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SOME EFFECTS OF PRECAMBRIAN BASEMENT ON THE DEVELOPMENT OF THE SACRAMENTO MOUNTAINS

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Abstract—High-intensity anomalies of gravity and aeromagnetic maps outline different blocks of Precambrian rocks within the Sacramento Mountains because the relief on the Precambrian basement rocks is generally negligible and Tertiary igneous rocks have negligible magnetism but do have mass. The positive aeromagnetic anomaly within the Sacramento Mountains appears to be the strongest and largest such anomaly within New Mexico. The anomaly is interpreted to be caused by abundant magnetite in the upper portion of a huge, layered, ultramafic Precambrian intrusive body. Late-stage intrusive bodies flanking it are represented by Pajarito Mountain and the gabbro stock drilled near Lincoln. The utramafic stock appears to be intruded along a failed, possibly Proterozoic, rift. Other Precambrian intrusives and metamorphic rocks surround the ultramafic stock. Strong facies changes occur in the overlying Paleozoic rocks of the Sacramento Mountains. Mississippian, Pennsylvanian and Permian reef patterns indicate uplift along the west edge of the basement block. Facies of the San Andres Formation over the anticlines of the Tinnie-Dunken anticlinorium indicate that the Precambrian basement blocks were rising during deposition of the limestones. The Sacramento Mountains began to rise in the early Mesozoic. A set of consequent streams developed on the east-dipping slope of the mountains. Simultaneously the Tinnie-Dunken anticlinorium began to rise. The Rios Hondo, Picacho and Felix, and Bluewater Creek are now antecedent streams that breach the anticlinorium. Molycorp is currently developing a large zirconium and yttrium deposit near Pajarito Mountain. Minerals of the ultramafic stock and related rocks of the Precambrian are buried beneath the San Andres, Yeso and Abo Formations but may become important resources in the future should the United States of America lose its sources of strategic minerals abroad.

INTRODUCTION

The purpose of this report is to discuss the probable nature of the basement rocks of the Sacramento Mountains (Fig. 1), to suggest how some of the basement structures created facies changes in Paleozoic strata, to discuss the role of the basement in the formation and development of the mountains, and to note the potential economic significance of a possible layered-ultramafic body beneath the Sacramento Mountains.

The Paleozoic rocks of the Sacramento Mountains range in age from Early Ordovician to middle Permian. Facies in Mississippian through Permian rocks indicate that structural features within the Precambrian basement were active throughout the late Paleozoic. Rocks of Devonian age and older are so poorly exposed and unstudied that it is not clear what effect movements of the Precambrian basement rocks may have had upon their deposition.

BASEMENT ROCKS

Precambrian exposures

The best-known Precambrian exposure is at Pajarito Mountain, within the Mescalero Apache Indian Reservation, at the southeast corner of T12S, R15E and southwest corner of T12S, R16E (Fig. 2). The Precambrian core rocks at Pajarito Mountain consist of syenite, nepheline syenite, alkali granite, quartz syenite and gabbro. The Precambrian intrusive is dated at 1135 to 1215 Ma (Kelley, 1971; Moore et al., 1988). The Yeso and the San Andres Formations onlap this feature that was subaerial during most of Phanerozoic time. Pajarito Mountain appears to have been subaerial since Permian time.

A small exposure of Precambrian rock occurs at Bent just south of US-70, between Mescalero and Tularosa (Fig. 3), secs. 25 and 36, T13S, R11E and secs. 30 and 31, T13S, R11E, Otero County. A thin sedimentary sequence previously identified as Pennsylvanian (Dane and Bachman, 1958) lies on this basement and is overlain by the Permian Abo Formation. Recent examination of part of the area just north of US-70 suggests that these strata, at least in part, may be older than Pennsylvanian (R. M. Colpitts, Jr., personal comm., 1991). Granodiorite was reported from the basement rocks exposed at Bent by Foster (1959, p. 143). The core of the dome, considered to be a weathered Precambrian stock, was an island in the Paleozoic. Structures to the south (Fig. 3) are traceable from the interior of the Sacramento Mountains through Bent to the anticline just east of the Sierra Blanca volcanics. This line of structures is overlain by Abo red beds and is observable at a few localities.

The other exposure of Precambrian rock in the Sacramento Mountains (Pray, 1961, p. 22–27) is at the foot of the western escarpment of the mountains just below the Bliss Sandstone. The shales and sandstones are only moderately metamorphosed and might be of Cambrian or Early Ordovician age, although no fossils were found.

Precambrian rocks in the subsurface

Numerous wells have penetrated Precambrian rocks in the subsurface. The Yates Petroleum Corporation No. 1 Munoz "ANN," in sec. 10, T10S, R15E approximately 8 km (5 mi) southwest of Lincoln, penetrated 36 m (110 ft) of Precambrian gabbro at the bottom of the hole. This gabbro was dated 1284 Ma by emission spectroscopy. The Yates Petroleum No. 1 Dog Canyon, sec. 15, T18S, R15E, penetrated 30 m (100 ft) of Precambrian diabase and gabbro with abundant antigorite. The Yates Petroleum Corporation No. 1 One Tree, sec. 18, T18S, R16E, penetrated 3.65 m (12 ft) of diabase that is about half antigorite. The Yates Petroleum Corporation No. 2 One Tree, sec. 29, T18S, R16S, penetrated 84 m (275 ft) of diabase with magnetite and abundant antigorite. The Gulf Oil Co. No. 1U, sec. 10, T18S, R16E, penetrated 116 m (380 ft) of Precambrian rocks at the bottom of the hole. The upper 23 m (75 ft) of the Precambrian is marble and talc; the lower 93 m (305 ft) is metarhyolite and talc. The Lubbock Machine and Tool No. 1 Randle Anderson, sec. 3, T16S, R16E, penetrated 15 m (48 ft) of pink granite or granite gneiss. The National Exploration No. 1 Picacho, sec. 21, T11S, R18E, terminated drilling in dark brown "granite," possibly a mafic igneous rock. The Southern Production Co. No. 1 Cloudcroft, sec. 5, T17S, R12E, penetrated 28 m (95 ft) of gabbro, diabase and monzonite.

The Precambrian rocks beneath the Sacramento Mountains appear to be andesitic, ultramafic and metamorphic. In contrast, the Precambrian of the Pecos slope east of the Sacramento Mountains is commonly quartzite, meta-arkose, metarhyolite, granitic gneiss and granite.

