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Thermal and Petroleum Generation History of the Mississippian Eleana Formation and Tertiary Source Rocks, Yucca Mountain Area, Southern Nye County, Nevada

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CONTENTS

ABSTRACT

A geochemical and geologic assessment of petroleum potential in the Yucca Mountain area indicates little remaining potential for significant oil and gas generation in the Mississippian Eleana Formation or related Paleozoic rocks and a good, but areally restricted potential, in Tertiary rocks in area 8 of the Nevada Test Site. Mesozoic age source rocks are not present in the Yucca Mountain area.

The Tertiary source rocks in Area 8 are typically carbon-rich, and where hydrogen-rich, are good oil-prone source rocks. These oil source rocks are immature to marginally mature with respect to oil and gas generation. The hydrothermally altered Tertiary source rocks at north Bare Mountain retain little generation capacity.

A thermal history reconstructed for the Yucca Mountain area based on the Eleana Formation indicates petroleum was generated in the Late Paleozoic and possibly the Early Mesozoic and the oil has since been lost or was metamorphosed to pyrobitumen during later heating probably related to igneous activity. The Tertiary rocks are still capable of generating oil and gas, but little potential exists for a major hydrocarbon discovery due to the restricted occurrence of the good source rocks and their marginal thermal maturity away from intrusions.

INTRODUCTION

Major oil and gas potential has been attributed to the rocks in the Yucca Mountain area by Chamberlain (1991). Chamberlain's well publicized assertion caused some concern about the location of the Yucca Mountain Nuclear Waste Repository. Because of these concerns, this study was initiated and by this report gives the results of organic geochemical analyses, thermal maturation measurements and thermal history reconstruction used to evaluate the oil and gas resources of the Yucca Mountain area.

Previous work includes Harris et al. (1980) who reported on the thermal maturation of the Yucca Mountain area. More recent thermal maturation results are reported in Harris et al. (1992) and Grow et al. (1994). Primarily, their thermal maturation results show a small area of Paleozoic rocks on the upper edge of the oil window in the Yucca Flat area, some 25 km northeast of Yucca Mountain. However, as Poole and Claypool (1984), Palacas et al. (1988) and the results reported in this paper show the Paleozoic rocks are generally overmature and now have little remaining potential for oil generation. In addition, Aymard (1989) reported geochemical data that if the lower vitrinite reflectance values, which are probably due to weathering, are ignored reconfirm the rank range found by Harris et al. (1980).

The purpose of this paper is to model likely thermal histories for the Yucca Mountain area and use these models to explore various scenarios of heating that can explain the observed thermal maturity.

METHODS

The well samples were collected from the USGS core library, Mercury, Nevada (well locations shown in figure 1). Surface samples were collected during Fall, 1992 from exposures west and northwest of Yucca Mountain along the eastern and northern edge of Bare Mountain. James Yount (USGS, Reno, Nevada) contributed samples of Tertiary rocks near Mercury, Nevada, exposed just north of Mercury ridge in Area 5 of the Nevada Test Site. Yount reported these samples to have a fetid odor when broken, a signal that is inconclusive as to hydrocarbon content, but in any case the samples were tested for source rock potential.

Fluid Inclusions

Phase transition temperatures in fluid inclusions were determined in a Fluid Inc. heating/freezing stage. Note that the use of commercial names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey. The calibration is periodically checked using SYNFLINC synthetic fluid inclusions or ice baths. These measurements indicate a general accuracy of the temperature determinations is +/- 1°C in heating mode and +/-0.2°C in freezing mode.

The petrography of fluid inclusions is crucial to interpretation. Most fluid inclusions are secondary resulting from fracturing and healing of the host after precipitation. Secondary fluid inclusion homogenization temperatures (T_h) indicate fluid temperature present when the fracture healed. Secondary fluid inclusions are usually recognized by their occurrence as planes of inclusions cross-cutting crystal features.

Primary or pseudosecondary fluid inclusions result from fluid trapped in crystal defects during growth. Primary or pseudosecondary fluid inclusion homogenization temperatures indicate the minimum fluid temperature at the time of crystal growth. Unless zoning is present, textural evidence of the processes of primary fluid inclusion trapping may not be clearly expressed in the rock and their origin may be obscure. Direct evidence of the primary nature of fluid inclusions is rare in sedimentary rocks.

If a minimum burial temperature estimate for a rock is required, then most fluid inclusions can yield significant data regardless of origin or composition and without pressure correction. Several exceptions exist but the two most common ones are: (1) fluid inclusions that have necked and closed with two phases present (ex: liquid and vapor) resulting in the trapping of variable phase ratios, and (2) trapping of a heterogeneous fluid in an inclusion (ex: noncondensible gas and water). To minimize these problems, we measured only those fluid inclusions, that within a mineral zone or secondary plane, had consistent vapor to liquid ratios. Most changes in a fluid inclusion that make geothermometry invalid result in variable vapor to liquid ratios and these inclusions should not be used to estimate minimum temperature of formation.

The most direct use of fluid inclusion T_h data is to assume it represents a minimum temperature of entrapment (or host mineral formation) and not apply a pressure correction. Further, the presence of natural gases dissolved in the fluid inclusion contents can make T_h approach the trapping temperature (T_t) (Hanor, 1980). Our preliminary studies suggest that gas is commonly present in fluid inclusions. For these reasons, a pressure correction is not applied to T_h measurements in this study.

Rock-Eval Pyrolysis

Rock-Eval pyrolysis and measurement of total organic carbon (TOC) qualitatively evaluate organic matter geochemistry and thermal maturity but must be used with qualification of results from lean (0.5% TOC) rocks (Peters, 1986). Specific definitions for Rock-Eval data reports are: S_1 and S_2 are the first and second peaks of hydrocarbon yield occurring during pyrolysis of the sample (Fig. 2); S_3 is the amount of CO_2 generated during pyrolysis; TOC is total organic carbon; T_{max} is the temperature at which the S_2 peak occurs during pyrolysis of kerogen; Hydrogen index (HI) = $(S_2/TOC)x100$; Oxygen index (OI) = $(S_3/TOC)x100$; PI = Transformation ratio = $S_1/(S_1+S_2)$; PC=pyrolysable carbon in the sample. Rock-Eval pyrolysis only gives a semiquantitative estimate of the organic matter properties and is best interpreted as grouped data and generally by ignoring outlier data which may or may not be significant. Even with these limitations, the trends shown by Rock-Eval results, if checked by other analyses such as organic petrography, can be a useful indicator of thermal maturation and petroleum generation potential. In clay-rich rocks containing less than 0.5 weight percent TOC from humic organic matter, the hydrogen index (HI) is likely to be too low and T_{max} too high. Samples with less than 0.5 weight percent TOC are usually ignored to avoid these problems. Recent general discussions of the interpretation of Rock-Eval data are: Katz, 1983; Peters, 1986; Langford and Blanc-Valleron, 1990.

Organic drilling mud additives often increase the hydrogen index (HI) and TOC. Samples contaminated by particulate mud additives were detected by examination under a binocular microscope and removed by sieving, blowing on the sample to float off the lighter organic materials and finally picking rock chips with tweezers.

Rock-Eval pyrolysis is also influenced by migrated oil or bitumen. Such migration produces an S_1 peak greater than 2 mg hydrocarbon/g rock, an anomalously high transformation ratio and low T_{max} as compared to adjacent samples, and a bimodal S_2 peak. The low T_{max} may also be related to weak S_2 peaks resulting from low TOC values and not from organic contamination. Generally no oil staining or immature bitumen was observed in these samples, so this easily pyrolysable hydrocarbon is not a common interference in the Rock-Eval analyses of these samples at least at the low power magnification level of observation. However, pyrobitumen was commonly observed in many Eleana samples. Reflectance analysis shows this material to be overmature to supermature and probably does not produce a bimodal S_2 peak. However, the common pyrobitumen in the Eleana Formation found by this study suggests the TOC measurements may not accurately reflect the hydrocarbon generation potential and may have in some cases led to optimistic predictions of hydrocarbon generation capacity. The combination of HI, TOC, and organic petrography used in this study is a more consistent indicator of petroleum potential.

Pyrobitumen and Vitrinite Reflectance

Samples for pyrobitumen reflectance analysis were taken from wells (UE-1L, UE-17a, ER-12) and one surface sample supplied by James Cole (USGS, Denver) of the Eleana Formation exposed at Oak Spring at the north end of area 8 (Fig. 1). Pyrobitumen reflectance was also reported by Pawlewicz in Palacas et al. (1988) in well UE-25-P1 (Fig. 1). Tertiary coal or carbonaceous mudstone samples for vitrinite reflectance analysis were taken from side wall cores (wells UE-8f and U8d-PS-3aa) and drill cuttings (well UE-8h) in area 8. Reflectance was measured on polished whole rock samples using vertical illumination on a Zeiss Universal microscope fitted with a MPM-01 microphotometric system. The photometer was restricted with a pinhole diaphragm to read a 3 micron spot on the sample at 500x total magnification, using a 40x/0.85 n.a. lens under oil immersion (n_e = 1.518). The system was calibrated by a Zeiss leucosapphire standard that has a reflectance of 0.58% and (or) glass standard with a reflectance of 1.6 % with filtered 546 nm light. In mixed samples of vitrinite and pyrobitumen, the modal reflectance for that peak that represents each particle type (such as reported in Palacas et al., 1988) is reported . In kerogen populations with one mode, the mean value is reported.

Thermal History Reconstruction

Thermal history reconstruction in this study uses Platte River Associates (Denver, Colorado) BASINMOD version 2.72 computer program for burial depth and temperature computations. The key methods we invoked in BASINMOD to compute the burial history are Falvey and Middleton (1981; for sediment decompaction), Burnham and Sweeney (1989; kinetics of vitrinite reflectance evolution). Compaction and variable heat flow were toggled on. The observed thermal maturation data (Table 2) and the temperature data presented below were used to constrain the burial history reconstruction. In our thermal history models of the Eleana Formation and related rocks, the vitrinite reflectance predicted from LLNL kinetic model after fitting the thermal history to predicted peak temperature, generally agreed with the measured pyrobitumen reflectance value when converted to vitrinite reflectance equivalents. In the Tertiary source rocks of area 8, direct comparison of predicted and measured vitrinite reflectance was possible.

DATA SOURCES

Thermal Data

Thermal data are required to document or estimate the temporal change in surface temperature, heat flow and rock thermal conductivity which fixes the paleogeothermal gradients. Like burial history, thermal history is difficult to reconstruct because the heat flow regime has often changed (Vitorello and Pollack, 1980; Chapman and Pollack, 1975) and the thermal conductivity is altered by diagenetic/metamorphic changes in porosity and mineralogy, pore fluid composition, and so forth. However, stable heat flow conditions are probably rare in geologic history, so these thermal models use variable heat flow even though it can only be loosely constrained using present day analogs.

Surface Temperature

At present the mean annual surface temperature is about 10°C in southern Nevada estimated from temperatures recorded from near Tonopah, Nevada (Darton, 1913), a value measured before the possibility of atmospheric greenhouse heating. Late Mesozoic to Tertiary paleosurface temperature was estimated here using fossil evidence for paleoclimate (Savin, 1977; Fig. 3). The reconstructions from fossil evidence and paleopole data suggest that the generally increasing surface temperature through the Mesozoic (to 20°C in our model) is related to the drift of the continent through equatorial climatic zones (Smith and Briden, 1977). These surface temperature trends were extrapolated into late Paleozoic time with the justification that the carbonate platform rock being deposited for most of this time (Cook, 1988) suggests a subtropical or tropical paleoclimate.

Heat Flow

Present heat flow at Yucca Mountain is reported by Sass et al. (1988). These measurements suggest an average heat flow of 40-50 mW/m^2 (milliwatts per square meter) in the unsaturated zone near the surface of Yucca Mountain. In deeper wells that penetrate the saturated zone they found a heat flow of about $70 mW/m^2$, a typical value for the Basin and Range Province. A value of 70 mW/m^2 was used as an estimate of the heat flow at present and also as the general paleoheat-flow in our model during times of igneous activity (Fig. 3).

This heat flow value is somewhat less than the typical heat flow measurement in the Andes of 90 mW/m^2 which is noted as a possible modern analog to the Basin and Range Province in the Mesozoic and Paleogene (Cook, 1988). During times of rapid extension and crustal thinning, heat flow may have been higher (Vitorello and Pollack, 1980, p. 985) than the 70 mW/m^2 measured at Yucca Mountain today. Extension ceased at Yucca Mountain at 11 Ma (Galloway et al., 1991) so there is time for cooling. Muffler et al. (1979) show heat flow measurement of up to 90 mW/m^2 just northeast of the Nevada Test Site. Further, magmatism and deformation also occurred in the Jurassic, Cretaceous and Tertiary in southern Nevada. The major periods of magmatism in the Yucca Mountain area are Cretaceous and Tertiary (Cornwall, 1972; Frizzell and Shulters, 1990). In the absence of data to the contrary, heat flow during these older magmatic periods in southern Nevada is assumed similar to that existing now (70 mW/m^2; Fig. 3). A heat flow of 90 mW/m^2 was used in only one case to explore if Mesozoic magmatism may have caused the thermal maturity levels observed without needing any Triassic deposition. During times of no magmatism or extension, a heat flow value of 60 mW/m^2 was used because it is the average continental heat flow (Chapman and Pollack, 1975).

Thermal Conductivity

Thermal conductivity measurements were recalculated to a decompacted value of porosity. In a sedimentary rock of consistent grain size and framework grain composition, changes in porosity with compaction is the greatest factor in thermal conductivity, if the pores remain filled with water. For this reason, contemporary thermal conductivity measurements must be adjusted (lowered) to the former (higher) levels of porosity (Buntebarth, 1984). Most burial modeling programs use the geometric method of recalculating thermal conductivity (Sass et al., 1971). The rock lithology input into BASINMOD is as shown in Table 1.

Some direct thermal conductivity measurements are available. Sass et al. (1988) found the nonwelded tuffs had a modal thermal conductivity (λ) of 1 $Wm^{-1}K^{-1}$ and welded tuffs had a modal λ of 2.1 $Wm^{-1}K^{-1}$. Sass et al. (1988) also measured an average λ of 4.9 $Wm^{-1}K^{-1}$ (n= 12, s= 0.25) for the Lone Mountain Dolostone and reported one measurement of λ for the Roberts Mountains Formation at 5.5 $Wm^{-1}K^{-1}$.

