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**Geologic Framework and
Hot Dry Rock Geothermal Potential of the
Castle Dome Area, Yuma County, Arizona**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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GEOLOGIC FRAMEWORK AND HOT DRY ROCK GEOTHERMAL POTENTIAL
OF THE CASTLE DOME AREA, YUMA COUNTY, ARIZONA

by

James T. Gutmann

ABSTRACT

The Castle Dome Mountains and surrounding ranges constitute a voluminous pile of silicic volcanic rocks within the Basin and Range province of southwestern Arizona. Previously reported as Cretaceous and Quaternary in age, these volcanics all are of late Oligocene to early Miocene age as indicated by five new K-Ar dates. Reconnaissance field studies indicate that the volcanic section locally has undergone large rotations that contrast with the usual structural style of the Basin and Range and resemble the thin-skinned rotational tectonics documented for earlier, mid-Tertiary extensional deformation in ranges to the north and northeast. The volcanic rocks rest nonconformably on Mesozoic metamorphic rocks. Exposures of pre-Tertiary rocks in the region are distributed around the margins of a large negative residual Bouguer gravity anomaly but are absent within the gravity low. Disposition of pre-Tertiary outcrops, and to some extent the gravity anomaly itself, may reflect cauldron subsidence associated with the copious silicic volcanism. Rotational deformation of the volcanic pile may have occurred during regionally controlled extension of the thick roof over a large Oligocene-Miocene batholithic complex that fed the volcanism and accounts for much of the negative gravity anomaly.

Significant geothermal potential of the Castle Dome area is suggested by a shallow depth to the Curie isotherm and by the apparent presence of a good electrical conductor at anomalously shallow depth in the crust. Warm wells exist in the area and Shearer (1979) reported a geothermal gradient of about 70°C/km in a dry well near the center of the gravity low. Radiogenic heat production in the silicic batholith inferred above constitutes a reasonable candidate for a shallow regional heat source. Potential

obstacles to economic development of geothermal energy include land availability since much, but not all, of the area is Federal land closed to energy development. Additional uncertainties for Hot Dry Rock (HDR) development at this time include actual reservoir temperatures and the hydraulic character of the basement, which probably will be strongly anisotropic. Yuma Proving Ground (United States Army) constitutes a possible, virtually on-site direct user of conventional or HDR geothermal resources. Otherwise, fluid temperatures adequate to support electrical generation should be sought since no other direct users are located in the area.

I. INTRODUCTION

The Castle Dome Mountains are located in southwestern Arizona about 60 to 80 km northeast of Yuma. Regional geophysical studies (West 1972, Aiken 1976) demonstrated the presence in this area of a substantial negative gravity anomaly of the sort that could indicate geothermal enhancement (Aiken 1976). Near the center of the gravity low, at Stone Cabin (Figs. 1 and 2), bodies of Quaternary rhyolite are shown on the Arizona State Geologic Map (Wilson et al. 1969). Furthermore, much of the area lies within a "quiet zone" of low-amplitude aeromagnetic anomalies interpreted to possibly indicate a shallow depth to the Curie isotherm (Sauck 1972). For these reasons the areas appeared particularly worthy of investigation under the aegis of the Los Alamos National Laboratory program charged with evaluation of the HDR geothermal potential of the United States.

The area of interest is broadly defined by the negative residual Bouguer gravity anomaly itself (Aiken 1976). This anomaly is about 45 km across, steep-sided in several places, and as much as 30 mgals in magnitude (depth below the highest closed contour). The anomaly covers an area of some 1500 km² that includes much of the Castle Dome Mountains together with parts of the adjacent Chocolate, Middle, and Kofa mountains and the intervening basins. It is centered in the northern Castle Domes, in the general vicinity of Stone Cabin (Figs. 1 and 2), a very small settlement along U.S. Route 95. Most of the area within the anomaly lies on either the Yuma Proving Ground (U.S. Army) or the Kofa National Wildlife Refuge (U.S. Fish and Wildlife Service) and is

Fig. 1.

Map of southwest Arizona showing location of various physiographic features.

Fig. 2.

Map of Castle Dome area location of Castle Dome Mountains, Kofa Mountains, U.S. Route 95, Stone Cabin (1), Chocolate Mountains (2), and Middle Mountains (3). Also shown are areas of pre-Tertiary metamorphic or sedimentary rocks (stippled pattern) after Wilson (1960), and residual Bouguer gravity contours (heavy hachured lines, values in mgals) from Aiken (1976). The heavy dashed line marks locations of relatively steep gravity gradient. Solid squares are stations of magnetotelluric survey. CDW is Castle Dome Heliport well. HJW marks two other warm wells.

closed to energy development. However, a belt of potentially open land extends north-south across nearly all of the gravity low and passes through its central region at Stone Cabin. Furthermore, Yuma Proving Ground itself represents a potential direct user. Both the belt of open land and the Proving Ground facilities are located generally near and west of the Castle Domes. Accordingly, this study concentrates on geologic relationships in that region, near the center of the Bouguer gravity low.

II. PRE-TERTIARY ROCKS

Outstanding syntheses of the geology and geochronology of west-central and southwestern Arizona have been provided recently by Reynolds (1980) and Shafiqullah et al. (1980). However, the region within the gravity low remains poorly understood, especially as regards geochronology, for almost nothing has been published on its bedrock geology since the pioneering work of Wilson (1933, 1960). In general, the area lies within the Basin and Range tectonic province of southwestern Arizona. The Castle Domes themselves are a north-northwesterly-trending range about 50 km long. Although rugged in many places, their relief above surrounding basins is only about 750 m.

Granitic basement rocks of Precambrian age crop out in the Yuma area about 60 km to the southwest (Olmsted et al. 1973) and in the Plomosa Mountains, near Quartzsite, a comparable distance to the north (Miller and McKee 1971). Crystalline terrane in the Muggins Mountains and Laguna Mountains, a few tens of km south of the Castle Domes, is shown as Precambrian in age by Shafiqullah et al. 1980 (Fig. 2). Where examined by the writer near Gila City, these rocks are tightly folded, heterogeneous, quartzofeldspathic biotite gneisses. In thin section they exhibit textures indicative of polymetamorphism involving retrogression to biotite-muscovite assemblages from some considerably higher metamorphic grade. Olmsted et al. (1973) report locally migmatitic, hornblende-bearing gneisses in this area.