Plagioclase grains dominate in the arkosic Permo-Pennsylvanian and Abo Formation sandstones and conglomerates on the east flank of the basement high that extends from the Sacramento Mountains north to-

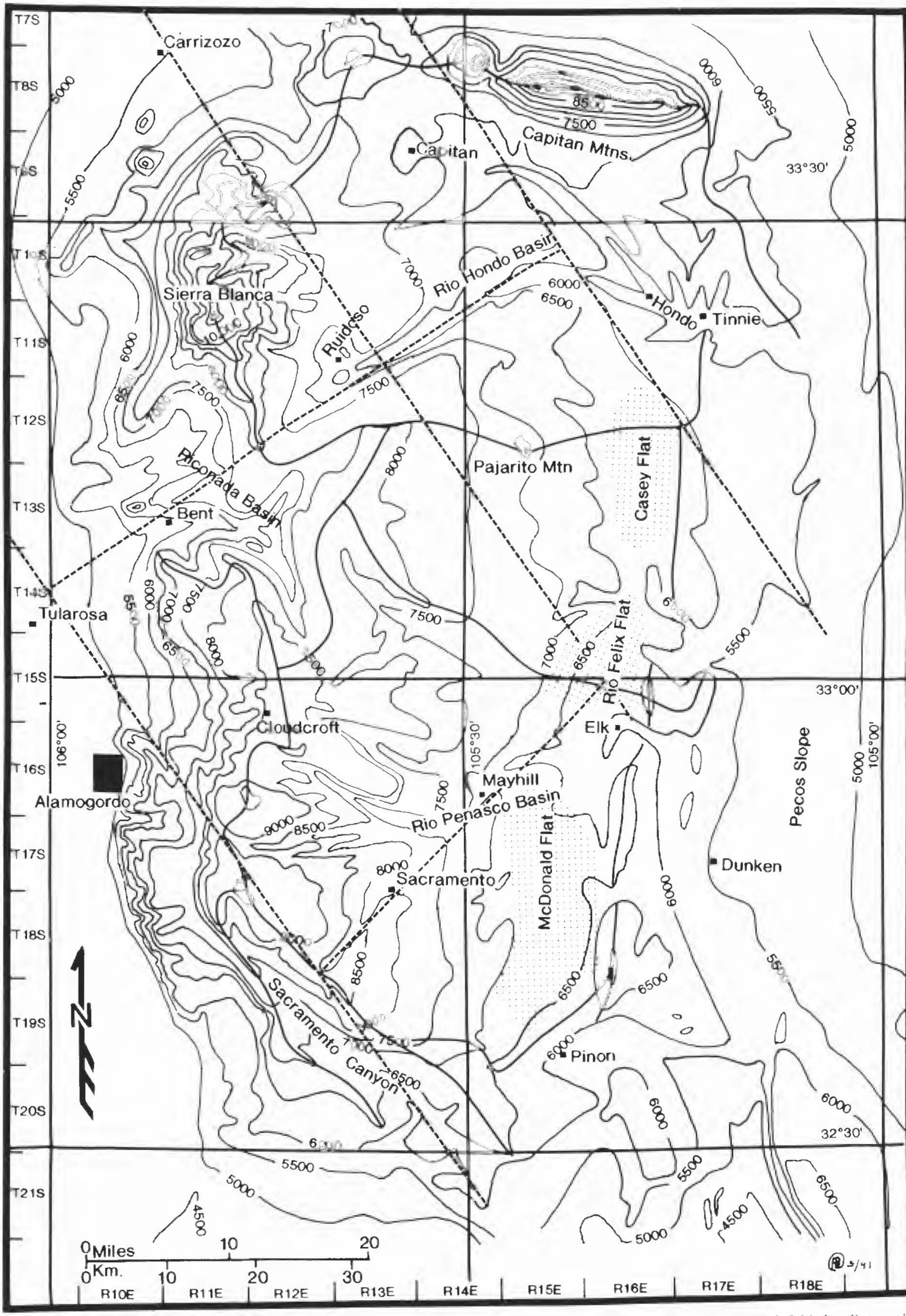

FIGURE 1. Reference map of the Sacramento Mountains, showing topography, drainage basins and linears. The dotted areas are infolded, relict erosional surfaces, i.e., McDonald Flat. The narrow sinuous lines mark approximate drainage divides separating drainage basins. The fine, dashed lines show relative positions of aeromagnetic linears. Modified from U.S. Geological Survey, 1985, Topographic map of state of New Mexico, scale 1:500,000.

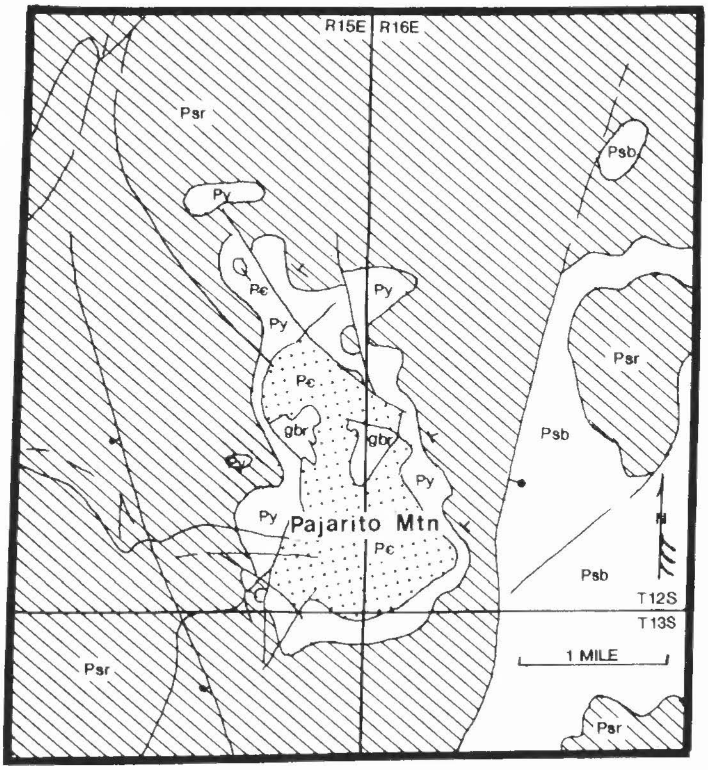

FIGURE 2. Geologic map of the Pajarito Mountain area. Map units are as follows: gbr—gabbro; PЄ—Precambrian syenites; Psb—Bonney Canyon Member of San Andres Formation; Psr—Rio Bonito Member of San Andres Formation; and Py—Yeso (Kelley, 1971, pl. 1; Sherer, 1990).