Erosion Estimates/ Original Strata Thickness

Reconstruction of how much rock was present and when it was removed are by their very nature crude, because the value must be estimated from the eroded rocks that no longer exist. If available, the restored thicknesses of rock units given in Peterson (1988; in press), Cornwall (1972) and Poole (personal communication, 1993) for the Paleozoic and Mesozoic. Galloway et al. (1991) and Frizzell and Shulters (1990) for the Tertiary were used as noted in Table 1. Other variations of reconstructed thicknesses were considered in the burial history cases presented below.

BURIAL HISTORY

Forrest G. Poole (U.S. Geological Survey, Denver; written communication, 1993) provided detailed thickness and age data for Paleozoic rocks in the Yucca Mountain area based on his mapping and measured sections. In this report, the summaries of geologic history by Cornwall (1972), Hintze (1985; Pioche, Nevada and northwest Las Vegas Basin, Nevada, composite sections), Peterson (1988), Frizzell and Shulters (1990), and Galloway et al. (1991) are used extensively as guides to the Mesozoic and Cenozoic thermal events, ages and lithology of deposition, and the general geology of the Yucca Mountain area.

Paleozoic

Silurian and Lower Devonian

Roberts Mountains Formation, Lone Mountain Dolostone and overlying Simonson Dolostone were only mentioned in the thermal history reconstruction because the Roberts Mountains Formation and Lone Mountain Dolostone in Well UE-25-P1 were studied for fluid inclusions. They are not considered in the burial history because they are supermature and are not oil sources and perhaps only marginal gas sources (Palacas et al., 1988).

Upper Devonian

The Guilmette Formation and related rocks through the Limestone of Timpi Canyon (Table 1), by analogy to the nearby production in some Railroad Valley oil fields, are potential reservoir and source rocks in the Yucca Mountain area. Harris et al.(1980) found the Upper Devonian to be overmature. Peterson (1988) suggested up to 0.9-1.2 km of Devonian rocks in Yucca Mountain area. The Upper Devonian Pilot shale, a potential source rock in other portions of east central Nevada does not extend into the Yucca mountain area (Peterson, 1988). The Upper Devonian strata are conformable with the overlying Mississippian strata and must be supermature in all cases of the burial history reconstruction presented below because the overlying Eleana Formation is overmature in the most realistic cases of thermal history.

Mississippian

The Eleana Formation and Chainman Shale were deposited east of the Antler orogenic belt of central Nevada (Larsen and Langenheim, 1979). The Chainman Shale is a major source of oil in eastern Nevada (Poole and Claypool, 1984). The clastic rocks of the Eleana Formation were derived from the west and deposited in a foreland basin where they mixed with prodelta deposits of the Chainman Shale which were derived from the east. The Eleana Formation is exposed just east of Yucca Mountain and seems to be the only potential Paleozoic source rock relevant to this study. Cornwall (1972) indicates 2.3 km of Eleana Formation in the Yucca Mountain area. The Mississippian strata are conformable with the overlying Pennsylvanian strata.

Pennsylvanian-Permian

The Tippipah Limestone was also deposited in a basin east of the Antler belt. It consists mostly of carbonate rocks in eastern Nevada grading west into clastic rocks near the Antler orogenic belt (Larsen and Langenheim, 1979). Projection of approximate isopachs shown in Peterson (1988) indicates about 600m of Pennsylvanian rocks and about 600-900m of Permian rocks in the Yucca Mountain area. This combined thickness includes the Tippipah Limestone which is in part Permian in age.

Mesozoic

The Yucca Mountain area is considered to have been a sediment source area during most of the Mesozoic contributing detritus to adjacent areas. Except for possibly some areally extensive deposition during the Triassic (Hintze, 1985) there was no other significant areal Mesozoic deposition in the Yucca Mountain area. Peterson (1988) shows the possibility that up to 1,500-1,800 m of Triassic strata were deposited in the Yucca Mountain area. No Mesozoic rocks remain in the southern Nye County (Cornwall, 1972) and it is possible that they were not deposited. Our models include both an arbitrary deposition thickness of 1.5 km for Lower Triassic rocks for use in the maximum burial depth cases and cases of nondeposition of Triassic.

The Jurassic and Cretaceous are times of general non-deposition or erosion possibly related to the Sevier orogeny which began in the late Mesozoic and persisted perhaps into the early Tertiary. The Cretaceous is a time of magmatic activity (Cornwall, 1972, Frizzell and Shulters, 1990) that resulted in higher heat flow. We believe that these intrusions enhanced the uplift of rocks and erosion in the area. A regional unconformity cut during the middle Mesozoic to middle Cenozoic suggests little topographic relief was present during this time (Vandervoort and Schmitt, 1990). This period of uplift and maintenance of low relief is the reason for continuing erosion through the Mesozoic in the model rather than having a period of nondeposition during this time. The Eleana Formation (and Chainman Shale) was locally exhumed and exposed at the surface during the Mesozoic (Barker and Peterson, 1991). Weathering of the kerogen at the surface can sharply reduce source-rock potential. Any intrusive or extrusive igneous rocks or related hydrothermal activity in the proximity of immature to mature strata of the Eleana Formation or Chainman Shale would rapidly increase thermal maturation and cause oil and gas generation and, with extreme heating, destruction of the oil to form gas and pyrobitumen.

Cenozoic

Paleocene

The Paleocene was a tectonically quiet time with no magmatic activity and a low heat-flow. There was low topographic-relief in eastern Nevada, and it was a time of either nondeposition or minor erosion. The Eleana Formation and Chainman Shale may have been exposed to weathering during this time. During the early Cenozoic, the Basin and Range Province, apparently including the Yucca Mountain area, was a highland shedding sediment to the east (Stewart, 1983; Cook, 1988). Faulting within these highlands may have locally produced subbasins where lacustrine sedimentation occurred (Stewart, 1983).

Eocene

The Eocene was a time of expansion of subbasins and lakes initially formed in the Paleocene leading to a wider deposition of lacustrine strata. These strata include parts of the Sheep Pass Formation, a rich potential source rock, in the area of the Railroad and White River Valleys.

Oligocene

Stewart (1983) relates the initial formation of present-day tectonic features with the start of renewed magmatic activity during the Oligocene. In southeastern Nevada, during the Late Oligocene, there was renewed magmatism (Frizzell and Shulters, 1990), and apparently a higher heat-flow is related to the widespread extrusive igneous activity. Volcaniclastic rocks related to the magmatism marks the beginning of renewed burial of Late Paleozoic and Tertiary source rocks in the Yucca Mountain area. Valley-filling clastic rock deposition, including local lake beds, starting with the Horse Spring and Pavits Spring Formation (30 Ma) derived from the erosion of the adjacent highlands (Frizzell and Shulters, 1990).

Neogene

The Neogene marks a time of major tectonic disruption of eastern Nevada with the late Tertiary and Holocene extensional faulting commencing about 30 Ma (Bartley et al., 1988) and later at about 20 Ma in southern Nevada (Axen et al., 1993). This tectonic disruption formed the Tertiary basins where burial by valley fill led to the oil that is now found in eastern Nevada. In the Yucca Mountain area, valley-filling alluvial deposition and local lake beds, includes the Furnace Creek Formation in the Amargosa Desert (McAllister, 1970; 1973) and the 3 Ma old Lake Tecopa Beds (Wright et al., 1991) and as described below, in the Tertiary basins found below many of the valleys in the Yucca Mountain area. The lake bed source rocks appear to be post-extension and deposited after the time of caldera formation in the southern Nevada volcanic field because they appear confined to extensional structures and have not been heated more than that induced by their present day burial. Extension with caldera formation stopped about 11 Ma in the Yucca Mountain area (Galloway et al., 1991). Deposition of the lake beds like those found in Nevada Test Site Area 8, in Joshua Hollow, just north of Bare Mountain (Fig. 1), and in the Amargosa Desert, near the Flederhoff Well (F-F-5-1, Fig. 1; Brocher et al., 1993) occurred between the onset of extension and the present. Lake beds related to calderas such as in the Bullfrog Hills (Cornwall and Kleinhampl, 1964; 30 km southwest of Yucca Mountain) would be potentially younger-- formed after the 17 Ma when activity in the southern Nevada volcanic field commenced (Table 1). As shown below, these lake beds are areally restricted and vary from poor to rich oil and gas source rocks. The thickness of these lake beds is highly variable but seem to be on the order of 100m to 1000m thick in the Yucca Mountain area (Carr, 1974; Frizzell and Shulters, 1990; Brocher et al., 1993). Thickness of Neogene valley fill and volcanic rock deposition also highly variable but are estimated and modeled at 0-2,500 m and 1,000-3,000 m thickness, respectively.

The deeper burial in the high heat-flow regime existing in the Neogene has locally increased the thermal maturity of the Chainman Shale, which locally is preserved from the late Paleozoic burial heating, into the oil generation range in eastern Nevada (Barker and Peterson, 1991). These burial history models show that renewed burial of preserved Paleozoic source rocks appears to have generated the oil discovered in eastern Nevada (Barker and Peterson, 1991). As shown below, in the Yucca mountain area, Late Paleozoic to early Mesozoic burial appears to have destroyed the oil potential and it appears that source rocks were not preserved past the Mesozoic, so renewed burial of the Paleozoic rocks in the Tertiary had little effect on oil generation in the Yucca Mountain area.

RESULTS

Rock-Eval Pyrolysis

For the Eleana Formation and the Tertiary lake bed source rocks, the Rock-Eval data suggest that two end member types of kerogen exist within various beds of the source rocks (Fig. 4). A kerogen of either nearly 100% type I or nearly 100% type III composition is indicated for both ages of source rock.

Source rock geochemical analysis indicates that Paleozoic rocks with potential for generating hydrocarbons (table 1, as well as Poole and Claypool, 1984; Palacas et al., 1988 and Harris et al., 1992), essentially restricted to the Eleana Formation in the Yucca Mountain area, are in a few cases mature but mostly overmature to supermature and generally too lean in hydrogen content (HI) to be presently capable of generating significant oil and gas. Tertiary age potential source rocks are areally restricted to Area 8 of the Nevada Test Site but apparent lithologic equivalents occur in altered exposures to the northwest of Yucca Mountain on the north end of Bare Mountain. The Tertiary source rocks in Area 8 (Table 1) are typically carbon-rich, and where hydrogen-rich (HI of about 500 mg HC/gC in well U8d), are good oil-prone source rocks. These hydrogen rich source rocks are marginally mature with respect to oil generation (T_{max} of about 400°C; but a PI of 0.01). The hydrothermally altered Tertiary source rocks at north Bare Mountain retain little generation capacity as indicated by the low HI at less than 35 mg HC/g C and the T_{max} about 500°C.

Pyrobitumen and Vitrinite Reflectance

Pyrobitumen, like the more commonly used maceral, vitrinite, shows increased reflectance with heating. Like vitrinite, pyrobitumen reflectance has been correlated with peak temperature (Barker and Bone, 1993) and vitrinite reflectance (Jacob, 1975). Pyrobitumen was commonly found in the Eleana Formation as small fracture and pore-filling blebs in a number of wells in the Yucca flat area. Many of these grains were two small to measure properly as the particle only partially filled the measuring aperture in the microphotometer but nevertheless suggest a minimum reflectance in this sample. A pilot reflectance study shows that pyrobitumen in the Eleana Formation has a mean random reflectance (Rb-r) range of 2.2 to 6-7% which correlates with a peak temperature of about 150°C up to 400°C (Barker and Bone, 1993). The surface sample of the Eleana Formation at Oak Spring exhibited a granular mosaic structure and a pyrobitumen reflectance of 6-7%Rb-r that taken together suggest rapid heating and high temperature likely associated with contact metamorphism (Barker and Bone, 1993)

Vitrinite was common in the humic coals and carbonaceous mudstones forming the Tertiary source rocks of Area 8. The coaly material here was mostly bi- or tri-macerites composed mostly of textinite or texto-ulminite. Corpocollinite and suberinite are present as well as rare porigelinite. These coals have not been buried deeply as shown by the low degree of compaction suggested by open, relatively undeformed plant cell lumens and the overall low rank. Some vitrinite-rich layers showed extensive gelification and compaction to telocollinite.

In the samples that did not appear to be metamorphosed, mean random vitrinite reflectance (Rv-r) ranged from 0.39% at 1184 feet (well U8d-PS-3aa) to 0.5% (well UE-8h) at 1090-1150 feet to 0.37 at 2100 feet (well UE-8f). This reflectance suggests these rocks are immature with respect to oil and gas generation.

The side wall core sample at 1215 feet in well U8d-PS-3aa showed vesiculation and flow banding, petrographic evidence that these coals are coked. Rv-r was 1.33% on this vesiculated material. The vesiculated material is semifusinite-like and seems to have increased in reflectance without much gelification. The somewhat low reflectance may be explained by analogy to rapidly heated vitrinite in rocks near dike contacts that often show a low reflectance for the degree of heating. Note that the sample at 1184 feet in this well had a reflectance of 0.4% Rv-r and shows no petrographic evidence of coking or fusinitization, so the heating event does not seem to be widespread. This coking may be related to blast metamorphism by the Baneberry nuclear detonation some 300-400 feet away (U.S. Geological Survey, 1974). Numerous faults and fractures cut the Baneberry area and perhaps these controlled access of the metamorphosing fluids or gases. However, when measured in Fall 1993, some twenty years after the blast, these samples were not radioactive above background levels. Local coking caused by contact metamorphism from a nearby pluton seems unlikely because igneous rocks do not cut the U8d-PS-3aa well bore nor are they observed in the 10 other wells in the immediate Baneberry area. It is also possible that a fire in the coal swamp before burial, or other natural causes, may have caused the locally increased reflectance seen in the 1215 feet sample.

The Baneberry nuclear blast unexpectedly vented gases to the atmosphere. I speculate that a portion of these gases may have came from devolitization of the kerogen and coals during an apparent blast metamorphism event. However, there is insufficient information to conclusively determine the contribution (if any) of the kerogen and coal to the gases vented by the Baneberry event.

Fluid Inclusions

Polished sections for a preliminary fluid inclusion study were prepared from core samples (provided by James G. Palacas, USGS, Denver) of the Lone Mountain Dolostone and Roberts Mountains Formation from Borehole UE-25-P1, some 2 kilometers east of Yucca Mountain (Fig. 1). Only the Roberts Mountains Formation near 5900 feet (1798 m) had a few useable secondary fluid inclusions within a carbonate vein. Fluid inclusions homogenized over a wide range of 200-300°C. Although only based on a few inclusions these data support high temperatures reached in the Upper Paleozoic rocks. Bish (1989) found a similar range of homogenization temperature in the nearby wells USW-G1 and USW-G2.