Within the Castle Domes themselves, two small masses of granitic rocks are reported by Wilson (1933, 1951) to be unconformably overlain by the Mesozoic metasediments with which they are associated. If so these may be of Precambrian age. However, Wilson (1960) shows these rocks as Laramide granites younger than the metasediments. The writer was unable to investigate this relationship owing to access difficulties. Wilson (1933) also reported a small mass of "syenite" apparently underlying the metasediments; field and thin section evidence suggests that this mass intruded the Mesozoic rocks, albeit prior to their metamorphism.

Perhaps the oldest rocks exposed in the Castle Domes are schists and gneisses cropping out in the southern part of the range and regarded by Wilson as Precambrian in age based on their degree of metamorphism (Wilson 1933, 1951) and later as Mesozoic in age (Wilson, 1960) when it was realized that the Mesozoic sedimentary and metasedimentary rocks of Yuma County can grade locally into schist (Wilson 1962). Where examined by the writer, these are

dominantly quartzofeldspathic muscovite schists containing chlorite + epidote + garnet, cut by quartz-stilpnomelane(?) veinlets, but bearing no evidence of former high metamorphic grade (c.f., Precambrian rocks near Gila City described above). Accordingly, the writer tends to concur with Wilson's (1960) Mesozoic age assignment for these rocks from the southern part of the range. They may represent exposures of the deeper and more highly metamorphosed parts of a thick sequence of Mesozoic metasediments whose Precambrian floor crops out yet further south, in the Muggins and Laguna Mountains.

Samples of basement rocks in the region are provided also as lithic inclusions in the mid-Tertiary ash-flow tuffs of the Castle Domes. In addition to schistose Mesozoic metasedimentary rocks and biotite gneisses, structurally more isotropic rocks (biotitic granitic rocks and biotite granofels) seem surprisingly well represented. Although these lithologies could constitute attractive reservoir rocks for purposes of HDR geothermal development, the depth of origin of the inclusions is not known and, in addition, they could have travelled considerable distances laterally within their ash flow hosts.

Rocks of Paleozoic age occur in the Plomosa Mountains about 40 km north of Stone Cabin (Miller and McKee 1971) but evidently are absent over a broad area south of that range.

By far the most widespread basement rock in the Castle Domes and surrounding ranges is a poorly known but evidently very thick sequence of volcanic and overlying clastic rocks of Mesozoic age. In most places these have been metamorphosed at fairly low grade. Basement rocks exposed nearest to Stone Cabin are 17 km to the northwest, on the Yuma Proving Ground. These were mapped as Mesozoic gneisses by Wilson (1960) in the late 1920's and early 1930's. The area has since been used for mine warfare, reportedly contains unexploded munitions, is closed to public entry, and was not visited by the writer. However, a contiguous group of rocks about 10 km further north in the southern Dome Rock Mountains, and also mapped as Mesozoic gneisses by Wilson (1960), is reported by Marshak (1980) to comprise principally low-grade meta-volcanic rocks including meta-basalts, meta-andesites, and meta-tuffs. According to Crowl (1979, cited in Reynolds 1980), an early to middle Jurassic U-Pb age was obtained by L. T. Silver from the volcanics of the Dome Rock Mountains, which form a section locally as much as 5 km thick. Basement rocks exposed in the Castle Dome region probably are correlative with a late Mesozoic clastic sequence, as described below, but Reynolds (1980) reports that

this sequence depositionally overlies the mid-Mesozoic volcanics. Accordingly, this very thick pile of low greenschist facies metavolcanic rocks could well be encountered as the reservoir rock in HDR geothermal development in the Castle Dome area. However, the overlying clastic sequence itself appears to be a more likely candidate.

Most rocks exposed beneath the mid-Tertiary volcanics of the Castle Dome Mountains are gray to greenish-gray phyllites, impure quartzites, limey phyllites, and abundant gray, poorly sorted, feldspathic arenites and conglomerates, commonly with weakly phyllitic matrices. Meta-andesite(?) flows occur locally in the pile, as do maroon phyllites. Lithic clasts indicate a mixed provenance including both a gneissic-plutonic terrane and a volcanic terrane. The volcanic clasts are chiefly of mafic rocks although felsic types occur locally. Metamorphic mineral assemblages typically include albite + epidote + chlorite + muscovite and indicate low greenschist facies conditions. The more fine-textured of these rocks are pervasively foliated. The metamorphic sequence is cut by numerous felsic quartz porphyry dikes, most of which doubtless are related to the overlying mid-Tertiary volcanic pile, and is the host rock for the lead-silver mineralization of the Castle Dome mining district.

This section of low-grade, metasedimentary rocks resembles thick Mesozoic clastic sequences as described from the southern Dome Rock Mountains by Marshak (1980) and from the Livingston Hills by Harding (1980). The section described by Marshak reportedly is about 5 km thick where it crops out some 30 km north-northwest of Stone Cabin. Marshak (1980) considers these rocks to be mid-Jurassic to late Cretaceous in age. Harding (1980) indicates that the Livingston Hills Formation is 3.6 km thick in the Livingston Hills, about 30 km northeast of Stone Cabin, and presents paleomagnetic evidence suggesting that the age of metamorphism is no younger than late Jurassic.

III. TERTIARY VOLCANIC ROCKS

Resting unconformably on these metamorphic rocks is a sequence of intermediate to silicic volcanic rocks that forms the bulk of the Castle Domes and adjacent ranges. The volcanics are separated from the metasedimentary rocks locally by several meters of pale reddish to brown, poorly sorted, tuffaceous sandstone rich in felsic volcanic clasts. Laharic(?) deposits also occur locally in paleotopographic lows along this contact, which evidently had relief of 30 to 50 m or more in the southern Castle Domes. Total preserved thickness

of the volcanic pile appears to be at least 0.5 km and probably is not substantially more than 1 km. Complications arising from numerous faults preclude any more precise estimate of stratigraphic thickness until considerably more mapping has been carried out.

