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Geophysics – DRAFT

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Weiss and others (1996) proposed that pyrite in pyritic Tram and Lithic Ridge Tuffs was deposited by in-situ hydrothermal activity and related it to the clay- and zeolite-mineral alteration in Yucca Mountain, which they believe to be hydrothermal alteration. However, the writers of this report believe that the pyrite predated this alteration (see below, section 5.7.4). Such alteration is typical of thick vertically-zoned tuffaceous sequences, and many workers have referred to such alteration as "diagenetic" alteration (Walton, 1975; Broxton and others, 1987; Hoover, 1968). The question of what to call this alteration is semantic; on the basis of clay mineralogy, Bish (1989) proposed alteration temperatures as high as 300° C at a depth of about 1800 m in hole G2, but still referred to the alteration as "diagenetic." In hole G3, the highest temperature proposed by Bish was about 70° C at a depth of about 1800 m where the main alteration phases are analcite and smectite. At the level of the pyritic Tram Tuff in hole G3 (about 1100 m), Bish estimates an alteration temperature of < 70° C. Although the alteration in hole G3 can be called "hydrothermal" because it was caused by warm water, no record could be found of analcite-smectite alteration related to economic hydrothermal metallic mineralization.

Regional altered areas shown by Weiss and others (1996) are misleading, because areas that are examples of hydrothermal alteration related to epithermal precious-metal mineralization such as in the Bullfrog mining and Wahmonie mining districts, are equated with an area at Yucca Mountain that is delineated by the location of deep drilling. Presumably, this delineation is based on intercepts of high-level clay mineral and zeolite alteration, along with deeper alkali-feldspar alteration in the YMCCA drill holes. The area of altered rock shown by Weiss and others in the YMCCA also appears to be drawn to include hole G3, which includes only clay mineral and zeolite alteration (Broxton and others, 1987). These are clearly altered rocks, and whether the alteration process should be called "hydrothermal" or "diagenetic" is debatable, but they should not be portrayed as altered rocks in the same sense as those in mining districts of the region. In addition, it is curious that Weiss and others do not show a large altered area on the Nevada Test Site that includes Pahute Mesa, Yucca Flat, and Skull Mountain, where USGS drilling indicated a large area of alteration to clay minerals, zeolite minerals (including analcite), silica minerals, and alkali feldspar (Hoover, 1983; Moncure, 1980). In fact, following the reasoning of Weiss and others (1996) a vast "hydrothermally" altered area could reasonably be predicted in the NTS (and elsewhere in the SWNVF) that includes all of the SWNVF with thick (>1000 m) sections of volcanic rock.

5.4. GEOPHYSICS

A large number of regional and local geophysical surveys have been completed in Nevada during the last 30 years in support of exploration for mineral deposits. Some of this work has been completed by the USGS and the NBMG, often in cooperative efforts, and the data have been made available to the general public. In the Yucca Mountain region, research and weapons testing at the NTS provided justification for additional geophysical studies, primarily using gravity, magnetic, and seismic techniques, and until recently, these data were generally less available to the public. A new phase of detailed and extensive geophysical studies has been underway since the mid 1970's in support of the national nuclear waste isolation program. This extensive data set is available to the public, mainly as open-file reports. These data and their interpretations have been reviewed in the present effort to evaluate the mineral potential of the proposed repository site and the larger YMCCA.

Most thorough mineral exploration or mineral resource evaluation projects include a substantial effort in geophysical data gathering and interpretation. The only alternative, close- spaced drilling to all depths considered possibly economic, is normally cost prohibitive. An appropriate geophysical program helps define regional and local geology and identifies anomalous subsurface features that should be addressed or tested.

Because substantial geophysical work has been conducted in the Yucca Mountain area and surrounding region, an extensive database is available for review (Agnew, 1994; Oliver and others, 1995). Most of the data were collected in support of near-surface to basement geological studies, especially identification of fault and fracture zones. As noted by Langenheim and others (1991), the survey work and interpretations were not designed for mineral exploration and resource evaluation. Thus, the sequence and types of surveys, and survey specifications, are often different from what would have been completed in a cost-effective mineral exploration program by industry. In this study the existing database and interpretations already completed by other scientists are used to indicate implications for metallic mineral resource potential and to examine the limits to which the existing geophysical data can be used to test for this potential.

5.4.1. Geophysics in nuclear waste isolation studies

Oliver (1987) provided a brief background for geophysical studies relating to the U.S. nuclear waste isolation program prior to the selection of the Yucca Mountain area as the first site for detailed geologic and engineering characterization. Wynn and Roseboom (1987) described the role of geophysics in identifying and characterizing potential repository sites and identified important characteristics of the various candidate rock types, including saturated and unsaturated zones in volcanic tuff. They described the principal geophysical methods, their main applications, and addressed the issues of resolution, delectability, and physical properties. The paper provides an excellent background for an evaluation of mineral potential based on the data available.

5.4.2. Quality assurance

Wynn and Roseboom (1987) described the role of Quality Assurance (QA) as applied to geophysical studies in the nuclear waste isolation program. They indicated that "any studies that may be used to support a licensing application will have to show that they were conducted in compliance with NRC's requirements for a quality assurance (QA) program that adequately documents the method used and the procedures carried out in the data acquisition and interpretation." They also noted that deviations from preplanned procedures (change orders) must be carefully documented and justified and that the written record must be so complete that a geophysicist peer would have a full understanding of equipment calibration, survey procedures and interpretation.

Geophysical exploration for mineral and petroleum resources has evolved as a cost- effective technology for siting drill holes that will directly test for or produce a natural resource. Survey equipment and procedures must perform under highly variable conditions including topography, geology, near-surface variability, weather, and artificial (man-caused) interference or "noise." Furthermore, these conditions frequently change during the surveys. Interpretations of the data collected may be subject to considerable ambiguity. Thus QA requirements are difficult to implement and represent a costly addition to geophysical exploration. Pre-existing data, even those of high quality, may not fully comply with NRC QA requirements. Peer Review forms an important part of the QA process for evaluating geophysical studies.

The present study is limited to a review and evaluation of existing data and earlier studies. It therefore incorporates QA procedures and limitations of these earlier studies. This study cites published and reported work to the extent possible. These studies have, at a minimum, been subject to professional, organizational, and peer review.

5.4.3. Metallic mineral exploration strategy

The mining history of Nevada, and of the Yucca Mountain region in particular, has been reviewed in preceding sections of this report. The geology and known occurrence of mineral deposits of an area dictate the resources of interest and determine the exploration strategy. Future exploration efforts in the Yucca Mountain region would probably focus on precious metals (Au, Ag), porphyry copper, and base metal vein deposits.

A typical metallic mineral exploration program would utilize existing gravity, magnetic, seismic, and electrical resistivity data to extend the known geology and evaluate the thickness of Tertiary volcanics and post-mineral cover (i.e., Quaternary alluvium and lake beds, slope wash; Paterson and Reeves, 1985; Blakeley and Jachens, 1991). Other information available from these data may relate to the presence and type of faulting, type of magnetic "basement" rocks, and location of possible intrusive rocks (Wright and others, 1985; Corbett, 1991; Ponce, 1991). Detailed aeromagnetic surveys and selective detailed gravity surveys might then be completed to better define targets related to concealed intrusives. Airborne electromagnetic surveys may be undertaken to detect conductive vein mineralization (including alteration minerals) or silicified (resistive) or altered (generally conductive) rocks related to precious metals mineralization (Pierce and Hoover, 1991). A variety of ground surveys, using electrical resistivity/induced polarization (IP), and electromagnetic (EM) techniques may then be completed to refine targets and recommend drill test locations (Ward and others, 1981; Hoover and others, 1991; Corbett, 1991). A state-of-the-art exploration strategy (Ward and others, 1981) would provide for qualitative and quantitative interpretation (numerical modeling) perhaps followed by physical property studies and more detailed geophysics following the initial drilling.

5.4.4. Magnetic studies

5.4.4.1. Aeromagnetic surveys - regional scale

The map shows magnetic field intensity anomalies in 25 nanotesla (nT) color bands.

Aeromagnetic data are available for interpretation at regional and local scales. Hildenbrand and Kucks (1988a) compiled a total intensity magnetic anomaly map of Nevada (TIMAM) from a diverse group of magnetic surveys for which digital data were available. Although limited by the original survey parameters and errors, and the accuracy of data merging techniques, this map (scale 1:750,000) provides a look at regional magnetic trends which often indicate subsurface geologic, tectonic and mineralization trends. Figure 8.1, a contoured version of this map, shows positive magnetic anomalies associated with the Calico Hills and Wahmonie areas. A broad (10- 20 km wide) trend of magnetic highs, cut by smaller lows, trends N70°W to west from the Wahmonie area across much of the YMCCA. The trend is interrupted by a low which trends north from Crater Flat. The Bullfrog Hills and Bare Mountain mineralized areas lie south of this trend. Mine Mountain lies to the north and is unrelated to the trend. No specific and continuous trends link the Mine Mountain known mineralization and the YMCCA.

Hildenbrand and Kucks (1988b) presented a series of five filtered magnetic anomaly maps created by applying a variety of analytical techniques to the digital magnetic data of the TIMAM described above. These techniques are often used to aid in the interpretation of regional and detailed aeromagnetic data for petroleum or mineral resource exploration. The reduction-to- the-pole operation accounts for the inclination and declination of the earth's present magnetic field and attempts to reposition magnetic anomalies and trends directly over the causative magnetic source areas. The residual total magnetic field reduced to the north magnetic pole (RTMFRTP) map (Hildenbrand and Kucks, 1988b, Sheet 1; scale 1:1,000,000) shows the Calico Hills and Wahmonie areas near the southeast margin of the positive magnetic trend which cuts across the YMCCA. However, the Bullfrog Hills, Bare Mountain and Mine Mountain mineralized areas do not appear to be extensions of this west- to N70°W trend. The first vertical derivative map (FVDM; Hildenbrand and Kucks, 1988b, Sheet 2) sharpens and resolves anomalies of limited areal extent, and does indeed show small positive anomalies near the Bullfrog Hills (BH), Bare Mountain (BM) and Mine Mountain (MM) mineralization. The positive trend associated with the Wahmonie (W) and Calico Hills (CH) areas is more apparent as a westerly trend of positive anomalies which terminate at Yucca Mountain, and as a north-northwest trending area north and west of the Timber Mountain caldera. The high-low pattern of the Calico Hills-Yucca Mountain area is not unusual - perhaps 30-40 percent of the State of Nevada shows a similar pattern on this map, with a variety of short wavelength trends which are mainly northwest in the Walker Lane region, but vary from east-west to north-south throughout the state.

Sheet 3 of Hildenbrand and Kucks (1988b) is a pseudo-gravity field (PGF) map (also scale 1:1,000,000) which transforms the RTMFRTP map to a pseudo-gravity anomaly map (Baranov, 1957) using a designated constant value of 1,000 nanoteslas/g/cm^3 (nT/g/cm^3). The transformation may have little significance when applied to metallogenic trends in the volcanic rocks of the Southwest Nevada volcanic field (SWNVF). Remanent magnetism may result in both positive and negative anomalies, and the resultant magnetic vector may be different from that of the present magnetic field. Thus the PGF may differ substantially from the observed gravity field. The PGF map for Nevada resembles a long wavelength (low-pass filtered) version of the total magnetic field, and in many areas it departs substantially from the true Bouguer gravity anomaly map of Nevada of Saltus (1988). On the PGF map, a pseudo-gravity high extends northwest from Wahmonie to Yucca Mountain and meets a broad northeast-trending high which extends through Pahute Mesa and includes the clustered calderas of the SWNVF. Wahmonie, Calico Hills, Bare Mountain and Bullfrog Hills all lie along a southern, west-trending border of this high.