This homogenization temperature range is roughly consistent with the CAI 4-5 for these rocks (Harris et al., 1980; Grow et al., 1994) which Nowlan and Barnes (1987) correlated with a temperature of about 200-300°C (Table 3). Further, Palacas et al. (1988) reports a modal vitrinite reflectance(Rv-mode) of 2.6% (modal pyrobitumen reflectance of 2.8%) for the Roberts Mountains Formation in UE-25-P1 well at 5916 feet. An empirical geothermometer based on vitrinite reflectance (Barker, 1993) would suggest a peak burial temperature of about 210°C, or if the rocks are hydrothermally altered, a peak temperature of about 275°C at a Rv-mode of 2.6%. The pyrobitumen reflectance geothermometer of Barker and Bone (1993) suggests an alteration temperature of about 200°C at 2.8%Rb-r.

Thermal and Petroleum Generation History

The thermal and petroleum generation history was modeled in four cases to allow for the major possibilities in the complex geological realm in the Yucca Mountain area. No Mesozoic rocks are found in southern Nye County area, but may have been deposited and eroded.

Tertiary units were only locally deposited and cannot be extrapolated regionally to estimate thicknesses. Thus, the Mesozoic and Tertiary burial history is largely notional because of the general conditions of spotty deposition in an area of general erosion or non-deposition.

Case 1.--Hypothetical near-maximum burial.

Case 1 is a hypothetical reconstruction that explores the result of stacking in one place all of the local, discontinuous deposition that occurred in Mesozoic to Tertiary times (Figs. 5a,b,c). This case also produces near maximum burial in the Late Paleozoic to Early Mesozoic by using a continuous deposition from Pennsylvanian to Permian as observed in the northwest Las Vegas Basin (Hintz, 1985) and by incorporating deposition of 1.5 km Triassic strata which was eroded in the Mesozoic. Tertiary deposition includes 3 km of Neogene volcanics, 1 km of lake beds and 2.5 km of valley fill.

A thermal history reconstructed for the Yucca Mountain area based on these strata thicknesses suggests that the Eleana Formation generated petroleum in the Late Paleozoic and possibly early Mesozoic (Fig. 5a, b,c). The result of Triassic deposition is that petroleum would reach the late gas stage in the Mesozoic. The Eleana Formation would reach metamorphic temperatures in the Neogene. In this case, there is also a fair match between the predicted and observed temperature and reflectance before Tertiary burial. Tertiary source rocks when buried under the maximum conjectured valley fill would reach maturity at present. However, the maturity calculated for this maximum burial of the Tertiary strata produces an unreasonably high predicted vitrinite reflectance. For example, in Area 8, Tertiary source rocks have been shown by direct measurement to be marginally mature versus the mature predicted value (Fig. 5b) for the Tertiary case. Of course, in this general case, 2.5 km of Tertiary valley fill is excessive for Area 8, which is now buried at about 300m and shows no evidence of erosion other than by local pitting from nuclear explosions.

Case 2.-- No Triassic deposition and realistic Tertiary strata thickness.

A realistic strata thickness means that there are some strata that are well known in age and thickness that must have affected the burial history; consequently they must be included in the reconstruction. Case 2 is like case 1 except no significant Triassic strata are deposited in accordance with the paleogeographic reconstructions of Walker (1988) (Figs. 6a, b, c). A 100 m of the Tippipah Limestone is allowed to be eroded during this time. Mesozoic and Tertiary history proceeds as in case 1.

As in case 1, a thermal history reconstructed for the Yucca Mountain area indicates the Eleana Formation generated petroleum in the Late Paleozoic and possibly early Mesozoic (Fig. 6a). In this case, the burial heating caused by the thick Tippipah Limestone section and upper portions of the Eleana Formation alone are sufficient to cause thermal maturation in deeper portions of the Eleana Formation. Deposition of Triassic rocks is not critical to generate oil in the Late Paleozoic strata but it is important if oil generation is to continue into the Mesozoic (Fig. 6b,c). The Triassic strata while not necessary to generate oil and gas, do seem necessary to elevate burial depths and temperature to levels consistent with the observed paleotemperatures and reflectance based on burial heating alone--even if a heat flow of 90 mW/m^2 is modeled during Mesozoic thermal events and at near peak burial, some Triassic deposition still seems necessary to match observed paleotemperatures and reflectance.

Tertiary source rocks when buried under the maximum local valley fill would reach maturity at present. However, the maximum local valley fill is not a good estimator of local conditions, so, in general the Tertiary is only marginally mature.

Case 3.-- Present Day Exposure of the Eleana Formation.

This case produces near minimum present day burial conditions in the Eleana Formation by having continuous deposition from Pennsylvanian into the Permian and incorporating deposition of 1.5 km of Triassic strata which was eroded in the Mesozoic (Fig. 7a,b,c). The Late Paleozoic rocks are eroded down into the Eleana Formation. In the Tertiary, 3,000m of Neogene volcanics are deposited but are then eroded away to zero thickness at present. No significant lake beds or valley fill are deposited in this case. This case models the situation observed just east of Yucca Mountain where erosion has exposed the Eleana Formation and other Paleozoic rocks (in fault contact with the Eleana) that are unconformably overlain by Neogene volcanics.

The results in this case for the Eleana Formation are similar to those found in case 2, except no Tertiary source rocks are considered. Again, the burial heating caused by the thick Tippipah Limestone section and upper portions of the Eleana Formation alone are sufficient to cause thermal maturation in portions of the Eleana Formation. Deposition of Triassic rocks is not critical to generate oil in the Late Paleozoic but is important if oil generation is to continue into the Mesozoic.

Case 4.--Tertiary hydrothermal event.

This is a hypothetical case, not illustrated, which explores the result of a 200 to 300°C hydrothermal system that affected the northern Yucca Mountain volcanic pile at 2 ,000 m deep occurring about 11 Ma (Bish, 1989; Mattson et al., 1992). Whether this hydrothermal system influenced the Paleozoic rocks below or laterally from the volcanic pile is speculative because these strata are not penetrated by wells in the area. Examples of hot fluid plumes rising in the crust and spreading laterally over relatively cool rocks are known (Ellis and Mahon, 1977), so the existence of a shallow hydrothermal system does not necessarily mean the complete extinction of the source potential in the more deeply buried Eleana Formation thought to occur below portions of the Yucca Mountain area. However, a magnetic anomaly trending west from Wahmonie-Calico Hills area to Yucca Mountain has been interpreted either as a buried intrusive or changes in magnetic signature of the Eleana Formation by contact metamorphism (Langenheim et al., 1991). The level of heating produced by a large intrusion or that required to induce a magnetic response in the Eleana Formation would extinguish any remaining source rock potential. The 11 Ma hydrothermal system may be a shallow expression of this intrusion, and if so, also suggests little source potential now exists below Yucca Mountain.

DISCUSSION

Oil migration in the Eleana Formation and Later Precipitation of Pyrobitumen

As noted by Barker and Peterson (1991), one of the important factors in finding oil in Nevada seems to be preservation of the Paleozoic source rock potential into the Cenozoic where burial heating should generate oil. The preservation of Paleozoic source rock potential has apparently not occurred in the Yucca Mountain area. The loss of source rock potential in the Eleana Formation by burial heating appears to have occurred before the Neogene and possibly as early as Triassic. This conclusion supports the map presented in Garside et al. (1988) which shows a low potential in the Yucca Mountain area.

Thermal history modeling suggests three likely times when the source rock potential of the Eleana Formation was lost: 1) deep burial during the Late Paleozoic (Pennsylvanian-Permian) and Triassic time; 2) Heating related to the Sevier orogeny and intrusion of the Climax and Gold Meadow stocks at about 100 Ma; and 3) the widespread and voluminous Tertiary igneous intrusions/volcanism. Any or all of these heating events could have caused the general overmaturity to supermaturity of the Eleana Formation in the Yucca Mountain area.

The common presence of bitumen in fractures and pores of the Eleana Formation indicates that oil migrated in this rock. The locally high TOC levels remaining in the Eleana Formation and generally not found in other Paleozoic formations suggests that oil has been indigenously sourced. After bitumen migrated in the Eleana Formation it was metamorphosed to a high reflectance. There is no evidence of producible oil remaining in the Eleana Formation. Burial History reconstruction presented below suggests the oil was likely generated in the Late Paleozoic to early Mesozoic and was subsequently metamorphosed in the later Mesozoic and Tertiary heating events related to igneous intrusion. Temperatures related to post early Mesozoic burial alone, in any reasonable regional paleogeothermal gradient, do not account for the observed high pyrobitumen reflectance.

The general overmaturity to supermaturity of the Eleana Formation (Harris et al., 1980; Poole and Claypool, 1984; Aymard, 1989; and others) argues that regional burial rather than Mesozoic-Tertiary contact metamorphism and high heat flow related to the calderas caused the loss of any remaining oil generation capacity in the Late Paleozoic rocks. Extensive igneous intrusion appears to have overmatured most of the remaining source rock potential (Langenheim et al., 1991) in the Yucca Mountain area even if it persisted past the Late Paleozoic. There is remaining gas potential in the Yucca Mountain area but there are no known gas fields in the Great Basin area after hundreds of wildcat wells have been drilled (Garside et al., 1988; Peterson, 1988) suggesting adequate seals and traps for commercial gas accumulations are rare or non-existent.

If the source rock potential is lost or even pushed into the late gas stage during the early Mesozoic as this thermal history reconstruction suggests then the hypothesis of A.K. Chamberlain (1991) is irrelevant. A.K. Chamberlain hypothesized a Late Mesozoic thrust system where the lower plate rocks would still have significant source potential. Because overmaturation of the Eleana Formation would be pre-thrust, the lower plate rocks would not be less mature. Further, this study shows that the thermal maturity at the top of the Eleana Formation is much less than the thermal maturity at its base some 2.3 km below. This variation in thermal maturity could explain the less mature portions of the Eleana Formation found by A.K. Chamberlain without invoking a thrust system. This thrust hypothesis also neglects that effect of thrust loading on thermal maturation because of increased burial heating. Structural cross sections constructed by R. Chamberlain (1991) show that Mississippian rocks still buried to 6 km in the Yucca Lake-Spotted Range area of his cross section were some 5 km deeper after Mesozoic thrusting and before Tertiary extension in his restored section. Burial heating by 11 km of overburden on top of the Mississippian source rocks during hypothesized Mesozoic thrusting in the Yucca Mountain area, assuming a conservatively low geothermal gradient estimate of 20°C/km, would be sufficient to destroy any oil generation potential remaining after Paleozoic burial.

CONCLUSIONS

1. A thermal history reconstructed for the Yucca Mountain area based on the Eleana Formation indicates oil and gas were generated in the Late Paleozoic and Early Mesozoic.
2. A geochemical and geologic assessment of petroleum potential indicates little remaining potential for significant oil generation in the Mississippian Eleana Formation or related Paleozoic rocks in the Yucca Mountain area. There is remaining gas potential in the Yucca Mountain area but there are no known gas fields in the Great Basin area suggesting adequate seals and traps for commercial gas accumulations are rare or non-existent.
3. The relatively high pyrobitumen reflectance suggests that oil migrated in the Eleana Formation but this oil was altered in the rock pores and fractures to the high-reflectance pyrobitumen observed today. The high-reflectance pyrobitumen is observed throughout the Yucca Mountain area and not just near igneous intrusions. These observations and burial history reconstruction suggests oil generation in the Late Paleozoic strata was followed by burial metamorphism of the oil in the Mesozoic and(or) Tertiary.
4. Burial heating caused by the thick Tippipah Limestone section and upper portions of the Eleana Formation alone are sufficient to cause thermal maturation in portions of the Eleana Formation. Deposition of Triassic rocks is not critical to oil generation in the Late Paleozoic strata but it is important if oil generation is to continue into the Mesozoic. The presence of Triassic strata does seem necessary to elevate burial depths and temperature to levels consistent with the observed temperatures and reflectance.
5. The rich Tertiary source rocks identified in this study are marginally mature and have not generated significant oil or gas in the areas that were sampled.

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FIGURE CAPTIONS

Figure 1.--Location of wells and selected features, Yucca Mountain Area, Nevada. Solid triangles are wells used in this study with well number shown. Solid squares are surface samples. Short dashed lines indicate the boundaries of the numbered areas inside of the Nevada Test Site.

Figure 2.-- Description of Rock-Eval analysis terminology. S_1 and S_2 are the first and second peaks of hydrocarbon yield occurring during pyrolysis (heating) of the sample; T_{max} is the temperature at which the S_2 peak occurs during pyrolysis of kerogen. See table 2 for further description of Rock-Eval analysis results derived from these parameters.

Figure 3. Heat flow and surface temperature versus geologic time as input into BASINMOD for thermal history reconstruction, Yucca Mountain area, Nevada. Surface temperature over geologic time modified from Savin (1977).

Figure 4.--Kerogen typing in regards to oil and gas potential using the correlation of total organic carbon versus the Rock-Eval hydrogen index (HI) for selected (a) Paleozoic rocks and (b)Tertiary rocks, Yucca Mountain Area, Nevada.

Figure 5.-- Generalized burial and temperature history, based on the Eleana Formation, Yucca Mountain area, Nevada. This reconstruction (Case 1) uses the maximum thickness values for Permian and Mesozoic strata. (a) Burial depth, temperature and predicted vitrinite reflectance; (b) Temperature at the top of the Eleana Formation and the Miocene lake beds and predicted vitrinite reflectance at the top of the Eleana Formation; (c) Temperature at the bottom of the Eleana Formation and the Miocene lake beds and predicted vitrinite reflectance at the bottom of the Eleana Formation. Note that (in b and c) the Eleana Formation initiates oil generation (at about 100°C) in the late Mississippian and has essentially completed the gas generation in the Triassic (at over 250°C) if 1.5 km Triassic strata were deposited. The time symbols used in this figure do not necessarily conform to current usage by the U.S. Geological Survey.

