, was considered by NWPA architects as a necessary part of site characterization, owing to intrinsic limitations of surface-based drillhole testing. As currently planned (DOE, 1988), the Yucca Mountain ESF will be two shafts connected by workings at the proposed repository level which is about 364 m deep. Drill-blast-muck methods will be used to mine each shaft, which will be lined with approximately 0.3 m of nonreinforced concrete to a depth of ~25 m below the repository level. The shaft collars for ES-1 will be approximately 218 m N50E of USW G-4 and ES-2 will be collared 91 m N75E of ES-1; both will be on the north side of Coyote Wash, near the canyon mouth. The shaft collars will therefore be above the calculated probable maximum-flood crest for the location (Fernandez et al., 1988). The two-shaft plan allows for extensive scientific work in Exploratory Shaft-1 (ES-1), concurrent with expedited penetration and development of the main test level that will use ES-2.

The stratigraphy at the location has been sampled at drillhole USW G-4, near the middle of Coyote Wash. The Tiva Canyon Member, exposed at the surface, is 43 m thick at G-4. Beneath this are about 27 m of nonwelded, bedded and ash-flow tuff, including the Yucca Mountain Member and the Pah Canyon Member of the Paintbrush Tuff. Underlying this is about 360 m of the Topopah Spring Member, consisting of partially welded and densely welded ash-flow tuff, with sub-zones containing lithophysal cavities (Stop 11). The proposed repository horizon lies in the lower nonlithophysal zone of the Topopah Spring Member. Beneath the thick vitrophyre at the base of Topopah Spring Member are tuffaceous beds of the Calico Hills consisting of about 107 m of altered nonwelded tuff with intercalated ash-flows and ash-falls. At the ESF location, the water table lies near the base of the Calico Hills unit, which has been extensively zeolitized throughout most of its thickness.

The in situ testing program in shaft ES-1 and at the main test level will address various geomechanical and hydrologic objectives, and include extensive mapping and sampling. Approximately 13,000 m of drilling is to be associated with the underground testing program. Monitoring holes will be drilled without liquid prior to shaft construction to obtain certain hydrologic and hydrochemical data under relatively undisturbed conditions. During excavation, the rock mass and the concrete liner geomechanical response will be monitored at several locations. A series of radial boreholes will be drilled from the shaft to sample and test hydrologic conditions, particularly at interfaces between welded and nonwelded units where capillary barrier effects and lateral diversion of moisture flux may be observed. A test room for monitoring will be excavated at about 183 m in a highly lithophysal portion of the Topopah Spring Member. A series of experiments using drillholes parallel to the shaft will investigate construction effects on the rock mass hydrologic characteristics.

Many geomechanical tests are planned at the main test level (DOE, 1988) including heater tests, a heated block test, a mine-by experiment, and a long-term heated room test simulating repository thermoelastic stress conditions. Geomechanical testing will investigate ground support requirements for the repository and other conditions necessary to maintain worker safety and retrievability of waste canisters for 50 yrs after emplacement. A series of in situ scaled heater tests will characterize the near-field waste canister environment for such conditions as temperature, moisture effects, and chemistry. Planned hydrologic tests include an in situ infiltration experiment, bulk permeability test, and diffusion experiment. In situ hydrologic testing objectives will characterize processes and phenomena. Long drifts at the main test level will intercept, observe, and characterize structural features such as the Ghost Dance fault to the west, Drill Hole Wash fault to the northeast (an inferred fault), and an imbricate normal fault zone to the east-southeast.

Stop 18, SAMPLE MANAGEMENT FACILITY (SMF), Donna Sinks[1], E.D. Davidson[1], and H.A. Perry[1].

The DOE operates a SMF which processes, documents, and preserves Yucca Mountain Project geologic samples to satisfy quality assurance requirements for licensing a geologic repository. In addition to management, quality assurance, and operations staff, the SMF includes the physical facility designed to process and preserve samples. A main staff responsibility is to document a sample from the time it is collected in the field, through transport, processing, analysis, storage, and archiving. The SMF restricts access to project samples so that an accurate record is made of every person who comes into contact with each sample. Samples and specimens are identified and tracked by a bar code system. Sample information is entered into a Curatorial Sample Inventory and Tracking System (CSITS), a computer data base that tracks all Project geotechnical samples and the associated records under control of the SMF.