Sheet 4 of Hildenbrand and Knucks (1988b) presents the magnitude of the horizontal gradient of the pseudo-gravity field (MHGPGF), which is designed to map steep boundaries of contrasting magnetization, as developed by Cordell and Grauch (1985). On this map, any spatial correlations with mineralization in the Yucca Mountain region are weak.

At regional scales (1:750,000 and 1:1,000,000) the total intensity magnetic anomaly map (TIMAM) and maps of three filtered transformations (RTMFRTP, FVDMF, PGF) show weak- to-moderate spatial correlations with mineralization trends surrounding the YMCCA. The general northwest trends which correlate with known mineral occurrences probably arise from magnetic features in pre-Tertiary bedrock occurring as outcrops or at shallow depth, along the southern margin of the volcanic caldera complex and within the Walker Lane structural zone. Some trends on these regional-scale maps transgress known geologic features. Fortunately, more detailed magnetic data are available to evaluate the geologic sources of magnetic anomalies in the Yucca Mountain region and to provide correlative relationships with mineralized areas.

5.4.4.2. Aeromagnetic surveys - area scale

Glen and Ponce (1991) compiled data from six detailed aeromagnetic surveys, without altitude adjustments, to form a mosaic aeromagnetic map of the Beatty Quadrangle at a scale of 1:100,000. The International Geomagnetic Reference Field (IGRF) was removed from each survey except the Yucca Flat survey and a constant was added to each survey to reference the surveys to the datum of the Timber mountain survey. This map includes the Bullfrog Hills and Bare Mountain areas on the west and extends across the proposed YMCCA to include the Calico Hills and Wahmonie areas on the east. Kirchoff-Stein and others (1989) merged eight separate surveys by removing the IGRF from each and then upward or downward continuing the data to a common level of 1,000 feet (305 m) above terrain to result in a preliminary, 1:100,000 scale aeromagnetic map of the Nevada Test Site and vicinity. The data were further processed to allow continuous contouring across survey borders. This map extends farther to the north than the Glen and Ponce (1991) map, but terminates over Crater Flat on the west, and does not include the Bullfrog Hills and Bare Mountain areas. Parameters of the original surveys include line spacings of 0.25 to 1 mile (400 m to 1.6 km), directions east-west and north-south, and flight elevations that vary from 400 ft (122 m) above ground (AG) to as much as 9000 ft (2743 m) barometric elevation (BE). The scale and detail of these composite maps are appropriate to identify major geologic and structural trends, and their correlation with mineralized areas that surround the YMCCA. However, in most cases the original survey data are more appropriate for detailed interpretation of individual anomalies.

The Wahmonie district mineralization and Calico Hills altered area are associated with positive magnetic anomalies (fig. 8.1). The anomalies form part of an east-west to northwest positive magnetic trend noted on the regional aeromagnetic map which extends through the YMCCA, across the northern edge of the Bare Mountain mining district and along the southern edge of the Bullfrog district. The Calico Hills anomaly has been studied in detail and will be discussed later. The Hornsilver Mine (Wingfield shaft) at Wahmonie lies within the source area of a well-defined positive magnetic anomaly (+450 nT at 1,000 ft. (305 m) AG). West of the YMCCA, much of the Bare Mountain district is expressed as a low-relief magnetic low, although a local 150 nT high, due in part to reduced terrain clearance over the mountain ridge, occurs in the northwestern part of the district.

The NTS 1:100,000 aeromagnetic map (Kirchoff-Stein and others, 1989) covers all of the YMCCA with magnetic field values upward or downward continued to a uniform 1000 feet (305 m) above the ground surface. At this height the complex magnetic expression due to magnetization changes within near surface (0-2 km) volcanic rocks is greatly reduced. A long wavelength anomaly with amplitude of about 60 nT extends west across the center of the YMCCA from the Calico Hills area and a single well-defined anomaly with amplitude of about +280 nT occurs along the northwest border of the YMCCA. Simple depth estimates based on the steep slope technique of Vacquier and others (1963) suggest a depth of about 400-800 m, within the upper part of the volcanic tuffs. Inspection of the original Timber Mountain area aeromagnetic map (U.S. Geological Survey, 1979) suggests the anomaly may be somewhat misrepresented by the gridding and continuation procedures, for the anomaly is much less of a "bullseye" on these maps, hence the depths to source suggested above may be inaccurate. This anomaly is discussed in more detail below.

Mineralization in the Bullfrog District is generally associated with relative magnetic lows (+20 to -60 nT) on data taken 400 feet (122 m) AG. The magnetic data suggest a possible east- trending structural control for the Original Bullfrog and Bullfrog mineralization. The Montgomery-Shoshone Mine occurs within a small (1-2 km) magnetic high (+50 nT); however this high may be due, in large part, to reduced terrain clearance over magnetic rocks on Montgomery Mountain.

The magnetic expression of mineralized areas in the Yucca Mountain region, at the level of detail of available data, is mixed. The Calico Hills and Wahmonie areas east of the YMCCA are associated with pronounced magnetic highs which would be observed even if the magnetic source rocks were buried beneath 500 to 1000 m of weakly magnetic overburden. The more important mineralization of the Bullfrog District and Bare Mountain District are associated with low- amplitude positive-to- negative anomalies which would be most difficult to recognize if the associated source rocks were buried beneath 500 m or more of weakly magnetic overburden. Magnetic trends suggestive of deep structural control extend eastward from the Bullfrog District, and westward from the Calico Hills and Wahmonie areas.

5.4.4.3. Detailed magnetic studies

The USGS has completed interpretations of several detailed, local aeromagnetic surveys in its evaluation of the proposed Yucca Mountain repository site. At map scales of 1:12,000 to 1:62,500 correlations with topography, geology and other ground-based geophysical data help reduce ambiguities in the interpretations. Most of the interpretations are strongly supported by magnetic physical property observations and computer modeling.

Physical Property Studies. Numerous boreholes through the volcanic rocks and good exposures of the volcanic sequence in the Yucca Mountain area have enabled a large database of magnetic properties to be assembled to aid in interpretation of magnetic field data. Nelson and others (1991) report geophysical logs and core measurements for 40 boreholes in the Yucca Mountain area, including magnetic susceptibility logs for eight boreholes and magnetic field measurements in 12 boreholes. Rosenbaum and Snyder (1984) completed a detailed analysis of magnetic properties and paleomagnetic directions made on thousands of samples of Miocene-age volcanics from drill core and surface localities in and around Yucca Mountain. They find that four widespread units, the Tiva Canyon, Topopah Spring, Bullfrog and Tram Tuffs, are potential sources of significant magnetic anomalies because of their remanent magnetization, susceptibility, and unit thickness. The Tiva Canyon and Tram Tuffs are reversed in polarity and the Bullfrog and Topopah Spring Tuffs are of normal polarity. Rosenbaum and Snyder (1984) computed the total magnetization for volcanic units sampled in drill holes G1, G2, GU3, G3, and VH-1, noting many variations in susceptibility, remanent intensity and field inclination.

Baldwin and Jahren (1982) conducted extensive studies of magnetic properties of rocks at Calico Hills. They proposed that strongly magnetized argillite of the Eleana Formation is the principal cause of prominent magnetic anomalies observed from the air and on the ground. No other older sedimentary rocks on the NTS have been shown to be strongly magnetized. Bath and Jahren (1984) determined that normally nonmagnetic argillite has been altered to magnetized rock, possibly by heating from an underlying intrusive body which converted pyrite to magnetite. The argillite is normally magnetized and 123 samples of drill core varied in intensity from nonmagnetic to 26.6 A/m. The average magnetization for samples collected from two intervals having a total thickness of 365.5 m (1,200 ft.) was 3.89 A/m (Baldwin and Jahren, 1982). These magnetizations and the thickness of the Eleana at Calico Hills combine to form a strong magnetic source which is the probable explanation for the Calico Hills magnetic anomaly.

Detailed Magnetic Surveys. The USGS has completed several detailed airborne magnetic surveys including, and peripheral to, the YMCCA. State-of-the-art techniques, including supporting ground surveys, physical property studies, geologic studies, and numerical modeling have been employed to complete detailed and quantitative interpretations of the survey data. The principal objective of these studies has been the identification of faults within the Miocene volcanics, and determination of direction and magnitude of movement along the faults.

Langenheim and others (1991) described the revision of the Lathrop Wells aeromagnetic survey, correcting data omissions and errors in the original survey. The aeromagnetic map of the Beatty 1:100,000 quadrangle (Glen and Ponce, 1991) includes these revisions. The Lathrop Wells survey covered an area immediately south and west of the YMCCA.

Ponce and Langenheim (1994) described detailed gravity and magnetic traverses across Midway Valley and Yucca Wash on the eastern flank of Yucca Mountain. The study evaluates faulting in the vicinity of surface facilities for the proposed repository and does not address mineral potential within the volcanic units or the deeper pre-Miocene sedimentary rocks. Oliver and Sikora (1994) completed gravity and ground magnetic profiles across the Ghost Dance Fault which is the only through-going fault within the potential repository site. The data from these surveys document offset of magnetic volcanic units but do not indicate the presence (or absence) of mineral potential.

Bath and Jahren (1984) described detailed aeromagnetic surveys of the Yucca Mountain area which cover all of the YMCCA. The survey data were obtained on flight lines about 0.25 mile (400 m) apart, and 400 ft (122 m) above terrain (AG). Two surveys were completed, one with east-west flight lines, and one with north-south flight lines. The survey detail is comparable to that of most surveys used in exploration for porphyry copper and skarn deposits, although some surveys for precious metals exploration are flown lower and with less line separation, to enhance the responses from accompanying electromagnetic instrumentation. The survey map is dominated by elongate, north-trending anomalies which arise from magnetic sources at shallow depths in the upper part of the volcanic section. Bath and Jahren (1984) made good use of extensive physical property data and volcanic unit thickness (e) to establish total magnetization (Jt) and the magnetization-thickness product (Jt*e) for numerical modeling of selected anomalies. They concluded that the Topopah Spring Tuff is the primary source of anomalies from faulted sequences of volcanic rock. Other short-wavelength anomalies over the site and the YMCCA were attributed to changes in lateral extent, or magnetic properties, of volcanic units beneath the Topopah Spring Member.