Figure 6.-- Generalized burial and temperature history, based on the Eleana Formation, Yucca Mountain area, Nevada. This reconstruction (Case 2) assumes no Triassic deposition and a realistic Tertiary depostional history. (a) Burial depth, temperature and predicted vitrinite reflectance; (b) Temperature and predicted vitrinite reflectance at the top of the Eleana Formation; (c) Temperature and predicted vitrinite reflectance at the bottom of the Eleana Formation. The time symbols used in this figure do not necessarily conform to current usage by the U.S. Geological Survey.

Figure 7.--Generalized burial and temperature history, based on the Eleana Formation, Yucca Mountain area, Nevada. (a) Burial depth, temperature and predicted vitrinite reflectance; (b) Temperature and predicted vitrinite reflectance at the top of the Eleana Formation; (c) Temperature and predicted vitrinite reflectance at the bottom of the Eleana Formation. This reconstruction (Case 3) uses a scenario of Eleana Formation exposed at the surface. The time symbols used in this figure do not necessarily conform to current usage by the U.S. Geological Survey.

Table 1
Selected Geologic Events, Formation Ages and Thickness For Burial History Reconstruction
Yucca Mountain Area, Southern Nye County, Nevada

Formation member (event)	Upper Contact[1]	Age Top[2] (Ma)	Age Bottom[2] (Ma)	Thickness[3] (location) [reference]	Lithology
Lathrop Wells Volcanics (heating event)	Unconfomable	0.2	0.3	N/A [Galloway et al., 1991]	Lava
(hiatus/erosion)					
Younger valley fill[5]	Unconformable	0	0.6	50m (assumed)	Co,Ss, Sltst
Younger lake beds[5]	Unconformable	0.1	3	100-1000m [Wright et al., 1991]	Co, Sh, Ls
Young Basalts (heating event)	Unconformable	1.2	3.7	N/a	Lava
Basalts (heating event)	Unconformable	6	10	N/A	Lava
Furnace Creek Formation Equivalents	Unconformable	3	11	up to 2 km [McAllister, 1970]	Co, Sh, Ls
Older Valley Fill[1]	Unconformable	0.6	11	0-2.5 km [Jachens and Moring, 1990]	Co, Ss, Sltst
Tiva Canyon main part	Unconformable	12.9	13.0	150m	Tuff (1.5)
Pah Canyon		13.0	13.1	60m	Tuff (1.5)
Topopah Spring		13.4	13.5	300m [Frizzell & Shulter, 1990]	Tuff (1.5)
Calico Hills, Prow Pass, Bullfrog Hills, &Tram Tuffs, Undifferentiated	Maybe conformable	13.5	14	490m minimum 580m maximum [Mattson et al., 1992]	Tuff (1.5)
Older Volcanics, Undifferentiated	Unconformable	15	17	2 km[6] [Galloway et al., 1991]	Tuff, Lava (1.5)

SW Nevada Volcanic Field development	N/A	11	17	Composite section to 8 km [Frizzell & Shulters, 1990]	Tuff, Lava
Pavits Spring/ Horse Spring	Unconformable	17(?)	30(?)	Both Fms. including tuffs may exceed 2 km [Frizzell & Shulters, 1990]	Ss, Sltst, Tuff, Ls
(hiatus/erosion)					
Climax & Gold Meadow stocks (heating event)		100	100	N/A [Frizzell & Shulters, 1990]	N/A
Jurassic and Cretaceous[7] (hiatus/erosion)		65	120	Local deposits possible[8]	Ss, Ls
Triassic Rocks	Unconformable	210	245	1.5km (?)	Co, Ss, Ls
(erosion or negligible deposition)		245	280		
Tippipah Ls	Unconformable	280	310	1060m [Cornwall, 1972]	Ls
Eleana[9]	Disconformable	320	370	some 2350 m [Cornwall, 1972]	Sh, Ls
Ls of Timpi Cyn	Disconformable?	335	340	76m (S. Spotted Range) [Poole data]	Ls
Mercury Ls	Disconformable?	340	350	64m (S. Spotted Range) [Poole data]	Ls
Narrow Cyn Ls	Disconformable?	350	360	65m (S. Spotted Range) [Poole data]	Ls, Sltst
West Range Ls	Disconformable?	360	365	43m (S. Spotted Range) [Poole data]	Ls
Guilmette Ls[10]	Conformable	365	370	425m (Spotted Range) [Cornwall, 1972]	Ls

Simonson Do	**Disconformable?**	**370**	**385**	**353m (Spotted Range) [Cornwall, 1972]**	**Do**
Dolostone of the Spotted Range[10]		**U Devonian**	**Silurian**	**m (S. Spotted Range) [Poole data]**	**Do**
Lone Mountain Dolostone	**Unconformable?**	**385**	**420**	**m (S. Spotted Range) [Poole data]**	**Do (4.9)**
Roberts Mountains	**conformable**	**420**	**435**	**198 (Bare Mountain) (USGS Map i-2201]**	**Ls, Do (5.5)**

Table 1 Notes:

1. Contact type from Cornwall (1972), Hintze (1985), Peterson (1988), Frizzell and Shulters (1990) and F. G. Poole (1993, USGS, Denver, written communication).
2. Formation boundary geologic stage or age from F. G. Poole (1993, written communication), Cornwall (1972), and Larsen and Langenheim (1979). Absolute ages from DIAG charts.
3. Thicknesses taken from Poole (written communication, USGS, Denver, 1993) for the Paleozoic rocks. Cornwall (1972), Peterson (1988) and Frizzel and Shulters (1990) for other rocks.
4. Lithology given for estimating thermal conductivity. Abbreviations: & = and, Cyn = canyon, Ss = sandstone, Sh = shale, Sltst = siltstone, Ls = Limestone, Do = dolostone, Co = conglomerate. BASINMOD does not allow conglomerate to be directly modeled, so it is modeled as a sandstone. Measured thermal conductivity (in W/m-°K) from shown in parentheses if reported. Sass et al. (1988) found welded tuffs had a modal thermal conductivity of 2.1 W/m-°K and non-welded tuffs had a modal thermal conductivity of 1.0 W/m-°K; we used and average of 1.5 W/m-°K as an approximation in these heterogeneous units.
5. The topography present at Yucca Mountain developed by 11 Ma, when extension ceased (Galloway et al., 1991). Valley fill is assumed to dominate burial of source rock after this time. The term younger refers to Neogene rocks that are mostly undeformed and not deeply cut by Basin and Range type structure. The term older refers to Neogene rocks that are mostly deformed and deeply cut by Basin and Range type structure.
6. 2000m thickness based on combined thickness of older and younger volcanics at Yucca Mountain of 3,000m (Galloway et al., 1991) and the younger volcanics are about 1,000 m thick (Mattson et al., 1992).
7. No Mesozoic rocks are found in southern Nye county area, but may have been deposited and eroded. Mesozoic and Tertiary burial history is largely notional because of the general conditions of spotty deposition in an area of general erosion or non-deposition.
8. Hintze (1985) indicates up to 2,000m of Cretaceous or Tertiary conglomerate in the Spotted and Pintwater Ranges.
9. Any organic matter present is presumed to decrease the amount of shale. An average kerogen content of 1% (Table 2) was used in the Eleana Formation.
10. F. G. Poole (1993, USGS, Denver, Personal Communication) indicates that the Upper Devonian rocks in the

southern part of the Nevada Test Site area are Guilmette Limestone and West Range Limestone. The Middle Devonian rocks are Simonson Dolostone. The basal part of the Guilmette Limestone is Late Middle (Givetian) Devonian. The Dolostone of the Spotted Range is Silurian and Early Devonian.

11. Carr in Galloway et al. (1991) indicates the simplified general Upper Paleozoic stratigraphy of the Nevada Test site area is from older to younger: Roberts Mountains Formation, Lone Mountain Dolostone, Simonson Dolostone, Eleana Formation, and Tippipah Limestone. This general stratigraphy was used as an approximation for the burial history reconstruction of the Upper Paleozoic rocks.

Table 2. Rock-Eval Analyses for the Yucca Mountain area, Southern Nye County, Nevada,

Analyses performed on a Delsi Rock-Eval II system. Abbreviations, units, and terminology used at the column headers mostly discussed by Espitalie et al. (1977) and Peters (1986). Specific definitions for Rock Eval data reports are: S_1 and S_2 are the first and second peaks of hydrocarbon yield occurring during pyrolysis of the sample (Fig. 2); S_3 is the amount of CO_2 generated during pyrolysis; TOC is total organic carbon; T_{max} is the temperature at which the S_2 peak occurs during pyrolysis of kerogen; Hydrogen index (HI) = $(S_2/TOC)x100$; Oxygen index (OI) = $(S_3/TOC)x100$; PI = Transformation ratio = $S_1/(S_1+S_2)$; PC=pyrolysable carbon in the sample.

Flederhoff Federal 5-1 (FF-5-1) data from Harris et al. (1992; only those results with a TOC over 0.5%).

Well (sample no.)	Section-Township-Range (Lat.(N); Long.(W))	Sample type	Sample top in feet	Depth bottom in feet	Formation or (age)	Sample Lithology	Tmax Celsius	S1 mgHC/grk	S2 mgHC/grk	S3 mgCO2/grk	PI	S2/S3 HC/CO2	TOC Wt.-%	HI mgHC/gC	OI mgCO2/gC
Paleozoic Rocks															
UE-1L	24-10S-52E	cuttings	400.00	410.00	Eleana	v dk gray mdst	449	0.06	0.41	1.45	0.13	0.28	1.28	32	113
UE-1L	24-10S-52E	cuttings	700.00	710.00	Eleana	v dk gray mdst	506	0.03	0.44	0.87	0.07	0.50	1.18	37	73
UE-1L	24-10S-52E	cuttings	1600.00	1610.00	Eleana	v dk gray mdst	483	0.06	0.53	1.03	0.09	0.51	1.53	34	67
UE-1L	24-10S-52E	cuttings	2510.00	2520.00	Eleana	v dk gray mdst	459	0.03	1.05	0.98	0.03	1.07	1.48	72	67
UE-1L	24-10S-52E	cuttings	3510.00	3520.00	Eleana	v dk gray mdst	452	0.04	0.20	1.11	0.17	0.18	0.97	20	114
UE-1L	24-10S-52E	cuttings	4290.00	4300.00	Eleana	v dk gray mdst	456	0.02	0.28	1.09	0.07	0.25	1.24	22	87
UE-1L	24-10S-52E	cuttings	5340.00	5340.00	Eleana	v dk gray mdst	441	0.04	0.41	0.95	0.09	0.43	1.18	35	82
U-8-a11	8-9S-53e	cuttings	1710.00	1720.00	(Paleozoic)	v dk gray mdst	394	0.06	0.26	0.37	0.17	0.70	1.29	20	28
U-8-a11	8-9S-53e	cuttings	1010.00	1820.00	(Paleozoic)	v dk gray mdst	400	0.10	0.65	0.37	0.14	1.75	1.17	56	31
U-8-a11	8-9S-53e	cuttings	1910.00	1920.00	(Paleozoic)	v dk gray mdst	453	0.09	0.41	0.45	0.18	0.91	1.33	30	33
U-8-a11	8-9S-53e	cuttings	1960.00	1970.00	(Paleozoic)	v dk gray mdst	429	0.07	0.38	0.47	0.18	0.80	1.40	27	33
UE-17e	3-10S-52E	core	801.50	801.50	Eleana	dk gray mdst	490	0.01	0.33	0.32	0.03	1.03	1.34	24	23
UE-17e	3-10S-52E	core	596.00	596.00	Eleana	dk gray mdst	494	0.05	0.56	0.84	0.08	0.85	1.70	32	38
UE-17e	3-10S-52E	core	401.30	401.30	Eleana	dk gray mdst	536	0.03	0.44	0.63	0.07	0.69	1.53	28	41
UE-17e	3-10S-52E	core	193.00	193.00	Eleana	dk gray mdst	535	0.02	0.24	0.89	0.08	0.26	1.63	14	54
UE 16d	14-10S-52E	cuttings	740.00	750.00	Eleana	v dk gray mdst	537	0.01	0.11	0.72	0.08	0.15	1.71	6	42
UE 16d	14-10S-52E	cuttings	2190.00	2200.00	Eleana	v dk gray mdst	524	0.02	0.31	0.64	0.06	0.48	1.84	20	41
UE 16d	14-10S-52E	cuttings	2400.00	2410.00	Eleana	v dk gray mdst	530	0.01	0.19	0.22	0.05	0.86	1.09	17	20
UE 16d	14-10S-52E	cuttings	2630.00	2640.00	Eleana	v dk gray mdst	515	0.04	0.63	0.56	0.06	1.12	1.60	39	35
UE 16d	14-10S-52E	cuttings	2800.00	2810.00	Eleana	v dk gray mdst	460	0.03	0.17	0.52	0.15	0.32	1.40	12	37
UE 16d	14-10S-52E	cuttings	2980.00	2990.00	Eleana	v dk gray mdst	459	0.03	0.25	0.51	0.11	0.49	1.47	17	34
UE-1p	31-10S-52E	cuttings	770.00	773.00	Eleana	med gray mdst	432	0.00	0.03	0.24	0.00	0.12	0.05	60	480
UE-16f	27-10S-52E	cuttings	195.00	200.00	Eleana	v dk gray mdst	468	0.04	0.70	0.91	0.05	0.76	1.11	63	81
UE-16f	27-10S-52E	cuttings	400.00	410.00	Eleana	v dk gray mdst	473	0.02	0.30	1.04	0.06	0.28	1.19	25	87
UE-16f	27-10S-52E	cuttings	650.00	660.00	Eleana	v dk gray mdst	480	0.01	0.33	1.27	0.03	0.25	1.15	28	110
UE-16f	27-10S-52E	cuttings	820.00	830.00	Eleana	v dk gray mdst	477	0.00	0.30	1.37	0.00	0.21	1.30	23	105
UE-16f	27-10S-52E	cuttings	1000.00	1010.00	Eleana	v dk gray mdst	506	0.03	1.67	0.47	0.02	3.55	4.38	38	10
UE-16f	27-10S-52E	cuttings	1200.00	1210.00	Eleana	v dk gray mdst	481	0.00	0.27	1.35	0.00	0.20	1.31	20	103
UE-16f	27-10S-52E	cuttings	1470.00	1480.00	Eleana	v dk gray mdst	493	0.00	0.25	0.84	0.00	0.29	1.11	22	76
USGS D	9-10S-53E	cuttings	1764.00	1769.00	Eleana?	med gray mdst	306	0.00	0.02	0.28	0.00	0.07	0.04	50	700
USGS D	9-10S-53E	cuttings	1730.00	1737.00	Eleana?	lt med gray mdst	367	0.00	0.03	0.39	0.00	0.07	0.04	75	975
USGS D	9-10S-53E	cuttings	1868.00	1872.00	Eleana?	med brown mdst	365	0.04	0.07	0.27	0.40	0.25	0.04	175	675
USGS D	9-10S-53E	cuttings	1920.00	1925.00	Eleana?	med brown mdst	312	0.06	0.10	0.33	0.37	0.30	0.05	200	660
UE 17a	10-10S-52E	cuttings	200.00	210.00	Eleana	v dk gray mdst	486	0.00	0.07	0.18	0.00	0.38	0.05	140	360
UE 17a	10-10S-52E	cuttings	500.00	510.00	Eleana	v dk gray mdst	573	0.03	0.94	0.56	0.03	1.67	5.09	18	11
UE 17a	10-10S-52E	cuttings	700.00	710.00	Eleana	v dk gray mdst	492	0.01	0.20	0.61	0.05	0.32	0.95	21	64
UE 17a	10-10S-52E	cuttings	1000.00	1010.00	Eleana	v dk gray mdst	528	0.02	0.21	0.42	0.09	0.50	1.77	11	23
UE 17a	10-10S-52E	cuttings	1100.00	1190.00	Eleana	v dk gray mdst	475	0.02	0.27	1.11	0.07	0.24	1.50	18	74
ER12-1	(37.1847;116.1836)	cuttings	1200.00	1200.00	Eleana	v dk gray mdst	361	0.01	0.01	0.08	0.50	0.12	0.10	10	80
ER12-1	(37.1847;116.1836)	cuttings	1350.00	1350.00	Eleana	v dk gray mdst	386	0.01	0.03	0.15	0.25	0.20	0.15	20	100
ER12-1	(37.1847;116.1836)	cuttings	1600.00	1600.00	Eleana	v dk gray mdst	528	0.00	0.01	0.10	0.00	0.10	0.09	11	111
ER12-1	(37.1847;116.1836)	cuttings	1850.00	1850.00	Eleana	v dk gray mdst	546	0.01	0.22	0.10	0.06	2.20	0.60	36	18
ER12-1	(37.1847;116.1836)	cuttings	2000.00	2000.00	Eleana	v dk gray mdst	531	0.02	0.36	0.07	0.06	5.14	0.83	43	8
ER12-1	(37.1847;116.1836)	cuttings	2250.00	2250.00	Eleana	v dk gray mdst	516	0.00	0.06	0.06	0.00	1.00	0.62	9	9
ER12-1	(37.1847;116.1836)	cuttings	2500.00	2500.00	Eleana	v dk gray mdst	434	0.00	0.08	0.05	0.00	1.60	0.55	14	8
ER12-1	(37.1847;116.1836)	cuttings	2750.00	2750.00	Eleana	v dk gray mdst	405	0.00	0.01	0.03	0.00	0.33	0.26	3	11
UE-1q	15-10S-53E	cuttings	2410.00	2420.00	Eleana	dk gray marble	521	0.00	0.01	0.28	0.00	0.03	0.02	50	1400
UE-1q	15-10S-53E	cuttings	2390.00	2400.00	Eleana	dk gray marble	360	0.01	0.10	0.22	0.10	0.45	0.04	250	550
UE-3LJ	15-10S-53E	cuttings	3000.00	3060.00	(Paleozoic)	lt brown gray ls	581	0.02	0.15	0.16	0.12	0.93	0.03	500	533
						Average	470	0.02	0.31	0.87	0.09	0.72	1.09	52	174