With the exception of a group of rhyolites near Stone Cabin, the age of these rocks is shown as Cretaceous on the Arizona State Geologic map (Wilson et al. 1969). The rhyolites near Stone Cabin are shown as Quaternary in age (Wilson et al. 1969). In fact, these rocks range in age from late Oligocene to early Miocene, as indicated by five new K-Ar mineral ages. These dates are summarized in Table I and evidently are the first radiometric ages obtained from rocks of the Castle Domes. Volcanism began in the Castle Dome region about 25 Myr ago, as indicated by the age of a dacite (sample CD-85, Table I) from a compound cooling unit of welded tuff at least 100 m thick and separated from the Mesozoic metasedimentary rocks by no more than 10 m of sandstone. This date is considerably younger than the age of inception of mid-Tertiary volcanism (at least 32 to 35 Myr ago) across the Colorado River in southeastern California (Crowe et al. 1979). However, it is very similar to the age of basal tuffs to the east-northeast in the Eagle Tail Mountains (24 Myr) (Shafiqullah et al. 1980) and Vulture Mountains (26 Myr) (Rehrig et al. 1980).

An ash-flow tuff from the upper part of the east-dipping volcanic section exposed in the range itself yields a K-Ar mineral age of 23.5 Myr (sample CD-75, Table I). Field evidence is ambiguous as to the stratigraphic position of the isolated rhyolite lava flows and tuffs mapped by Wilson (1960) near Stone Cabin. These were assigned a Quaternary age by Wilson et al. (1969), as were some flow-banded rhyolites with a similar and distinctive phenocryst assemblage cropping out on the other (east) side of the range near its northern end. However, samples of two of these units collected by the writer at and south of Stone Cabin gave mineral ages of 22.28 Myr and 22.20 Myr (Shafiqullah and Damon, personal communication 1980) (Table I). Thus, they are of earliest Miocene age (following Berggren 1969). Evidently the volcanics exposed at Stone Cabin and south along U.S. Route 95 have been downfaulted to their present positions relative to the main mass of the Castle Dome volcanic pile to the east.

Wilson et al. (1969) maps several areas of Quaternary basalt on the east side of the Castle Domes near their southern end. At least several, if not all, of these areas are underlain by flows of what may better be termed

TABLE I

K-AR AGE DETERMINATIONS OF VOLCANIC ROCKS FROM THE CASTLE DEOM MOUNTAINS, ARIZONA

Sample No.	Rock type and Locality	Age (Mry)	Mineral	%K	$^{40}\text{Ar}_{\text{rad}}/\Sigma^{40}\text{Ar}$	Laboratory
CD-85	Dacite welded tuff, base of volcanic sequence, Honkidori Hill, 32°58.78'N Lat., 114°09.08'W Long.	25.0 ± 1.0	Biotite	6.230	0.544	Geochron
CD-75	Rhyolitic ash-flow tuff, Little White Tanks, 33°08.49'N Lat., 114°06.61'W Long.	23.5 ± 0.9	Biotite	6.284	0.533	Geochron
CD-92	Rhyolitic ash-flow tuff, zeolite workings 4 km S of Stone Cabin, 33°13.78'N Lat., 114°14.98'W Long.	22.28 ± 0.47 ^a	Biotite	--	--	Laboratory of Isotope Geochemistry, Univ. of Ariz.
CD-77	Rhyolite lava flow, Stone Cabin, 33°15.99'N Lat., 114°14.67'W Long.	22.20 ± 0.47 ^a	Biotite	--	--	"
CD-72	Basaltic andesite dipping ca. 10°, base of range, E side, 33°03.45'N Lat., 113°57.65'W Long.	20.39 ± 0.43 ^a	Plagioclase Concentrate	--	--	"

^aM. Shafiqullah and P. Damon, personal communication 1980.

basaltic andesite (see Table II and discussion below). One such flow, resting with apparent unconformity(?) on the underlying volcanics and dipping 10° east-northeast, yielded a K-Ar age of 20.39 Myr (Shafiqullah and Damon, personal communication 1980) (sample CD-72, Table I). This probably is the youngest volcanic rock, or nearly so, within the area of the negative gravity anomaly. It may represent an eastward extension of unit Cb of Crowe et al. (1979), a group of mafic and intermediate flows in southeastern California ranging in age from 22 to 13 Myr and separated by a distinct age gap from the underlying silicic volcanic rocks (Crowe et al. 1979).

Major-element analyses of four of the volcanic rocks, including three of the radiometrically dated samples, are presented in Table II together with CIPW norms. The chemical data available at this time are too few to fully characterize the suite, but the volcanics appear to be generally calc-alkaline and similar to the 28 to 22 Myr silicic volcanic sequence described by Crowe et al. (1979) from southeastern California. The youngest of the Castle Dome rocks (sample CD-72) would be classified as a basalt following Irvine and Baragar's Fig. 7 (1971) but as an andesite following Streckeisen (1979). Probably this rock is best termed a basaltic andesite, especially in view of its borderline character with respect to criteria such as silica content and plagioclase composition. Of the other three analyzed rocks, the 25 Myr basal ash-flow tuff (CD-85) is a dacite and the other two are rhyolites (following Streckeisen 1979).

The Castle Dome volcanic pile appears rhyodacitic or rhyolitic (nomenclature of Streckeisen 1979) in overall composition. As in the mid-Tertiary volcanics of southeastern California (Crowe et al. 1979) andesite is markedly subordinate in volume. Of the several dozens of volcanic units examined, no more than one-fifth are andesite or basaltic andesite, another fifth are approximately dacitic and three-fifths appear more nearly rhyolitic. Among the felsic volcanic units, about two-thirds are ash-flow tuffs, of which over half are welded to some degree. All are porphyritic, usually with plagioclase and biotite. Over half of the felsic units carry phenocrystic sanidine and nearly half contain quartz phenocrysts. Hornblende also occurs in half of the rocks examined. Clinopyroxene phenocrysts are present in a few of the felsic units.

