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HYDROTHERMAL ALTERATION AND TECTONIC SETTING OF INTRUSIVE ROCKS FROM EAST BRAWLEY, IMPERIAL VALLEY: AN APPLICATION OF PETROLOGY TO GEOTHERMAL RESERVOIR ANALYSIS

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INTRODUCTION

Petrologic and geochemical analysis of subsurface materials can be important in assessment of the potential of a geothermal well and in construction of an appropriate reservoir model for the resource. Qualitative information can be gained relating to the reservoir's thermal evolution, the nature and distribution of fluid flow at depth, and the geologic/tectonic environment controlling the underlying geometry and mechanisms of heat and mass transfer in the reservoir. Geologic models based on petrologic analysis of the Salton Sea and Cerro Prieto geothermal fields (e.g., Younker, et al., 1982; Elders, et al., 1982) have clearly proven the value of such geologic input in efficient and accurate field assessment and development. In addition to providing data for production and drilling decisions, geologic characterization of the resource can assist in appropriate parameter selection for numerical reservoir modelling and aid in interpretation of geophysical, geochemical, and well log data.

The Imperial Valley lies within the Salton Trough (Fig. 1), a tectonic depression which represents an extension of the spreading center underlying the Gulf of California. During the Cenozoic this basin was filled by a thick sequence of predominantly fluviatile, lacustrine, and deltaic sediments derived from the Colorado River system. The Salton Trough is an area of crustal thinning and extension, characterized by active tectonism, Quaternary silicic and basaltic magmatism, and high regional heat flow (Elders, 1979), leading to its high potential as a geothermal resource. The magmatic activity in the Imperial Valley has few surface manifestations other than the Cerro Prieto and Salton Sea volcanics (Fig. 1), and descriptions of subsurface igneous intrusives from geothermal drillholes have previously been limited and/or proprietary.

Recently, a geothermal well near East Brawley intersected a series of thin (3-35m) diabasic to dioritic intrusives. The petrology and chemistry of these meta-igneous rocks can provide insight into the thermal and fluid chemical characteristics of the reservoir and into the processes of magma generation at depth. A description of the rock types and their hydrothermal alteration is presented in order to increase the petrologic data base relating to this important facet of the geothermal potential of the Salton Trough and to provide a case study illustrating how detailed petrologic examination of well cuttings can provide important input in the construction of a geothermal reservoir model.

PETROCHEMISTRY OF THE INTRUSIVES

The presence of hornfelsic margins both above and below these thin igneous units and their fine to moderate grain size suggest a shallow intrusive origin. The intrusives, which cut thinly interbedded deltaic calcareous sandstones, siltstones, and claystones, are generally calc-alkaline in their chemical affinities (Fig. 2) and similar to diabasic sills from the Salton Sea and Heber areas and to Cenozoic Gulf of California volcanics. These units are slightly more K-rich and alkaline than typical basalts from oceanic spreading ridges (Kay, et al., 1970).

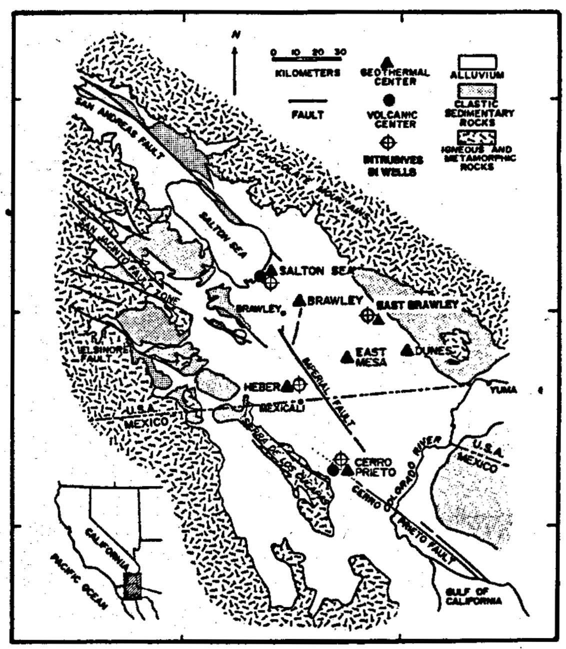

Figure 1. Generalized geologic map of the Salton Trough, modified from Elders, 1979. Locations of reported Quaternary igneous intrusive and volcanic rocks are indicated.