The SMF is in Area 25 of the Nevada Test Site, about 10 km west of the potential site. There are physical facilities to handle the following: (1) shipping and receiving of geological samples and specimens of these samples; (2) processing of samples, including logging, marking, cutting, crushing, splitting, washing and drying of drill cuttings, microscopic examination of core and cuttings, photography, and packaging; (3) viewing of core and samples; (4) storage of research and archive samples, specimens, remnants, and related records; and (5) administration.

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Figure Captions

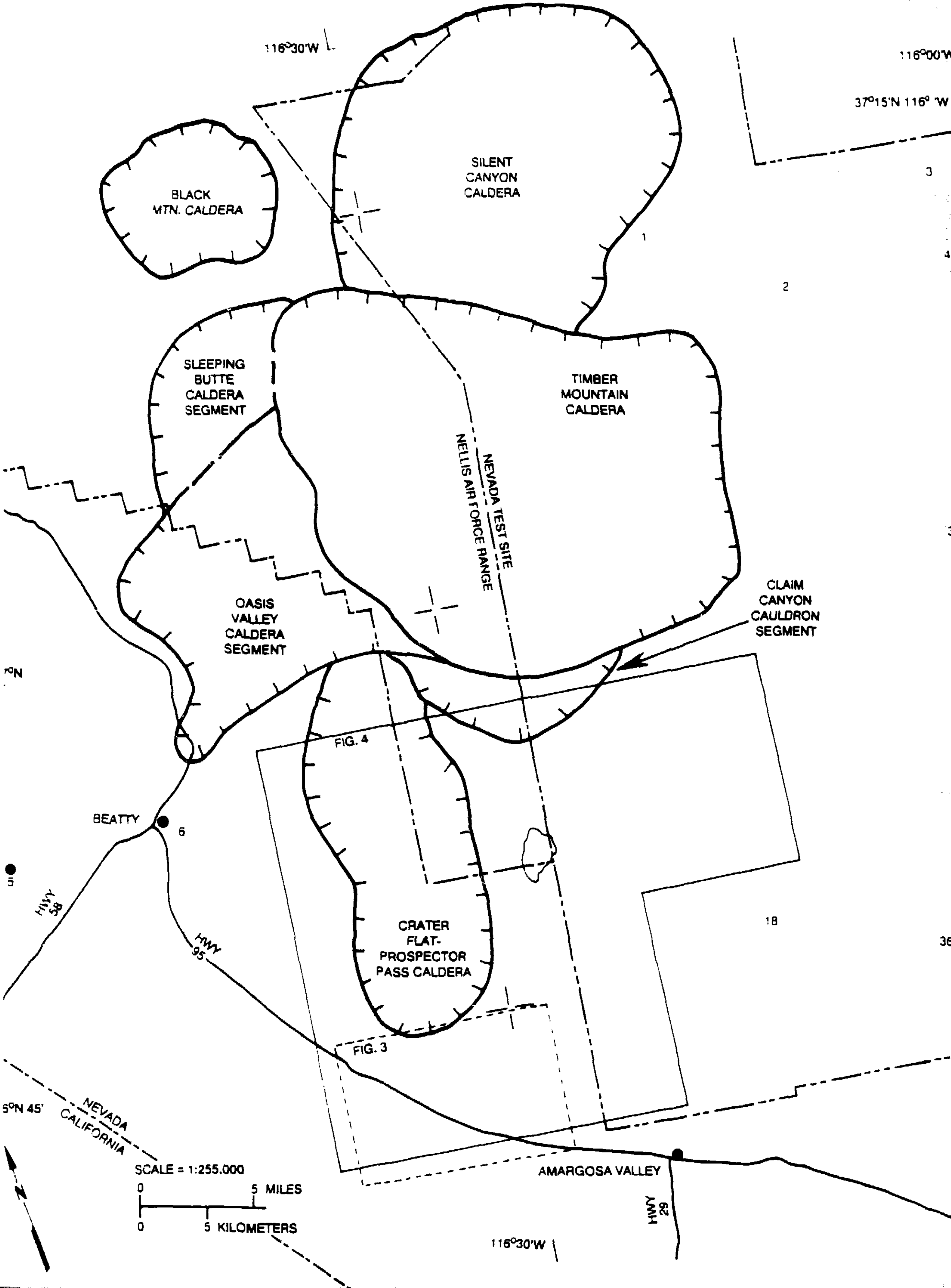
Figure 1, False color composite satellite image (infrared) of the Yucca Mountain region; TM 4 (0.76 to 0.90 μm) as red, TM 3 (0.63 to 0.69 μm) as green, and TM 2 (0.52 to 0.60 μm) as blue. Reproduced by permission of Earth Observation Satellite Company, Lanham, Maryland and processed by EG&G/EMG. Stop locations marked, except where they are found on other figures. The proposed projection of the perimeter drift of the repository is the lemon shaped area in the central portion of the photograph.