Evidently about one-third of the Castle Dome pile consists not of ash flows but of ordinary lava flows of rhyolitic composition. Some of these are boudinaged, flow-banded rhyolites masquerading as densely welded tuffs in the

TABLE II
MAJOR-ELEMENT COMPOSITIONS^a AND CIPW NORMS^b OF VOLCANIC ROCKS
FROM THE CASTLE DOME MOUNTAINS,^c SOUTHWESTERN ARIZONA

Oxide	CD-72	CD-85	CD-106	CD-77
SiO ₂	53.6	67.2	72.0	70.2
Al ₂ O ₃	17.2	15.8	14.9	15.2
TiO ₂	1.28	0.39	0.23	0.24
FeO ^d	7.88	2.59	1.83	1.63
MgO	5.15	1.48	0.57	0.43
CaO	8.79	4.23	1.19	1.68
Na ₂ O	3.30	3.99	3.71	3.85
K ₂ O	1.33	3.09	4.78	5.68
MnO	0.11	ND	ND	ND
Total	98.64	98.77	99.21	98.91
q	3.8	21.7	28.4	21.9
or	7.79	18.4	28.4	33.4
ab	27.8	33.6	31.5	32.5
an	28.4	16.1	5.84	7.51
c	--	--	1.43	--
wo	6.42	1.98	--	0.35
en	12.9	3.71	1.41	1.10
fs	5.28	0.66	0.53	0.40
mt	3.94	1.85	1.39	1.16
il	2.43	0.76	0.46	0.46
100an/ab + an	50.5	32.5	15.7	18.8
normative c.i.	30.9	8.96	3.79	3.47
Ab + An:Or:Q	83:11:6	55:21:24	40:30:30	42:35:23

^aAnalyses by Jamie N. Gardner, Los Alamos National Laboratory, by electron microprobe techniques on fused, powdered samples.

^bCalculated from analyses as reported and setting Fe₂O₃ equal to the least of the following: 3.0%, or TiO₂ + 1.5% (Irvine and Barāgar 1971), or FeO^d/2.

^cSample locations are given in Table I for all but CD-106, which is from an extra ordinarily thick, welded ash-flow tuff at the mouth of Palm Canyon, Kofa Mountains, ca. 5 km north of north end of Castle Dome Mountains.

^dTotal iron as FeO. ND = not detected.

field but all are essentially devoid of vitroclastic texture and must have been emplaced as lava flows of very high viscosity. Such flows probably would not have moved long distances from their vents and, together with the presence of especially coarse-textured, block-and-ash avalanche(?) deposits, their abundance suggests the former occurrence of vents and magma sources in or near the Castle Domes.

The gross stratigraphy of the mid-Tertiary volcanic pile of southwestern Arizona is virtually unknown. This stratigraphy has been well worked out in southeastern California by Crowe et al. (1979), who recognize a 35 to 26 Myr basal sequence of overall dacitic composition and a generally younger (28 to 22 Myr) silicic sequence, which is quartz latitic in overall composition. According to Wilson (1962), the volcanic section of the Castle Dome and Kofa Mountains is predominantly andesitic in its lower parts and andesitic to rhyolitic in its upper portion. Wilson (1960) mapped andesitic and overlying andesitic-to-rhyolitic units separately on the Yuma County geologic map. The writer examined the andesitic unit (Ka of Wilson 1960) in several places. Although it can contain relatively dark-colored lava flows, locally in abundance, silicic welded tuffs (e.g., rhyolite sample CD-106, Table II) generally are present as well, whereas andesite apparently can be entirely absent from the section in places.

Is Wilson's (1960) andesitic lower unit real? Olmsted et al. (1973) note that the oldest rocks of the Tertiary volcanic sequence in the Yuma area apparently are of andesitic composition. These are exposed chiefly in the easternmost Chocolate Mountains of California, near the Colorado River, but are missing in the Laguna Mountains to the southeast (Olmsted et al. 1973). It seems likely that (a) many of the rocks mapped as andesites by Wilson are really silicic rocks of dark color; (b) the lower parts of the volcanic pile, which demonstrably are less silicic than the overlying rocks in California (Crowe et al. 1979) may also be so in parts of westernmost Arizona (Wilson 1960) but are not as mafic in overall composition as andesite; and (c) this less silicic lower unit pinches out eastward and is thin or absent in the vicinity of the Castle Domes and perhaps the Kofas as well. Both overall rock composition and the 25 Myr age of inception of volcanism support correlation of the Castle Dome volcanics (Kofa volcanics of Wilson 1960) with the silicic sequence of Crowe et al. (1979), to the apparent exclusion of the basal, less silicic sequence.

Volcanic rocks of the Castle Domes are cut by numerous quartz porphyry dikes and scattered plugs. The dikes occur in north-northwesterly trending swarms near the crest of the range and especially in the Castle Dome mining district, along the west flank of the range. A northeasterly trending swarm of thick dikes occurs near the Keystone mine, on the east side of the range. Wherever examined, these intrusions were intensely fractured, often on closely spaced (ca. 1 mm) subparallel fractures, and were either sericitized or kaolinized. In at least one instance, shear strain appears to have developed not later than alteration/recrystallization at elevated (300°C?) temperatures, i.e., fracturing occurred while the terrane still was warm. An intriguingly similar set of dikes is described by Rehrig et al. (1980) from the Vulture Mountains, about 140 km to the northeast. There, 26 to 16 Myr calc-alkaline volcanics, also believed to have come from nearby sources, are cut by north- to north-northwest-trending silicic porphyritic dikes; some of these dikes postdate listric normal faults whereas others apparently are cut by the faults (Rehrig et al. 1980). There, too, the dikes locally trend northeast instead of north-northwest, evidently reflecting control of dike orientation by a basement fracture fabric of Laramide age (Rehrig et al. 1980; Rehrig and Heidrick 1976). The plutonic sources of these dikes are not exposed either in the Vulture Mountains or in the Castle Domes.