In hand specimen, the dikes are fine to medium grained black to dark green equigranular igneous material, with moderate amounts of calcite, chlorite, and quartz veining suggesting post-solidification fracturing. Texturally, the intrusives originally ranged from glass + crystals (hypocrystalline - now recrystallized to very fine grained crystalline matrix) to equigranular, holocrystalline coarser diabasic material. The very fine grained chips may represent more rapidly chilled thinner intrusives or chilled rims on thicker bodies - vertical control from well cuttings is not precise enough to distinguish between these possibilities.

These rocks had an original mineralogy of euhedral plagioclase (phenocrysts up to 4mm and fine swallowtail laths) + skeletal magnetite + ilmenite + pyroxene + olivine in a fine grained to glassy matrix. This assemblage is appropriate for their normative classification based on ICP analyses (Table 1) ranging from andesite to latite andesite to basalt (Fig. 3). Microprobe analyses permit more precise identification of the opaques as ilmenite + titanmagnetite, of the pyroxenes as augite, and of the few unaltered feldspars as oligoclase, consistent with a diorite to diabase composition.

K-Ar AGE DATES

To distinguish whether the igneous material in this well is related to relatively young Quaternary volcanism (associated with crustal spreading and rifting within the Salton Trough) or represents the older Tertiary to pre-Cambrian basement complex, K-Ar age dates were obtained for three samples (Table 2). The dates are quite consistent (8.1-10.5 million years) and indicate a Pliocene age. The sediments at depths below 10,000 feet in the Imperial Valley may be Miocene or older (Elders, 1979), and hence these intrusions can be related to volcanism which occurred after rifting and sedimentation in the Salton Trough were well established.

TABLE 2: K-Ar Age Dates for Igneous Intrusives from East Brawley

	Age Range (Millions of Years)	% K
Quartz Latite Andesite 1	8.1 ± 0.9	0.624
Basalt/Diabase 5	10.5 ± 0.9	0.870
Diabase 10	8.2 ± 0.8	0.920

K-Ar dates can be affected by slow cooling rates of the intrusion and by later metamorphism, and hence should be regarded as minimum ages. Although the intrusives do show considerable alteration, the plagioclase, which is the probable host for most of the K and Ar, is relatively fresh in these three units. The concordant dates for all three intrusions - much older than the downhole alteration due to the present hydrothermal system - lend credibility to the age dating.

Although no similar dike materials have been reported from other deep wells in the Brawley area, similar diabasic sills and dikes have been encountered during drilling in Cerro Prieto, the Salton Sea geothermal area, and from Heber (Elders, 1979; Robinson et al., 1976; Bird and Norton, 1981; Browne, 1977). Young volcanoes in Cerro Prieto and near the Salton Sea (<1 million years old) also attest to the presence of continued igneous activity in the area.

HYDROTHERMAL ALTERATION OF THE DIKE ROCKS

The dike rocks have been pervasively altered to Greenschist facies mineral assemblages similar to those described by Browne (1977) for the Heber diabase intrusives. Although appearing relatively fresh in the chips, in thin section the mafic minerals and the glassy matrix can be seen to be extensively replaced by chlorite + calcite + amphibole + epidote + sphene. Plagioclase and magnetite appear less

TABLE 1: Whole Rock Chemical Analyses of Igneous Intrusives from the Salton Trough