27a

Baker Table 2-1

Well (sample no.)	Section-Township-Range (Lat.(N);Long.(W))	Sample type	Sample top in feet	Depth bottom in feet	Formation or (age)	Sample Lithology	Tmax Celsius	S1 mgHC/grk	S2 mgHC/grk	S3 mgCO2/grk	PI	S2/S3 HC/CO2	TOC Wt.%	HI mgHC/gC	OI mgCO2/gC
Tertiary Rocks															
U6d-ps-3aa	8-9S-53e	SW core	1184.00	1184	(Tertiary)	brown carb mdst	439	0.25	36.10	5.71	0.01	6.32	7.62	473	74
U6d-ps-3aa	8-9S-53e	SW core	1215.00	1215	(Tertiary)	brown carb mdst	439	0.43	31.01	4.78	0.01	6.48	6.14	505	77
UE 8I	8-9S-53e	SW core	2140 00	2140	(Tertiary)	dk gray mdst	506	0.00	0.05	0.64	0.00	0.07	0.59	8	108
UE 8I	8-9S-53e	SW core	2080.00	2080	(Tertiary)	dk gray mdst	432	0.41	34.44	18.05	0.01	1.90	25.11	137	71
UE 8I	8-9S-53e	SW core	2085.00	2085	(Tertiary)	dk gray mdst	424	0.13	1.00	1.20	0.12	0.83	1.26	79	95
UE-8I	8-9S-53e	SW core	2150.00	2150	(Tertiary)	dk gray mdst	507	0.02	0.14	0.41	0.12	0.34	0.97	14	42
UE-8h	8-9S-53e	cuttings	1040.00	1050	(Tertiary)	v dk gray mdst	423	0.25	5.21	2.15	0.05	2.42	3.25	160	66
UE-8h	8-9S-53e	cuttings	1090.00	1100	(Tertiary)	v dk gray mdst	440	0.44	17.76	4.60	0.02	3.86	6.89	257	66
UE-8h	8-9S-53e	cuttings	1140.00	1150	(Tertiary)	v dk gray mdst	435	0.66	34.36 *	16 61	0.02	2.06	26.43	130	62
(JT-92-25)	(36.6992;115.9328)	outcrop	0	0	(Tertiary)	lt gray ls	532	0.01	0.17	0.23	0.06	0.73	0.03	666	766
(JT-92 29)	(36.7081;115.9514)	outcrop	0	0	(Tertiary)	lt gray ls	413	0.01	0.12	0.36	0.08	0.33	0.03	400	1200
(92-NTS-CB-4)	(36.8805;116.6315)	outcrop	0	0	(Tertiary)	dk gray ls	384	0.00	0.08	0.15	0.00	0.53	0.09	88	166
(92-NTS-CB 7s)	(36.9043; 116.6500)	outcrop	0	0	(Tertiary)	dk gray mdst	501	0.02	0.32	0.14	0.06	2.28	1.59	20	8
(92-NTS-CB-7mw)	(36.9043; 116.6500)	outcrop	0	0	(Tertiary)	dk gray mdst	508	0.04	0.41	0.14	0.09	2.92	1.19	34	11
F-F 5 1	5-16S-50E	cuttings	700.00	700	(Tertiary)	med. gray mdst	422	0.08	4.20	1.64	0.02	2.56	1.32	318	124
						Average	454	0.18	11.02	3.79	0.04	2.24	5.60	213	196

UE 6 d---- although reported to have intersected Tertiary lake beds, none were found and this well was not sampled

27b

Barker Table 2-2

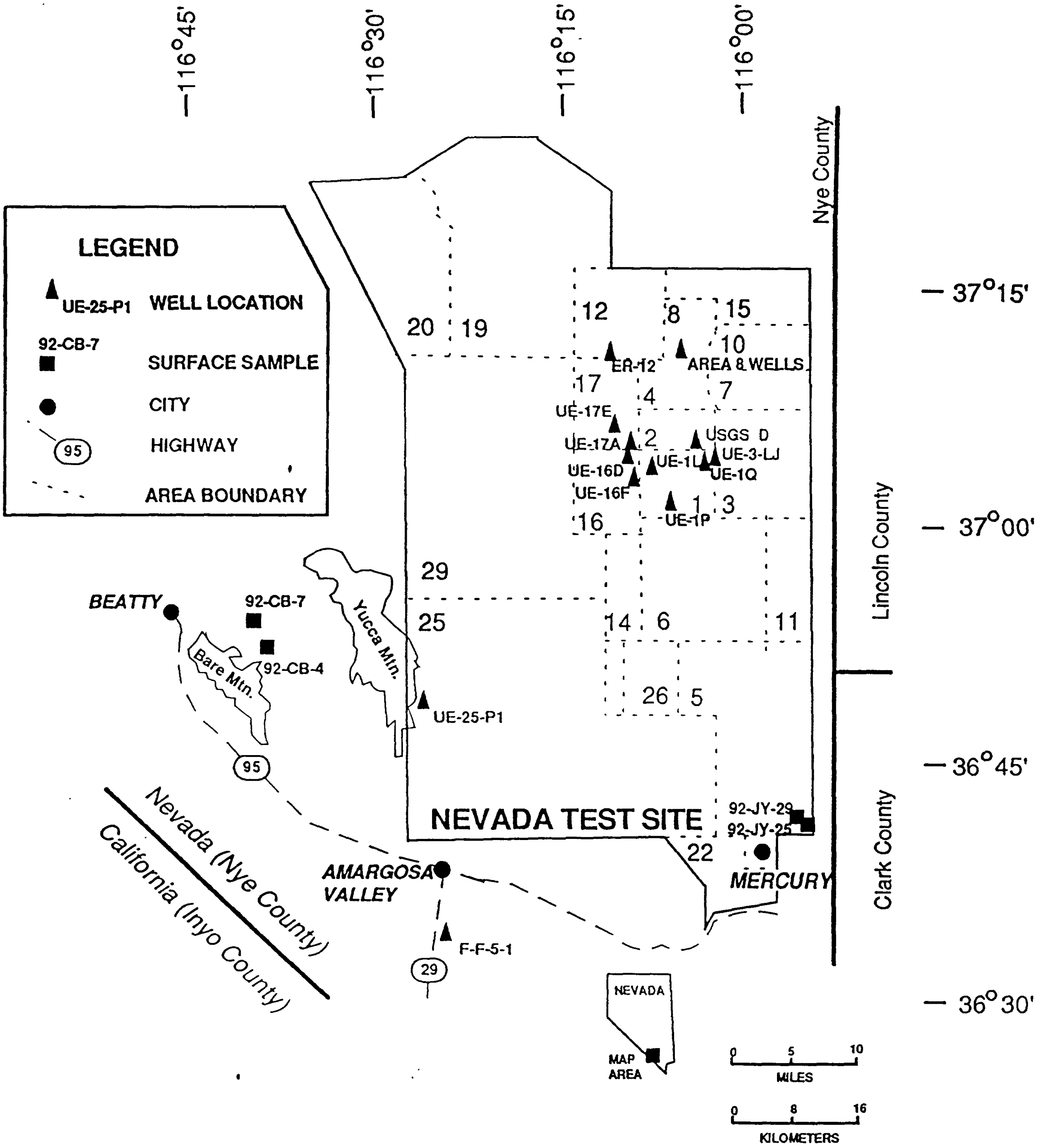
Table 3. Correlation of rank parameters compared to vitrinite reflectance in type III organic matter (OM) and(or) coal and peak temperature calibration for burial diagenesis (this paper). Rank parameter correlations from Teichmuller and Durand (1983), Poole and Claypool (1984), Nowlan and Barnes (1987), Robert (1988). Note that the peak temperature calibration has an upper data limit at about 200°C and the extrapolation beyond this range to reach CAI 5 is tenatative. Also biogenic gas generation ceases at near 90°C, the known upper limit of life.

Correlation of Rank Parameters With Ro for Type III DOM or coal

Hydrocarbon Generation Event	Ro	Tmax	Transform Ratio	CAI	TAI	%C	%V.M.	Burial Tpeak (celsius)

Correlation of Rank Parameters With Ro for Type III DOM or coal

Hydrocarbon Generation Event	Ro	Tmax	Transform Ratio	CAI	TAI	%C	%V.M.	Burial Tpeak (celsius)
Biogenic Gas>	0.2	410			1	60	70	6
	0.3	415		1		60	60	39
Early condensate>	0.4	420		1	2	71	52	62
Near End, Biogenic Gas>	0.5	427		1.5	2.5	73	46	80
Onset of Oil generation>	0.6	435	0.1	2		77	44	95
Thermogenic Gas, Coal>	0.7	440		2		77	40	107
	0.8	445	0.2	2-3	3		37	118
	0.9	452	0.4	2-3			35	128
Peak Oil>	1	460	0.6	2-3	3.5		33	136
Onset Wet Gas	1.1	465	0.7	3				144
	1.2	472		3		87	28	151
Oil end>	1.3	480	0.85	3		87	28	157
	1.4	485		3				163
	1.5	490	0.9	3	4		22	169
	1.6	498		3			19	174
Limit of oil preservation?>	1.7	503	0.98	3				179
	1.8	510		3				184
	1.9	515		3-4			14	188
Dry Gas From all OM types>	2	520		3-4				192
	2.1	528		3-4			12	196
	2.2	535		4				200
	2.3	540		4			10	204
	2.4			4				207
	2.5			4	5			210
	2.6			4		91	8	213
	2.7			4				217
	2.8			4				219
	2.9			4			6	222
	3			4				225
	3.1			4			5	228
	3.2			4			5	230
	3.3			4			5	233
	3.4			4				235
No Economical Gas?>	3.5			4		93.5	4	238
	3.6			4				240
	3.7			4				242
	3.8			4				244
	3.9			4				246
	4			4			3	248
	5			4				266
	6			4				280
	7			4				290
	8			5				303



116°45'
116°30'
116°15'
116°00'
37°15'
37°00'
36°45'
36°30'
LEGEND
UE-25-P1 WELL LOCATION
92-CB-7 SURFACE SAMPLE
CITY
95 HIGHWAY
AREA BOUNDARY
Nye County
Lincoln County
Clark County
NEVADA TEST SITE
BEATTY
AMARGOSA VALLEY
MERCURY
Bare Mtn.
Yucca Mtn.
Nevada (Nye County)
California (Inyo County)
ER-12
AREA 8 WELLS
UE-17E
UE-17A
UE-16D
UE-16F
UE-1L
USGS D
UE-3-LJ
UE-1Q
UE-1P
UE-25-P1
F-F-5-1
92-CB-7
92-CB-4
92-JY-29
92-JY-25
20
19
12
8
15
10
17
4
7
2
1
3
16
29
25
14
6
11
26
5
22
95
29
NEVADA
MAP AREA
0 5 10
MILES
0 8 16
KILOMETERS