IV. MID-TERTIARY GEOLOGIC EVOLUTION

Centered a few km south of Stone Cabin is a crudely circular region about 45 km across within which pre-Tertiary basement rocks evidently are not exposed although they do crop out all around its periphery (Fig. 2). This region corresponds closely with the position of the large negative Bouguer gravity anomaly noted earlier. In many places the margins of the gravity low are steep and sharply defined (Fig. 2), suggesting lateral density contrast at relatively shallow depth. Although the gravity anomaly presumably must to some extent reflect Basin and Range fault block structures, the correspondence between its locally steep margins and those of the region of concealed basement rocks suggests that cauldron subsidence may have occurred here. Indeed, the copious outpourings implied by some of the ash-flow cooling units exposed in the Castle Domes and northwestern Kofas seemingly must have been associated with subsidence in some form, albeit perhaps distributed over a broad region. The edge of the gravity anomaly is steepest and most sharply defined in the

northeastern third of its periphery. Along most of this third, the edge of the gravity low lies over sediments filling what could be deep and steep-sided basins. However, it also cuts across the northwestern end of the Kofa Mountains. Where it does so, Wilson (1960) maps two faults, each several km long. The geographic coincidence of these faults and the sharp edge of the gravity low may be fortuitous; but the orientation of and sense of motion on these faults, as indicated by Wilson (1960), is appropriate if they represent part of a fracture system bounding a region of cauldron subsidence to the south and west.

Other pertinent structural features are indicated in the Castle Domes themselves. This block-faulted range has a steep western face, and its volcanic layering dips predominantly east-northeastward at gentle to moderate angles. The principal strike direction both of this layering and of the silicic dikes is N30-35W, parallel to the trend of the range and to its chief morphologic lineaments. Trends of faults and prominent outcrop fracture sets in the volcanics fan from north to west-northwest; few lie outside this directional range, although a small population of cross fractures, topographic lineaments, and dikes trend approximately northeast. Whereas layering in much of the Castle Domes is inclined east-northeastward, gentle southwesterly dips occur over broad areas in the east-central part of the range, as does apparent gentle warping of the strata. The gently dipping areas terminate abruptly against terrane characterized by moderate to steep northeasterly dips and local sharp reversals of dip.

The abrupt changes of dip through 70 to 80° within this volcanic pile imply large rotations across faults. Repetition and rotation of the mid-Tertiary volcanic pile in the Vulture Mountains to the northeast has been ascribed to listric faulting (Rahrig et al. 1980), a structural phenomenon, which in the Basin and Range province has only been recognized recently (Stewart 1978). The occurrence of listric faulting about 15 to 20 Myr ago has been documented to the north of the Castle Domes (Davis et al. 1980) as well as to the northeast. Rehrig et al. (1980) suggest that the shallow crustal extension and north-northwest-trending listric normal faulting in the region was genetically related to and facilitated by dike or pluton emplacement. Occurrence of swarms of north-northwest-trending dikes in the Castle Domes, some of which evidently were sheared while still warm, fits with this model. On the other hand, listric faulting in the Castle Domes seems weakly developed

at best in comparison with that described from nearby areas (Rehrig et al. 1980, Davis et al. 1980). These downward-flattening structures were not directly observed in the Castle Domes, perhaps owing to lack of exposure to deep structural levels. They are exposed in the Vultures, but only rarely (Rehrig et al. 1980). Further studies in the Castle Domes, which are both warranted and planned, will be required to determine the nature of the north-northwest-trending faults.

Whatever their geometry, it seems likely that these faults were penecontemporaneous with mid-Tertiary magmatism. Only minor tilting of structural blocks has occurred in southwestern Arizona since 12 Myr ago (Damon et al. 1973), the time of inception of Basin-Range block faulting in this region (Eberly and Stanley 1978). Yet large blocks of the volcanic section in the Castle Domes dip at angles ranging from 20 to at least 60°. Several recent contributions (Rehrig and Heidrick 1976, Shafiqullah et al. 1980, Rehrig et al. 1980) emphasize the distinction between the thin-skinned rotational tectonics of the mid-Tertiary orogeny, which dominated this area until about 15 to 17 Myr ago, and the vertical tectonics associated with the ensuing episode of basin subsidence along steep normal faults. Evidence presented by Crowe (1978) indicates that topographic disruption by motion along north-northwesterly-trending normal faults began at least 26 Myr ago in southeastern California and probably prior to 32 Myr ago. Clearly this region was undergoing extension both before and after Castle Dome volcanic activity. Yet the relatively gentle dip of the 20.4 Myr basaltic andesite from the eastern Castle Domes, together with the flat-lying attitude of a basaltic andesite from the Kofas dated at 18.3 Myr (Shafiqullah et al. 1980), indicate that rotational events had largely ceased in this particular area by 18 to 19 Myr. These events evidently were penecontemporaneous with Castle Dome volcanism.

Anderson (1971) and Wright (1976) have suggested that Basin-Range extension accommodated by normal faulting at shallow crustal levels may have been accompanied by emplacement of plutons at depth. Modelling of the source of the large negative Bouguer gravity anomaly centered in the northern Castle Domes has been carried out by Carlos Aiken, University of Texas, Dallas. Following removal of the effects of very high-level density contrasts (e.g., due to Basin-Range or cauldron-bounding faults), the anomaly is closely modelled (± 1 mgal) by a low-density mass with a bottom 20 km down (base of the crust) and a top 8 km (assuming 0.1 g/cc density contrast) to 10 km down (assuming

0.2 g/cc density contrast) (C. L. V. Aiken, personal communication 1980). Such a mass could be the silicic batholithic source of the mid-Tertiary volcanic pile. Deformation of that pile could have occurred due to instabilities in the batholith's roof. However, the regular Cenozoic tilt patterns of southwestern Arizona (Stewart 1980), into which the Castle Domes and surrounding ranges fit neatly, could not have been controlled by such a batholith. They are of far wider regional extent. These extensive patterns of fracturing and intrusion (Stewart 1980, Rehrig et al. 1980) are more evident in the structural geology of the Castle Domes than is the influence of such a batholith. Nevertheless, the voluminous ignimbrites, gravity low, and distribution of pre-Tertiary basement outcrops vis a vis that gravity low all suggest that one or more very large silicic intrusions of early Miocene age occur at depth in the Castle Dome area.