	East Brawley Intrusive Rocks										Cerro Prieto	Salton Sea			
wt. %	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	54.1	53.1	54.9	55.6	51.3	53.1	56.2	55.3	51.1	51.7	68.6	73.6	52.2	71.4	51.9
Al_2O_3	13.7	14.4	15.2	13.5	12.9	13.7	15.6	15.0	14.4	12.7	15.6	13.5	14.7	12.8	14.1
FeO	8.9	11.9	8.5	11.1	9.8	11.1	5.6	7.4	12.2	11.6	3.6	1.8	6.2	4.9	11.8
MgO	3.7	4.0	3.7	3.6	3.3	3.7	3.8	3.9	4.5	3.9	0.9	0.2	6.8	0.6	4.8
MnO	<.1	0.2	0.1	0.2	0.1	0.1	<0.1	0.1	0.1	0.2	0.1	0.1	0.2	-	0.1
CaO	7.3	7.7	6.9	5.9	9.9	7.0	6.5	7.0	8.7	7.0	4.7	0.9	10.4	8.8	6.0
K_2O	1.8	1.3	0.7	1.3	1.3	1.3	2.9	2.3	1.0	0.9	1.3	4.1	0.4	5.4	3.1
Na_2O	2.8	2.7	4.9	4.3	3.4	3.6	2.7	2.9	3.5	3.2	2.7	4.5	3.6	3.1	4.4
TiO_2	1.4	2.6	1.9	2.3	1.9	2.2	0.7	1.2	2.4	2.3	0.5	0.04	1.8	0.5	2.4
P_2O_5	0.2	0.3	0.3	0.5	0.3	0.3	0.2	0.2	0.3	0.5	-	-	-	0.1	0.2
BaO	<0.1	<0.1	<0.1	0.7	<0.1	<0.1	0.1	<0.1	0.3	0.9	-	-	-	0.2	0.1
ppm															
Zn	85	118	75	83	84	79	76	71	76	86	-	-	-	-	-
Pb	25	11	<10	<10	<10	<10	<10	<10	<10	<10	-	-	-	-	7
Cu	32	23	5	28	14	17	14	17	26	33	-	-	-	55	30
Ni	18	16	16	36	12	12	16	18	17	17	-	-	-	81	82
Zr	71	118	91	210	88	107	49	75	77	164	-	-	-	500	240

1-10: Analyses by inductively coupled plasma spectroscopy.
FeO: Total Fe.
1,2,7: Quartz-latite-andesite.
8: Quartz monzodiorite.
3,5,10: Basalt/diabase.
4,9: Latite-basalt.
6: Monzodiorite.

11. Average of 2, from Elders, 1979.
12. Average of 4 samples from Obsidian Butte, from Elders, 1979.
13. Average of 5 basaltic xenoliths, from Elders, 1979.
14. Average of 5 subsurface silicic rocks, from Robinson, et al., 1976.
15. Average of 6 subsurface basalts, from Robinson, et al., 1976.

altered, although microprobe/optical analyses indicate incomplete albitization of the feldspars. Secondary growth of white mica, pyrite, hematite, chalcopyrite, rutile, and sphalerite has also been noted. Textural associations of sphene, Ti-magnetite/ilmenite, and chlorite represent the breakdown of Ti-bearing pyroxenes. By analogy with theoretical/experimental data on mineral stability and by comparison with mineralogical and textural zonation with temperature determined by Elders and his coworkers, these rocks correspond to temperatures in the range of 300-320°C - the Calc-Aluminum Silicate Zone of Elders (1979).