Much of the work by Bath and Jahren (1984) was devoted to a quantitative analysis of the low-frequency positive anomaly in the YMCCA which extends west from the Calico Hills area and which is apparent on high altitude area- and regional-scale magnetic maps. They concluded that "almost all" of the positive anomaly is due to a deep source, probably strongly magnetized Eleana Formation, 800 m thick and at a depth of 2.25 km. This conclusion bears directly on the possibility of mineral potential within the YMCCA. Their interpretation is based on sound and established techniques but does raise some important questions: 1) how much of the magnetic anomaly is actually due to volcanic units from the surface to 1 km depth? 2) what is the size of the intrusive necessary to produce the heating required to convert pyrite to magnetite for such an extensive source?, and 3) does the magnetic argillite which was drilled at the Calico Hills really extend 20 km west to the YMCCA? An alternative interpretation (this study) of the high altitude survey data (2450 m above sea level), using the steepest slope and depth indices method of Vacquier and others (1963) yields magnetic source depths of 700 to 1300 m for vertical prism-shaped bodies. These depths would indicate a substantial part of the magnetic source lies within the volcanic section, as interpreted from gravity and refraction seismic data (Ackermann and others, 1988) and drilling results at drill hole UE25 a-1. The proposed intrusive source responsible for the heating of the argillite could also be a significant contributor to the magnetic anomaly, by virtue of its probable depth extent and total magnetization (by analogy to the Climax stock; Bath and others, 1983). The depth to the proposed magnetic source could be better determined by more detailed (full profile) curve matching and three-dimensional modeling. If the magnetic source depth is 2 km or more, it is unlikely that intrusive and argillite parts of the magnetic source can be well resolved through additional modeling.

A 219 nT anomaly maximum (recorded on the 2450 m above sea level survey) occurs near the northwest margin of the YMCCA. Bath and Jahren (1984) interpret this as the combined effects of near-surface volcanic rocks and the buried sedimentary rocks that have been metamorphosed by an underlying intrusive. The anomaly also occurs as a 280 nT maximum on the 1:100,000 scale aeromagnetic map of the Nevada Test Site (Kirchoff-Stein and others, 1989). The anomaly is located over the higher elevations of Yucca Mountain (1400+ m) near The Prow. The Timber Mountain Tuff (Rainier Mesa member) and the Topopah Spring Tuff crop out in the anomaly source area (as mapped by Faulds and others, 1994). Simplified depth estimates, based on the method of Vacquier and others (1963), suggest the primary source is increased magnetization within the volcanic section at depths between the surface and 1 km. The magnetic anomaly is quite coherent on survey data flown at 8000 feet (2450 m) barometric elevation, while most anomalies due to faulting within the volcanics are quite subdued at this elevation. The anomaly occurs as an elongate, north-trending 450 nT high on the Timber Mountain survey which was flown at 400 ft AG. Simple depth estimates indicate much of the source occurs at or near the surface and is in the volcanic rocks. The anomaly is attenuated at higher levels but retains a strong, long-wavelength component, indicating a composite source, probably with a substantial depth extent. An intrusive body is a possible explanation for the magnetic source, but this may not be required in view of the strong and variable magnetization within these volcanic rocks.

Bath and Jahren (1985) attempted to determine the source of a prominent aeromagnetic anomaly of 290 nT which has been mapped along the southwest margin of the proposed repository site. Their review of terrain clearance flight records, ground magnetic traverses and numerical modeling suggested: (1) reduced distance between the aircraft and the ground surface; (2) increased magnetization within the Topopah Spring Tuff; and (3) an increase in the distance between the air datum and the Solitario Canyon fault all contributed to the anomaly. A small intrusive body could also help explain the anomaly, but geologic information does not support this possibility (Bath and Jahren, 1985). There is no reason to believe that it is an indication of mineral potential.

A recent report by Feighner and Majer (1996) described the effort by a contractor (Earthfield Technology Incorporated - ETI) to determine depth to Paleozoic basement in the Yucca Mountain area by recompiling available (qualified) survey data and using automated interpretation techniques not well-suited to the observed magnetic data and the known geology. Vertical relief on a weakly magnetic or nonmagnetic Paleozoic sedimentary rock surface would not be expected to give rise to significant magnetic anomalies when deeply buried. They concluded that most of the short-wavelength anomalies correlate with mapped offsets in shallow magnetic tuffs, and that deeper magnetic sources are overwhelmed by the shallow or surface volcanic signatures. We concur with these observations. Future efforts to obtain improved depth determinations should be directed at full-profile curve matching using finite-length two- dimensional and three-dimensional models.

Other magnetic studies by the USGS addressed magnetic anomalies in Midway Valley and Yucca Wash (Ponce and Langenheim, 1994), Crater Flat (Sikora and others, 1995), the Amargosa Valley, and elsewhere in the Yucca Mountain area. Ponce and Oliver (1996) summarized the results of many of these studies. They noted that circular magnetic anomalies in Crater Flat and northwest of the town of Amargosa Valley (formerly Lathrop Wells) correlate with known cinder cones and that other anomalies may be related to buried mafic volcanic rocks. This igneous activity probably has little bearing on the mineral potential of the YMCCA.

Volcanic areas throughout the world are typified by complex aeromagnetic expressions and numerous magnetic anomalies arising from topographic features, from magnetization contrasts due to faulting within volcanic units, intrusive rocks and alteration zones within the volcanic sequence, and from the underlying geology. Studies of the SWNVF, the Nevada Test Site, and the Yucca Mountain area in particular show a similar spectrum of magnetic sources and anomalies. The detailed physical property studies reported by the USGS indicate the wide range of magnetization contrasts within volcanic rocks of the SWNVF, and show that remanent magnetization is a major contributor to magnetic intensity, often more important than magnetic susceptibility of the tuff units. Without a well-defined anomaly pattern suggestive of an intrusive or extensive alteration, magnetic anomalies arising from depths within the volcanic sequence should be considered low- priority targets for metallic mineral resources.

In summary, magnetic data and their interpretation show that almost all magnetic features within the YMCCA can be attributed to magnetization changes within the volcanic section. A broad coherent anomaly near the northwestern part of the YMCCA may be due, in part, to an intrusive source less than one km deep. Regional magnetic features associated with mineralized areas to the east trend west toward the YMCCA. One such magnetic anomaly may arise from strongly magnetized Eleana formation and/or intrusive rocks at depth beneath the volcanic section (depths of 1.5 to 2.5 km) in the eastern part of the YMCCA. The magnetization within the argillite (if present) has been attributed to heating effects of an underlying intrusive. There is no direct evidence of significant mineral potential associated with the argillite or underlying intrusive, and within the YMCCA.

5.4.5. Gravity studies

5.4.5.1. Regional gravity data

Regional gravity data are available for the state of Nevada at 1:750,000 (Saltus, 1988a), as well as regional, residual, and derivative gravity maps at 1:1,000,000 and 1:2,500,000 (Saltus, 1988b). These maps are useful to provide a general setting for more detailed gravity maps, and include the Bullfrog and Bare Mountain mining districts which are not included on the more detailed Nevada Test Site gravity maps. The state-wide gravity maps also provide useful comparisons with aeromagnetic data of the same scale. The dominant gravity features in the vicinity of the YMCCA on these maps are large Bouguer gravity minima associated with Crater Flat, Yucca Flat, and the SWNVF caldera cluster. Mineralized areas in the Wahmonie, Calico Hills, Bare Mountain, and Bullfrog mining districts all lie near the -150 mGal contour on a W-NW trending gravity gradient shown on figure 8.2 (part of the Bouguer gravity anomaly map of Saltus, 1988). The trend is interrupted by a -15 to -20 mGal minimum at the south end of Crater Flat and Yucca Mountain. The -150 mGal gravity contour appears to correspond to more dense (2.60-2.75 gm/cm^3) Paleozoic, Precambrian, and pre-Tertiary intrusive rocks that crop out or occur at shallow depth, in contrast to less dense Tertiary volcanics and alluvial deposits.

The expression of some of the important regional features noted above is shown very well on a larger sale (1:100,000) Bouguer anomaly gravity map of the Nevada Test Site (Healey and others, 1987). Ponce and others (1988) compiled a isostatic gravity map for the Nevada Test Site at this scale. The dominant features on the NTS Isostatic Gravity Map are extensive lows of -34 mGal and -28 mGal over Frenchman Flat, -50 mGal north of Timber Mountain, and -36 to -42 mGal over the Shoshone Hills. These major features compare with isotatic gravity values of -10 mGal in the Calico Hills, Jackass Flats, and Skull Mountains where more dense pre-Tertiary rocks are present at the surface and at shallow depth. A substantial, but less extensive low of -38 mGal indicates a thick section of lower density Miocene volcanics in the Yucca Mountain area.

5.4.5.2. Physical properties (density)

Rock density data, so important to quantitative interpretation of gravity data, was measured by three different methods in Yucca Mountain area studies (Muller and Kibler, 1985; Nelson and others, 1991). The methods included: continuous logging that measured gamma-gamma scattering; borehole gravimetry which permitted calculation of interval densities; and direct laboratory measurements of the weight and volume of core samples (Nelson and others, 1991). Snyder and Carr (1984) also utilized direct density measurements for about 100 surface samples. Thus a substantial density database was available to support numerical modeling studies by USGS scientists.

5.4.5.3. Interpretative results

The principal objectives of gravity surveys conducted by the USGS at Yucca Mountain were to delineate bodies of different densities and determine their shape, thickness, and boundaries. These were used to interpret geologic structures, rock types, and depths to pre- Tertiary rock. Gravity data are rarely used to explore for mineral deposits directly, except perhaps for shallow massive sulfides, lead-zinc replacement deposits, and massive magnetite deposits. Shallow deposits of these types are not expected at Yucca Mountain.

Snyder and Carr (1982, 1984) described a comprehensive study of a 400 km^2 area centered on the YMCCA. They reported a nearly linear increase in density of 0.26 g/cm^3 in the thick tuff sequence which underlies Yucca Mountain and used this relationship and other density data to support numerical interpretations. They concluded that Miocene tuff, at least 2000 m thick, fills a large steep-sided depression in the pre-Tertiary rocks beneath much of Yucca Mountain. They also proposed that the Cenozoic section is about 4000 m thick beneath Crater Flat, which they interpreted as a caldera depression. In addition, Snyder and Carr (1984) state that gravity modeling results are ambiguous with regard to the presence of a deeply buried intrusive body at Yucca Mountain and beneath the nearby Calico Hills. The density contrast between most intrusives and Paleozoic rocks, if deeply buried beneath Yucca Mountain, is too small to provide a resolution to this question.

Ackermann and others (1988) presented an integrated interpretation of two high quality seismic refraction profiles, the Yucca Mountain gravity database reported by Snyder and Carr (1982, 1984), and density and velocity data, to arrive at the most definitive interpretation of the Bare Mountain-Crater Flat-Yucca Mountain gravity data. They presented several well-supported conclusions: (1) a fault on the east side of Bare Mountain downdrops exposed Paleozoic rocks about 2,600 m into Crater Flat; (2) volcanic rocks have a maximum thickness of about 3.2 km in Crater Flat; and (3) the pre-volcanic surface exhibits some 2,000 m of relief between the south end of Yucca Mountain and the center of Crater Flat. Thus the contact between Tertiary volcanic rocks and pre-Tertiary rocks probably rises to depths of 1.3 km below the surface at southern Yucca Mountain.

