AMERICULTURE

EXHIBIT

2

EVIDENCE FOR LARGE-SCALE LARAMIDE TECTONIC INVERSION AND A MID-TERTIARY CALDERA RING FRACTURE ZONE AT THE LIGHTNING DOCK GEOTHERMAL SYSTEM, NEW MEXICO

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ABSTRACT—Stratigraphy in a recent intermediate depth (2100 ft) geothermal test hole is interpreted along side previous deep (7001 to 7404 ft depth) exploration holes to study large-scale structural controls for the Lightning Dock geothermal system and refine the stratigraphic and structural characterization of the shallow reservoir. Laramide compression and large-scale tectonic inversion of a northwest-trending Late Jurassic-Early Cretaceous extensional structure at the Lightning Dock geothermal site represents deformation that may exceed Neogene extensional processes in magnitude and duration and provide potential for a significant volume of shattered rock. Also, volcanic stratigraphy supports the hypothesis of Elston et al. (1983) for a mid-Tertiary caldera ring fracture zone in the vicinity the geothermal area. Northeast- and north-trending Neogene normal faults that cross cut older structures provide additional preparation of fractured ground. A north-trending Pleistocene normal fault may reopen older fractures that are favorably oriented and allow concentration and upward flow of deep-seated geothermal fluids. Because the Lightning Dock geothermal system is "blind" and has no surface manifestations, a better understanding of structures buried beneath Neogene alluvial basin fill may have application in geothermal exploration to find similar "blind" geothermal systems elsewhere in southern New Mexico and southeastern Arizona.

LOCATION AND GEOTHERMAL USE

The Lightning Dock geothermal system is located in the Swallow Fork Peak 7.5 minute quadrangle, Animas Valley, Hidalgo County, New Mexico near Cotton City in the Mexican Highland section of the southern Basin and Range Province (Fig. 1). The Lightning Dock geothermal system is "blind" or without surface manifestations and the resource was fortuitously discovered during cable tool well drilling for crop irrigation in 1948 (Summers, 1976). The currently known productive portion of the geothermal system is within a small, but intense, heat-flow anomaly. Production wells that tap the shallow outflow plume are used to supply heat for the thirty-acre Burgett Geothermal Greenhouse and the AmeriCulture tilapia (food fish) farm (Witcher et al., 2002).

PURPOSE

A preliminary geologic analysis of the stratigraphy in a new intermediate depth (2100 ft) geothermal test hole is compared with geologic relationships observed in previous deep (7001 to 7404 ft depth) exploration holes in the area. Borehole geologic analysis suggests potential pre-Basin and Range geologic controls for the system. A better understanding of Paleogene and older structure may have application in geothermal exploration to find similar "blind" geothermal systems elsewhere in southern New Mexico and southeast Arizona. In particular, evidence for local large-scale Laramide compression inversion of Late Jurassic-Early Cretaceous extensional structures at the Lightning Dock geothermal site is presented. Also, borehole volcanic stratigraphy is reviewed with reference to the Elston et al. (1983) hypothesis that a mid-Tertiary caldera ring fracture zone exists in the vicinity of the Lightning Dock geothermal area.

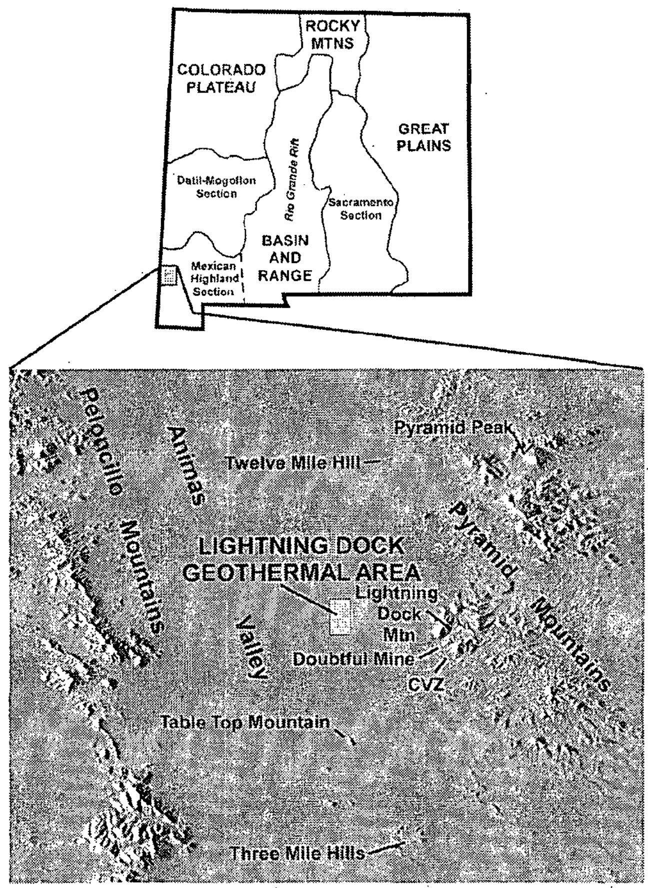

FIGURE 1. Shaded relief topographic location map of the Lightning Dock geothermal area.

PREVIOUS GEOLOGICAL AND GEOPHYSICAL STUDIES

Elston et al. (1983), a primary reference for the Lightning Dock geothermal system, described the mid-Tertiary volcanic framework observed in the Pyramid Mountains. Other important outcrop geologic studies for the adjacent Peloncillo and northern Pyramid Mountains are found in Armstrong et al. (1978), Bayona and Lawton (2000 and 2003), Flege (1959), Gillerman (1958), Smith (1987), and Thorman and Drewes (1978). Cunniff and Bowers (1988) provide a brief summary of the Steam Reserve Federal 55-7 exploratory test well drilled to 7001 ft. Thompson et al. (1978) and Thompson (1982) tabulate formation tops in the 7404 ft deep Cockrell 1 Pyramid Federal well. Electrical geophysical surveys for the area are summarized in Jiracek et al. (1977) and Smith (1978). Aeromagnetic, gravity, and seismic data and studies of the Animas Valley and surrounding region are published in Ackermann et al. (1994), Klein (1995), Kucks et al. (2001), and Sauck and Sumner (1970).