Epidote is never present in the great abuncance reported from metasediments from other

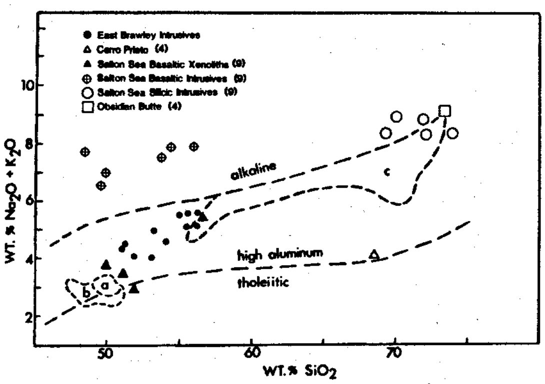

Figure 2. Classification of igneous rock types (in terms of total alkali versus wt. percent silica) from the Salton Trough and Gulf of California. Rock association boundaries are from Gastil, et al., 1979. Numbers in parentheses refer to source of the data in the reference list. Fields "a" and "b" provide average values for Juan de Fuca and Mid-Atlantic ridge basalts from Kay, et al., 1970. Field "c" represents rocks from the Pleistocene Gulf of California volcanic province (Gastil, et al., 1979).

geothermal areas in this temperature range. Its presence in the meta-diabase proves that temperatures were adequate for its stability, and its is believed that inappropriate fluid composition (high fugacity of CO_2, low fugacity of O_2) in the sediments (as evidenced by the persistence of calcite to these depths) inhibits the development of epidote and other calcium aluminum silicates. This suggestion is supported by both theoretical and experimental work on the stability of calcium aluminum silicates (e.g., Allen & Fawcett, 1982). Estimates of f_{S2} and f_{O2} based on the coexistence of anhydrite + hematite + pyrite + magnetite in the dike rocks can also be used to corroborate geochemical estimates from brine analyses and as an indicator of whether the observed mineral assemblages and the brine are in thermal and chemical equilibrium.

FRACTURE ASSEMBLAGES

The petrologic features of the East Brawley reservoir result from the superimposition of flow features on mineralogical/textural changes in response to the high geothermal

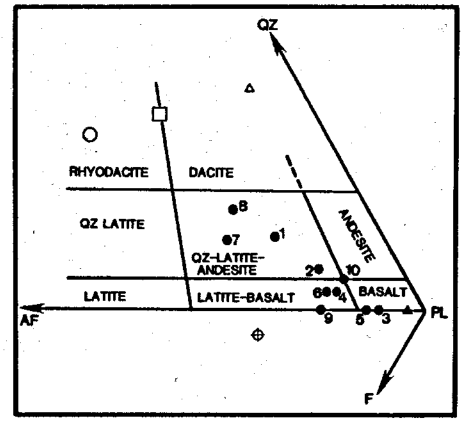

Figure 3. Normative classification of East Brawley intrusive rock types based on ICP analyses shown in Table 1. Symbols for other Salton Sea rocks (some are averages) are shown in Figure 2. AF = Alkali feldspar; F = Feldspathoids; QZ = Quartz; PL = Plagioclase feldspar.

gradient. As such it does not correspond directly to simple models proposed in the literature for other fields.

Production or flow zones in the subsurface can be recognized from well cuttings by diagnostic mineral features. In the shallower metasediments, thick aquifer-type sandstone units bear evidence for significant hot-water flow by the presence of abundant chlorite. SEM photographs of sandstones reveal both euhedral overgrowths on detrital grains (Fig. 4) and dissolution features indicative of dynamic response to flow at depth.

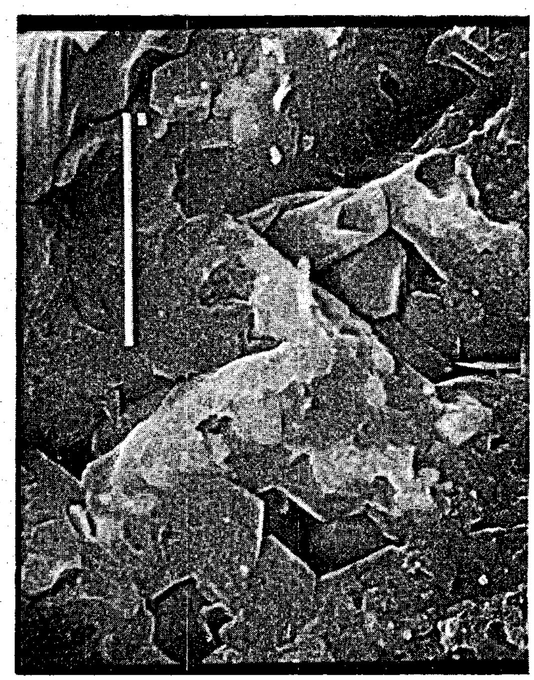

Figure 4. SEM photograph of quartz overgrowths in sandstone/quartzite from a geothermal flow zone at East Brawley. Bar = 10 microns.