Langenheim (1995) used detailed modeling of gravity and magnetic data to establish constraints on the structure of Crater Flat. Gravity models for three distinct geometries for the fault(s) bounding the east side of Bare Mountain (multiple high-angle normal faults, a single high- angle normal fault, and a low-angle normal fault) all fit the observed data well, and all models indicate 2 to 4 km of tuff within Crater Flat, and approximately 2 km of tuff overlying denser pre- Tertiary rocks beneath the proposed repository site at Yucca Mountain. Snyder and Carr (1982) modeled gravity data to predict a depth to Paleozoic rocks of about 3,500 ft (1,070 m) at Busted Butte and about 4,750 ft (1,450 m) at the nearby gravity saddle. The depth to Paleozoic basement at drill hole UE25 p#1 p1 was estimated to be about 4,000 ft (1,220 m). Drilling of hole UE25p1 p1 revealed Paleozoic dolomite at a depth of 4,080 ft (1,244 m; M. D. Carr and others, 1986), indicating the accuracy of their gravity modeling. A three-dimensional gravity model indicated an increasing thickness of lower density Cenozoic rocks to the west beneath the proposed repository site, perhaps reaching 10,000 ft (3,000 m) beneath Crater Flat (Snyder and Carr, 1984). Langenheim and Ponce (1995) presented the results of an iterative modeling procedure to predict the thickness of Cenozoic sedimentary and volcanic rocks beneath Crater Flat and Yucca Mountain. Their isopach map suggests a 1 to 4 km thickness of these units beneath much of Yucca Mountain, but substantially underestimates the thickness of Cenozoic deposits at drill hole UE25 p1 (600 m) compared to the known 1244 m Paleozoic basement depth.

More recent models of the Paleozoic-Tertiary contact are in Clayton and Zelinski (1996) and Clayton and others (in review). Although these models show major differences (as noted in section 5.3.2 above), they all show the contact in the area of drill hole p1 at essentially the same depth (an elevation of about 500 feet below sea level) that agrees with the depth of intersection in the drill hole. In addition, these interpretations indicate that the Paleozoic-Tertiary contact may rise to elevations only slightly above that in drill hole p1, and that it is much deeper in the north and west parts of the YMCCA.

my tak see the 3D model stuff

A number of detailed gravity and magnetic studies have been completed to address the structure and offset along specific structures in the YMCCA (e.g., the Ghost Dance Fault; Ponce and Langenheim, 1995) but these studies have little information regarding the presence of economic mineral potential.

Ponce (1984) completed a detailed study of the gravity and magnetic anomalies in the Wahmonie District, about 20 km east of the YMCCA (plate 1). Ponce used more than 250 density measurements for control in numerical modeling, and integrated geologic, electrical resistivity, and seismic refraction data to deduce the presence of a granitic intrusive body as the source of this positive 15-mGal anomaly. Two small outcrops of Tertiary granodiorite occur near the eastern margin of the anomaly source area. The presence of alteration and mineralization at the Hornsilver Mine in the Wahmonie district raise the possibility of additional mineralization associated with this intrusive in the subsurface. A weakly-defined gravity high continues N60°W from Wahmonie, becoming a 10 mGal positive anomaly that includes the Calico Hills. The major aeromagnetic anomaly associated with altered Eleana sedimentary rocks mentioned above suggests intrusive rocks as part of the source of this gravity anomaly as well. A negative gravity gradient that trends N30°E to N50°E across the eastern margin of the YMCCA terminates the positive gravity trend associated with the Calico Hills and Wahmonie areas.

5.4.6. Seismic studies

A variety of seismic techniques have been used to map structural elements and velocity units in and around the YMCCA. Unfortunately, reflection seismic studies have yielded generally disappointing results even with rigorous field acquisition and processing procedures, due largely to the extreme attenuation of seismic energy by the volcanic tuffs (Wynn and Roseboom, 1987; Ackermann and others, 1988; Brocher and others, 1996). Seismic refraction surveys have been used for shallow engineering surveys, mapping the thickness of alluvial and volcanic rocks, and estimating crustal thicknesses (Oliver and others, 1990). Seismic refraction data have provided useful independent control on gravity interpretations, and this is useful in appraising mineral potential of the YMCCA. Oliver and others, (1990) Mooney and Schapper (1995), Brocher (1995), and Evans and Smith (1995) provided useful summaries of numerous seismic surveys and interpretations. The seismic data are not directly applicable to the evaluation of mineral potential, but interpretations in terms of upper crustal structure, and especially depth to pre-Tertiary rock, are important in addressing the economic aspects of potential mineral deposits at depth.

5.4.6.1. Seismic refraction studies

Oliver and others (1990) and Mooney and Schapper (1995) described several refraction surveys in the Yucca Mountain area and described interpretation problems and results. Oliver and others (1990) noted that a large structural depression, deepening to the west, extends from the eastern flank of Yucca Mountain to the Bare Mountain front. Mooney and Schapper (1995) reported interpreted depths to higher-velocity rocks (Paleozoic basement) to be 3.2 km beneath Crater Flat, and 1.1 km beneath Jackass Flats when discussing a 40-km long velocity section which extends eastward from Bare Mountain across Yucca Mountain and into Jackass Flats. This section indicates that about 2 km of Tertiary tuffs lie beneath the potential repository site. These estimates are based on earlier studies by Ackermann and others (1988) discussed above in the gravity section. Seismic velocities vary from 1.5 km/s for near-surface Tertiary units to 4.7 (fractured) and 5.7-6.3 km/s for pre-Tertiary rocks at depth. When integrated with the more continuous gravity data and jointly modeled, the refraction studies help define depths to pre-Tertiary rock beneath Crater Flat and southern Yucca Mountain (Ackermann and others, 1988).

5.4.6.2. Seismic reflection surveys

Oliver and others (1990) summarized the history of seismic reflection surveys at Yucca Mountain through 1989. These include shallow, high-resolution reflection profiling (SHRRP) for near-surface structural studies in the immediate Yucca Mountain area, and intermediate-depth reflection surveys (IDRS) and deep reflection profiles (DRP) peripheral to the YMCCA. Severe signal attenuation in the low-velocity volcanic tuffs appears to have been a serious limitation to almost all shallow surveys, to the extent that McGovern and others (1983) recommended against any additional reflection surveys in the YMCCA. In 1993, Lawrence Berkeley Laboratory personnel completed three short high-resolution reflection profiles totaling 5 km which indicated that the Ghost Dance fault is part of a complex zone of faulting and fracturing that is several hundred meters wide (Oliver and others, 1995).

A hybrid source reflection survey designed to map the Tertiary-pre-Tertiary interface across Crater Flat and Yucca Mountain was completed in 1994 and this effort (finally) resulted in useful and very significant reflection seismic data (Brocher and others, 1996). Two lines were completed using a mix of seismic sources including vibrators, Poulter shots, minihole patterns, and explosive shot holes. Line 2 of this survey extended 26 km northeast from the Amargosa Desert through Steve's Pass, across southern Crater Flat and Yucca Mountain, terminating near drill hole UZ16. Line 3 of the survey trended easterly across Yucca Mountain, Forty-mile Wash, and Jackass Flats for a distance of 11 km. Data processing and interpretation were supported by vertical seismic profiles (VSPs) and well logs. Reflection quality was stated as "fair- to-good" for Crater Flat and Jackass Flats, with "useful, lower-quality data" for the Yucca Mountain part of the profiles (Brocher and others, 1996). Of particular interest is a reflection mapped discontinuously at depths of about 2100 to 1800 m depth between the Ghost Dance Fault and Jackass Flats which was interpreted as the Paleozoic-Tertiary contact. This information indicates that any mineralization hosted by Paleozoic rocks beneath Yucca Mountain would be quite deep, and difficult and costly to explore and develop. The reflection seismic data contribute no significant information regarding mineral potential within the Tertiary volcanics.

5.4.6.3. Teleseismic tomography studies

Teleseismic tomography studies have been completed at Yucca Mountain and the adjacent Nevada Test Site to search for the presence of magma chambers, partial melt zones and deep tectonic structures that could relate to long term repository performance. Neither the physical properties measured or inferred (P-wave travel times, travel-time residuals, and P-wave velocities) nor the earth volume resolution are appropriate for the discrimination of economic mineral deposits. However, geologic information derived from the studies, may have some bearing on the potential for mineral deposits. Oliver and others (1990) and Evans and Smith (1995) reviewed teleseismic studies for the Yucca Mountain area.

Evans and Smith (1995) presented the current models for regional-scale (NTS) and detailed scale (Yucca Mountain) teleseismic velocity structure in the area. Fine-scale models of the crust and upper mantle beneath the Yucca Mountain area can distinguish two or three crustal levels and horizontal areas as small as about 4 km. Evans and Smith (1995) concluded that the low-velocity Cenozoic section that fills the Crater Flat depression dominates the shallow crustal structure, and noted that the observed teleseismic signature of this feature correlates closely with the isostatic gravity anomaly for the same region reported by Evans and Oliver (1987). Tomographic inversion of the teleseismic data indicates that the east edge of the Crater Flat basin falls near or inside the western side of the repository block. Evans and Smith (1995) removed the effects of basin fill and found that a significant low-velocity anomaly, 2-3% lower than the velocity beneath Yucca Mountain, remains in the middle and lower crust beneath Crater Flat. The implications for mineral potential are that mineralization in pre-Tertiary rocks, such as that at the Sterling Mine on Bare Mountain to the west, is prohibitively deep or not present along the western margin of the YMCCA. The potential for mineralization within low-velocity, low-density Tertiary volcanic rocks in not addressed by these data.

5.4.7. Electrical and electromagnetic studies

Electrical resistivity, expressed in ohm-m, is a basic physical property of rocks and minerals that may vary through many orders of magnitude - a range of more than 10^6 for minerals, and as much as 10^4 for bulk rock volumes measured in place with surface geophysical methods. Bulk rock resistivity is a function of fluid content, mineral composition and temperature. Electrical geophysical methods are commonly used to characterize rock types (including surveys for precious metals exploration [Hoover and others, 1991]), to search for very low resistivity (highly conductive) massive sulfide deposits, and to identify disseminated sulfide deposits through induced polarization (IP) measurements which record minerals with high ionic-exchange capacity (Oliver and others, 1990; Corbett, 1991). Some methods are used mainly for determining the variation of electrical resistivity with depth.

5.4.7.1. Magnetotelluric surveys in the Yucca Mountain region

Klein (1995) presented a short description of the magnetotelluric (MT) method and described regional MT surveys in the Amargosa Desert and Nevada Test Site areas. MT surveys, which measure the earth's electric and magnetic fields at frequencies between 0.0003 and 100 hertz (Hz), are used to probe the earth's resistivity structure to crustal or upper mantle depths (2-50 km). Although it is capable of yielding information on resistivities at great depth, the MT method has relatively poor resolution and high cost per station. MT stations are typically separated by 5 to more than 20 km. Higher frequency natural field methods (Audio-frequency or AMT; 4-20,000 Hz) typically result in higher-resolution near-surface (0-2 km) electrical resistivity distributions.