V. GEOTHERMAL POTENTIAL

The only land in this area potentially open to commercial energy development is a north-south belt about 2 to 10 km wide and more than 60 km long. This belt extends south from Quartzsite along U.S. Route 95 to a boundary about 5-km north of the Castle Dome Heliport well (Fig. 2). Throughout most of its length it separates Yuma Proving Ground on the west from Kofa National Wildlife Refuge on the east. Although this belt covers only a small portion of the total area of the gravity anomaly, it appears well positioned for geothermal energy purposes in view of its span across the center of the gravity low from the north side nearly to the south. The tiny settlement of Stone Cabin lies within this land corridor, and gas and electrical power transmission lines run through it. In addition to ordinary commercial development, consideration should be given to the possibility that a demonstration direct-use (?) geothermal resource might be developed in some part of the Yuma Proving Ground with the cooperation and to the economic advantage of that facility.

Two sets of geophysical evidence suggest that the Castle Dome area may be anomalously hot at depth. Most of the area underlain by the gravity low is characterized by "subdued" aeromagnetic anomalies, possibly indicating a relatively shallow depth to the Curie isotherm (Sauck 1972). A recent depth-to-Curie-isotherm analysis indicates that the 500°C isothermal surface is located at about 7- to 8-km depth in the Castle Domes (C. L. V. Aiken, personal

communication 1980). For comparison, average depth to the Curie isotherm in north-central Arizona is about 20 km below sea level (Byerly and Stolt 1977).

In addition, preliminary analysis of data from a deep magnetotelluric survey being performed in Arizona and New Mexico (Aiken and Ander, in press 1981) also suggests geothermal potential. The survey is designed primarily to yield regional information on deep electrical conductors in the crust and/or upper mantle. Anomalous shallow crustal conductors are of direct geothermal interest as possible indicators of elevated temperatures, although interpretation of the data plainly must be done with caution since apparent shallow conductivities can be generated in various ways, not all indicative of geothermal anomalies (Aiken and Ander, in press 1981). One leg of the present survey passes north from Yuma essentially across the center of the gravity low; the magnetotelluric stations are shown in Fig. 2. Preliminary one-dimensional analysis of the magnetotelluric data indicates that the top of the deep electrical conductor is located at anomalously shallow depth, about 10 km down, in the Castle Dome area (M. E. Ander, Los Alamos National Laboratory, personal communication 1980). Two-dimensional analytical results could differ and are awaited with interest.

Published heat flow measurements nearest to the gravity low are those of Roy et al. (1968), who reported a mean value of 2.4 heat flow units (HFU) for five holes in the vicinity of Quartzsite, Arizona, about 44 km north of Stone Cabin. Preliminary results from heat flow measurements at a site near the Colorado River, a comparable distance west-northeast of Stone Cabin, indicate a normal Basin-Range heat flow of ~ 2.0 HFU (J. Sass, U.S. Geological Survey, personal communication 1980).

The only published geothermal gradient measurement within the gravity low was obtained by Shearer (1979) in a drill hole at Stone Cabin (33°16.0'N lat., 114°14.6'W long.). Shearer reports the gradient measured over each of four depth intervals from 130- to 310-m depth; the indicated gradients range from 54 to 85°C/km and the average gradient is about 70°C/km (Shearer 1979). The hole reportedly is an 8-in. well, was "powder dry," and bottomed at 1040 ft (informal memo in files of Water Resources Div., U.S. Geological Survey, Yuma Office).

Inasmuch as the conductivity of the materials in the hole is unknown, the implication of these strikingly high-gradient measurements is not clear. A normal Basin-Range heat flow is possible given unconsolidated material of

sufficiently low conductivity. Olmsted et al. (1973) state that the average geothermal gradient for dry materials beneath "Upper Mesa" south of Yuma is about $92^{\circ}\text{C}/\text{km}$ ($2.8^{\circ}\text{C}/100\text{ ft}$). Yet rhyolite bedrock crops out within a few tens of meters from the reported drill site at Stone Cabin, increasing the likelihood that the high gradient may in fact reflect high heat flow. Since Stone Cabin lies within a narrow belt, noted earlier, which is the only land in the area potentially open for geothermal development, measurement of heat flow there would appear to be one of the most logical investments to further assess the HDR geothermal potential of this region.

Water supplies within this corridor of private land evidently are scanty at best. Likelihood of direct use geothermal development appears reduced as a result. Reservoir temperatures adequate to support electrical power generation should be sought. Assuming a linear gradient of $54^{\circ}\text{C}/\text{km}$ (the least value observed by Shearer 1979) and a mean surface temperature of 20°C , a reservoir temperature of 200°C would occur at about 3.3-km depth. This probably would place the top of the reservoir below the base of the mid-Tertiary volcanic section and within the 3- to 5(?) -km-thick section of low-grade metasedimentary rocks. Prediction of reservoir rock type in this area is complicated by the possible presence of crystalline overthrusts as reported in the Little Harquahala Mountains about 70 km to the northeast (Reynolds et al. 1980). In addition, tectonic or erosional removal of the metasedimentary rocks could have occurred so that the underlying metavolcanic section would constitute the HDR reservoir. However, low-grade, commonly phyllitic metasediments evidently are the most likely rock suite to be encountered at pertinent depths. Thus, the projected HDR reservoir rocks would be anisotropic with weak to perhaps well-developed schistosity. Unless abundant water could be secured nearby, successful HDR geothermal development would require a tight reservoir. Permeability of the metasedimentary rocks presumably would be strongly anisotropic; whether or not losses from the system would be acceptably low is unclear.