REGIONAL SETTING

Southwestern New Mexico and southeastern Arizona have a strong west-northwest (WNW) structural grain that is characterized by several bands of deformation with repetitive Precambrian through Tertiary heritage (Titley, 1976). The WNW basement grain is easily discerned in regional aeromagnetic maps (Kucks et al., 2001; Sauck and Sumner, 1970). The WNW grain is intruded by Tertiary volcanic eruptive centers and obliquely overprinted by north-striking Basin and Range normal faults. Important post-Paleozoic and pre-Oligocene angular unconformities show missing section, ranging from Precambrian to lower Tertiary in boreholes and in the mountain ranges in the immediate Lightning Dock area. Lower Cretaceous and lower Tertiary subcrops suggest two major vertical uplifts prior to mid-Tertiary volcanism and Basin and Range extension. The following is a brief summary of the tectonic settings and their stratigraphic records.

Paleozoic Marine Shelf

During the late Paleozoic, the area was a marine shelf on the northern flank of the WNW-trending Pedregosa basin and west and southwest of the WNW-trending Florida uplift (Kues and Giles, 2004). Predominantly shallow marine or carbonate shelf deposition occurred from Cambrian and Ordovician into Early and possibly mid-Permian (Kues and Giles, 2004; Ross and Ross, 1986; Ross, 1978). Today, Permian rocks are preserved about 16 km west of Lightning Dock in the Peloncillo Mountains (Bayona and Lawton, 2000, 2003; Gillerman, 1958) and Pennsylvanian limestone is observed in collapse megabreccia of the mid-Tertiary Muir cauldron in the Pyramid Mountains about 7 km northeast of Lightning Dock and in isolated outcrops just northwest of the Three Mile Hills area about 7.5 km south of Lightning Dock (Elston et al., 1983).

Bisbee Rift

During the Late Jurassic and Early Cretaceous, a WNW-trending rift extended across the area and appears to have reactivated older Precambrian and Paleozoic structural zones (Lawton, 2000, 2004; Lawton and McMillan, 1999; Lucas and Lawton, 2000). The area of the present day

Burro Mountains, about 50 km northeast of Lightning Dock, demarcated the WNW-trending thermal rift shoulder (Mack et al. 1988). As rifting waned, thermal subsidence progressed, and the rift shoulder eroded, the region around Lightning Dock was blanketed by more than 610 m (2,000 ft) of Bisbee Group sediment (Lawton, 2004; Mack et al., 1988).

The nearest outcrops of Bisbee rift sediments are found 9 km to the south of the Lightning Dock area in the Three Mile Hills and consist of poor exposures of possible Mojado and U-Bar Formations (Elston et al., 1983). Other outcrops of possible Mojado Formation are found about 15 km north in the Pyramid Mountains (Thorman and Drewes, 1978). In the Peloncillo Mountains about 16 km to the west of Lightning Dock, several sections of Bisbee Group rocks are described in detail in Bayona and Lawton (2000, 2003), using the nomenclature of Gillerman (1958).

Laramide Orogeny

The Late Cretaceous and early Tertiary Laramide Orogeny exhibits deformation with reverse faults, folding, and thrust faults in scattered but roughly aligned WNW zones that obliquely cross present day, north- to south-oriented mountain ranges in southwest New Mexico and southeast Arizona. Corbitt (1988), Drewes (1978, 1980, 1981), and Woodward and Duchene (1981) interpret the zones as evidence of large-scale, thin-skin regional "overthrust" and invoke transport of the allochthon northeast more than 10 km to as much as 100 km on regional low-angle thrust faults at or near the Cambrian (base of Phanerozoic sediment cover) and Precambrian (basement) contact.

More recent studies argue that horizontal shortening by Laramide folding and thrust faulting is subordinate to vertical deformation. Most higher amplitude folds and nearly all thrust faults are confined to Phanerozoic cover rocks on the margins of compressional uplifts and show limited or only local horizontal transport. The Precambrian-cored compressional uplifts again follow regional WNW basement anisotropicity (Brown and Clemons, 1983; Clemons, 1998; Davis, 1979; Lawton, 2000; Lawton and Clemons, 1992; Seager, 1983, 2004; Seager and Mack, 1986). Some of these studies also presented evidence for reactivation and tectonic inversion of the older Bisbee rift extensional structures and for local transpression or oblique compression.

Lawton (2000) summarizes Laramide reactivation models of the older Bisbee rift structures by inverting the rift basins into uplifts in a compressional stress regime. Structural inversion and the complementary stratigraphic record along WNW zones in the Peloncillo Mountains west and southwest of the Lightning Dock area is described in detail by Bayona and Lawton (2000, 2003). In the Peloncillo Mountains, Laramide basin fill is overlain by folded Eocene andesite and consists of clastic and tuffaceous sediments with local Laramide volcanic, Mesozoic, Paleozoic and Precambrian basement provenance (Bayona and Lawton, 2000, 2003).

Mid Tertiary ignimbrite volcanism

Elston et al. (1983) described the evolution and configuration of a mid-Tertiary ignimbrite caldera, the Muir cauldron, in the Pyramid Mountains east of the Lightning Dock geothermal anomaly. Elston et al. (1983) inferred that the outer ring fracture moat or topographic wall of the cauldron could traverse the Lightning Dock geothermal anomaly subsurface. The collapse of the Muir cauldron began about 35.3 Ma with the eruption of the Tuff of Woodhaul Canyon (Elston et al., 1983; McIntosh and Bryan, 2000). At the top of the Tuff of Woodhaul Canyon, an additional ash-flow tuff is represented by the Tuff of Graham Well, which appears to be associated with shallow and late final enlargement of the Muir cauldron (Elston et al., 1983). The Latite of Uhl Well and the Rhyolite of Pyramid Peak represent post collapse ring fracture lava flows and domes.

Post Muir cauldron silicic volcanism buried the region and is designated locally as the Rimrock Group by Elston et al. (1983). Age dating, paleomagnetic, and chemistry studies of McIntosh and Bryan (2000) correlate the Rimrock Group ash-flow tuffs with specific cauldron sources in southwestern New Mexico that have ages 1 to 5 million years younger than the Muir Cauldron ignimbrites and ring fracture flows and domes.

Basin and Range

Heat flow, gravity, resistivity, and refraction seismic data place the Lightning Dock geothermal anomaly over a small, buried, Neogene uplift, the Hot Wells horst, which projects northward as a short prong into the southeast part of the lower Animas graben of the Animas Valley (Fig. 2; Jiracek et al., 1977; Smith, 1978). Gravity data also indicate that significant north- and northeast-trending normal fault systems bound the buried Hot Wells horst block on the west, east, and north.