Klein (1995) reviewed the application of MT surveys in the vicinity of the NTS and discussed the results. Early (pre-1980) regional MT surveys at the NTS identify a shallow, thin, low-resistivity (10 ohm-m or less) zone at depths of 2 to 6 km, and a deep low-resistivity zone at depths of 10 to 50 km. Furgerson (1982) reported on the first remote-reference, seven-component tensor MT survey in the NTS region, a set of 16 soundings. In 1986 the USGS completed a single profile of MT stations across the Bare Mountain-Crater Flats-Yucca Mountain- Jackass Flats area. Station spacings along this profile vary between 5 and 10 km, and many soundings indicate 2-D and 3-D effects (Klein, 1995). Figure 8.3 shows the location of five MT stations nearest to the YMCCA reported by Furgerson (1982) and Klein (1995). Only one site, station 31, lies within the YMCCA and one station, 32, was located in the Calico Hills area. Numerical modeling of the data reported by Klein (1995) indicated the following: (1) a surface layer of generally low resistivity (10-100 ohm-m) extends to depths of 0.5 to 2 km; and (2) an upper crustal layer of low-resistivity is present at depths of 10 to 30 km. Klein noted that the upper crust above about 5 km is quite inhomogeneous. The MT data provide limited information about the regional and local resistivity structure near Yucca Mountain but would not be expected to, and do not, indicate the presence or absence of mineral deposits in the areas surveyed. On the basis of these widely separated MT stations, Klein inferred generally low electrical resistivity and considerable inhomogeneity in the surface to 2 km depth range.

5.4.7.2. Electrical resistivity and controlled-Source electromagnetic methods

A variety of electrical and electromagnetic surveys have been completed by the USGS or by contractors under USGS supervision within the NTS and adjacent areas, and these were described and reviewed by Oliver and others (1990). Individual reports describe the results of resistivity, IP, Schlumberger vertical electric soundings (VES), and time-domain electromagnetic (TDEM) methods in substantial detail. Collectively these studies provide additional detail on the resistivity distribution surrounding Yucca Mountain to considerable depth (VES, AMT, TDEM, dipole-dipole), and detect and delineate faults and fracture zones within and peripheral to the YMCCA (Slingram, very low frequency-VLF, Telluric-ratio, dipole-dipole). Oliver and others (1990) provided a useful critique of the main results and effectiveness of the various methods, which will not be repeated here.

Figure 8.3 shows the location of three of the more significant electrical surveys at Yucca Mountain. Profiles E1 and E2 include 14 Schlumberger VES soundings by Senterfit and others (1982). The observed data were interpreted as one-dimensional layered earth models and then presented as geoelectric cross sections showing the resistivity distribution to depths of about 600 m. Profile E1 trends south-southeast from Yucca Wash and the geoelectric cross section shows interpreted resistivities of 100 to 1000 ohm-m for near-surface volcanic rocks. At a depth of about 300 m resistivities begin to decrease to about 100 ohm-m at depths of 600 m (Senterfit and others, 1982). Significant lateral variations are present. Profile E2 trends southeast in Drillhole Wash and shows sharp changes in resistivity from 100 to 1000 ohm-m for depths of 80-350 m, and a general decrease to less than 270 ohm-m at greater depths.

Frischknecht and Raab (1984) completed a detailed time-domain electromagnetic (TDEM) profile of 16 soundings from the east flank of Yucca Mountain across Jackass Flats (fig. 8.3). They showed that TDEM emphasized changes in the geoelectric section with depth when compared to dipole-dipole resistivity results (fig. 8.4), and derived a geoelectric section indicating a low resistivity (20-35 ohm-m) layer at depths of about 1000 m. Frischknecht and Raab (1984) noted that the lower resistivities correspond to lower resistivities beginning at depths of 600 m indicated by induction logs in drill hole H4, and an increase in alteration of tuffs to clay and zeolite minerals below a depth of 981 m in drill hole G1 reported by Spengler and others (1981). They concluded that Schlumberger and large-offset, frequency-domain sounding curves appear to be more distorted by lateral variations than the TDEM sounding curves. Neither the TDEM or VES resistivity data indicate the presence of metallic (or other) economic mineral deposits, but they do indicate a wide range of earth resistivities that could include such deposits.

Seven dipole-dipole resistivity profiles with induced polarization (IP) were completed by the USGS and selected profiles (of 61 m, 152 m, and 305 m dipoles) were quantitatively interpreted with two-dimensional modeling (Ross and Lundbeck, 1978; Hoover and others, 1982; Smith and Ross, 1982). These type of data are often used by mining companies in exploration for porphyry copper (and other disseminated sulfide) mineralization. The profiles and subsequent interpretation resolved a major fracture zone, indicated by resistivity discontinuities and low resistivities, in Drill Hole Wash along the eastern flank of Yucca Mountain. The data also identified a large area with uniformly high resistivity, and low to moderate frequency effects (IP of 0.3 to 2.5 PFE), west of Drill Hole Wash. Background frequency effects observed throughout this survey were about 1.0 to 1.5 PFE. The slightly elevated frequency effects (1.5-2.5 PFE) were attributed to clay and zeolite minerals in the altered volcanic rocks.

Figure 8.4 shows the interpreted resistivity sections for the Quaternary alluvium and Tertiary volcanic section beneath TDEM Line #1 (Frischknecht and Raab, 1984), and the dipole- dipole line E9 (Line B' in earlier reports) reported by Smith and Ross (1982). Dipole-dipole profile E9 is located about one km north of TDEM Line #1 and extends farther to the west. When numerically modeled, it defined a second layer of higher resistivity (600-1000 ohm-m) in agreement with corresponding Schlumberger data (Senterfit and others, 1982). The dipole-dipole model for line E9 detected a third layer of lower resistivity (200-550 ohm-m) where the TDEM sees a layer of lower resistivity (50-100 ohm-m) at comparable depths. The dipole-dipole model is not well-constrained below 600 m depth. The low-resistivity units present at depths of about 1000 m (20-36 ohm-m and 10-15 ohm-m, from TDEM #1) probably correspond to altered volcanic tuff with clay minerals that is present below the water table (Frischknecht and Raab, 1984). These low-resistivity units may preclude the deep current penetration of induced polarization arrays required for direct detection of sulfide mineralization at depths greater than 1000 m. The more responsive bodies (IP of 2.5 PFE) modeled at depths of 300 to 500 m on dipole-dipole Line 9 suggest some possibility of low sulfide (less than 0.5 weight percent) in rocks, if all of the response could be attributed to sulfide mineralization. — how likely is this ?

A single dipole-dipole resistivity profile with 305 m dipoles was completed by the USGS at the Wahmonie Flat area to test for the presence of an intrusive body. Numerical modeling of this profile indicated the presence of a fracture zone, and a minimum of 1 to 2 weight percent sulfides, based on observed values of 3 to 4.9 PFE and modeled (intrinsic) values of 7.5 PFE at depths below 305 m (Smith and others, 1981; Hoover and others, 1982). The estimation of sulfide content from resistivity and IP data is described by Nelson and Van Voorhis (1983). To our knowledge, this is the most convincing evidence of mineralization potential in the electrical geophysical database published for the Yucca Mountain region. The Wahmonie area lies 25 km east of the YMCCA, along magnetic and gravity trends discussed earlier.

5.4.8. Data coverage

As shown in figure 8.3, electrical geophysical surveys were only conducted over a small part of the potential repository site and the YMCCA. Areas not covered by survey profiles have not been tested directly for resistivity structure or the presence of sulfide or other mineralization, and those areas that were covered have been tested only to limited depths. Only one resistivity/IP line, E9, tests for the presence of sulfide mineralization to depths of 450-600 m, so less than five percent of the YMCCA has been surveyed with IP to these depths. We can infer from drilling and other geophysical results (gravity, magnetic, refraction seismic) that the depth to pre-Tertiary bedrock exceeds 1000 m in most of the YMCCA. This substantially exceeds the depths tested, and the depths that can be substantially tested, by electrical resistivity/induced polarization and electromagnetic methods. The possible presence of sulfide mineralization in the volcanic tuffs is likewise not tested, due to lack of resistivity/IP coverage and/or depth penetration. Additional testing for the presence of disseminated sulfide and other mineralization could be undertaken in the Calico Hills and Wahmonie areas, but these areas are outside of the YMCCA and need not be addressed further.

A number of shallow-penetration electrical resistivity and electromagnetic surveys (Slingram, VLF, Turam; Oliver and others, 1990) have been used in investigation of possible fault and fracture zones at Yucca Mountain, and elsewhere on the NTS. The surveys collectively appear to have been successful in detecting resistivity contrasts across faults, and detecting shallow, low-resistivity zones associated with alteration and fracture zones within the Tertiary volcanic rocks. In this sense the data may offer evidence of fluid flow paths and alteration in the volcanic rocks, but mineralogical and geochemical studies to date offer no indication of potentially economic mineralization associated with these shallow features.

5.4.9. Aerial gamma-ray surveys

Oliver and others (1990) described the availability of National Uranium Resource Evaluation (NURE) aerial gamma-ray spectrometry data for the Nevada Test Site and nearby regions. Data for the Death Valley NTMS (1:250,000) quadrangle were collected along north- south flight lines spaced 1.6 km apart. Duval (1987) compiled the survey data for the state of Nevada at a scale of 1:750,000, and Duval and Pitkin (1988) provide an interpretation for these data. Oliver and others (1990) recommend study of these data to determine the geologic significance of the data and to determine the location of follow-up ground surveys if warranted. We are unaware of any detailed gamma-ray spectrometry studies which relate to the YMCCA. Examination of the data produced during the National Uranium Resource Evaluation

(NURE) study of the Death Valley 1:250,000 quadrangle (Geodata International, 1979) did not indicate the presence of radiometric anomalies in the YMCCA or nearby.

5.4.10. Borehole geophysical studies

Borehole geophysical logs might well be expected to give some indication of mineral potential independent of visual and analytical studies. Nelson and others (1991) presented a thorough study of 40 boreholes at Yucca Mountain, and reduced-scale composite logs for these boreholes. They also reviewed a large number of earlier studies completed on these boreholes. Nelson and others (1991) addressed mineralogy indications in the logs, and conclude that porosity is usually the most important control on density, neutron, velocity, and resistivity logs, and that resistivity is low where zeolites and clays are abundant. Porosity often relates to the degree of welding of the tuffs. High gamma ray radiation, generally greater than 150 API units, is attributed to the potassium in the alkali feldspars and to their alteration products. They noted that induced- polarization logging would normally be diagnostic for zeolites, but this does not appear to be the case in Yucca Mountain drill holes. There seems to be little indication of economic mineral potential in borehole geophysical studies reported to date. Geochemical and mineralogical studies of drill hole core and cuttings are discussed in earlier sections of this report.

5.4.11. Discussion

The Yucca Mountain area, the NTS, and surrounding regions are adequately covered by a series of aeromagnetic surveys of sufficient detail and quality to assist in a metallic mineral assessment of the YMCCA. The surveys have been properly adjusted and merged, using state-of-the-art techniques, to form regional surveys of the Nevada Test Site, the Beatty 1:100,000 quadrangle, and the State of Nevada. These regional surveys provide the basis for identifying regional trends which may relate to major geological structures which control or are associated with economic mineralization. Positive magnetic anomalies that may arise from pre-Tertiary crystalline or intrusive rock at shallow depths within Walker Lane structural blocks include mineralized areas in the Calico Hills and Wahmonie Districts, which appear to be part of a northwest-striking zone that extends into the area of the northern Yucca Mountain and Tram Ridge-Thompson Mine mineralized areas. This trend projects along the northeast boundary of the YMCCA (fig. 5.5). Positive magnetic anomalies at Calico Hills and Wahmonie probably arise from intrusive sources and the alteration of pyrite to magnetite as a result of heating pre-Tertiary argillite overlying the intrusives. The Oak Spring District also overlaps with an intense positive aeromagnetic anomaly that probably reflects the presence of the Climax intrusion. Weak magnetic anomalies related to intrusive activity may be present in the Bullfrog District, but the northwesterly zone of intense anomalies trends to the north of this important precious-metal district. Aeromagnetic intensity is relatively weak over Crater Flat and the south part of the YMCCA, and the Mine Mountain and Bare Mountain Districts do not correspond with regionally significant anomalies (figure 5.5). Specific numerical modeling should be completed to determine if a 280 nT anomaly near the northwest part of the YMCCA could arise from a buried intrusive within the volcanic section.