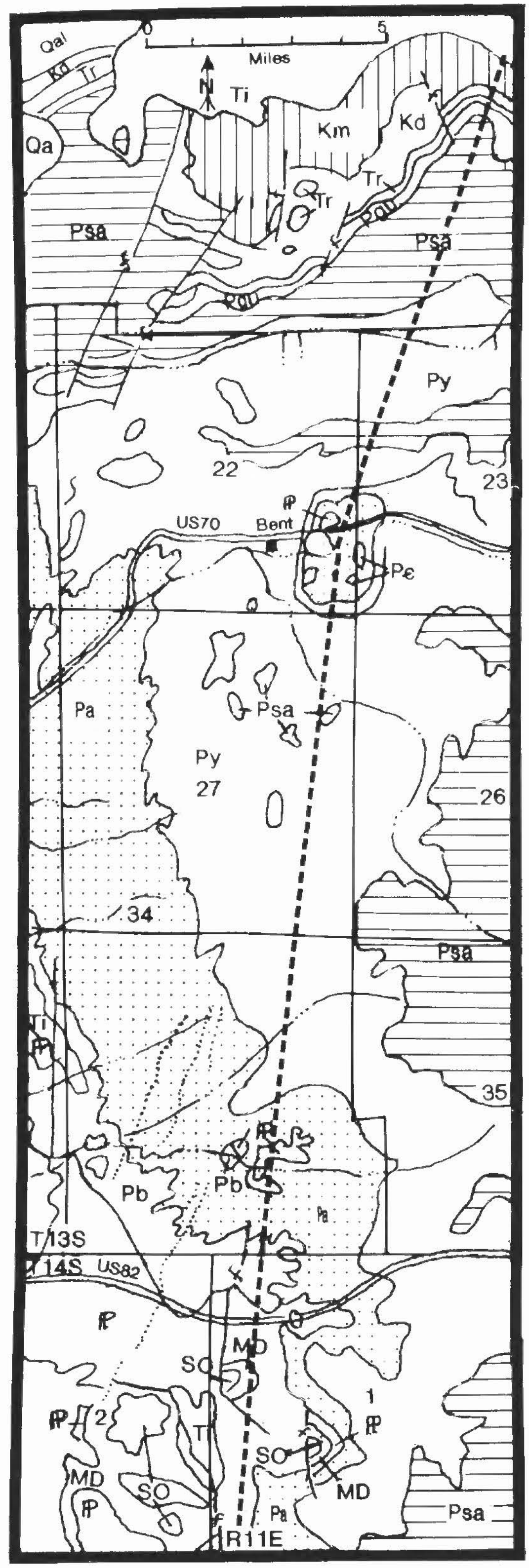

FIGURE 3. Geologic map of the Bent area and south along the front of the Sacramento Mountains, modified from Dane and Bachman (1958). The dashed line is the proposed trend of faults and anticlines extending from Arcente Canyon north to Bent and to the anticline lying just east of Sierra Blanca basin. Symbols: PЄ—Precambrian; SD—Silurian-Devonian; MD—Devonian-Mississippian; IP—Pennsylvanian, undivided; Pa—Abo Formation; Py—Yeso Formation; and Psa—San Andres Formation.

ward the Pedernal Hills (north of Fig. 1). The arkosic sediments were derived from the basement rocks of the Sacramento Mountains. The source terrain was composed of alkalic or ultramafic rocks rich in plagioclase feldspars.

Abo and Upper Pennsylvanian Holder Formation rocks south and west of the Sacramento Mountains commonly contain arkosic zones. Many of these zones contain large- and medium-sized sand grains and granules of pink orthoclase. The granitic source of the orthoclase grains is unknown.

INTERPRETATION OF AEROMAGNETIC AND GRAVITY MAPS

General

Bouguer gravity (Keller and Cordell, 1983) and composite, residual, total-intensity aeromagnetic (Cordell, 1983) maps of New Mexico were reprinted in 1985 by the New Mexico Energy Research and Development Institute. These maps, used by the author to locate anticlines and domes for drilling in eastem Lincoln County, show that the top of the Precambrian was a slightly undulating, nearly planar surface, except adjacent to some fault zones. The anomalies of the aeromagnetic map (Fig. 4) probably reflect various amounts of magnetite within Precambrian basement blocks.

The aeromagnetic anomaly over the Sacramento Mountains (up to 2600 gammas) is one of the most prominent anomalies in New Mexico. The gravity anomaly over the same area is about 50 milligals (Fig. 5). The pairing of these two types of anomalies is unique in the state.

Analogy with the Bushveld complex

The literature on gravity, magnetics and igneous rocks suggests that layered ultramafic rock would produce the patterns seen in the magnetic and gravity features in the Sacramento Mountains (Hutchison, 1985; Wager and Brown, 1967; Windley, 1984; Wyllie, 1979). The sequence of cumulates shown by Hutchison (1985) for the Bushveld complex of