It is reasonable to suppose that the marked anisotropy of a penetratively foliated, phyllitic reservoir rock might in fact be turned to advantage through HDR reservoir design at once depending and capitalizing on that anisotropy, e.g., to guide fluid from a single injection well to a surrounding cluster of extraction wells. Such a system should be of considerable interest as a test of the feasibility of employing HDR geothermal strategies within strongly anisotropic reservoirs. As noted above, reservoir tightness,

including fracture permeability, may be especially important here in order to minimize fluid loss. In this connection it should be noted that the area around Stone Cabin is situated at the junction of the northeast-trending Chocolate Mountains and the north-northwest-trending Castle Domes. Rhyolitic outcrops in the area did not appear unusually highly fractured; however, variability of structural attitudes and of rock types along strike suggests that faults are at least as abundant in the vicinity of Stone Cabin as elsewhere in the region.

Listed in Table III are the locations and depths of water wells within the area underlain by the gravity low. This list does not include some shallow wells, numerous wells on the Yuma Proving Ground south of the gravity low, and perhaps also other wells inasmuch as no truly comprehensive file of such data exists. Nevertheless, several fairly deep wells exist, which might be utilized to determine more about geothermal gradients in the area.

Apart from the data provided by Shearer (1979), water temperatures from certain wells on the Yuma Proving Ground suggest that the area is thermally enhanced. A well located at the Castle Dome Heliport, near the southern margin of the gravity low (Fig. 2; Table III) bottoms in volcanic rocks at 304 m depth (Click 1971). In 1977 depth to water in this well was 193 m and water temperature was 45°C (Slater, personal communication 1980). Two other wells on the Yuma Proving Ground located adjacent to U.S. Route 95 about 12 km further south (Point HJW, Fig. 2) both yield water at 42°C although these wells are only 153 m deep (Slater, personal communication 1980). Arrangements might be sought to obtain geothermal gradient data from one or more of these wells. In any event, demonstrated occurrence of these warm fluids at such shallow depths and near Yuma Proving Ground facilities suggests that a direct-use geothermal resource might be developed economically, e.g., to provide absorption refrigeration (for air conditioning) in this hot climate.

In conclusion, this study suggests that the Castle Dome area may be underlain by a silicic batholithic mass approximately 20 Myr in age. Younger volcanism is evidently absent. Radiogenic heat from such a mass could account for at least part of regional thermal enhancement apparent in the depth-to-Curie isotherm, magnetotelluric, geothermal gradient, and water temperature observations cited above. Little was known of the Castle Dome region before this study, and much remains to be done, especially as regards stratigraphy and structure. However, it seems likely that reservoir rocks for HDR

TABLE III
WELLS OF INTEREST IN THE CASTLE DOME AREA^a

Location	Well Depth (m)	Depth to Water (m)	Ownership	Remarks
T2N R18W SEC 9 SE1/4	54.5	38	U.S. Gov't	24°C water
T2N R18W SEC 9 SE1/4	31.4	16	U.S. Gov't	
T2N R18W SEC 16 NE1/4	211	?	Private	5 gpm
T2N R18W SEC 24 SE1/4	?	11	Private	
T1N R21W SEC 23 SE1/4	149	47	U.S. Gov't?	
T1S R18W	?	20	?	
T2S R17W SEC 1 SW 1/4	123	?	U.S. Gov't?	
T2S R17W	?	56, 34	U.S. Gov't?	About 10 wells in this area, probably including "Kofa Deep Well" in SEC 27 SE1/4. Avg. gradient 70°C/km; see Shearer (1979). Reportedly is deepest of 10 dry holes in area.
T2S R19W	320	dry hole	Private	
T3S R22W	185	?	U.S. Gov't	
T4S R16W SEC 22 NE1/4	153	125	U.S. Gov't	
T5S R15W SEC 29 NE1/4	446	?	?	
T5S R19W SEC 19 NW1/4	308	210	U.S. Gov't	At Castle Dome Heli- port. 45°C water; see Click (1971).
T5S R21W SEC 19 SW1/4	73.8	5	Private	
T5S R21W SEC 11 NE1/4	166	98	U.S. Gov't	
T6S R18W SEC 32 SW1/4	225	164	U.S. Gov't	

^aAs indicated in records chiefly of Water Resources Division, U.S. Geological Survey, Tucson, Arizona. For King Valley area, between Castle Domes and Kofas, only wells deeper than ~100 m are shown above. Additional data for many of these wells are available from the U. S. Geological Survey, Tucson, Arizona.

geothermal purposes would be hydraulically anisotropic, low-grade metasedimentary or metavolcanic rocks of Mesozoic age. Critical data for assessing probable reservoir temperatures could be gained from studies utilizing existing water wells, from heat flow measurements at Stone Cabin and elsewhere, and from additional geophysical studies and refinements of existing geophysical data. Consideration should be given to the feasibility of developing a direct-use geothermal resource to the advantage of the Yuma Proving Ground. Otherwise, reservoir temperatures adequate to support electrical generation should be sought, for neither direct users nor water are abundant in this geothermally attractive area.

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REFERENCES

- Aiken, C. L. V., "The Analysis of the Gravity Anomalies of Arizona," Ph.D. Dissertation, Univ. of Arizona, Tucson, (1976) 127 p.
- Aiken, C. L. V. and M. E. Ander, "A Regional Strategy for Geothermal Exploration with Emphasis on Gravity and Magnetotellurics," Jour. Volc. Geoth. Res. (in press 1981).
- Anderson, R. E., "Thin Skin Distension in Tertiary Rocks of Southeastern Nevada," Geol Soc. Amer. Bull. 82, 43-58 (1971).

Berggren, W. A., "Cenozoic Chronostratigraphy, Planktonic Foraminiferal Zonation and the Radiometric Time Scale," *Nature* 224, 1072-1075 (1969).

Byerly, P. E. and R. H. Stolt, "An Attempt to Define the Cure Point Isotherm in Northern and Central Arizona," *Geophysics* 42, 1394-1400 (1977).

Click, D. E., "Development of a Ground-Water Supply at Castle Dome Heliport, Yuma Proving Ground, Arizona," unpublished report prepared by U.S. Geological Survey in cooperation with U.S. Army Yuma Proving Ground (1971) 14 p.