Figure 1

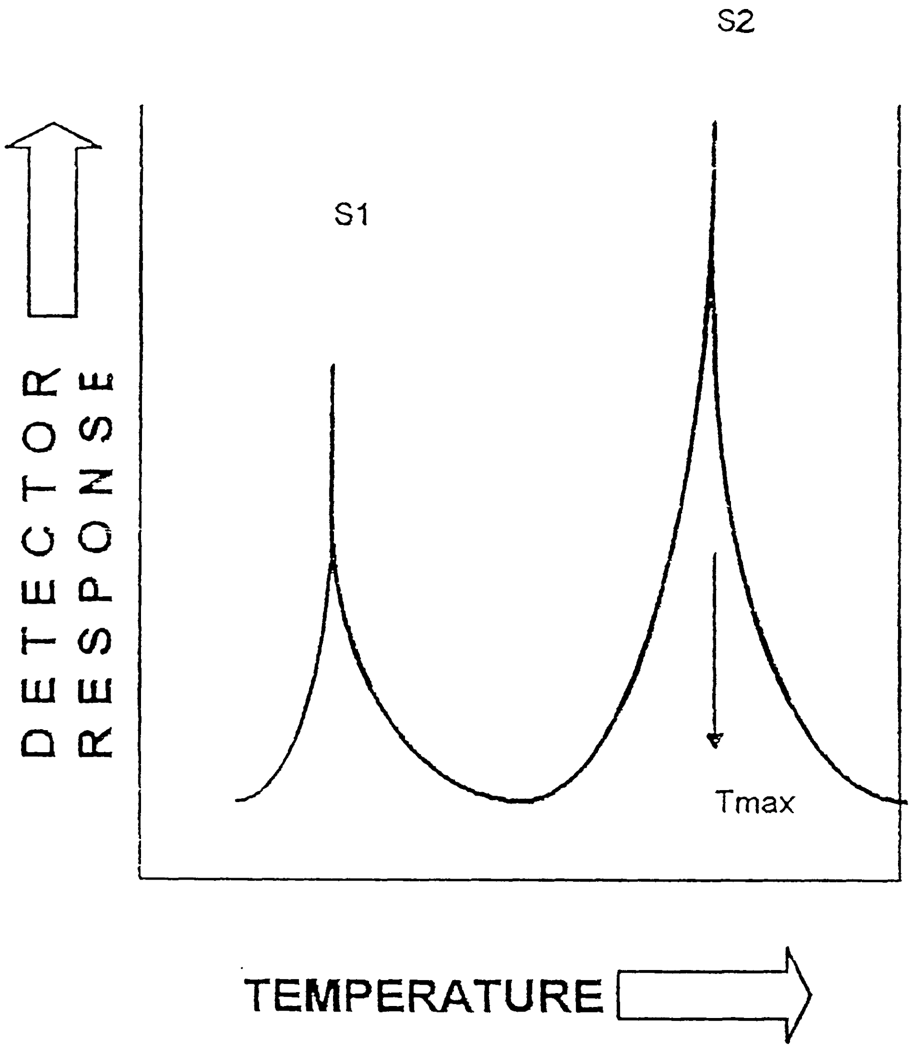


Figure 2

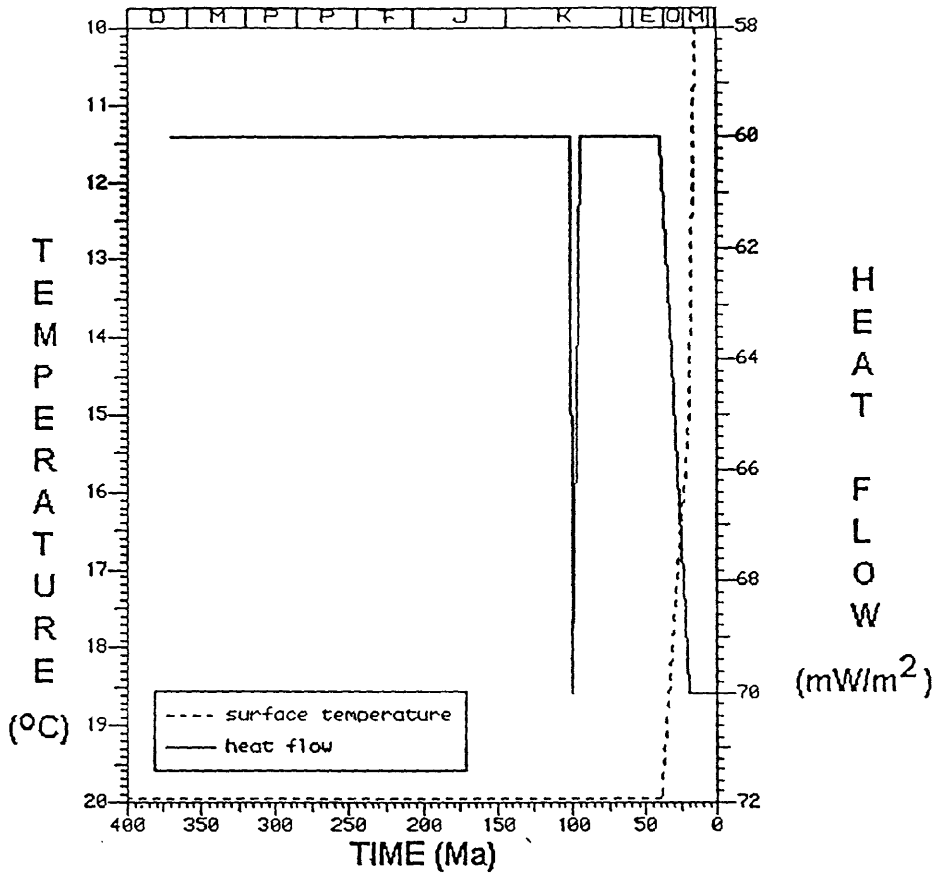
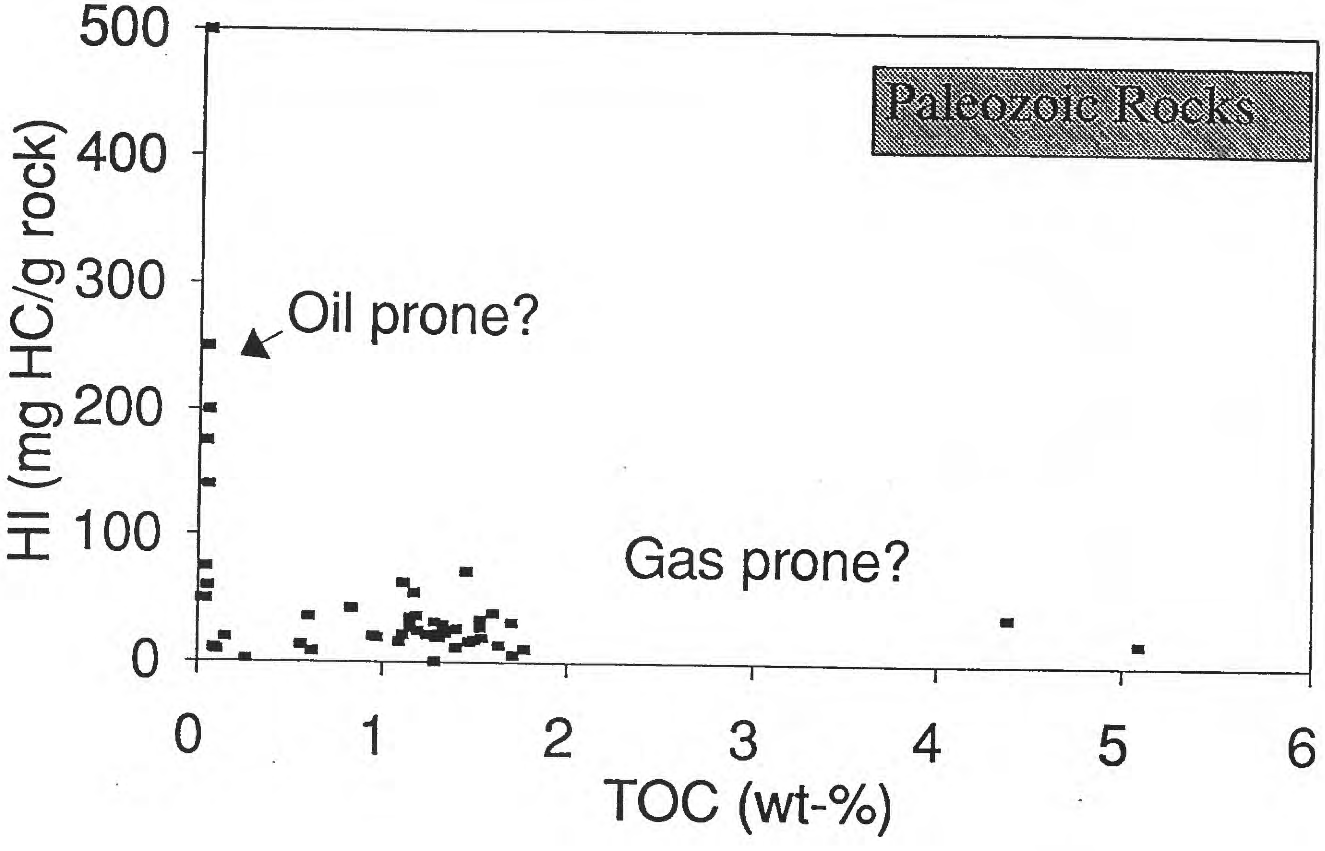

D M P P T J K E O M
TEMPERATURE (°C)
10
11
12
13
14
15
16
17
18
19
20
HEAT FLOW (mW/m2)
58
60
62
64
66
68
70
72
surface temperature
heat flow
400 350 300 250 200 150 100 50 0
TIME (Ma)

Figure 3



500
400
300
200
100
0
HI (mg HC/g rock)
Paleozoic Rocks
Oil prone?
Gas prone?
0
1
2
3
4
5
6
TOC (wt-%)

Figure 4a

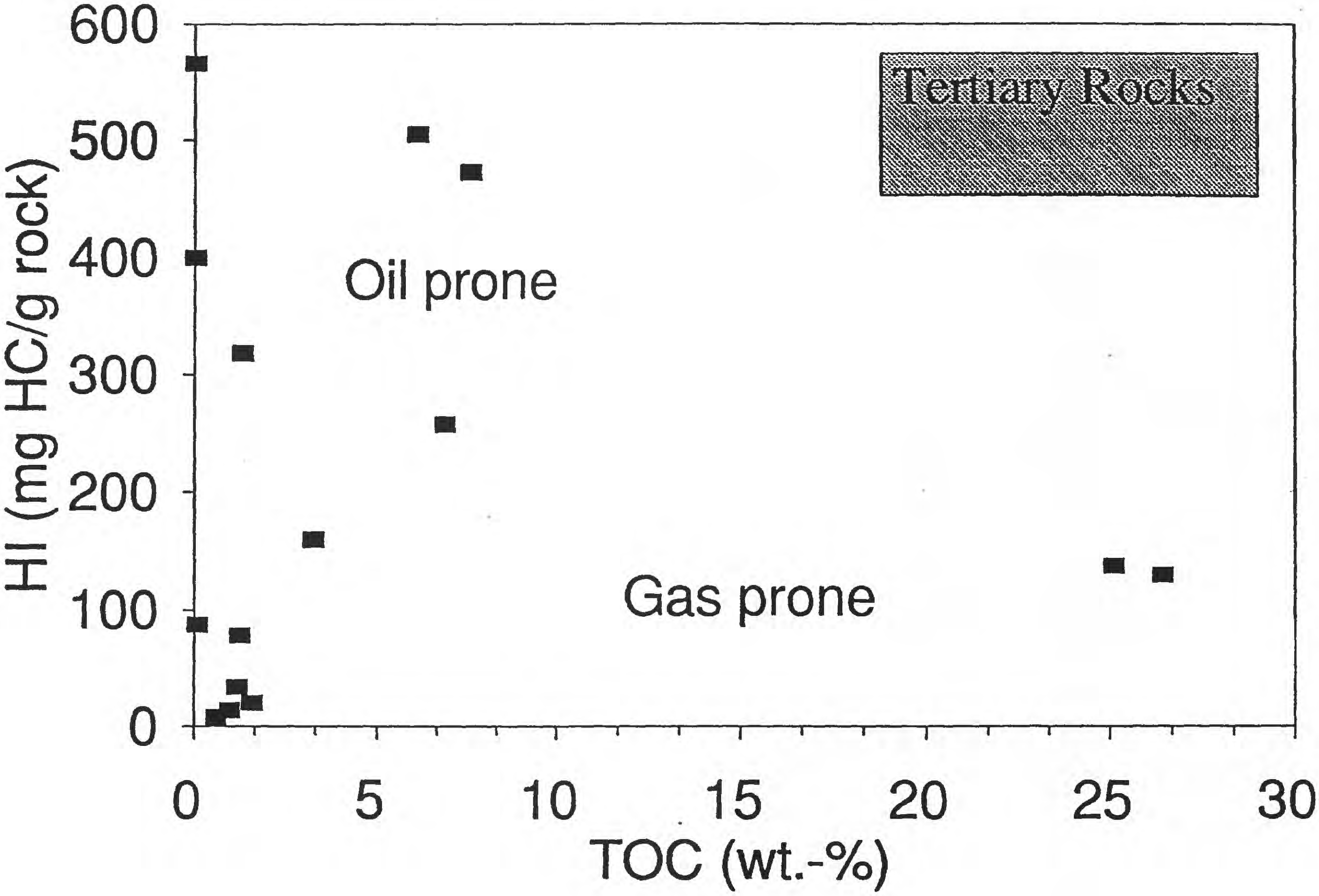

Tertiary Rocks
Oil prone
Gas prone
HI (mg HC/g rock)
TOC (wt.-%)
600
500
400
300
200
100
0
0
5
10
15
20
25
30