Aerial photos and ground reconnaissance show that the youngest segment of the north-trending late Pleistocene Animas Valley fault (Elston et al., 1983) ends just east of the Lightning Dock geothermal area. The fault segment was originally identified as a possible Pleistocene high stand of Lake Animas (Flege, 1959). However, Fleischhauer and Stone (1982) presented evidence for a tectonic origin. The fault scarp displaces Quaternary calcic soil and cuts diagonally south across elevation contours. This fault segment is apparently the most recently active normal fault in the lower Animas graben. A possibly older segment of the fault is observed to the south. While the southern fault trace is poorly defined, this segment is in more easily eroded distal alluvial-fan deposits and may not have preserved its topographic scarp as well as the northern and apparently younger segment.

The fault appears to be a young incipient structure with only limited Quaternary displacement. The fault lacks a discrete or uniquely attributable steep gravity gradient or anomaly (Fig. 2). Gravity and resistivity survey information infer other larger normal faults, both synthetic and antithetic to the Pleistocene Animas Valley fault between the Lightning Dock geothermal anomaly and the Pyramid Mountain front (Fig. 2; Smith, 1978).

GEOLOGY OF DEEP WELLS IN THE AREA

The following summary of deep wells in the area identifies key stratigraphic units with regard to the regional geologic setting. Brief descriptions of the units provide supplemental information for interpretation. Most discussion is centered on the AmeriCulture State 2 well as it is the best geologically characterized borehole.

AmeriCulture State 2 Well

The 2100 ft deep AmeriCulture State 2 test provides a benchmark to interpret generalized geologic logs for two nearby deep exploration boreholes, the 7001 ft depth Steam Reserve Federal 55-7 and the 7404 ft depth Cockrell 1 Pyramid Federal well (Fig. 3). The AmeriCulture State 2 well was initially drilled with both rotary air and rotary mud to 958 ft depth, then drilled with continuous wireline core from 958 to 1688 ft, and finally completed with rotary mud to 2100 ft total depth. Figure 4 is a summary graphic geologic log.

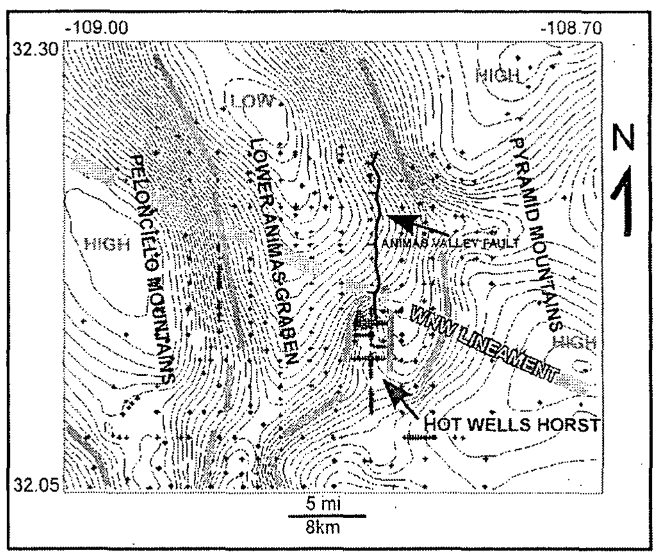

FIGURE 2. Complete Bouguer gravity map of the lower Animas graben and surrounding horst blocks. Gravity contour interval is 1 milligal. Small crosses are gravity measurement stations. Gravity data from Geonet gravity depository (Geonet, 2008). The WNW lineament is based upon the aeromagnetic interpretation in Figure 6. Buried faults along steep gravity gradients are shown as thick gray lines.

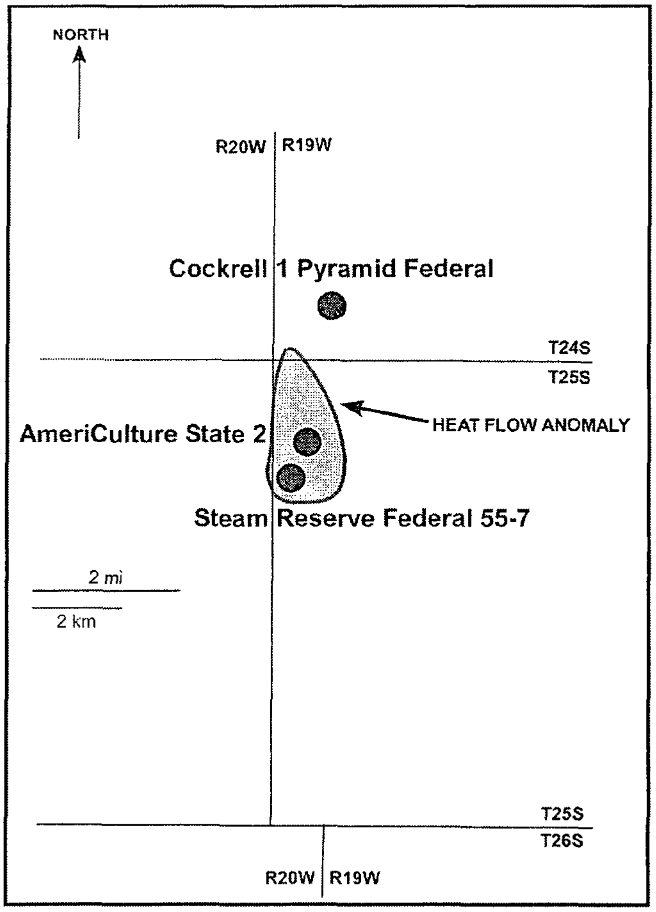

FIGURE 3. Location of deep test wells in the Lightning Dock geothermal area. The shaded area shows the approximate extent of heat flow greater than 250 mW/m^2 (milli-watts per meter squared).

The upper 645 ft of the hole consists of alluvial basin fill deposits. From the surface down to 280 ft, sandy gravel, clayey gravel, and minor clay are largely unconsolidated. This unit represents uppermost Miocene-Pliocene to Holocene mid and distal alluvial-fan deposits shed from the Pyramid Mountains. At 280 ft depth, orange gummy clay with gravel(?) rests upon hydrothermally silicified sandy conglomerate at 284 ft depth. The gummy clay is unique in the hole and appears to be important in terms of geothermal processes or possibly Neogene structural evolution as either a hydrothermal alteration product or as a thick paleosol(?), although a calcic horizon is missing or unidentified in drill cuttings. On the other hand, the gravelly(?) gummy clay may only record a local alluvial-fan mudflow that acts as an aquitard over the principal geothermal outflow plume reservoir. Unfortunately, the borehole was drilled with air across this interval and no core is available to study.