Crowe, B. M., "Cenozoic Volcanic Geology and Probable Age of Inception of Basin-Range Faulting in the Southeasternmost Chocolate Mountains, California," *Geol. Soc. Amer. Bull.* 89, 251-264 (1978).

Crowe, B. M., J. C. Crowell, and D. Krummenacher, "Regional Stratigraphy, K-Ar Ages, and Tectonic Implications of Cenozoic Volcanic Rocks, Southeastern California," *Am. Jour. Sci.* 279, 186-216 (1979).

Damon, P. E., M. Shafiqullah, and D. J. Lynch, "Geochronology of Block Faulting and Basin Subsidence in Arizona," *Geol. Soc. Amer. Abs. with Programs* 5, 590 (1973).

Davis, G. A., J. L. Anderson, and E. G. Frost, "Regional Miocene Detachment Faulting and Early Tertiary(?) Mylonitization, Whipple-Buckskin-Rawhide Mountains, Southeastern California and Western Arizona," in Guide to Arizona Geological Society 1980 Spring Field Trip (Arizona Geological Society, Tucson, 1980) p. 4-12.

Eberly, L. D. and T. B. Stanley, Jr., "Cenozoic Stratigraphy and Geologic History of Southwestern Arizona," *Geol. Soc. Amer. Bull.* 89, 921-940 (1978).

Harding, L. E., "Petrology and Tectonic Setting of the Livingston Hills Formation, Yuma County, Arizona," *Ariz. Geol. Soc. Digest* 12, 135-145 (1980).

Irvine, T. N. and W. R. A. Baragar, "A Guide to the Chemical Classification of the Common Volcanic Rocks," *Canad. Jour. Earth. Sci.* 8, 523-548 (1971).

Marshak, S., "A Preliminary Study of Mesozoic Geology in the Southern Dome Rock Mountains, Southwestern Arizona," *Ariz. Geol. Soc. Digest* 12, 123-133 (1980).

Miller, F. K. and E. H. McKee, "Thrust and Strike-Slip Faulting in the Plomosa Mountains, Southwestern Arizona," *Geol. Soc. Amer. Bull.* 82, 717-722 (1971).

Olmsted, F. H., O. J. Loeltz, and B. Irelan, "Geohydrology of the Yuma Area, Arizona and California," *U.S. Geol. Survey Prof. Paper* 486-H (1973) 227 p.

Rehrig, W. A. and T. L. Heidrick, "Regional Tectonic Stress During the Laramide and Late Tertiary Intrusive Periods, Basin and Range Province, Arizona," *Ariz. Geol. Soc. Digest* 10, 205-228 (1976).

Rehrig, W. A., M. Shafiqullah, and P. E. Damon, "Geochronology, Geology, and Listric Normal Faulting of the Vulture Mountains, Maricopa County, Arizona," *Ariz. Geol. Soc. Digest* 12, 89-110 (1980).

Reynolds, S. J., "Geologic Framework of West-Central Arizona," Ariz. Geol. Soc. Digest 12, 1-16 (1980).

Reynolds, S. J., S. B. Keith, and P. J. Coney, "Stacked Overthrusts of Precambrian Crystalline Basement and Inverted Paleozoic Sections Emplaced Over Mesozoic Strata, West-Central Arizona," Ariz. Geol. Soc. Digest 12, 45-51 (1980).

Roy, R. F., E. R. Decker, D. D. Blackwell, and F. Birch, "Heat Flow in the United States," Jour. Geophys. Res. 73, 5207-5221 (1968).

Sauck, W. A., "Compilation and Preliminary Interpretation of the Arizona Aeromagnetic Map," Ph.S. Dissertation, Univ. of Arizona, Tucson (1972) 147 p.

Shafiqullah, M., P. E. Damon, D. J. Lynch, S. J. Reynolds, W. A. Rehrig, and R. H. Raymond, "K-Ar Geochronology and Geologic History of Southwestern Arizona and Adjacent Areas," Ariz. Geol. Soc. Digest, 12, 201-260 (1980).

Shearer, C. R., "A Regional Terrestrial Heat-Flow Study in Arizona," Ph.D. Dissertation, New Mexico Institute of Mining and Technology, Socorro (1979) 184 p.

Stewart, J. H., "Basin and Range Structure in Western North America - A Review," in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, R. B. Smith and G. P. Eaton, Eds. (Geol. Soc. Amer. Memoir 152, 1978) p. 1-31.

Stewart, J. H. "Regional Tilt Patterns of Late Cenozoic Basin-Range Fault Blocks, Western United States," Geol. Soc. Amer. Bull. Part I 91, 460-464 (1980).

Streckeisen, A., "Classification and Nomenclature of Volcanic Rocks, Lamprophyres, Carbonatites, and Melilitic Rocks: Recommendations and Suggestions of the IUGS Subcommittee on the Systematics of Igneous Rocks," Geology 7, 331-335 (1979).

West, R. E., "A Regional Bouguer Gravity Map of Arizona," Ph.D. Dissertation, Univ. of Arizona, Tucson (1972) 186 p.

Wilson, E. D., "Geology and Mineral Deposits of Southern Yuma County, Arizona," Univ. of Arizona, Ariz. Bur. Mines Bull. 134, (1933) 236 p.

Wilson, E. D., "Arizona Zinc and Lead Deposits - Castle Dome District (Yuma County)," Univ. of Arizona, Ariz. Bur. Mines Bull. 158, 98-115 (1951).

Wilson, E. D., "Geologic Map of Yuma County, Arizona," Univ. of Arizona, Ariz. Bur. Mines, 1:375,000 (1960).

Wilson, E. D., "A Resume of the Geology of Arizona," Univ. of Arizona, Ariz. Bur. Mines Bull. 171 (1962) 140 p.

Wilson, E. D., R. T. Moore, and J. R. Cooper, "Geologic Map of Arizona," U.S. Geol. Survey map, 1:500,000 (1969).

Wright, L. "Late Cenozoic Fault Patterns and Stress Fields in the Great Basin and Westward Displacement of the Sierra Nevada Block," Geology 4, 489-494 (1976).

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