Figure 2, Geologic map of area along HWY 95.

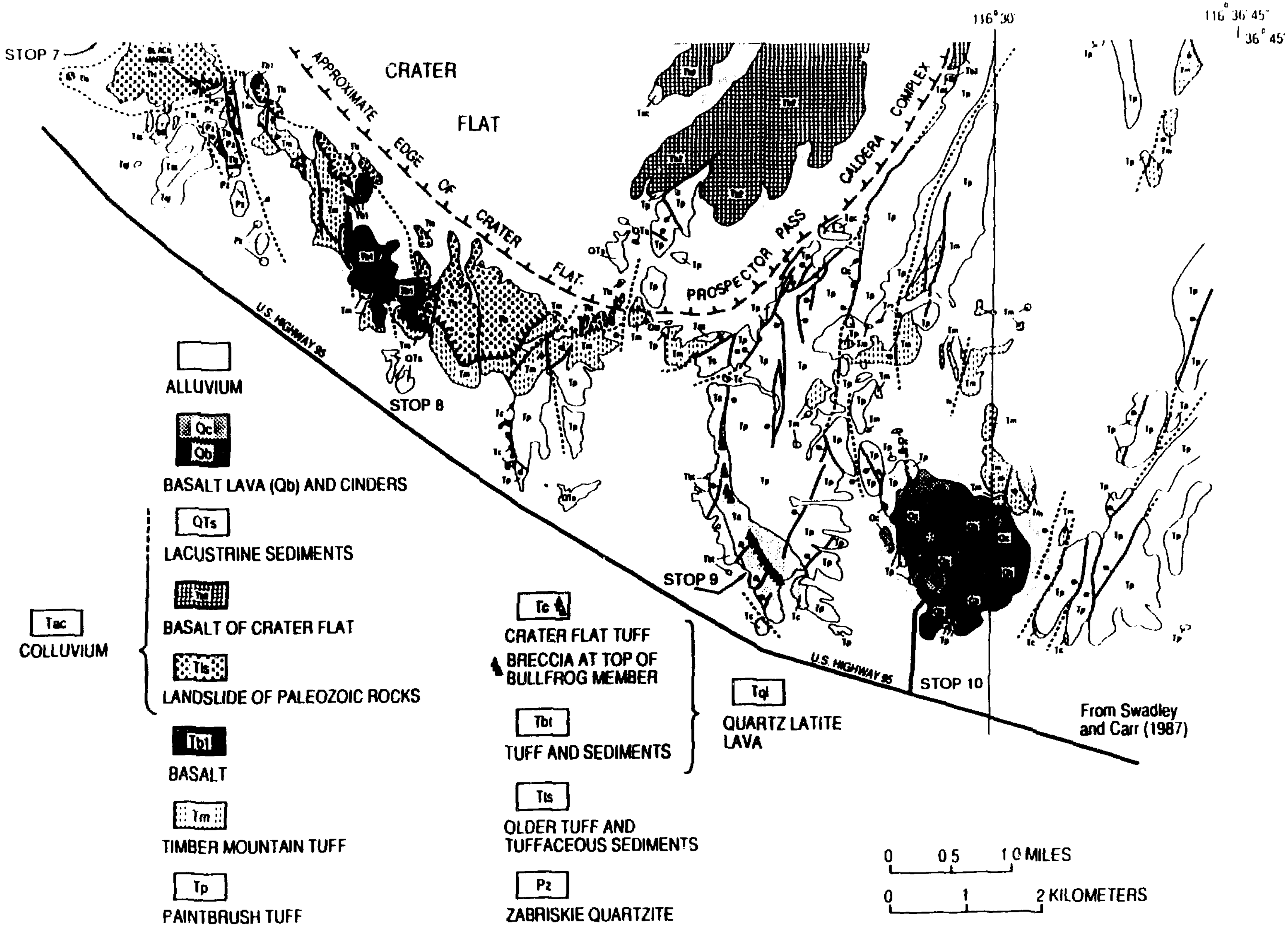
Figure 3, Generalized geologic map of Yucca Mountain and vicinity showing selected stratigraphic and structural framework features (TM, approximate southern boundary of the Timber Mountain-Oasis Valley caldera complex; R, approximate extent of the candidate repository. Geology modified from Swadley et al.(1984).