The intensely silicified sandy conglomerate below 284 ft depth contains rounded clasts of andesite, ash-flow tuff, and rhyolite. Clasts float in a light brick red-to-orange, silicified, silty-to-fine sand matrix. The highly silicified nature of the unit and clasts of tuff and rhyolite have resulted in the erroneous label "rhyolite or volcanics" in rotary drilling logs of wells at Lightning Dock. Hydrothermal quartz cement in the unit is most intense between 284 and about 400 ft depth. Below 400 ft, the unit is indurated, but not as strongly silicified. The silicified sandy conglomerate from 284 to 570 ft depth represents a major phase of Basin and Range sedimentation that corresponds with the Gila Conglomerate in southwest New Mexico and southeast Arizona. The silicification is believed to be associated with the present-day geothermal system outflow plume. At about 570 ft the alluvial deposits, become more coarse-grained with much less fine and medium sand and silt. The coarse deposits are found to a total depth of about 645 ft and represent another Gila Conglomerate unit or facies. The Gila Conglomerate at Lightning Dock may range in age from late Oligocene to late Miocene.

A biotite "rhyolite" was drilled from 645 to 860 ft depth. Besides biotite, only minor plagioclase phenocrysts are observed and sanidine and quartz phenocrysts are absent in drill cutting samples. The upper part of the unit from 645 to 730 ft and the lower part of the unit from 830 to 860 ft is intensely altered to white and light apple green "clay" with euhedral biotite phenocrysts preserved. The upper and lower units may represent altered ash deposits associated with the middle unaltered rhyolite unit (W. E. Elston, personal commun. 2007).

The unaltered middle of the unit from 730 to 830 ft displays some very diagnostic textures. From 730 to 760 ft, a vitrophyre with perlitic texture is observed. The perlitic texture is pervasive even across devitrified zones developed around glassy cores. The

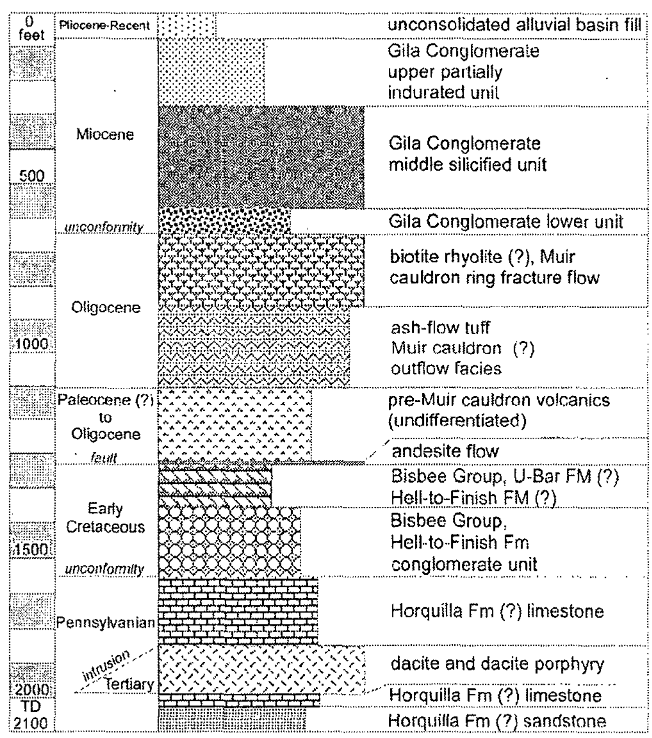

FIGURE 4. Summary geologic log of the AmeriCulture State 2 well.

perlitic texture shows blocky elongated fractures (banded perlite) rather than arcuate or circular microcracks (classic perlite) (McPhie et al., 1993). Farther down from 760 to 830 feet, the volcanic glass is devitrified and contains a few isolated spherulites and abundant lithophysae. Extremely fine-grained, gray granophyric patches appear to fill lithophysae in a light brown aphanitic matrix. Overall, the unit from 730 to 860 ft depth appears to represent a rhyolite flow and no eutaxitic textures or fiamme are observed (Cas and Wright, 1988).

The abundant biotite, 3 to 10 %, may place this unit with early volcanism associated with the Muir cauldron. Studies by Elston et al. (1983) and McIntosh and Bryan (2000) point out that silicic volcanic units in the region with abundant hydrous mineral phases, such as biotite, are mostly associated with the early phases of ignimbrite volcanism. The biotite "rhyolite" is tentatively assigned to a ring fracture dome and flow unit of the Muir cauldron and may be correlative with the Rhyolite of Pyramid Peak, based in part upon the vitrophyric and perlitic nature of drill cuttings (W. E. Elston, personal commun. 2007).

A welded vitric crystal ash-flow tuff (98 ft thick) from 860 to 958 ft depth shows a matrix texture of devitrified granophyre with ghost eutaxitic textures that are outlined by hematite. About 10 to 20 % of the rock contains crystals of plagioclase, quartz, and biotite, but no sanidine. The tuff of Graham Well on the northern slopes of Lightning Dock Mountain has similar attributes (Elston et al., 1983). This unit may be an outflow facies of The Tuff of Graham Well, the youngest major ignimbrite of the Muir cauldron.

A thicker ash-flow tuff unit (147 ft thick) was cored from 958 to 1105 ft depth. This light brown-to-buff, crystal-rich, lithic tuff is partially welded with heterolithic lapili mostly between 0.5 and 2 cm. Pumice is altered and shows moderate eutaxitic texture. This unit is tentatively correlated as an outflow facies of the Tuff of Woodhaul Canyon, the initial major ignimbrite of the Muir cauldron (W. E. Elston, personal commun. 2007).

An interbedded sequence of mostly tuffaceous volcaniclastic sand and gravel was cored between 1105 and 1326 ft depth. Clast compositions include andesite, felsite, and basalt. This interval may represent volcanic ash, lahars, and sediment shed from small local eruptive centers prior to the Muir cauldron collapse.

An andesite porphyry (8 ft thick) was cored from 1326 to 1334 ft depth and may be correlative with Eocene (Hidalgo volcanics) or other (Laramide) andesitic units. The base of this unit is missing and cut by a normal fault, and the stratigraphic position is consistent with the andesite of Holtkamp Canyon (Elston et al., 1983).

The Upper Jurassic to Lower Cretaceous Bisbee Group is encountered below the fault at 1334 ft depth. From 1334 to 1456 ft, the Bisbee Group consists of interbedded calcareous sandstone, shale, calcareous shale, limestone, and dolomite. Pending additional study of core, this 122 ft thick interval is tentatively assigned to the Hell-to-Finish Formation instead of the U-Bar Formation because of a lack of abundant and distinctive rudist fossils.