Gravity data, both detailed and regional, are also of adequate quality and coverage to aid in the evaluation of metallic mineral potential in the YMCCA, although these data are only indirect indications of mineral potential. Gravity trends are present, but, as in the case of the magnetic data, they are discontinuous at Crater Flat and weak at Yucca Mountain. The interpretation of gravity data, even with good control on the density of geologic units, is subject to considerable ambiguity. The USGS has made good use of refraction seismic data to reduce the ambiguity of gravity interpretations in the Crater Flat-Yucca Mountain area, especially with respect to depth to pre-Tertiary rocks. An integrated interpretation of gravity and seismic refraction data by Ackermann and others (1988) indicates depths to pre-Tertiary bedrock exceed 1,300 m beneath most of the YMCCA, and this has been corroborated by later interpretation of gravity data (Clayton and Zelinski, 1996; Clayton and others, in review). Recent seismic reflection results suggest Paleozoic rocks may be even deeper (1,800 to 2,100 m) beneath most of the YMCCA (Brocher and others, 1996). Figure 8.5 shows the area where low density Cenozoic volcanics and alluvium probably exceed 1.5 km, as inferred from gravity, seismic reflection, and seismic refraction data, and drill results. The exact nature of the Crater Flat feature is still open to debate although numerical models indicate the geometry of the basin could arise from a graben- like structural feature rather than a caldera.

Teleseismic and magnetotelluric data do not contribute significant information regarding the mineral potential within the YMCCA. Electrical resistivity and electromagnetic methods (TDEM, VLF) cover only a limited part of the YMCCA, and these surveys address structures, stratigraphy, and alteration within the (near-surface) volcanic tuffs. Combined with the inferred depth to pre-Tertiary rock, the low resistivities at depth suggest poor current penetration to pre-Tertiary rock depths for mineral exploration methods (such as induced polarization) presently favored by the mineral exploration industry. The widely-spaced electrodes required for deep exploration, and resistivity and chargeability variability within the volcanic tuffs, suggest electrical methods exploration to depths in excess of 1000 m would likely be unsuccessful within the YMCCA. Dipole-dipole resistivity/IP surveys at Wahmonie, more than 25 km east of the YMCCA, suggest a broad area of buried disseminated sulfide mineralization that is associated with a magnetic anomaly and low resistivities (indicated by Schlumberger VES) that indicate the presence of alteration and mineralization (Hoover and others, 1982). Magnetic and gravity trends extend from the Wahmonie area toward the YMCCA, but based on gravity studies and available drill sampling, sulfide mineralization in pre-

Tertiary rocks (if present) would occur at depths in excess of 1,000 m. Sulfide enrichment at such depths probably could not be detected or resolved by present day electrical exploration methods, even at great care and cost.

The geophysical data and interpretations reviewed in this study do not directly indicate the presence of metallic (or other) mineral potential within the YMCCA. On the basis of geochemical studies there is some possibility of mineralization in pre-Tertiary rock. The depth to this rock and low- to moderate electrical resistivities in overlying volcanic tuffs make it doubtful that electrical methods would be able to resolve the presence of mineralization at depth with any confidence. Electrical methods do indicate low electrical resistivities associated with fracture zones and alteration zones within the Tertiary tuffs but where these have been evaluated geochemically there is no direct indication of the presence of significant metallic mineralization. Limited induced polarization measurements indicate some weak polarization zones within the volcanic tuffs but above background polarization could arise from clay and zeolite minerals as well as from sulfide mineralization. Interpretation of numerically modeled IP and resistivity data suggests sulfide (pyrite) concentrations could be as great as 0.5 weight percent if the IP responses observed were entirely due to sulfides.

One area of possible exploration interest within or adjacent to the YMCCA is the source area of a magnetic anomaly which occurs along the northwest margin of the YMCCA (fig. 8.5). There is some possibility that the source is an intrusive body at depths of 400-1000 m within the volcanic tuffs. The source area could be tested for the presence of sulfide mineralization to depths of about 600 m with state-of-the-art resistivity/IP, but the effort could be inconclusive for mineralization at greater depths.

5.5. REMOTE SENSING

Castor and others (1990) reported on remote sensing alteration work using thematic mapper imaging in the Yucca Mountain region and found that such evidence of alteration is confined to bedded tuff units in part of the YMCCA whereas it crosses lithologic units in nearby mining districts and mineralized areas. Remote sensing work done for this study used similar technology and showed

Remote sensing with thematic mapper images has been employed in mineral exploration programs to detect alteration minerals that contain hydroxyl ions, chiefly clay minerals, using the band ratio TM5/TM7. In the false color images in plates 3-5, such occurrences are shown as red areas. Unfortunately, other rock types, including light colored tuffs and metasedimentary rocks also have a

3/24/97 version

always in the cores of pyrite grains. Metallic gold was not noted in this sample, but this may be because gold is present at low concentration relative to gold ore.

The origin of the pyrite in the stylolitic fractures is not clear. Stylolites are considered to form by dissolution in carbonate rocks. In general, material in stylolites is thought to accumulate as insoluble minerals during dissolution, such as clay, iron oxide, and carbon compounds that build up during this dissolution. Although the sulfide may have accumulated in this way, it was probably introduced following stylolite formation by hydrothermal activity, which also introduced the gold and other trace metals.

Three types of evidence suggest that gold enrichment in hole p1 is similar to gold mineralization at the Sterling Mine. These include the presence of gold in Paleozoic carbonate rock that is partly silicified and clay altered, similar trace element suites, and the presence of arsenic-bearing pyrite. Stylolitic fractures that carry sulfide have not been reported at the Sterling Mine, but could easily have been missed.

6. CONCLUSIONS

6.1. INTEGRATION OF GEOLOGICAL, GEOCHEMICAL, GEOPHYSICAL, AND REMOTE SENSING DATA

Although no economic metallic mineral resources have been identified, there is clear evidence for hydrothermal activity at depth in the northern part of the YMCCA. Clay mineral assemblages indicate that temperatures of about 250° C at a depth of 1500 m and as high as 300° C at 1800 m were attained during alteration in the north part of the YMCCA, but rocks at 1500 m in the south part of the YMCCA were exposed to temperatures of less than 75° C during alteration (Bish, 1987). On the basis of this, Bish and Aranson (1993) postulated a hydrothermal system related to Timber Mountain Group magmatism at depths in excess of 1100 m in the north part of the YMCCA.

Surface geologic work and geophysical and remote sensing evidence suggest that intrusive activity with attendant hydrothermal activity may have taken place along a west-northwest trending zone extending from the Wahmonie district on the southeast, through the Calico Hills district and the Claim Canyon and northern Yucca Mountain mineralized areas, to the Tram Ridge-Thompson Mine mineralized area on the northwest. Such a zone would extend along but mainly north of the northeastern border of the YMCCA.

In the Wahmonie District, which contains quartz-adularia veins with high-grade silver-gold mineralization, is in an area of widespread limonitization and clay-mineral alteration that can be seen on remote sensing imagery (Plate 5). The alteration and mineralization at Wahmonie is in 13-Ma intermediate volcanic rocks, is spatially associated with exposures of intrusive granodiorite, and is speculatively related to this intrusive activity (Castor and Weiss, 1992). K-Ar isotopic ages of adularized intermediate flow rock date this mineralization at 12.6 ± 0.4 and 12.9 ± 0.4 Ma (Jackson, 1988).

In the southern part of the Calico Hills District, a large area of shallow acid sulfate alteration and hematitization, which is strikingly displayed by remote sensing imagery (Plate 4), occurs in rocks as young as 12.7 Ma. This altered area contains low-grade mercury mineralization with slightly elevated selenium. On the basis of samples collected for the present study, the Calico District contains little evidence for base- or precious-metal mineralization except in veins in Paleozoic rocks in the north part of the district that may be unrelated to alteration in the southern part of the district. It is possible that the southern Calico Hills hydrothermal alteration is a high-level representation of the more deeply exposed Wahmonie hydrothermal system, and earlier workers have proposed that deeply buried intrusive activity caused structural doming and mineral alteration in the Calico Hills. K-Ar isotopic ages of alunite date this mineralization at 10.4 ± 0.3 Ma (Jackson, 1988).

The Claim Canyon and northern Yucca Mountain areas have trace element contents similar to those in the Calico Hills District (mainly minor mercury enrichment). The alteration areas associated with this mineralization are relatively small and weak as shown by remote sensing imagery (Plate 4), and by analogy to the Calico District may be related to minor amounts of deeply buried intrusive activity. Altered rocks in these two areas include rocks of the Paintbrush Group and the hydrothermal activity must therefore have been younger than 12.8 Ma; however, as pointed out by Weiss et al. (1993), older activity is indicated by sinter within Crater Flat Group rocks in the northern Yucca Mountain area.

The Tram Ridge-Thompson Mine mineralized area is in a large area of hydrothermally altered rock as shown by remote sensing imagery (Plate 4) and by field work done for this study. The alteration mineralogy and trace element chemistry is similar to that in the southern Calico Hills. The youngest rocks affected by alteration appear to be rocks of the Rainier Mesa Tuff and alunite from the area has been dated at 11.6 ± 0.4 Ma and 12.9±0.5 Ma (McKee and Bergquist, 1993, as cited in Mattson, 1994).

Geophysical work supports the presence of a large buried igneous intrusion in the Wahmonie District (Ponce, 1981; Hoover and others, 1982), and a west-northwest-trending zone of positive aeromagnetic anomalies extends from Wahmonie, through the Calico Hills, Claim Canyon, and northern Yucca Mountain, to the Tram Ridge area. These anomalies may be due in part to buried intrusions similar to that at Wahmonie, although they are clearly also partly due to extensive exposures of the Topopah Spring Tuff. This general pattern is also indicated by gravity highs in the Wahmonie and Calico Hills areas, although as noted in section 5.4.5 the gravity data suggests en-echelon east-west anomalies to the west of the Calico Hills. ??

The youngest stratigraphic units affected by the hydrothermal activity in this postulated zone of buried intrusive activity are rocks of the Paintbrush Group. In the YMCCA, Paintbrush Group rocks, whether exposed or intersected by drilling, are not hydrothermally altered or mineralized (except for local fumarolic activity). In addition, glassy rhyolitic flow rocks in the Calico Hills Formation intersected in hole WT16 in Yucca Wash are unaltered, whereas the same rocks in the southern Calico Hills nearby are locally to pervasively clay-altered and silicified. It therefore appears that the post Paintbrush alteration and mineralization that is present within a few kilometers of the YMCCA in the Calico Hills and in Claim Canyon does not extend into the YMCCA.