Figure 5. Authigenic albite (center) and euhedral quartz crystals in fracture-dominated flow zone from East Brawley. Bar = 1 micron.

Although with increasing depth primary porosity in the reservoir is, in general, decreased as the result of alteration, zones of euhedral quartz crystals (mm-size) within the metasediments and the dike rocks suggest that fracturing (renewable porosity) provides the dominant control on deep subsurface flow. Authigenic albite (Fig. 5), adularia, pyrite, calcite, quartz, and chlorite, all in apparent equilibrium with the present flow system, can further define the chemical characteristics of the geothermal fluids by permitting activity constraints to be calculated. Abundant chlorite in veins and silicification in the sediments adjacent to the dikes further attest to equilibrium between these rocks and the present hydrothermal system. SEM and thin section textural relations suggesting concurrent (simultaneous) growth for most of these vein/fracture minerals are in agreement with fluid inclusion-derived temperature and salinity data.

RELATION OF IGNEOUS ACTIVITY TO THE GEOTHERMAL RESOURCE

These basaltic/dioritic intrusives at depth appear to have a significant relationship to the productivity of the well. Intrusives with ages greater than 8 million years cannot be invoked as direct heat sources for the reservoir. They are, however, probably directly related to deeper continuing dike injection associated with rifting in the Salton Trough. Composition, age, and spatial associations - when compared to basalts from the Gulf of California and from other oceanic spreading centers - suggest that these intrusives are part of a dike swarm (sheeted dike complex) typical of such a tectonic environment.

The change in physical properties with depth due to hydrothermal alteration and local contact metamorphism/silicification (increased density and competence) results in a transition from flow regimes controlled by primary (sandstone) porosity in the upper portion of the reservoir to combined dissolution/matrix porosity to fracture-dominated (secondary) flow at depth. These fractures, which are not easily resealed by mineralization and remobilization of carbonates and sulfates, provide an efficient conduit system which may permit upwelling of thermal solutions and an increase in the local geothermal gradient (a "thermal bulge") in the East Brawley area.

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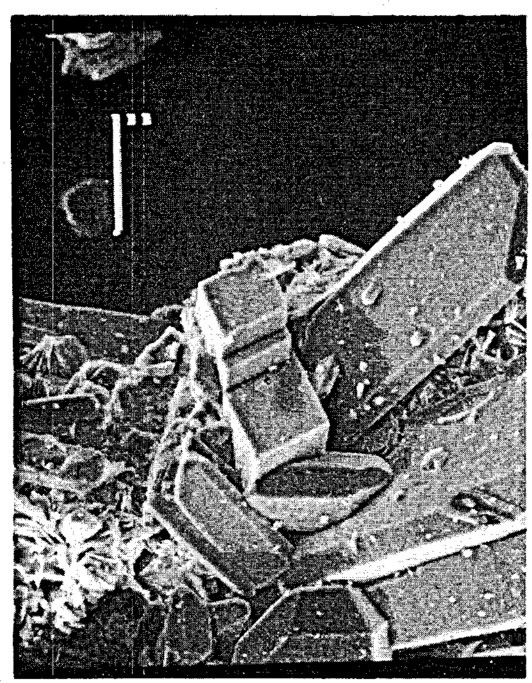

Figure 6. Euhedral quartz crystals, calcite rhombs, and leafy aggregates of chlorite (lower left) indicate equilibrium growth in assemblages lining fractures. Bar = 100 microns.

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