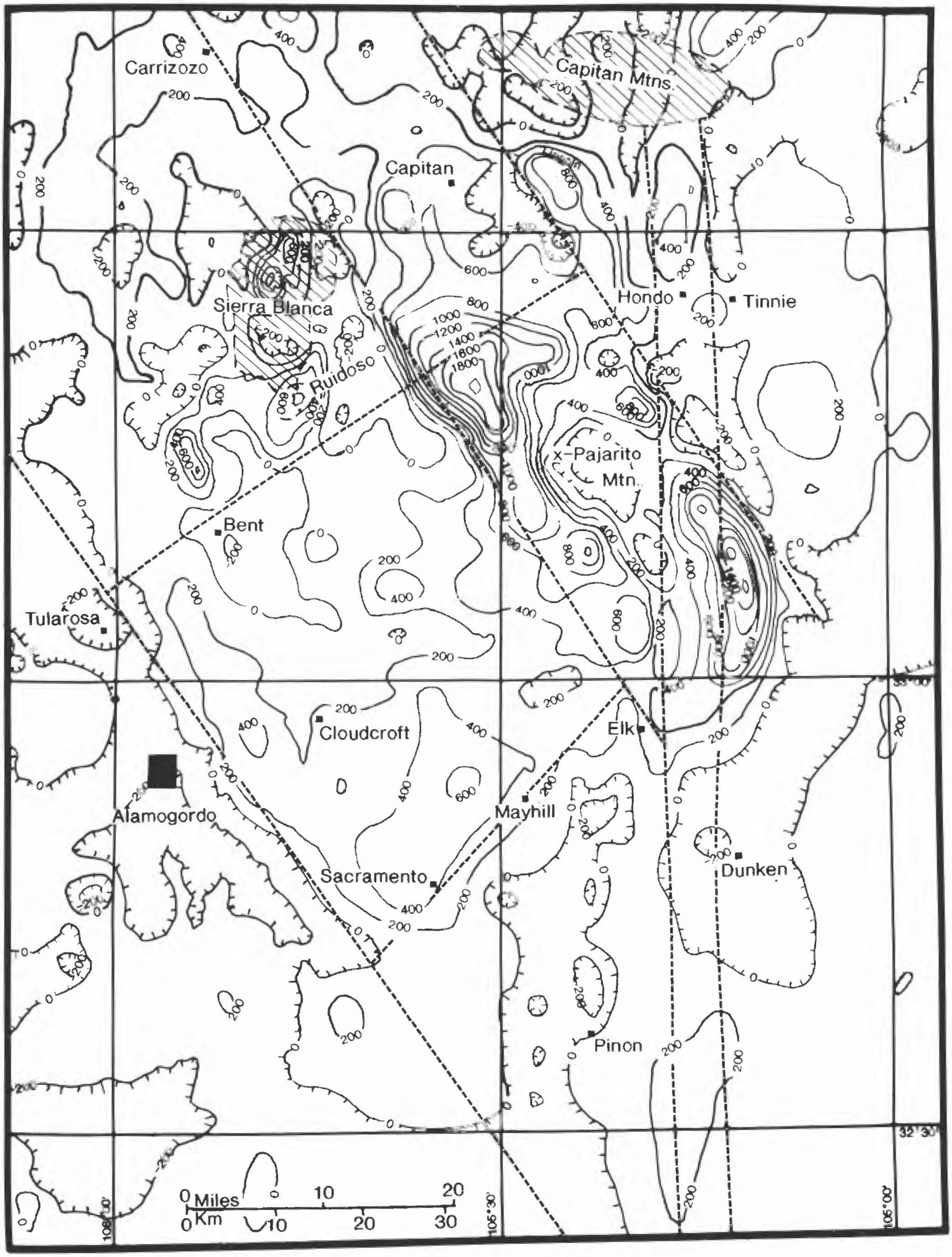

FIGURE 4. Aeromagnetic map of the Sacramento Mountains. Modified from Cordell (1983) with significant linears added. The 2600-gamma positive anomaly may represent a large Precambrian, layered ultramafic intrusive in Precambrian rocks. Linears (heavy dashed lines) mark the southwest and northeast sides of the anomaly. The 1600-gamma negative anomaly is correlated to the syenites at Pajarito Mountain with a low magnetic flux.

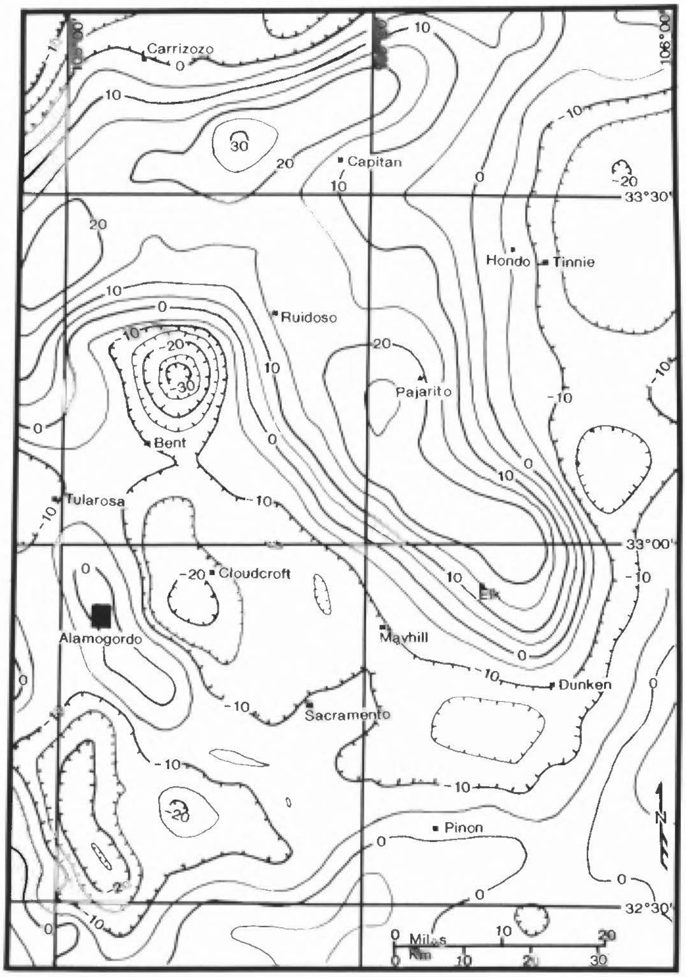

FIGURE 5. Gravity map of the Sacramento Mountains (Cordell, 1983). The large anomaly, 50 milligals, in the central part of the map is coincident with the layered ultramafic intrusive and includes the Pajarito intrusive. The gravity of the syenites and the layered ultramafic intrusive appear to be nearly equal, although Pajarito is a negative magnetic anomaly, whereas the ultramafic is a strongly positive magnetic anomaly. Elevation of the Precambrian surface and thickness of the Paleozoic sediment is of minor significance to the value. Lithologic types in the basement are the key to the aeromagnetic and gravity patterns. Diabase sills in part of the area in the Yeso Formation give insignificant changes of values.

South Africa offers a potential model for the mechanism that may have concentrated magnetite and produced the associated anomalies in the Sacramento Mountains. The Bushveld complex is about 7330 m (24,042 ft) thick in the eastern Transvaal section. The mineral trends within this layered intrusive change character upward in the body. The main chromite seam is in the lower layered levels with large quantities of chromium, platinum and other platinum-group minerals. These levels are high in aluminum and low in iron. The upper layered levels contain very large quantities of magnetite.

Wager and Brown (1967, p. 406) suggested that the upper layers of the Bushveld upper zone (Hutchison, 1985, fig. 6.4) of layered ultramafic intrusives be called ferro-syenodiorites. They are the latest differentiates of the Bushveld layered sequence and contain magnetite seams. Magnetite in a layered-ultramafic intrusive, similar to the Bushveld complex, may be the source of the large magnetic anomaly (Fig. 4) associated with the Sacramento Mountains.

The Bushveld complex (2095 Ma) occupies an area of about 65,895 km^2 (27,000 mi^2) and is the largest layered ultramafic complex in the world (Wager and Brown, 1967; Hutchison, 1985). The Great Dyke of Zimbabwe in eastern Africa is a north-trending linear body that is 2160 km^2 (742 mi^2) in size. Age dating shows that the dike is at least 2530 Ma. The Sudbury Basin of Ontario, Canada, a layered ultramafic lopolith, is about 5125 km^2 (2100 mi^2) in size (Wyllie, 1979). The Sudbury rocks are dated between 1600 and 2000 Ma. The Stillwater complex, Montana and Wyoming, is a differentiated, layered, mafic and ultramafic intrusive body of late Archean age, 1950 to 2530 Ma (Page and Zientek, 1985).