A well-indurated, sandy cobble-to-boulder, mostly clast-supported conglomerate (197 ft thick) was cored between 1456 and 1653 ft. Rounded clasts consist predominantly of limestone and minor chert. The conglomerate is tentatively assigned to the Hell-to-Finish Formation of the Bisbee Group. This unit may be equivalent to the Glance Conglomerate in Arizona (Bilodeau, 1978). The overlying Bisbee Group sediments are conformable. The Hell-to-Finish conglomerate represents a proximal basin fill unit of Late Jurassic-Early Cretaceous Bisbee rift grabens and is unconformable on the underlying Paleozoic limestone.

A fossiliferous gray-to-dark grey limestone with very little chert and several fusulinid horizons was cored from 1653 to 1850 ft depth. These Permian or Pennsylvanian age rocks are consistent with a carbonate shelf depositional environment. The lower 70 ft from 2030 to 2100 ft is grey siltstone and fine sandstone. Between 1850 and 1990 ft, the unit is intruded by a mid-Tertiary(?) dacite and dacite porphyry. The unit is tentatively assigned to the Horquilla Formation, pending identification of fusulinids. The 70 ft thick siltstone and sandstone interval may indicate Permian strata instead of Pennsylvanian rocks (Gillerman, 1958).

Steam Reserve Federal 55-7

Subsurface geology in the Steam Reserve Federal 55-7 test well is summarized by Cunniff and Bowers (1988) and relies upon formation tops interpreted by S. Thompson III (unpub, NM Bureau of Mines and Mineral Resources, memo, 1986). Table 1 lists the formation tops for the Steam Reserve Federal 55-7 well along with formation tops for the AmeriCulture State 2 and Pyramid Cockrell 1 Federal wells. Compared to the AmeriCulture State 2 well, the base of the valley fill (unconsolidated alluvial basin fill deposits) has only 6 ft difference in the Steam Reserve 55-7 Federal well. Silicified Gila Conglomerate, while most likely present in the Steam Reserve Federal 55-7 well, appears to be included with the Tertiary volcanics (Cunniff and Bowers, 1988).

The top of the Bisbee Group in the Steam Reserve Federal 55-7 is at 1422 ft depth. The Paleozoic top is 189 ft deeper in the Steam Reserve Federal 55-7 well than in the AmeriCulture State 2 well and the apparent thickness of the Bisbee Group also increases to the south by 83 ft in the Steam Reserve Federal 55-7 well. While the composite Paleozoic section drilled in the Steam Reserve Federal 55-7 borehole is roughly consistent with regional isopach information, Tertiary intrusions may have thickened or faulting may have eliminated some of the Paleozoic units.

Cockrell 1 Pyramid Federal

Formation tops for the Cockrell 1 Pyramid Federal well are from Thompson (1982) (Table 1). Shallow unconsolidated alluvial basin fill deposits overlie the Gila Conglomerate at 385 ft depth. Tertiary volcanic rocks are found at 1890 ft depth in the Cockrell 1 Pyramid Federal well, while volcanics are only 645 ft depth in the AmeriCulture State 2 well. This difference suggests a Basin and Range fault zone that lacks surface expression and has 1200 ft of throw between the AmeriCulture State 2 and Cockrell 1 Pyramid Federal wells. A steep gravity gradient (Kucks et al., 2001; Smith, 1978) between the wells defines the location of this northeast-striking Neogene normal fault (Figs. 2 and 7).

TABLE 1 Formation tops for deep exploration wells at the Lightning Dock geothermal area.

Well Data	Steam Reserve 55-7 Federal	AmeriCulture 2 State	Cockrell 1 Pyramid Federal
Section/Township/Range	sec. 7, T25S, R19W	sec. 7, T25S, R19W	sec. 31, T24S, R19W
Section line footage	2329S, 2412E	319N, 825E	1980N, 660E
Footage units	ft	ft	ft
Elevation	4217.6 KB	4217 GL	4244 KB
Quaternary alluvium	0	0	0
Gila Conglomerate	290 (?)	284	385
mid-Tertiary volcanics	290 (?)	645, Fic 60deg	1890
Laramide volcanics	?	1326, Fbc 35deg	1890 (?)
Bisbee Group	1422	1334, Ftc 35deg	m
U-Bar/Hell-to-Finish ss, ls	1422	1334, Fic 35deg	m
Hell-to-Finish cgl	1539 ?	1456, Fic 60deg	m
Horquilla	1842 Ti	1653 Ti	m
Escabrosa	4770 Ti	nd	5795 Ti
Percha	5609	nd	6680 Ti
Montoya	5982	nd	6860 Ti
El Paso	6201 Ti	nd	6980 Ti
Bliss	6781	nd	7130 Ti
Precambrian granite	6858	nd	7340
TD	7001	2100	7404
Reference	Cunniff and Bowers (1988)	this study	Thompson (1982)

Notes: Ti - intrusive; Fic - faulted unit in core; Ftc - fault top unit in core; Fbc - fault bottom unit in core; 35deg - fault dip 35 degrees; 60deg - fault dip 60 degrees, KB - kelly elevation; GL - ground elevation; nd - not drilled; m - missing

One of the more intriguing features of the Cockrell 1 Pyramid Federal well is the 3905 ft thick "Tertiary" volcanic section from 1890 to 5795 ft depth. The volcanic rocks rest upon Mississippian rocks instead of Lower Cretaceous rocks and are much thicker than the volcanic section in the AmeriCulture State 2 well. A thick Laramide sequence of andesitic rocks is observed in the Peloncillo Mountains to the west and in the northern Pyramid Mountains to the northeast (Bayona and Lawton, 2000, 2003; Gillerman, 1958; Thorman and Drewes, 1978). The Rimrock sequence of mid-Tertiary rocks is apparently not present in the AmeriCulture State 2 well and may be preserved in the Cockrell 1 Pyramid Federal well. Rotated and west-dipping outcrops of Rimrock ignimbrites are exposed at Twelve Mile Hill about 4 km northeast of the Cockrell 1 Pyramid Federal well.

DISCUSSION

Lawton (2000) presents a model and several examples of tectonic inversion along major WNW-trending basement structures in southwest New Mexico that may apply at Lightning Dock. During the Late Jurassic and Early Cretaceous, grabens developed across the region along WNW-striking normal faults and became depositional sites for Bisbee Group sediments. Afterwards, during the Late Cretaceous to early Eocene, the WNW-striking normal faults evolved into reverse faults with the opposite sense of displacement in the Laramide compressive stress field.