Figure 4b

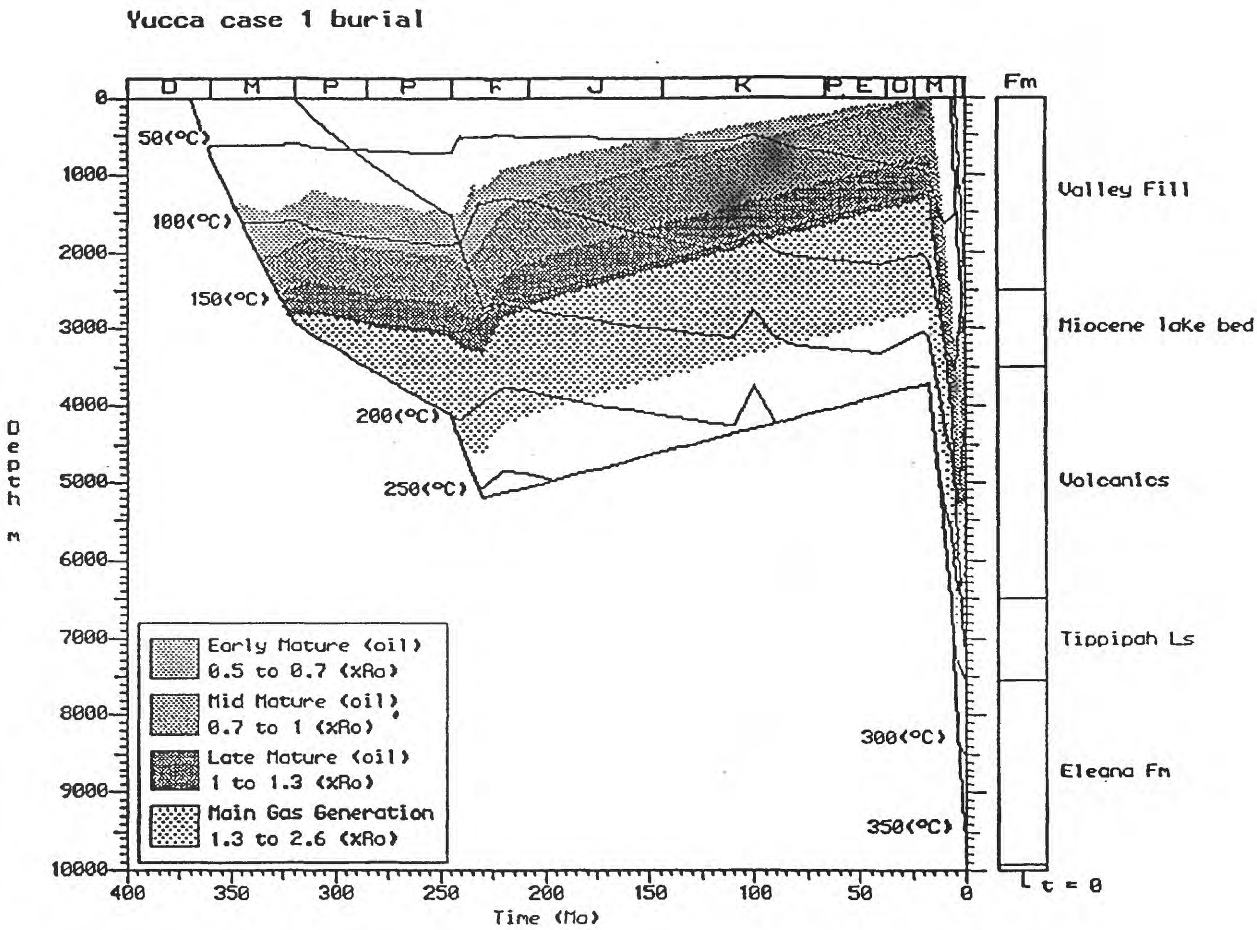

Yucca case 1 burial
D
M
P
P
F
J
K
P E O M
Fm
50(°C)
100(°C)
150(°C)
200(°C)
250(°C)
300(°C)
350(°C)
Depth m
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
400
350
300
250
200
150
100
50
0
Time (Ma)
Early Mature (oil)
0.5 to 0.7 (%Ro)
Mid Mature (oil)
0.7 to 1 (%Ro)
Late Mature (oil)
1 to 1.3 (%Ro)
Main Gas Generation
1.3 to 2.6 (%Ro)
Valley Fill
Miocene lake bed
Volcanics
Tippipah Ls
Eleana Fm
t = 0

Figure 5a

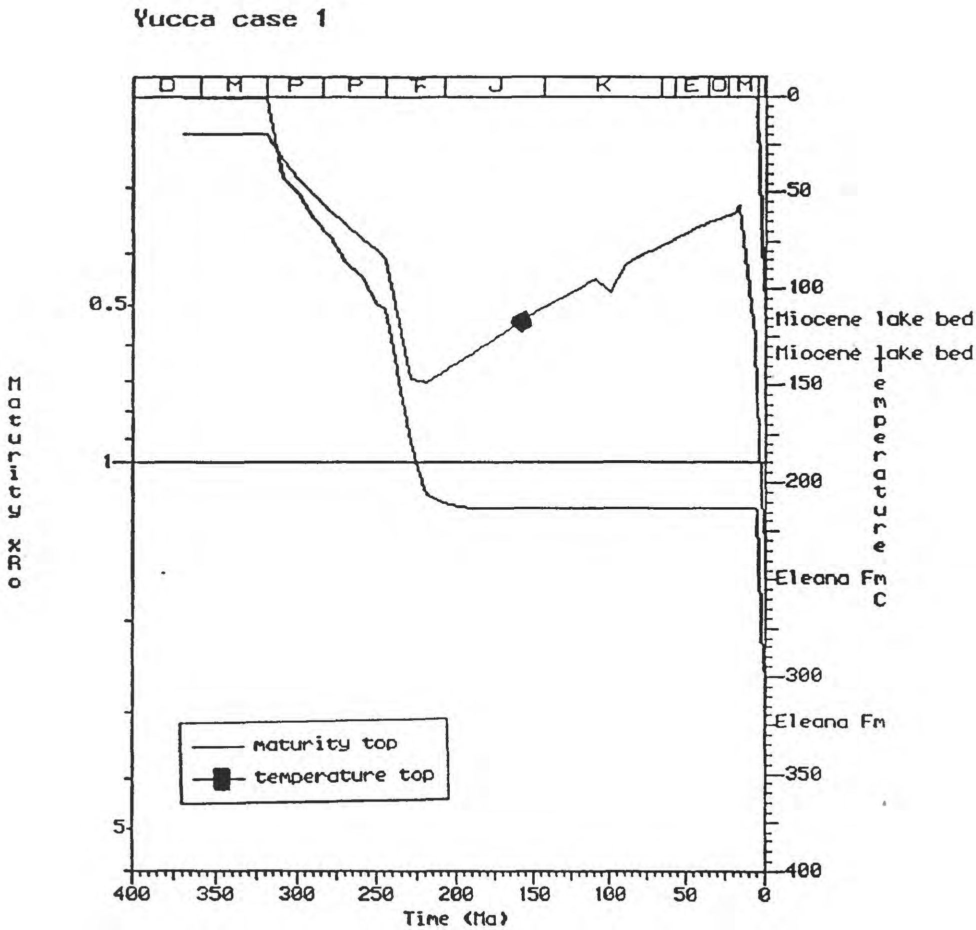

Yucca case 1
D
M
P
P
F
J
K
E
O
M
0
50
100
150
200
300
350
400
Miocene lake bed
Miocene lake bed
Eleana Fm
Eleana Fm
Temperature C
0.5
1
5
Maturity %Ro
maturity top
temperature top
400
350
300
250
200
150
100
50
0
Time (Ma)

Figure 5b

Yucca case 1 burial

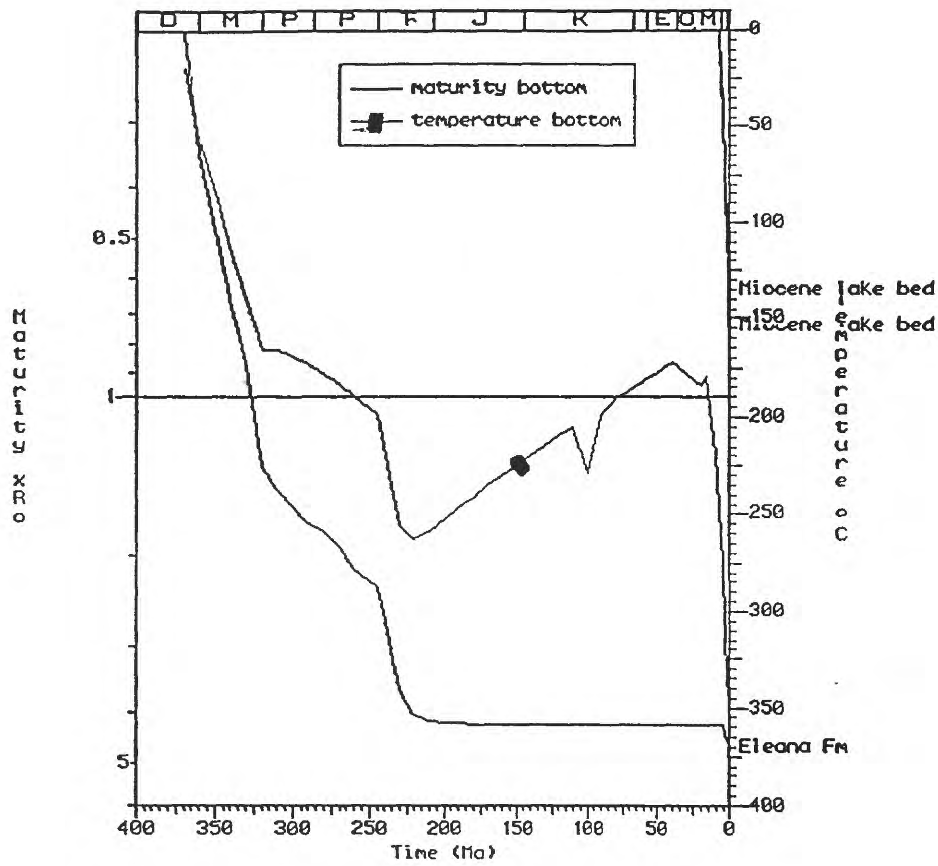
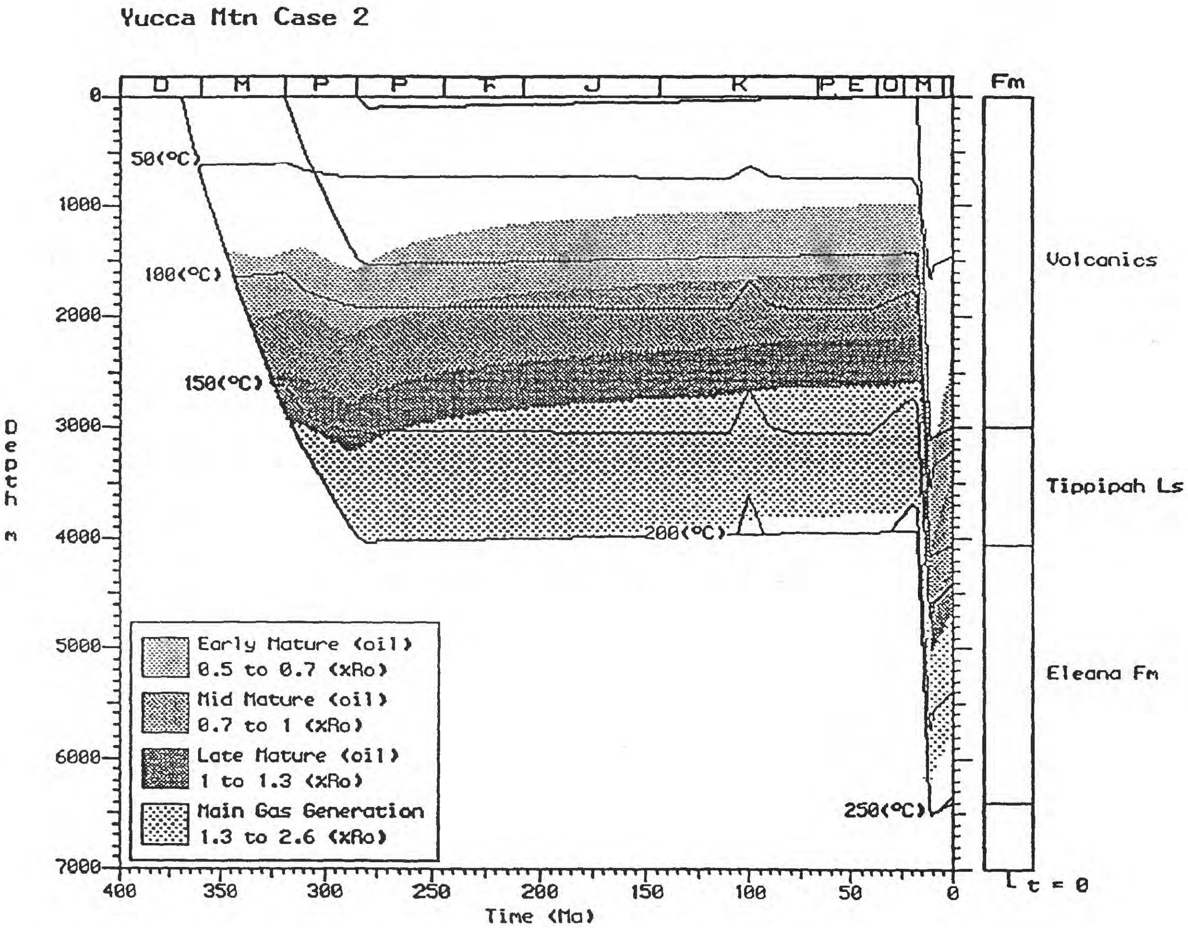


Figure 5c



Yucca Mtn Case 2
D
M
P
P
F
J
K
P
E
O
M
Fm
0
1000
2000
3000
4000
5000
6000
7000
Depth m
50(°C)
100(°C)
150(°C)
200(°C)
250(°C)
Volcanics
Tippipah Ls
Eleana Fm
Early Mature (oil)
0.5 to 0.7 (%Ro)
Mid Mature (oil)
0.7 to 1 (%Ro)
Late Mature (oil)
1 to 1.3 (%Ro)
Main Gas Generation
1.3 to 2.6 (%Ro)
400
350
300
250
200
150
100
50
0
Time (Ma)
t = 0