The areal extent of the proposed layered ultramafic intrusive in the Sacramento Mountains is about 1080 km^2 (450 mi^2). This intrusive appears to be only part of a much larger area of basement rocks, as indicated by the pattern of high gravity and high intensity aeromagnetic features. The total area is about 4440 km^2 (1850 mi^2) in areal extent. The southwest and southeast sides of this area of anomalies is shown on Fig. 4 by dashed lines. The area is characterized by positive magnetic anomalies of about 200 gammas. The large area of high intensity magnetics forms a complex surrounding the ultramafic stock.

The layered ultramafic intrusive of the Sacramento Mountains, as proposed herein, may be the second largest layered ultramafic body in the world. Most of the known mafic and ultramafic intrusives in the North American continent (Wyllie, 1979) appear to be much smaller than the proposed New Mexico complex.

The aeromagnetic map of the Sacramento Mountains (Fig. 4) contains strong linear features with northwest-southeast the most dominant trends. The long dimension of the layered ultramafic intrusive is oriented in the same direction as major linears of the aeromagnetic and gravity maps and is bounded on the northeast and the southwest by major basement faults. This relationship suggests that the intrusive was injected along a rift zone.

The Border Hills, Six Mile and Y-O buckles (Kelley, 1971), lying on the Pecos slope east of the Sacramento Mountains, trend southwest from the vicinity of the Pecos River and end at the east side of the Tinnie-Dunken anticlinorium (Fig. 6). The Border Hills buckle may cut transversely through the Tinnie-Dunken anticlinorium or may be cut by it. An indistinct fault, extending southwest from Elk, trends the same direction as, and is aligned with, the Border Hills buckle but is offset well to the west of it. The structural relationship is not known. The long, linear buckles (Kelley, 1971) show strong displacement in the Permian San Andres limestone. The buckles are linear northwest-trending ridges on the surface. The folded and contorted San Andres is developed into anticlines and synclines along the trend that may have more than a hundred meters of amplitude. Locally, faults are obvious along the trends. There is evidence to suggest Recent or near-Recent movement at places along the buckles. They appear to be right-lateral, strike-slip faults that originated in the Precambrian basement and were propagated to the surface by recurrent movement.

The major linear features running northwest and the flexure zones running northeast are obvious on topographic, gravity and magnetic maps. The writer believes the faults are propagated from the basement. Important faults and horsts within the Sacramento Mountains are not so obvious on the gravity and aeromagnetic maps. One of these, interpreted by the writer, is a line of obscure faults and folds that runs southward through Bent and onward for a significant distance within the Sacramento Mountains. This feature appears to swing slightly where it runs along the eastern margin of the Sierra Blanca basin. It is obscure because it is mostly covered by Abo red beds (Fig. 3). This fault and ancillary fold trend is primarily Early Pennsylvanian in age because of the stratigraphic relations over the basement blocks and the unfaulted Abo over it. Truncation of Ordovician and probably younger pre-Pennsylvanian strata on basement blocks is not known but is suspected. Absence of Early Pennsylvanian strata over uplifted fault blocks of the basement is believed to reflect renewed uplift of old Precambrian fault zones. These zones have been active during several periods of geologic time.

The Tinnie-Dunken anticlinorium along the east side of the Sacramento Mountains is another fold-fault system that trends north in the Sacramento Mountains (Fig. 6). The anticlinorium is interpreted by the writer to be a Precambrian horst that contains a series of north-trending strike-slip faults in the basement. The effect of these faults on Paleozoic sedimentation, the Tertiary uplift of the zone, and the presence of extensive north-trending shears in the tops of anticlines suggest that

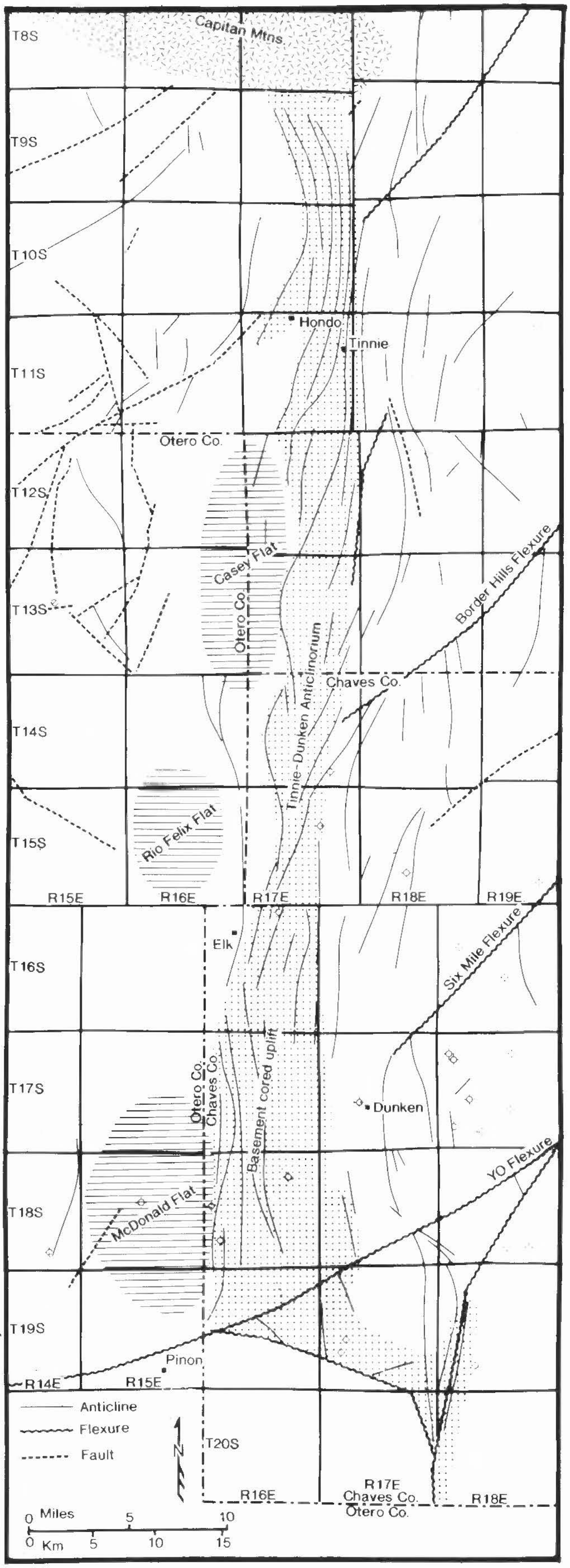

FIGURE 6. The Tinnie-Dunken anticlinorium modified from Kelley (1971), with faults, anticlines and fracture zones added. The trend of the anticlinorium is indicated by the stippled pattern. The anticlines in this trend are basement-cored uplifts generally overlain by the Abo or Yeso Formation with older strata missing.

they are rejuvenated Precambrian features. The basement horst at the south end is upthrown about 1220 m (4000 ft) above the basement on either side. The uplift of the horst gradually decreases to the north. The pattern of the uplift appears to terminate at the south side of Capitan Mountains (Fig. 6). Vertical shear zones up to 30 m (100 ft) wide and extending for up to 30 km (20 mi) occur on the crests of some anticlines of the Tinnie-Dunken anticlinorium. Most of the uplift occurred in Atokan (Early Pennsylvanian) time, although the ancestry of the faulting is probably Precambrian. The younger faulting is rejuvenation of the Precambrian fault zones and their trends. Paleozoic stratigraphic relations indicate that the most important time of movement for the basement horst was Early Pennsylvanian.