Jurassic-Early Cretaceous (Bisbee Rift) Normal Fault

Figure 5 is a diagrammatic cross section that illustrates an interpretation of geologic relationships at Lightning Dock. The absence of several thousand feet of Pennsylvanian and Permian(?) rocks and Bisbee Group sediments in the Cockrell 1 Pyramid Federal well requires explanation. A large Late Jurassic-Early Cretaceous normal fault between the AmeriCulture State 2 well and the Cockrell 1 Pyramid Federal well apparently uplifted the Cockrell 1 Pyramid Federal well site and all Permian(?) and Pennsylvanian rocks were eroded down into the Mississippian in the normal fault footwall.

The Bisbee Group sediments observed in the Steam Reserve Federal 55-7 and AmeriCulture State 2 wells are unconformable on Pennsylvanian(?) rocks in the hanging wall. The proximal and basal conglomerate deposits of the Hell-to-Finish Formation in the normal fault hanging wall at the AmeriCulture State 2 site are only 9500 ft south of the Mississippian-Tertiary unconformity in the footwall or horst block at the Cockrell 1 Pyramid Federal well site. These Hell-to-Finish deposits seem to require a high-to-moderate angle Early Cretaceous normal fault with a minimum 4500 ft throw, using borehole formation tops for Pennsylvanian rocks in the AmeriCulture 2 State well and the Mississippian rocks in the Cockrell 1 Pyramid Federal well as control datum.

It is conceivable that another large Early Cretaceous normal fault exists south of the Steam Reserve Federal 55-7 well. The

Hell-to-Finish Formation observed in the AmeriCulture State 2 well may be on lap deposition of a pediment with an eroded Permian section on the footwall of the fault. The inferred fault is not shown in Figure 5. If the fault exists, cumulative normal fault throws in the immediate region may approach 10,000 ft.

Laramide Tectonic Inversion

Tectonic inversion of the Early Cretaceous normal fault zone by Laramide reverse faulting can account for the relatively small maximum elevation difference of about 500 ft on the Precambrian surface today (Fig.5). When Neogene Basin and Range normal fault throw of 1200 ft between the Steam Reserve Federal 55-7 (or AmeriCulture State 2) and the Cockrell 1 Pyramid Federal wells is subtracted, a high-to-moderate angle Laramide reverse fault with a minimum 4000 ft throw is required to roughly match up the Precambrian surface elevation between the two wells.

Also, Laramide uplift and subsequent erosion of the hanging wall may account for the relatively thin Lower Cretaceous Bisbee Group section of 319 and 420 ft thickness in the AmeriCulture State 2 and Steam Reserve Federal 55-7 wells when compared to measured sections in the Peloncillo Mountains which range between 247 and 833 m (810 and 2723 ft) thick (Bayona and Lawton, 2000, 2003). If Laramide uplift and erosion has eliminated most of the Bisbee Group, reverse fault throw may greatly exceed 4000 ft.

It is likely that the Bisbee Group, especially the Mojado Formation, once blanketed the entire area prior to Laramide tectonic inversion (Mack et al., 1988). Outcrops of possible Mojado Formation are observed in outcrop about 15 km north of the Cockrell 1 Pyramid Federal well site (Thorman and Drewes, 1978). A missing Bisbee Group section suggests that the Cockrell 1 Pyramid Federal site also resides on a local or regional uplifted Laramide terrain. An early phase of Laramide deformation along another Laramide reverse fault (not shown in Figure 5) between the Cockrell 1 Pyramid Federal site and the Mojado(?) outcrops to the north may have uplifted the AmeriCulture 2 State site in concert with the Cockrell 1 Pyramid Federal site. A later phase of Laramide deformation with differential uplift between the two sites resulted in tectonic inversion at the AmeriCulture 2 State site. Alternatively, transpressional oblique folding on the compressed footwall basin may have allowed erosion of the Bisbee Group on a local anticline at the Cockrell 1 Pyramid Federal site prior to infill of Laramide basin sediments and volcanics.

If the mid-Tertiary volcanic section in the Cockrell 1 Pyramid Federal well is assumed to be roughly equal in thickness with the Steam Reserve Federal 55-7 and AmeriCultureState 2 wells, a thick sequence of Laramide volcanics and sediments rests uncon-