Figure 4, Cross-section of Yucca Mountain showing the major volcanic units and distribution of clinoptilolite-rich zeolitized horizons. Numerals I to IV indicate major stratigraphically contained zones of zeolitization (I = heulandite zone above the basal vitrophyre of the Topopah Spring Member, II = zeolitized interval including the nonwelded base of the Topopah Spring Member, the Calico Hills, and the nonwelded top of the Prow Pass Member, III = zeolitized interval including the nonwelded base of the Prow Pass Member and the nonwelded top of the Bullfrog Member, IV = zeolitized zone spanning the upper Tram and lower Bullfrog Members of the Crater Flat Tuff.) The cross section is based drill holes indicated at the top of the figure.

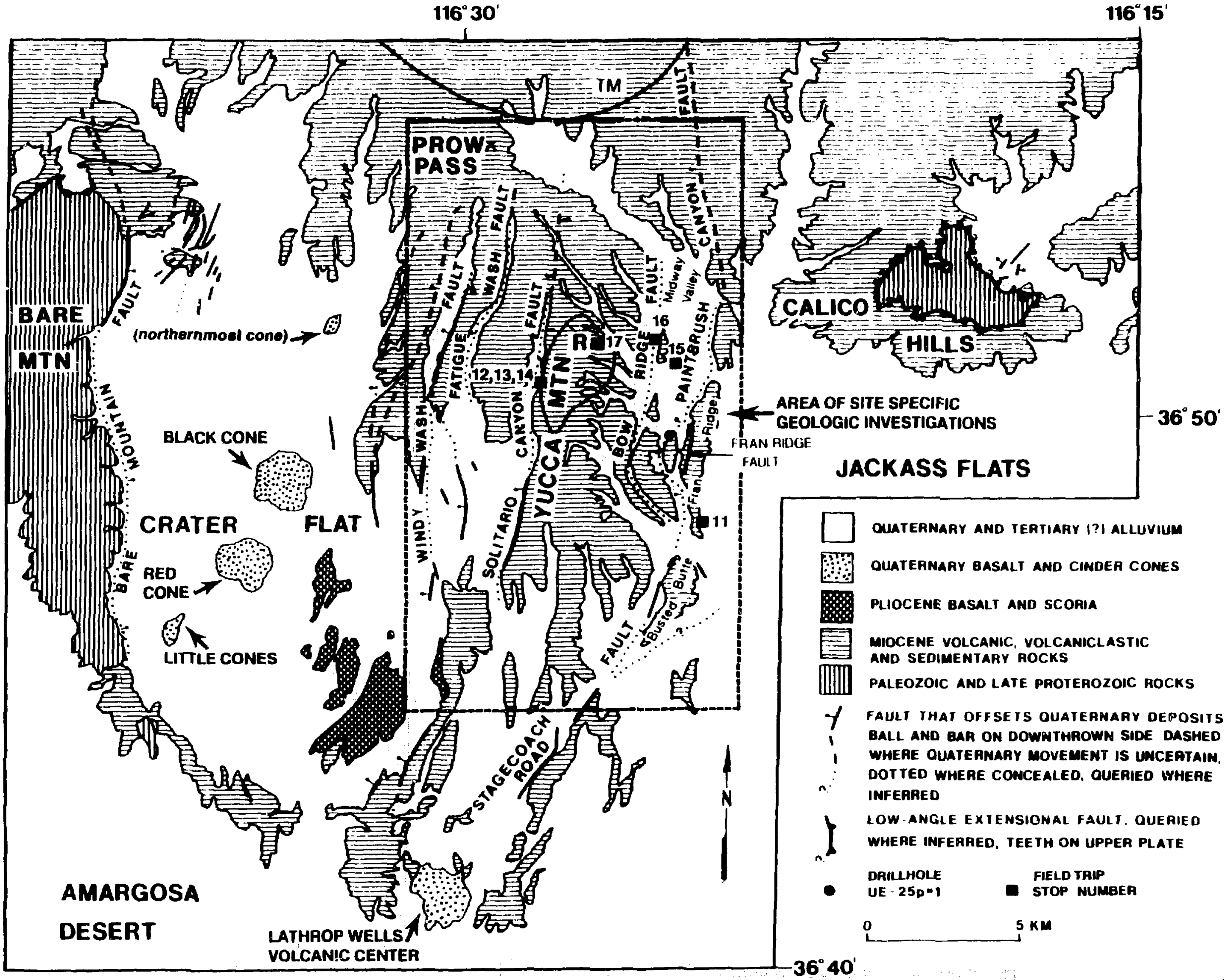
Figure 5, Simplified map of the south wall of Trench 14, Nevada Test Site.