Hydrothermal alteration and slightly elevated pathfinder element anomalies are present below the level of the Calico Hills Tuff in the YMCCA, particularly in hole G2. On the basis of drill core and cuttings examined and sampled for the present study and during earlier studies (Caporuscio and others, 1982; Castor and others, 1992; Castor and others, 1993), samples from drill hole G2 show the most compelling evidence for hydrothermal activity in Tertiary volcanic rocks in the YMCCA that cannot be explained as the result of local minor fumarolic activity (as in the Paintbrush Group) or of inclusion of previously altered and mineralized material (as in the pyritic Tram Tuff). The evidence for hydrothermal activity in hole G2 consists of pyrite and other minerals (such as barite) in veins as well as the presence of propylitic and alkali feldspar alteration at depths in excess of 1600 m. In addition, hematite and manganese oxide veins in hole G2 contain elevated amounts of the pathfinder elements arsenic and antimony at depths as shallow as 700 m. Minor amounts of similarly veined rock with slightly elevated antimony were sampled by drill holes to the south of G2, such as in hole a1, c1, c2, and c3, but such rock is relatively rare, as is alteration of probable hydrothermal origin.

The presence of pre-Paintbrush Group hydrothermal activity in the northern Yucca Mountain area has been suggested by Weiss and others (1996) as an important factor in the evaluation of the YMCCA for epithermal precious-metal deposits. The implication of such occurrences is that Paintbrush Group rocks in the YMCCA may overlie, and thus mask, areas of mineralization in Crater Flat Group and older rocks. However, the trace element chemistry of samples from the northern Yucca Mountain area do not include elevated precious metal contents, and while such occurrences demonstrate that local hydrothermal activity took place during Crater Flat Group magmatism, they do not provide evidence for precious-metal mineralization at that time.

Areas of economic precious-metal deposits or clear potential for such deposits in the Yucca Mountain region include some possible pre-Paintbrush Group episodes of mineralization. Hydrothermal activity represented by altered and pyritized ejecta in the Tram Tuff is older than 13.45 Ma; however, the location of the hydrothermal system that supplied these fragments is not known and precious metal contents are low (Castor and others, 1994). Adularia from Wahmonie is as old as 12.9 Ma ± 0.4 Ma (Jackson, 1988) and is in the 13-Ma Wahmonie Formation which is overlain by the Topopah Spring Tuff. Precious-metal mineralization in the Bare Mountain area is also relatively old and hydrothermal alteration minerals have yielded dates as old as 12.9±0.4 Ma (Nobel and others, 1991). However, the inclusion of fragments of Paintbrush Group tuff in mineralized breccia from the Diamond Queen (Goldspar) Mine and alteration adjacent to the Secret Pass deposit that extends into the Paintbrush Group, as noted by Castor and Weiss (1992), indicates that this mineralization is post Paintbrush. It is clear that mineralization from neither of these areas is old enough to be coeval with sinter deposition beneath the 13.25-Ma Bullforg Tuff in northern Yucca Mountain.

In addition to the mineralization in the Calico Hills, Claim Canyon, northern Yucca Mountain, and Tram Ridge-Thompson Mine areas, which clearly postdate Paintbrush rocks, the Yucca Mountain region contains other examples of post-Paintbrush mineralization. The most important precious-metal deposits in the Yucca Mountain region — those of the southern Bullfrog District, are clearly younger than the Paintbrush Group, about 9-10 Ma (Jackson, 1988; Nobel and others, 1991; Eng and others, 1996). In addition, alunite from Mine Mountain yielded a date of 11.1±0.3 Ma (Castor and Weiss, 1992) but this may be unrelated to base-metal dominated mineralization in Paleozoic rocks at Mine Mountain.

In summary, although hydrothermal activity that has produced economic or potentially economic mineralization occurs in volcanic rocks to the west, north, and east of the YMCCA, no clear evidence for extension of this mineralization into the YMCCA exists. Although Tertiary volcanic rocks at depth in the north part of the YMCCA contain features that are suggestive of hydrothermal activity, there is no direct evidence for potentially economic precious-metal mineralization. Drill hole samples from areas with suggestive alteration, vein mineralogy, and pathfinder element abundance have low gold, silver, and base metal contents.

6.2. POTENTIAL FOR UNDISCOVERED METALLIC MINERAL DEPOSITS IN THE YMCCA BY MODEL TYPE

FROM 2ND 3D MODEL
CLAYTON AND OTHERS, IN REVIEW

contacts, although the primary source for fault trace locations outside the central block was the "Map Showing Fault Activity in the Yucca Mountain Area" (Simonds and others, 1995; qualified). Lithologic contacts from ESF mapping were incorporated for the North Ramp area (Barr and others, 1996).

2.2 GEOPHYSICAL DATA

Seismic, gravity, and magnetic profiles provided important information for construction of the geologic framework in the ISM2.0 (Plate 4). Where specific interpretations are given, these have been incorporated in the model. Gravity and magnetic profiles detected a feature interpreted as a horst beneath Midway Valley (Ponce and others, 1993). The authors interpreted fault offsets of 50 meters (164 feet) on the two bounding faults. This feature is included in the ISM2.0 as integrated with geologic map information by the USGS specifically for the ISM2.0.

Seismic reflection profiles (Brocher and others, 1996; Majer and others, 1995) have been used to formulate three-dimensional fault geometries and interpret stratal tilts.

The depth to top of Paleozoic strata in the ISM2.0 was calculated from gravity data (Majer and others, 1996). This surface was also modified to tie to faults, and is discussed in detail in section 6.1.1. 7.1.1 ?

References, data tracking numbers, accession numbers, Q status, and TDB submittal for geophysical data are shown in Appendix B.

2.3 MODEL ELEMENTS FROM OTHER SOURCES

The M&O provides updates of Exploratory Studies Facility (ESF) and potential repository plans in a volume model format compatible with 3D modeling software. The most recent ESF and repository layouts are incorporated into the framework model for display in plan maps and cross sections. The repository layout plan available during creation of the ISM2.0 is shown on Plate 1 (Stanley, 1996). The layout is being updated. The repository and ESF layouts are qualified data.

The Prow Pass Tuff (Plates 33-35) welded and lowe. .orth-south-trending lobe or axis of thickening that approximately co... ..da Test Site boundary (Moyer and Geslin, 1994).

The Bullfrog Tuff shows a thickening trend to the southwest in both total thickness and the thickness of the welded zone (Plates 37-39). The welded interior of the unit is 135 meters (481 feet) thick in borehole G-3.

The Tram Tuff (Plate 41) thins rapidly to the north from Drill Hole Wash. The unit has an axis of thickening extending from the head of Drill Hole Wash southward to drill hole USW G-3.

On the western side of the model area, the Prow Pass Tuff and older units dip moderately to the east, steeper than the shallower units (Plates 47-49). This geometry is shown in the regional seismic profiles where the east-dipping reflections are interpreted as artifacts (Brocher and others, 1996). The results of the 3D model suggest that the reflections are real, and that they represent the east-dipping lower Tertiary units.

7.1.1 Interpretation of the Paleozoic Unconformity

Two representations of the top of the Paleozoic surface are incorporated in this model. One is derived from the geophysical (gravity) intrepretation of the unconformity at the top of the Paleozoic rocks by Majer and others (1996), which does not incorporate offset by the major block-bounding faults (Plate 43A). The other is the same surface with interpretive offset along block-bounding faults (Plate 43B). The two interpretations differ by as much as 5000 feet locally beneath the potential repository area.

An interpretation of deep seismic profiles (Brocher and others, 1996) places a fault with major pre-Topopah offset (age unknown) under the repository block. The seismic data are of only fair interpretive quality, however, because of topographic, geometric, and geologic complexities. The interpreted fault occurs at the intersection of the two seismic lines, and is only apparent when the two lines are taped together (that is, literally cut with scissors and taped together); it is not apparent in the individual profiles. The interpreted fault has a probable strike (based on comparison with gravity data and gravity inversions) of NNE and becoming more northeasterly to the south, which is parallel to the Solitario and Paintbrush faults; yet for the seismic interpretation to be valid the fault must have ceased activity at least before the Paintbrush Group rocks were deposited (based on the constraints in the ISM2.0). We do not incorporate this interpretation in the ISM2.0 for four reasons. First, it would not be consistent with regional observations to assume that a major fault in a favorable orientation would have ceased activity while nearby parallel faults reached their peak activity. Second, the interpreted fault appears to be an artifact of taping the two seismic profile printed copies together. Third, attempts at corroborating the interpretation by gravity modeling along the line invoke density values which are not consistent with borehole gravimeter data. Fourth, the seismic signature of Paleozoic rocks intersected by borehole p#1 along the seismic profile can not be carried to the west because the Paleozoic-Tertiary contact in p#1 is a fault contact (the Paintbrush Canyon fault; down to the west) and the amount of offset of the Paleozoic rocks along this fault is not known.

In terms of 3D geometry and modeling, the interpretation of deep seismic profiles (Brocher and others, 1996) can not be spatially reconciled with the Paleozoic unconformity calculated by inversion of gravity data (Majer and others, 1996; Plate 43A). The gravity interpretation places the down-to-the-west scarp farther east than the seismic interpretation (Plate 44; the seismic scarp is at the west end of the green line), and provides a viable tie to known faulting not possible with the seismic interpretation. Plotted on top of the seismic profiles in Plate 44, the gravity interpretation provides a satisfactory interpretation because it places the highly reflective parallel reflections in the lower Tertiary units rather than in the highly deformed Paleozoic units, which would not be expected to produce organized reflections. The ISM2.0 incorporates the Majer and others (1996) interpretation because of its better tectonic and geometric fit with the rest of the model. The ISM2.0 Paintbrush fault's approximate location is dashed in Plate 44.

Two significant features of the Paleozoic unconformity of Majer and others (1996) can be related to surface features. The large down-to-the-west scarp or gradient west of the potential repository block can be tied to the Solitario Canyon fault (Plate 43B). Discussions with the PIs who performed the gravity inversion to calculate this surface reveal that their intent was to tie this gradient to the Solitario Canyon fault (personal communication, 12/1996). The second and largest down-to-the-west gradient or scarp passes just east of the potential repository block and is almost exactly parallel for its entire length (as far south as the Amargosa Desert) to the Paintbrush Canyon fault and its correlaries south of the model area.

We interpret the eastern scarp to be related to the Paintbrush Canyon fault (Plate 43B) based on their parallel trends, appropriate offset amounts, and spatial position. We interpret the Paintbrush Canyon fault as dipping 60 degrees in the upper kilometer and 50 degrees below that. We further interpret the scarp to be possibly a composite of several down-to-the-west offsets that can not be resolved by gravity methods. If the Paintbrush Canyon fault were not interpreted to be part of the Paleozoic unconformity offset, no viable tie of the fault to the unconformity would be possible; the fault would be required to pass through with little or no offset despite the fact that it offsets the Paintbrush Group rocks by 450 meters (1500 feet) and has the largest offset of any mapped fault in the model area.