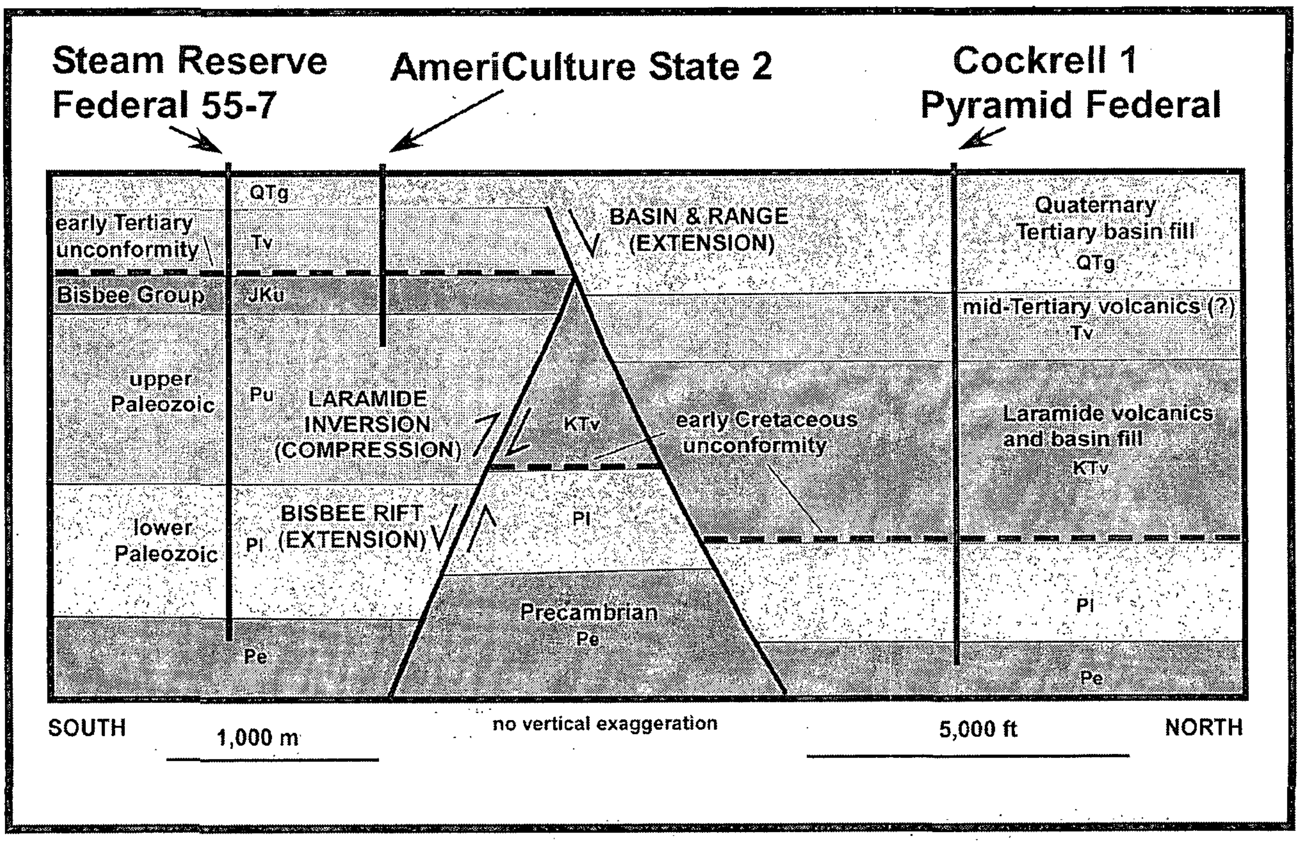

FIGURE 5. Diagrammatic cross section showing geologic relationships and structural evolution interpreted from deep wells in the Lightning Dock geothermal area.

formably on Mississippian rocks. A Laramide basin on the footwall would accommodate early Tertiary (Laramide) volcanics and sediments at the Cockrell 1 Pyramid Federal site.

The actual structural configuration is no doubt far more complex than Figure 5 suggests. Folding and other large faults probably exist because formation dips in Mesozoic and Paleozoic drill core in the AmeriCulture State 2 well are variable up to 25° maximum. The large inverted Bisbee-Laramide fault as shown in Figure 5 is for concept illustration and to show gross borehole relationships. Laramide transpressional or oblique deformation is possible and not ruled out by the geologic relationships gleaned from the boreholes.

Muir Cauldron

The mid-Tertiary volcanic section cored in the AmeriCulture State 2 well seems to confirm that the Lightning Dock geothermal system is on or near the topographic wall of the Muir cauldron as hypothesized by Elston et al. (1983). The biotite "rhyolite" at 730 to 830 ft depth with distinctive perlitic and vitrophyre facies could be a ring fracture extrusive and has many attributes similar to the Rhyolite of Pyramid Peak that is in outcrop on the northern topographic wall of the Muir cauldron (Elston et al., 1983). The underlying ignimbrite units may represent proximal outflow facies of the Tuff of Graham Well and Tuff of Woodhaul Canyon that were erupted during caldera collapse.

A northwest lobe or extension of collapse along the ring fracture zone of the Muir cauldron could extend into the Cockrell 1 Pyramid Federal well area and serve to host or preserve a thick volcanic section. Local removal of part of the Paleozoic and all the Bisbee Group section by ring fracture zone collapse could explain the Tertiary subcrop and an apparently slightly thinner lower Paleozoic section below the Mississippian Escabrosa Formation when compared to the Steam Reserve Federal 55-7. Precambrian and Pennsylvanian megabreccia blocks are observed in the lower cauldron fill (Tuff of Woodhaul Canyon) in the Pyramid Mountains 7 km to the northeast (Elson et al., 1983). However, these outcrops probably represent ring fracture zone collapse in the northern sector of the Muir cauldron.

Summary

While ring fracture zone collapse could explain the Tertiary subcrop of Mississippian rocks in the Cockrell 1 Pyramid well, the proximal Hell-to-Finish conglomerate that is unconformable on Pennsylvanian (Permian?) rocks in AmeriCulture State 2 well immediately to the south, strongly supports a large Late Jurassic-Early Cretaceous normal fault and footwall uplift of the Cockrell 1 Pyramid site. Laramide tectonic inversion has apparently returned Precambrian basement to equivalent elevation on both sides of the inverted structure. Also, apparent removal of most of the Bisbee section by erosion on the Laramide uplift or hanging wall block in the Steam Reserve Federal 55-7 and AmeriCulture State 2 wells may explain why the Bisbee Group sections observed in the nearby Peloncillo Mountains by Bayona and Lawton (2000, 2003) are much thicker.

The composite maximum thickness of the post Muir cauldron Rimrock volcanic sequence ranges from 702 to 871 m (2304 to 2859 ft) in the Pyramid Mountains (Elston et al., 1983). While the actual thickness of the Rimrock sequence at specific locations across the region is likely to be less and highly variable due to paleotopography and distance from eruptive centers, it is clear that the 689 ft of pre-Rimrock sequence mid-Tertiary volcanics that is observed in the AmeriCulture State 2 well probably does not characterize the total possible contribution of mid-Tertiary volcanics in the Cockrell 1 Pyramid Federal well. Coupled with the potential for a significant Laramide and younger Eocene-Oligocene andesite at the site, a tectonic inversion model is preferred over a caldera topographic wall slump or structural collapse model to explain the "Tertiary" volcanic subcrop of Mississippian limestone in the Cockrell 1 Pyramid Federal well.

GEOTHERMAL RESERVOIR GROUND PREPARATION

The margins of Laramide basement-cored uplifts are highly fractured and appear to provide potential flow paths and storage for geothermal fluids (Witcher, 1991, 2007). Examples in New Mexico include Rincon, San Diego Mountain, Montezuma Hot Springs, and Hot Springs (TorC). Many geothermal systems in southern New Mexico are found on or in close proximity to mid-Tertiary cauldron ring fracture zones (Chapin et al., 1978; Elston, 1981; Witcher, 1988). The majority of convective geothermal systems in the region are hosted in low elevation horst blocks or structural highs that are sometimes covered by relatively thin Neogene basin fill deposits (Witcher, 1988). An incipient and evolving fault tip of a young Pleistocene fault segment may provide stresses that are highly favorable for open fracture permeability and may enhance fractures associated with tectonic inversion, caldera collapse, and earlier extensional strain.

A WNW aeromagnetic lineament at Lightning Dock may be the geophysical expression for the inverted WNW-trending basement structure (Fig. 6). The middle of the mapped extent of the Muir cauldron straddles the lineament. The younger segment of the Pleistocene Animas Valley fault appears to have a fault tip or termination in the WNW zone.