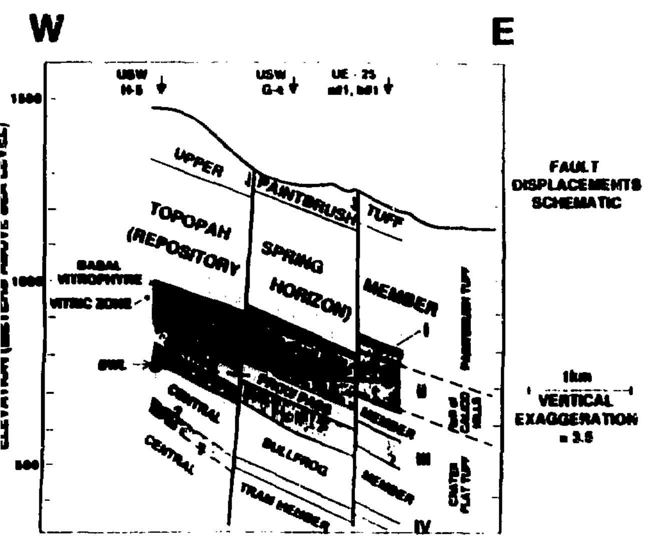
116°30'W
116°00'W
37°15'N 116° 'W
3
SILENT
CANYON
CALDERA
BLACK
MTN. CALDERA
1
4
2
SLEEPING
BUTTE
CALDERA
SEGMENT
TIMBER
MOUNTAIN
CALDERA
NEVADA TEST SITE
NELLIS AIR FORCE RANGE
OASIS
VALLEY
CALDERA
SEGMENT
CLAIM
CANYON
CAULDRON
SEGMENT
FIG. 4
BEATTY
6
5
HWY 58
HWY 95
CRATER
FLAT-
PROSPECTOR
PASS CALDERA
18
FIG. 3
NEVADA
CALIFORNIA
SCALE = 1:255,000
0
5 MILES
0
5 KILOMETERS
AMARGOSA VALLEY
HWY 29
116°30'W