On the aeromagnetic map Pajarito Mountain overlies a fairly large negative anomaly with strong intensity of over 1500 gammas, compared to the proposed layered ultramafic intrusive beneath the Sacramento Mountains (Fig. 4). This negative magnetic anomaly is part of a large positive anomaly on the gravity map (Fig. 5). The Pajarito igneous mass is a late-stage, non-magnetic, Precambrian pluton that intruded along the side of the large, ultramafic intrusive. The gabbro drilled in the Munoz No. 1 well is just north of the main intrusive. This gabbro, a stock, is represented on the aeromagnetic map as a smaller dipolar anomaly. The writer believes it, too, is a later intrusive that arose alongside the main ultramafic pluton. The syenite at Pajarito Mountain and the gabbro at Munoz No. 1 range in age from 1100 to 1250 Ma (Proterozoic). The age of the main intrusive is unknown but it may be considerably older.

Precambrian ultramafic rocks

The Archean and the Proterozoic are characterized worldwide by different types of mineralization. "Iron formations and massive or stratiform sulphide deposits are characteristic of the Proterozoic. They differ from such deposits in the Archean in that there is no direct association with volcanic formation, though an indirect association can be invoked with volcanic rocks in contiguous formations. They occur in large epicontinental basins close to Archean cratons and are assumed to have a volcanic-exhalative origin . . ." (Hutchison, 1985, p. 214). "A highly characteristic feature of the Archaean crust is the evidence of elongated greenschist facies, mafic-ultramafic igneous and associated metasediments (greenstone belts) within more extensive areas of granites and gneisses in the shield areas of all continents" (Hutchison, 1985, p. 196).

Layered ultramafic rocks are characteristically Archean in age. "The Bushveld layered sequence of the complex was emplaced 2095 Ma . . ." (Hutchison, 1985, p. 105). Most studies of Precambrian in New Mexico have considered the basement rocks of the Sacramento Mountains to be Proterozoic. The oldest dates available for Precambrian rocks at Pajarito Mountain and the Munoz No. 1 are 1250 Ma. However, the writer believes the rocks at Pajarito Mountain and the stock at the location of Munoz No. 1 are late intrusives that were intruded along the flanks of an older main ultramafic intrusive whose age is not yet known. Magnetic characteristics of the rocks suggest that the body is a layered ultramafic intrusive, perhaps Archean in age. It is not necessary that the ultramafic intrusive of the Sacramento Mountains be as old as Archean.

Hoover et al. (1985) suggested that 4460 m (14,629 ft) of basement rocks drilled by the North American Royalties Company No. 1 Nellie on the Central Basin Platform of Wink County, Texas, may represent a large, layered ultramafic intrusive. A similar layered ultramafic intrusive beneath the Sacramento Mountains is a possibility. Such an intrusive would not be likely to produce the same suite of minerals as

Bushveld but it could be a very important source of strategic minerals in the future. The possibility is suggested by the characteristics of layered ultramafic complexes such as the Bushveld complex where "by far the most important mineral deposits are the sulphide ores" (Hutchison, 1985, p. 110). Platinum-group minerals, gold, chromite, vanadiferous magnetite, tin and magnesite are produced from the Bushveld ultramafic complex.

Sherer (1990) reported on the yttrium-zirconium deposits being investigated at Pajarito Mountain by Molycorp under contract with the Mescalero Apache Indians. The writer believes that this is a small indication of the large potential for mineral wealth in the Precambrian rocks of the Sacramento Mountains.

TECTONIC HISTORY OF THE SACRAMENTO MOUNTAINS

The Precambrian history of the Sacramento Mountain region is surmised from magnetic and gravity anomaly maps and the structural-sedimentational patterns of the surface rocks. The anomalies indicate that a long history of intrusions is represented in the Precambrian basement rocks of the Sacramento Mountains, although the sequence of injection of magnetic and non-magnetic bodies is not known. The differing intensities of the gravity and magnetic data suggest the presence of wide-ranging types of igneous, metasedimentary and metavolcanic rocks. A rift-zone interpretation is possible from the lineations in the gravity and magnetic maps (Figs. 4, 5). The northwest trend appears to have dominated, perhaps indicating influence of similar but older trends at the time of intrusion of the pluton, creating the strongly positive magnetic and gravity anomalies. The age of the large, intrusive pluton is not known. Younger, ancillary intrusive rocks are dated at 1135–1215 Ma (Kelley, 1968) and 1150 Ma (Moore et al., 1988) at Pajarito Mountain and 1284 Ma for the gabbro in the Munoz No. 1 well.

The pluton interpreted as a layered ultramafic is controlled by a northwest-trending rift. The northwest linears associated with this rift are distinctive on the gravity and magnetic maps but are not obvious in the present topography. The linear shown on Fig. 1, extending northwest along the Sacramento River, appears to continue northwest beyond the western limits of the Sacramento Mountains (Figs. 1, 4). The north-trending fault and fold zones, as at Bent and in the Tinnie-Dunken anticlinorium, appear to be a part of a strong set of Precambrian strike-slip fault zones that extend north from the Sacramento Mountains. The north-trending system appears to be younger than the northwest-trending set because there are several sets of northwest-trending faults that appear to terminate at north-trending fault zones in southeast New Mexico. The Tinnie-Dunken anticlinorium is one example.

The northeast-trending flexures east of the Sacramento Mountains (Figs. 1, 4) appear to terminate on the west end at the Tinnie-Dunken anticlinorium. However, the relation between the two sets is not confirmed.

The impact of these different Precambrian fault systems on early Paleozoic rocks is not known. The earliest Paleozoic strata, Ordovician Bliss Sandstone to the Devonian, seem to have onlapped a relatively smooth Precambrian surface along the Pecos slope (Kelley, 1971). These strata onlap the Precambrian from the southeast near Roswell and from the south in the Sacramento Mountains (Grant and Foster, 1989). They thin updip and are partly eroded. The Abo oversteps each of these units to rest on the basement. The wedge-out appears to swing west and then west-northwest to the vicinity of Tularosa (Fig. 1), almost in a continuous pattern. It is interrupted only the Tinnie-Dunken anticlinorium. The uplifted basement of the Tinnie-Dunken anticlinorium, over much of its length, is overlain by the Abo Formation. Southward in T17S, a thin section of Bliss Sandstone and El Paso dolomite is on top of or within slices of fault blocks beneath the Abo Formation, at the top of the basement of the Tinnie-Dunken anticlinorium. The three sets of fault and fold zones have been accentuated by Tertiary and probably by Recent movement. The three zones are distinctive surface features on Landsat and photo images.