Mineralization described by Elston et al. (1983) on the western and southwestern slopes of Lightning Dock Mountain straddles the aeromagnetic lineament. A vertical calcite vein zone (CVZ) between 2 to 60 m wide and between 150 to 600 m long shows subordinate manganese oxides and quartz. The CVZ has WNW vein orientations that are directly on strike with the modern geothermal system in the valley. The Doubtful Mine site at the western base of Lightning Dock Mountain is a second nearby site in a similar shear zone that trends NNW. The overall mineralogy is the same as the CVZ except that zones of green fluorite and more quartz is present. A late Miocene and younger age is reasonable for the mineralization at both sites.

The overall dimensions and character of the Doubtful Mine and the CVZ structures and mineralization may provide clues on the dimensions and character of the upflow zone for the current Lightning Dock geothermal system. The geometry and size of adjacent Neogene fossil geothermal systems at CVZ and Doubt-

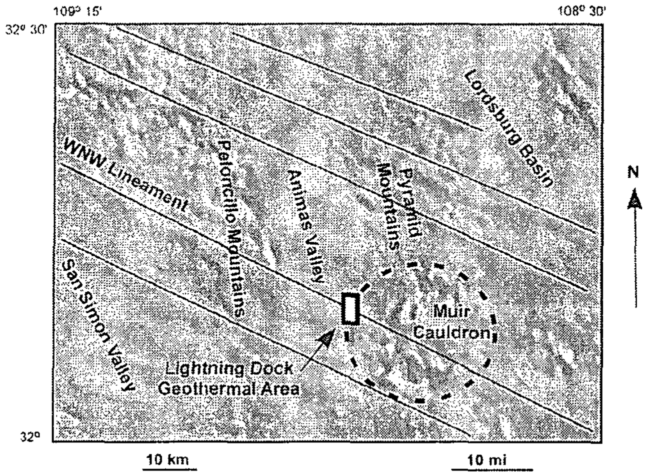

FIGURE 6. Shaded relief aeromagnetic map of the Lightning Dock region with WNW aeromagnetic lineaments. Gridded aeromagnetic data are from Kuchs et al (2001).

ful mine suggest that the main upflow zone of the Lightning Dock geothermal system could be confined to a relatively-small, dilated structural zone. The range of thermal and geochemical characteristics from fluid inclusions at the Doubtful mine are similar to the modern geothermal system temperatures and salinities at Lightning Dock (Elson et al., 1983).

CONCLUSIONS

Silicified and fractured Gila Conglomerate, which buries the Hot Wells horst block, is the host for the shallow outflow plume for the Lightning Dock geothermal system. The silicified Gila Conglomerate has been misidentified as rhyolite by drillers and previous workers in the area.

The Lightning Dock geothermal reservoir upflow is apparently controlled by the intersection of four regional tectonic features: 1) a major WNW-striking basement structural zone that appears to show Late Jurassic to Early Cretaceous extension followed by tectonic inversion during Laramide compression; 2) proximity to the mid-Tertiary Muir cauldron topographic rim and ring fracture zone; 3) the buried Hot Wells horst block within the lower Animas graben; and 4) an incipient and late Pleistocene normal fault segment which ends in the area of the thermal anomaly (Fig. 7). The local area has the potential for a large volume of shattered rock in the subsurface due to repetitive extensional deformation. Bisbee rift extension and Basin and Range extension bracket Laramide compression and transpression deformation in time. Pleistocene extension along the Animas Valley fault has probably opened favorably oriented fractures for vertical permeability and upflow of deep-seated hot water where all the tectonic features converge.

The mid-Tertiary silicic magmatism and volcanism is too old and cannot be a heat source for Neogene hydrothermal activity. The Lightning Dock geothermal system is more likely the result of advective processes that sweep up background heat across a regional ground-water seepage or flow system in bedrock and then leak upward across a hydrogeologic window (Witcher, 1988). The intersection of structures creates open fractures with vertical permeability and storage to collect and allow deep-seated fluids to flow upward through the structural hydrogeologic window to shallow depth.

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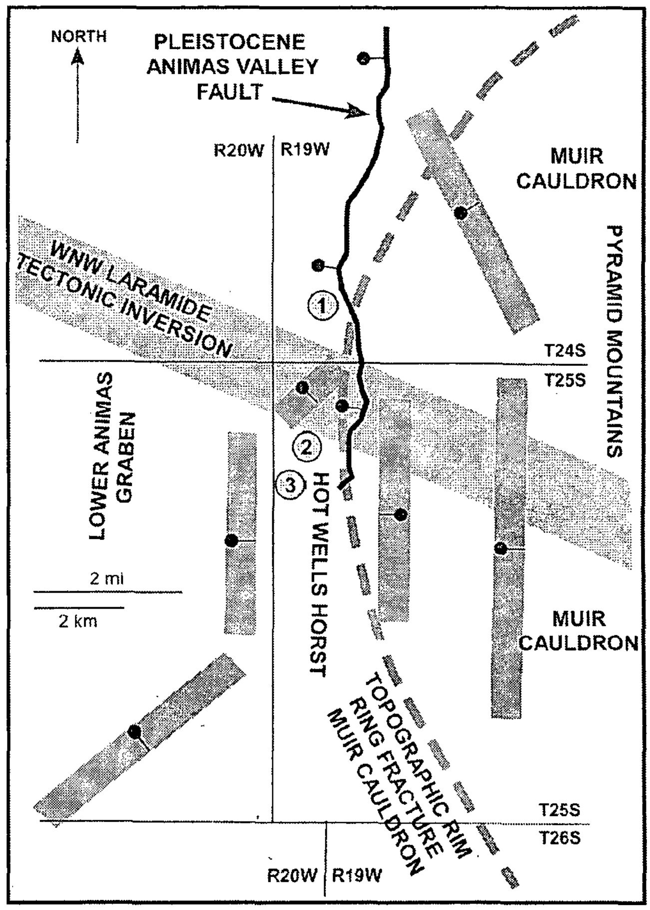

FIGURE 7. Interpretative tectonic map of the Lightning Dock geothermal area. Numbered circles are deep wells: 1) Cockrell 1 Pyramid Federal; 2) AmeriCulture State 2; and 3) Steam Reserve Federal 55-7. Shaded bars are geophysical (gravity) normal faults with ball on hanging wall. Dashed line is the approximate topographic rim of the mid Tertiary Muir cauldron ring fracture zone.

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