At borehole UE-25 p#1, the top of the Paleozoic rocks is a fault contact interpreted to be the Paintbrush Canyon fault (Carr and others, 1986), which the original authors refered to as the "Fran Ridge fault". This data point provides three important geometric constraints for interpreting the Paleozoic surface. First, because the borehole intercept is in the fault plane, the unconformity surface is probably higher to the east by some small amount (probably less than roughly 30-40 meters or the resolution limit of gravity data). Second, the Paleozoic rocks in the borehole dip 45 degrees to the north, which could not produce organized reflections in a seismic profile. Third, the unconformity immediately to the west is downdropped by some unknown amount greater than 450 meters (1500 feet--the post-Paintbrush Group offset) and possibly much more, which makes tenuous any correlation of reflections from p#1 to the west. Because the seismic profile interpretation is heavily dependent on the tie from p#1 to the west, the geometry at p#1 places doubts on the interpretation. If, however, the ruling assumption of the seismic interpretation is valid (namely, that the Paleozoic rocks produce parallel, ringing, low-frequency, high-amplitude reflections), then the seismic interpretation could be valid. Because this interpretation is geometrically inconsistent with the rest of the model, however, it is not incorporated in the ISM2.0.

A significant feature of the Paleozoic unconformity that is not yet understood is the east-trending down-to-the-north scarp or gradient that truncates the largest down-to-the-west scarp. In Plate 43B it is shown with a more northeasterly trend, which in a more regional view ties to an apparent continuation of that scarp northeast of the Calico Hills.

7.2 INTERPRETATION OF FAULTS

The overall pattern of faulting at Yucca Mountain is that of increasing fault offsets, fault density, and stratal tilts toward the southwest (Fridrich and others, 1996). Faults within the model area can be classified as N-S trending block-bounding (a significant deformation boundary), NW-SE trending high-angle, or intrablock (or non-block-bounding; Day and others, 1996). The block-bounding faults in the ISM2.0 are the Paintbrush Canyon, Bow Ridge, Solitario Canyon, Fatigue Wash, and Windy Wash faults. All others that strike N-S are considered intrablock faults, and probably play minor roles in the overall deformation of the mountain.

The tectonic model favored by the geologic representation in the ISM2.0 is a coupled normal-strike slip regime as part of the interplay between the Las Vegas shear zone, Basin and Range-style extension, and faulting related to the Southwest Nevada Volcanic Field (Fridrich and others, 1996).

The northerly-trending fault system appears to have been dominated by a few faults, namely the Solitario Canyon and Paintbrush faults. The Windy Wash fault is also a major structure, but only a small part of it is present in the model volume. The Bow Ridge and Fatigue Wash faults bound blocks, but do not have offsets as large as the Solitario Canyon and Paintbrush faults. The large blocks of rock between the block-bounding faults were subjected to widespread fracturing which produced variably abundant faults with minor offsets. To match borehole p#1 and the Paleozoic surface, we interpret the Paintbrush Canyon fault as dipping 60 degrees in the upper kilometer and 50 degrees below that, and that the Paintbrush Canyon fault is one of the major contributors to the down-to-the-west downstep in the Paleozoic unconformity.

The main strand of the Paintbrush Canyon fault passes along the west side of Fran Ridge (Plate 1). Previous documents have labelled this segment as the Fran Ridge fault and have shown the Paintbrush Canyon fault bowing west around the boomerang-shaped hill between Fran Ridge and Bow Ridge(Carr and others, 1986; Scott and Bonk, 1984). Modeling in three dimensions and accounting for geologic mapping and the fault intercept in borehole p#1 require that the main strand of the Paintbrush Canyon fault be located on the west side of Fran Ridge and that

2nd 3-D Model, Clayton & others,

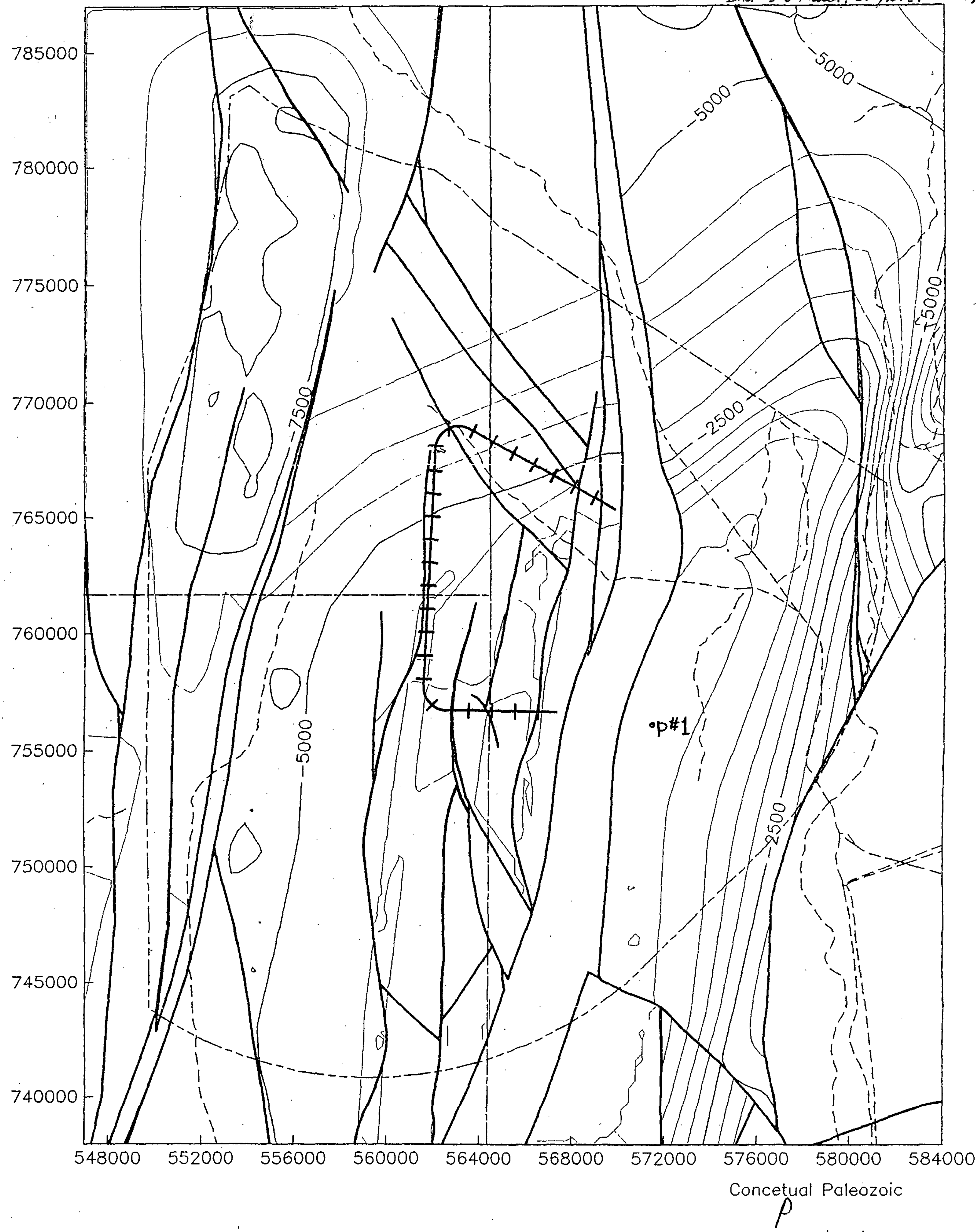
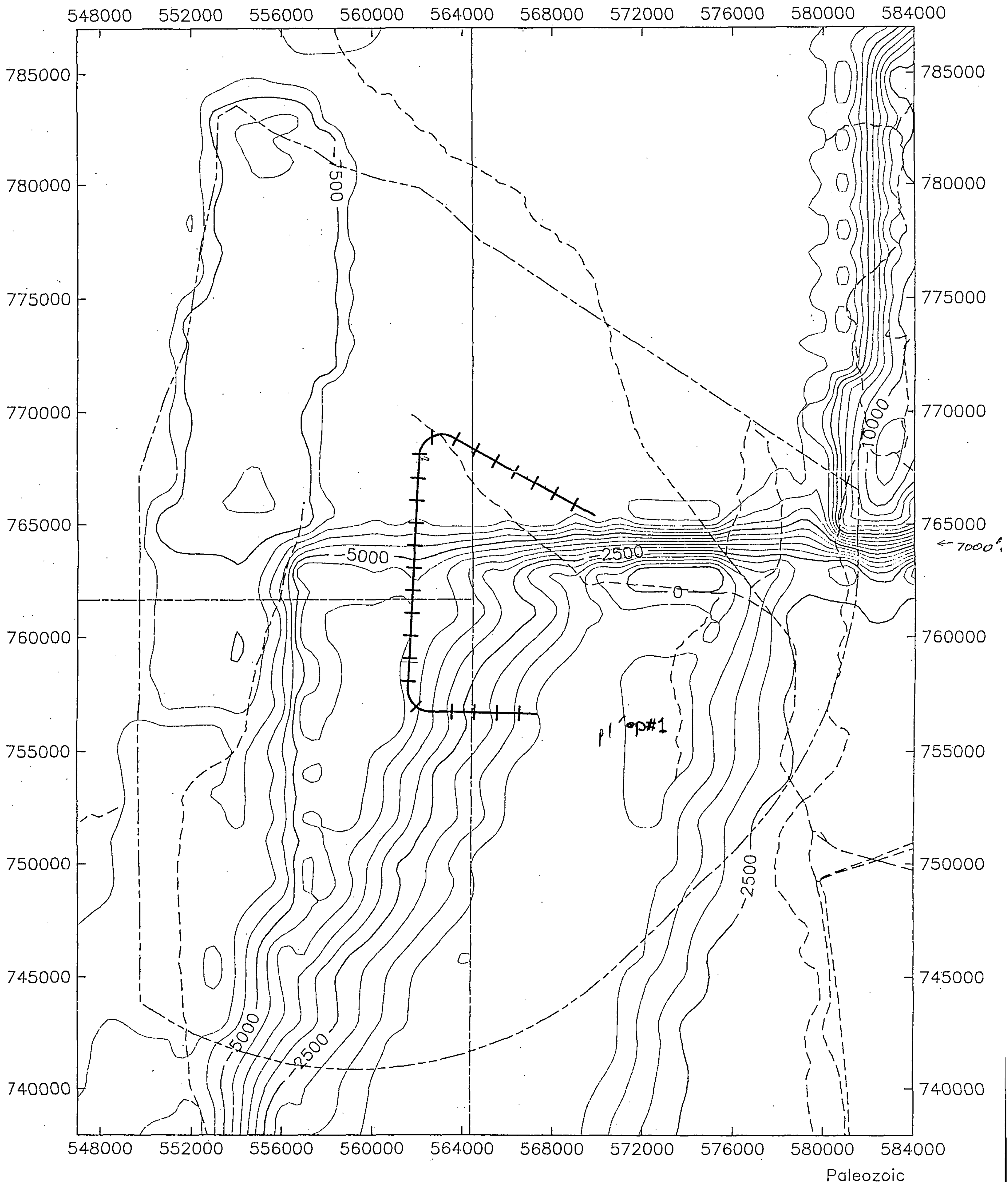


Plate 43B. A conceptual representation of offsets of the Paleozoic unconformity along the Paintbrush and Solitario Canyon faults. The fault contact in borehole p#1 is accounted for in this conceptual interpretation. Contour interval is 500 feet. Amounts of offset shown on the Paintbrush and Solitario Canyon faults are conceptual only.

7



5000'/inch

Plate 43A. Structure contours on the Paleozoic-Tertiary unconformity, as calculated from gravity data (Majer and others, 1996). Notice that this interpretation is inconsistent with the faulted contact in borehole p#1, as is the seismic interpretation of Brocher and others (1996).

where is