Movements of the western edge of the Sacramento block

Some features of the Devonian in the Marble Canyon area along the west front of the Sacramento Mountains suggest that Devonian movements of the Sacramento Mountains block occurred. It is reasonable that the faulting on the front of the mountains is derived from Precambrian features and that it affected the Ordovician, Silurian and Devonian strata by uplift of the west edge of the block. However, there are no data to relate the deposition to uplift along older features.

It is certain that the western edge of the Sacramento Mountains basement fault block had risen by early Mississippian time, relative to the block in the Tularosa Valley west of the Sacramento Mountains. The Sacramento Mountains block formed the shelf-edge over which the drape of sediments from shelf to basin created the Mississippian Lake Valley reefs of the Alamogordo area (Bowsher, 1986; Fig. 7).

Movement at the western edge of the Sacramento block created a line of faults and anticlines passing through Bent and Andrecito Canyon (south edge of Fig. 3). This movement occurred in Atokan time and resulted in the development of the Gobbler carbonate banks along the front of the escarpment (Pray, 1961) and at the tunnel near High Rolls on US-82, sec. 6, T16S, R11E (Bowsher, 1986, fig. 1). Very little Missourian and Virgilian sediment was deposited over the Gobbler bank along the front of the escarpment. Missourian strata onlap slightly onto the north end of the Desmoinesian carbonate bank. The Desmoinesian bank was emergent throughout most of Missourian and Virgilian time. The Lower Permian Abo Formation lies directly on the bank but thins appreciably southward within the central part of the Sacramento Mountains. The Southern Production Company No. 1 Cloudcroft was drilled at the top of the highest anticline in the range, sec. 5, T17S, R12E, 9 km (6 mi) south of Cloudcroft. It encountered a fairly normal sequence from Bliss to San Andres. The sediments show little effect of the uplift or tilt of the basement block. It appears that the intense movement along north-trending strike-slip faults at Andrecito Canyon and Bent did not affect the sediments at this well site.

The Missourian and Virgilian rocks are absent or thin on top of the Desmoinesian fault blocks. The thick Holder (Virgilian) sequence in Dry Canyon, about 7 km (4.5 mi) northeast of Alamogordo, is confined to a down-faulted shelf lying just west of the Desmoinesian carbonate bank (Bowsher, 1986) at the tunnel on US-82 about 8 km (5 mi) northeast of Alamogordo. The western part of the Holder Formation between the Tularosa Valley and the US-82 tunnel contains prominent phylloid reef banks (Toomey and Wilson, 1977; Bowsher, 1986; Toomey, 1991, this guidebook; Fig. 8). The shelf on which these reefs formed is a block bounded by faults trending northward and lying west of the

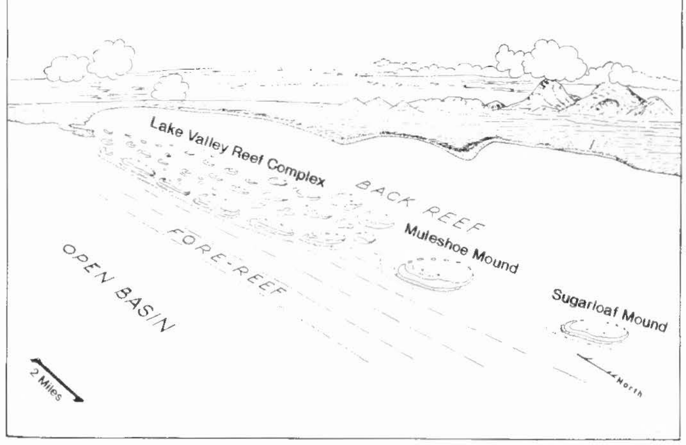

FIGURE 7. Writer's concept of the tectonic setting for the Lake Valley reef complex (Mississippian); lower right comer of the diagram is south (from Bowsher, 1986, p. 55). The Orogrande Basin lies to the left or west. Reef growth was caused by shoal water on the uplifted western margin of the Sacramento block relative to the Orogrande block. The relationship between the blocks is not simple. Only Sugarloaf and Muleshoe Mounds are present south of the main part of the complex.

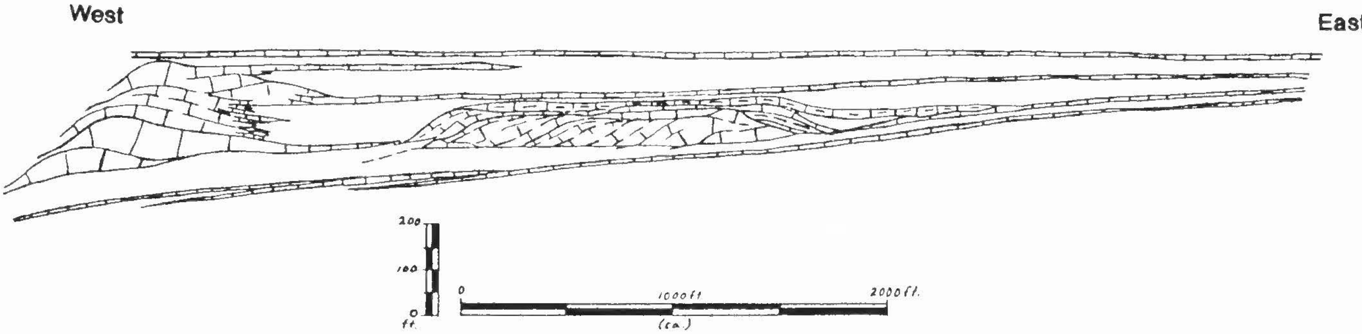

FIGURE 8. Cross section of carbonate sedimentary structures of the Holder Formation in Dry Canyon (from Bowsher, 1986, p. 61). Reefs were influenced by uplift of the western edge of the Sacramento Mountain block in Late Pennsylvanian time. The Tularosa Valley block moved down and received basinal Virgilian sediments, the Panther Seep Formation (Kottlowski et al., 1956), that are equivalent to the carbonates of the Holder Formation of Dry Canyon.

fault zone that borders the block in which the US-82 tunnel is cut. There has been subsequent movement along this fault zone in the Tertiary and Quaternary.