GEOLOGIC MAP OF AREA BETWEEN CRATER FLAT AND U.S. HIGHWAY 95



116°30'
116°15'
TM
PROW PASS
FAULT
CANYON
BARE MTN
FAULT
(northernmost cone)
WINDY WASH FAULT
FATIGUE WASH FAULT
SOLITARIO CANYON FAULT
YUCCA MTN
BOW RIDGE FAULT
Midway Valley
PAINTBRUSH CANYON
CALICO HILLS
R
16
17
15
12,13,14
11
AREA OF SITE SPECIFIC GEOLOGIC INVESTIGATIONS
36°50'
FRAN RIDGE FAULT
Fran Ridge
JACKASS FLATS
BLACK CONE
CRATER FLAT
BARE MOUNTAIN
RED CONE
LITTLE CONES
Busted Butte
FAULT
STAGECOACH ROAD
N
AMARGOSA DESERT
LATHROP WELLS VOLCANIC CENTER
36°40'
QUATERNARY AND TERTIARY (?) ALLUVIUM
QUATERNARY BASALT AND CINDER CONES
PLIOCENE BASALT AND SCORIA
MIOCENE VOLCANIC, VOLCANICLASTIC AND SEDIMENTARY ROCKS
PALEOZOIC AND LATE PROTEROZOIC ROCKS
FAULT THAT OFFSETS QUATERNARY DEPOSITS BALL AND BAR ON DOWNTHROWN SIDE DASHED WHERE QUATERNARY MOVEMENT IS UNCERTAIN, DOTTED WHERE CONCEALED, QUERIED WHERE INFERRED
LOW-ANGLE EXTENSIONAL FAULT, QUERIED WHERE INFERRED, TEETH ON UPPER PLATE
DRILLHOLE UE-25p#1
FIELD TRIP STOP NUMBER
0
5 KM


W
E
USW H-5
USW G-4
UE-25 a#1, b#1
UPPER
PAINTBRUSH
TUFF
TOPOPAH
(REPOSITORY
SPRING
HORIZON)
MEMBER
BASAL VITROPHYRE
VITRIC ZONE
BULLFROG
MEMBER
TRAM MEMBER
CENTRAL
I
II
III
IV
FAULT DISPLACEMENTS SCHEMATIC
1km
VERTICAL EXAGGERATION = 3.5
1500
1000
500