Figure 6a

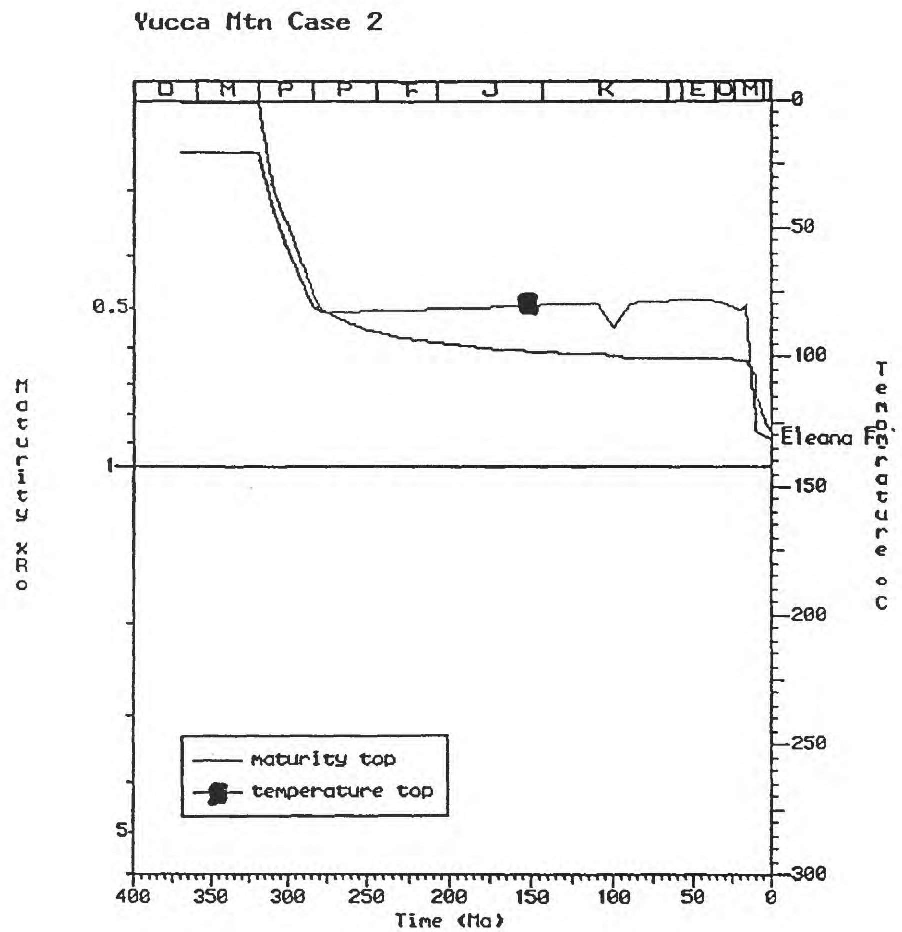

Yucca Mtn Case 2
D
M
P
P
F
J
K
E
O
M
0.5
1
5
Maturity %Ro
0
50
100
150
200
250
300
Temperature oC
Eleana Fm.
maturity top
temperature top
400
350
300
250
200
150
100
50
0
Time (Ma)

Figure 6b

Yucca Mtn Case 2

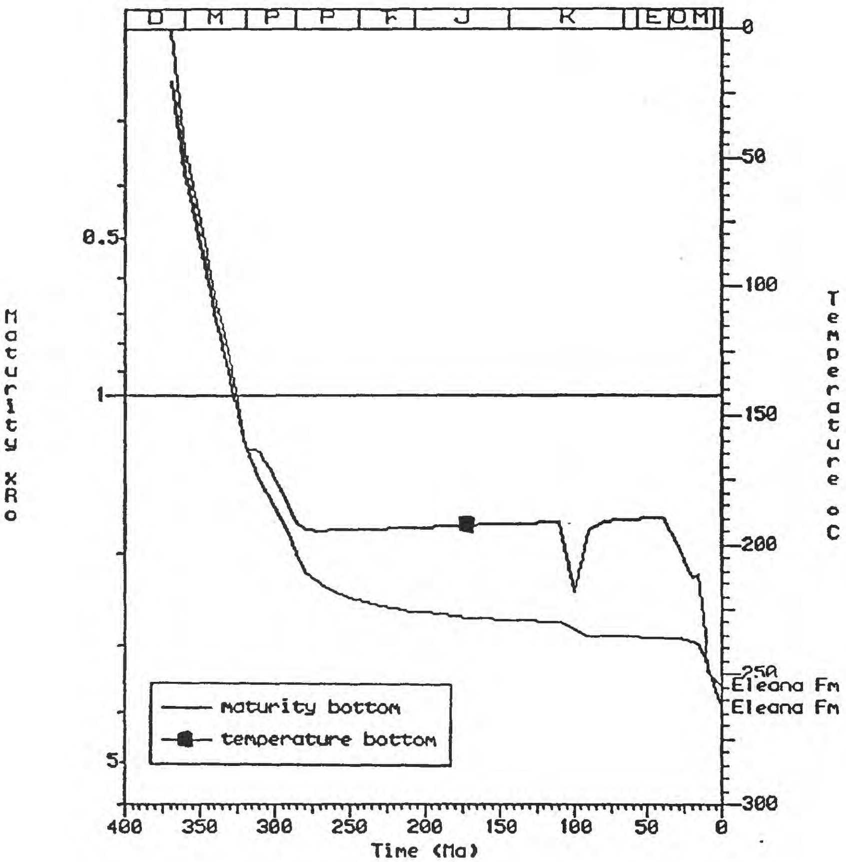


Figure 6c

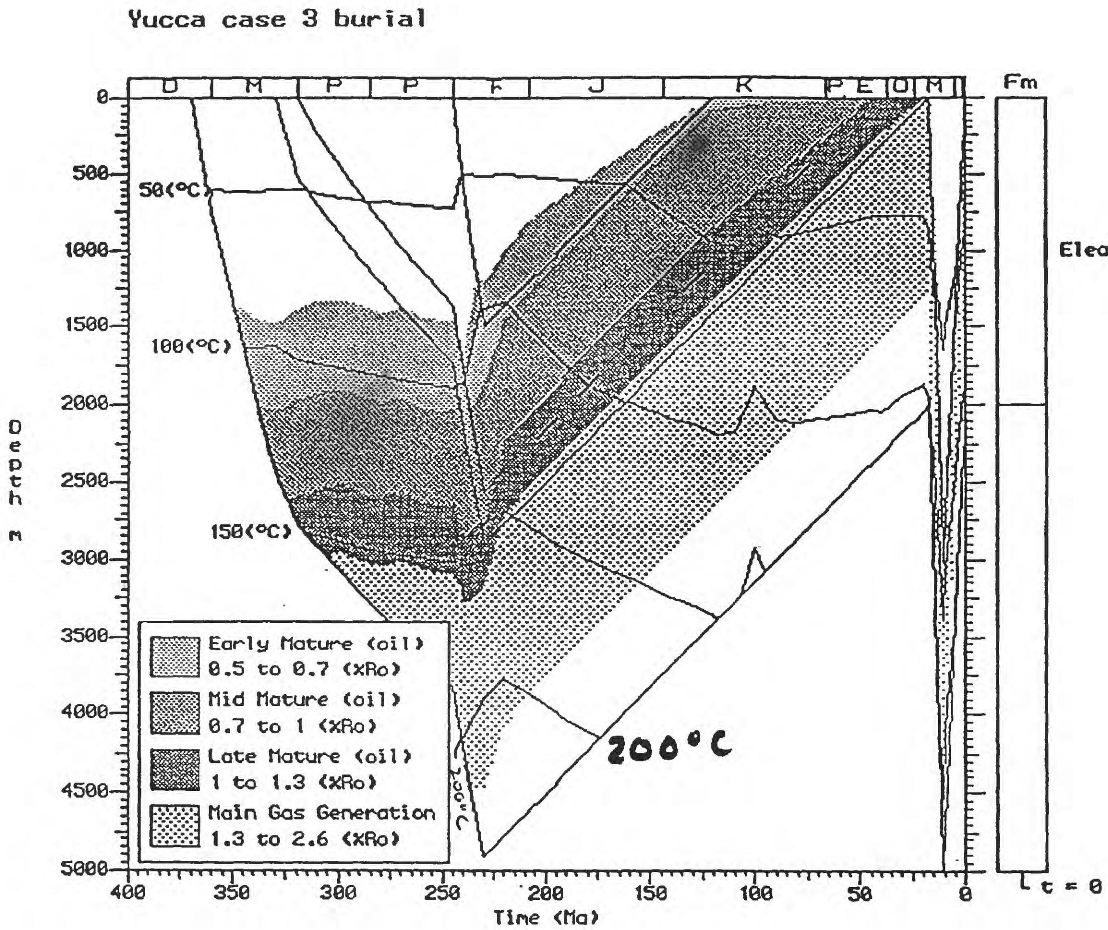

Yucca case 3 burial
D
M
P
P
F
J
K
P
E
O
M
Fm
Eleana Fm
50(°C)
100(°C)
150(°C)
200°C
Early Mature (oil)
0.5 to 0.7 (%Ro)
Mid Mature (oil)
0.7 to 1 (%Ro)
Late Mature (oil)
1 to 1.3 (%Ro)
Main Gas Generation
1.3 to 2.6 (%Ro)
Depth m
Time (Ma)
t = 0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
400
350
300
250
200
150
100
50
0

Figure 7a

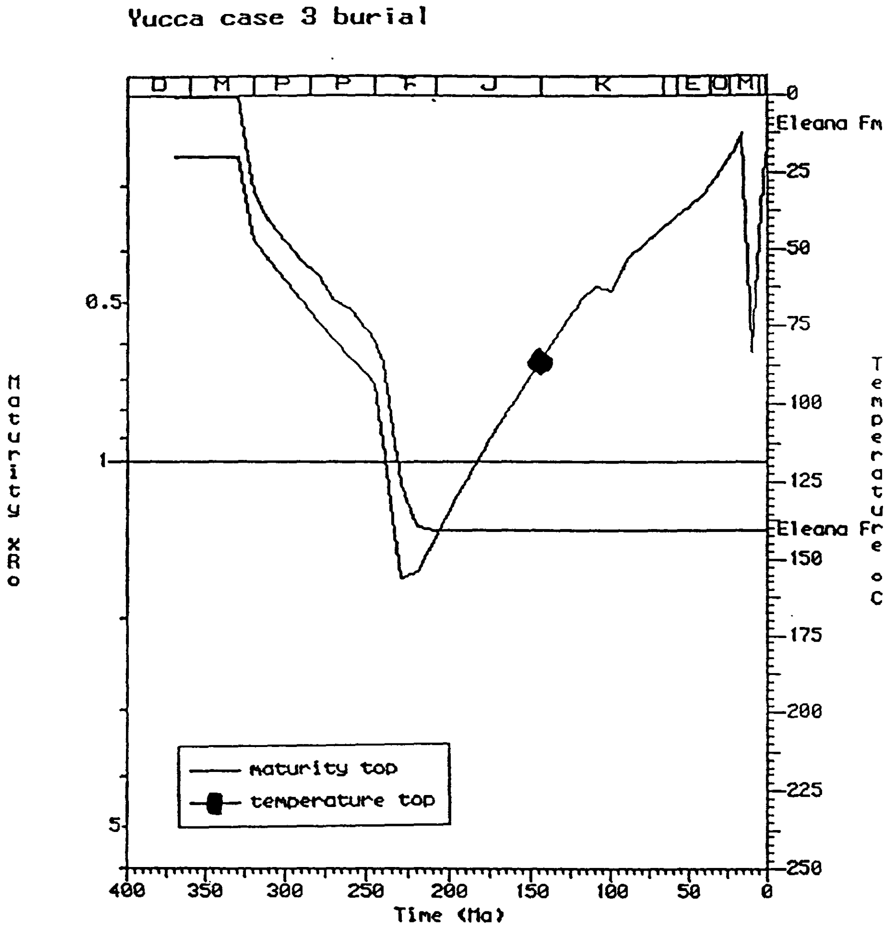

Yucca case 3 burial
D
M
P
P
F
J
K
E
O
M
0.5
1
5
Maturity %Ro
0
Eleana Fm
25
50
75
100
125
Eleana Fr
150
175
200
225
250
Temperature oC
maturity top
temperature top
400
350
300
250
200
150
100
50
0
Time (Ma)

Figure 7b

Yucca case 3 burial

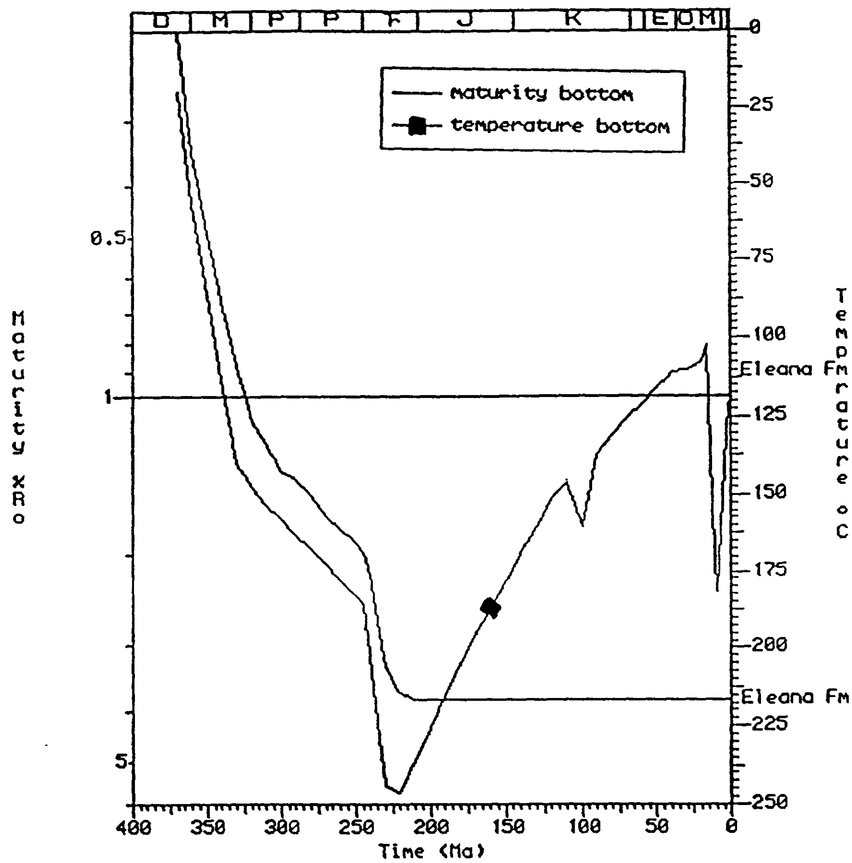


Figure 7c