Uplift of the eastern side of the Sacramento block

The basement beneath the Tinnie-Dunken anticlinorium (Fig. 6) is shallow and lies just beneath the Abo; nine wells have penetrated thin sequences of the Ordovician Bliss and El Paso Formations. The major uplift along this belt of strike-slip faults was in Atokan (Early Pennsylvanian) time. The pre-Pennsylvanian strata a few kilometers on either side of a ridge of uplifted-basement fault blocks appear to be fairly typical and were not affected by uplift of the Precambrian rocks. The Desmoinesian strata on each side of the ridge are dark, very fine-grained, highly organic, basinal limestones. Because it is not present on the ridge, the Abo rests on basement, and appears to be thicker close to the ridge. It was uplifted in both Early and Late Pennsylvanian time. This relationship is similar to that on the Sacramento escarpment at the west edge of the fault block. The north-trending line of uplift and faulting at the Tinnie-Dunken anticlinorium marks the eastern edge of the Sacramento Mountains and was affected by movements of the basement during the same periods.

The Abo Formation is a clastic sequence that was derived from the uplifted parts of the Sacramento Mountains Precambrian and Paleozoic rocks. By the end of Paleozoic time, most of the Sacramento Mountains area was covered by a shallow sea, in which carbonates such as the San Andres Formation were forming. The Tinnie-Dunken anticlinorium was rising during San Andres time. The shoal caused reefs to form and carbonate sediment prograded east and west off each growing anticline. The sediments transported east from the anticlinorium were fine grained and prograded basinward (east) across an undulating shoal. Unique deep-water faunas are present in the upper carbonate of the San Andres Formation in the Scarborough highway-metal quarry south of NM-83, a short distance east of the Y-O Crossing junction with NM-13. These strata contain detritus, including oolites, that were swept off the shoal of the Tinnie-Dunken anticlinorium and off the shoals of the forereef area in the western part of the Pecos slope (Kelley, 1971).

The area from Elk to just west of Mayhill along US-82 is underlain by thick-bedded layers of backreef calcarenite trapped west of the anticlinorium. This belt is about 8 km (5 mi) wide and extends north along the west flank of the anticlinorium. Westward in T16S, R13E on US-82 the San Andres and the Yeso limestones are calcilutites, of mid-shelf, quiet-water facies with sponge faunas. Farther west the carbonates become coarse grained. Just east of Cloudcroft the San Andres facies are calcarenites and calcirudites typical of the immediate backreef.

These facies patterns indicate that the San Andres was deposited across a broad bank with shoal facies in the central part and shelf-edge and reef facies flanking the platform. The correlative strata of the San Andres Formation bordering the Sacramento Mountains are off-reef and basin carbonates. In mid-Permian San Andres time, the basement block was a relatively stable and nearly flat feature called the Sacramento shelf.

No evidence exists of rocks younger than San Andres being deposited over the Sacramento Mountains. Dane and Bachman (1958) included a thin sliver of Dakota in a fault zone in the northwest corner of T15S, R12E, in a canyon which is traversed by NM-24. Kelley (1971, p. 26–29) wrote, "From the northern exposures of Dakota in T. 6 S. of this area where it may rest on 200 to 300 feet of Chinle, the Dakota steps gradually downward to meet the Santa Rosa in T. 10 S., the Grayburg in Ts. 11, 12 S., and the Bonney Canyon Member of the San Andres from Ts. 12 to 15 S. This is an angular convergence of 25 to 30 feet per mile, which is too steep a gradient for the Dakota to have been spread as a blanket. Therefore, the underlying rocks must have been tilted northward and levelled between Jurassic and Early Cretaceous time by something like 20 to 25 feet per mile." The age of the final tilting of the Sacramento block down to the east is not known but it is likely to have been in Early Oligocene time. It appears from the notes of Dane and Bachman (1958) that the syncline underlying the White Mountain volcanic pile may have begun to warp downward before Jurassic time.

The consequent drainage of the Rios Hondo, Picacho and Felix, and Bluewater Creek began rapidly to erode down into the rising anticlines of the Tinnie-Dunken anticlinorium as the Sacramento block tilted down to the east and was uplifted relative to the Tularosa Basin west of the Sacramento Mountains. Today, these antecedent streams cut through the Tinnie-Dunken anticlinorium. To the west they become consequent streams on the old erosional surface of the mountains, part of which is still intact (Fig. 1). During the past uplift and today, relict surfaces at McDonald Flats, along the Rio Felix and at Casey Flat have remained relatively untouched by erosion (Fig. 1).

A syncline, into which a very thick sequence of Tertiary volcanics was deposited, formed northwest of the Sacramento Mountains. This syncline, the Sierra Blanca syncline, formed along the northwest side of the Sacramento ultramafic intrusive. Extensive downfolding or faulting of the Precambrian was required to form this structure. The Tertiary volcanics of Sierra Blanca and adjacent areas may have come up through the crust along the margin of the Precambrian intrusive. The Sierra Blanca volcanic pile is alkalic, not a common rock type in New Mexico.

SUMMARY

A Precambrian complex in the basement area of the Sacramento Mountains was a metamorphosed block by the end of the Precambrian. Erosion had reduced the plutonic-volcanic mass and associated rocks to a broad, low, positive topographic swell. It is not known if the deposition of Ordovician (Bliss Sandstone) to Devonian strata were affected by the geomorphology of the basement surface except as the sediments onlapped the Precambrian high. Younger Mississippian, Pennsylvanian and Permian strata were affected by the geomorphology and movements of the Precambrian rocks. Facies of these Paleozoic rocks reflect these movements and their effects.

The pronounced gravity and magnetic anomalies are interpreted possibly to come from a layered ultramafic intrusive of Precambrian age. The upper age is limited by younger flanking intrusives, with ages from

1100 to 1250 Ma. The Precambrian layered ultramafic intrusive is possibly much older than the syenite intrusive of Pajarito Mountain and the gabbro of the Munoz No. 1 well. The layered ultramafic intrusive and associated igneous and metamorphic rocks may be significantly rich in strategic minerals.

The Pajarito Mountain intrusive was a highlands area standing above the latest sediments of the San Andres Formation. The thickness of the San Andres and Yeso Formations increases away from the stock, so much of the Precambrian of the ultramafic complex is covered by about 730 m (2400 ft) of red shale, sandstone and limestone and locally by thick diabase sills. This overburden will greatly affect the economics of any proposed mining venture. However, minerals of the complex may become very important if strategic minerals today imported by the United States from the USSR, Union of South Africa and other countries are lost or threatened.

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Discussion of geology around the Molycorp Questa molybdenum mine at Day 1, Stop 1 of the 1990 NMGS Fall Field Conference. Mine workings form skyline behind assembled participants. Speaker is Bob Leonardson of Molycorp. Illustration by Louann Jordan of Santa Fe, 1990.