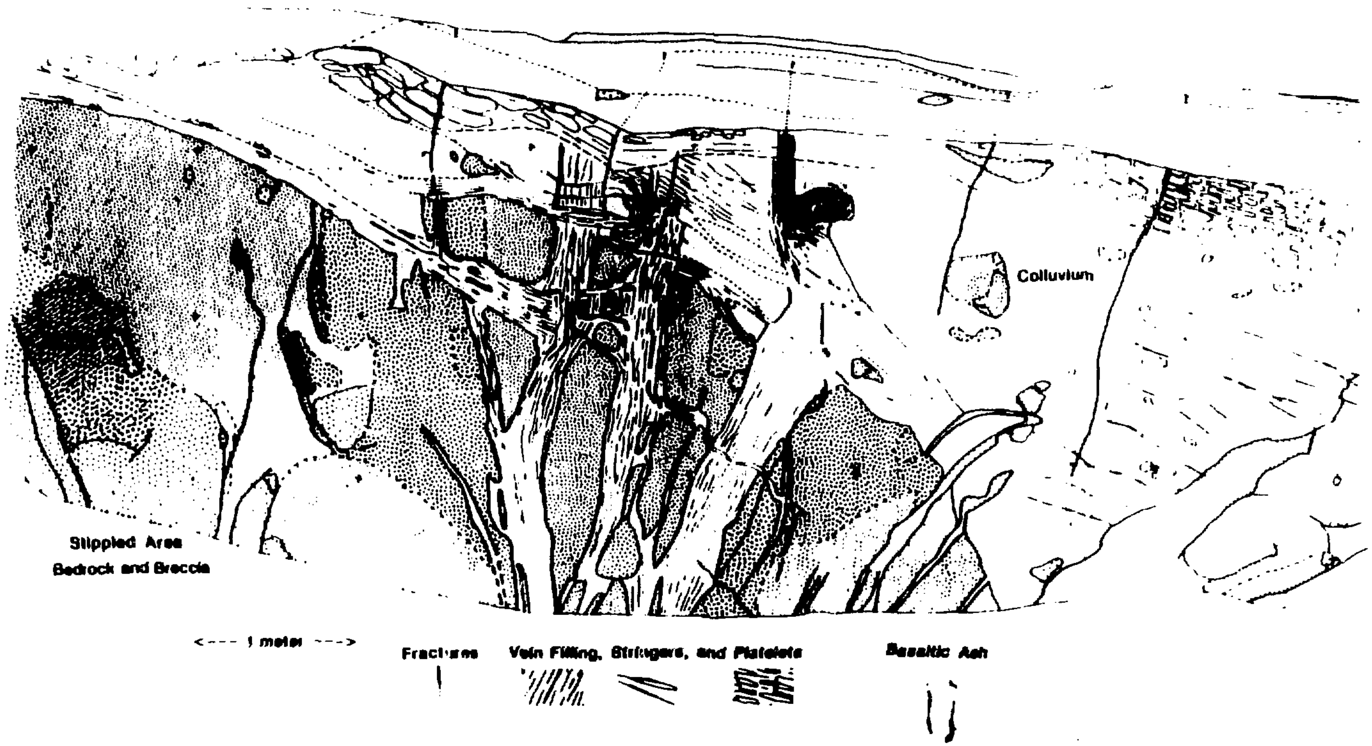

Colluvium
Stippled Area
Bedrock and Breccia
<--- 1 meter --->
Fractures
Vein Filling, Stringers, and Platelets
Basaltic Ash

TABLE I. PRINCIPAL CENOZOIC VOLCANIC AND SEDIMENTARY UNITS

Modified from Orkild, 1982; Dockery et. al., 1984; Carr, et. al., 1986.

Formation, Member	Inferred Volcanic Center	General Composition	Approximate Age (m.y.)
YOUNGER BASALTS	NUMEROUS	Basalt (hawaiite)	0.3-7
THIRSTY CANYOUN TUFF	BLACK MOUNTAIN CALDERA	Trachytic soda rhyolite	7-9
RHYOLITE OF SHOSHONE MTN.	SHOSHONE MOUNTAIN	High-silica rhyolite	9
BASALT OF SKULL MOUNTAIN, EMAD	JACKASS FLAT(?)	Quartz-bearing basaltic andesite	10
TIMBER MOUNTAIN TUFF	TIMBER MOUNTAIN CALDERA	Rhyolite to quartz latite	10-12
Intracaldera ash-flow tuffs			
Ammonia Tanks Member			
Rainer Mesa Member			
PAINTBRUSH TUFF	CLAIM CANYON CALDERA	Rhyolite to quartz latite	12-13
Intracaldera ash-flow tuffs			
Tiva Canyon Member			
Yucca Mountain Member			
Pah Canyon Member			
Topopah Spring Member			
WAHMONIA AND SALYER FORMATIONS	WAHMONIE-SALYER CENTER	Dacitic tuffs and lavas	13-13.5
CRATER FLAT TUFF (coeval	CRATER FLAT (?). Calderas buried under basalt and alluvium	Rhyolite (coeval with tuffs of Area 20)	13.5-14
Prow Pass Member			
Bullfrog Member			
Tram Member			
STOCKADE WASH TUFF	UNCERTAIN (coeval with Crater Flat Tuff)	Rhyolite	14
BELTED RANGE TUFF	SILENT CANYON CALDERA	Peralkaline Rhyolite	14-15
Grouse Canyon Member			
Tub Spring Member			
TUFF OF YUCCA FLAT	UNCERTAIN	Rhyolite	15
REDROCK VALLEY TUFF	UNCERTAIN	Rhyolite	16
FRACTION TUFF	CATHEDRAL RIDGE CALDERA	Rhyolite	17
ROCKS OF PAVITS SPRING	DISPERSED (underlies Crater Flat Tuff)	Tuffaceous sediments	14-?
HORSE SPRING FORMATION	DISPERSED	Mostly sediments	30