MAGMATISM AND VOLCANISM IN THE SALTON TROUGH

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INTRODUCTION

The Salton Trough, the landward extension of the Gulf of California, is a rift zone partially filled by continental deltaic sediments of the Colorado River (Elders et al., 1972). It provides the only opportunity in the continental United States to investigate the transition from a divergent plate boundary (the East Pacific Rise) to a transform plate boundary (The San Andreas Fault system). Rift zones are by far the most important tectonic regimes of the earth, often progressing to fully developed marine basins floored by oceanic crust. Thus an analysis of the processes of new crust formation in the Salton Trough will lead to a better understanding of the crustal construction and magmatic processes in early rift systems, such as the proto-Atlantic rift.

The Salton Trough and its geothermal systems have been fairly extensively investigated; among the numerous investigators, the Geothermal Resources Project at the University of California, Riverside (UCR) has, since its inception in 1968, contributed significantly. Many of these earlier investigations have been summarized by Elders (1979). Within the Trough north of the international border, about 130 deep wells have been drilled in the several geothermal fields and three power plants, each of 10 MW, are in operation and two more of 50 MW are under construction (Figure 1, see also Figure 1, McKibben et al., this volume). The Cerro Prieto geothermal field in the Mexican part of the Salton Trough now has 115 wells deeper than 1 km, one as deep as 4.2 km, and has an operating power plant of 185 MW with a further 440 MW under construction (Manon-Mercado, 1984).

The origin of the heat in storage in the geothermal reservoirs of the Salton Trough is still a matter of speculation at present. As most geothermal fields occur in volcanic terrains, the existence of numerous geothermal reservoirs in deltaic sediments may seem to be an anomaly. Magmatic activity is, however, one of the features expected in an environment of crustal spreading associated with a leaky transform fault system. By analogy with studies in the Gulf of California, it has been suggested that new crust is forming by emplacement of sheeted dike swarms in zones of dilation in "pull-apart" structures between "leaky" transform faults (Elders et al., 1980).

Presumably the difference between the "pull-apart" basins in the Gulf and the geothermal fields of the Salton Trough is that the latter have been filled in by the sediments deposited by the Colorado Delta. This interpretation is consistent with a quantitative model for the heat source of the Cerro Prieto geothermal field. As shown in Figure 2, our calculations show that the heat

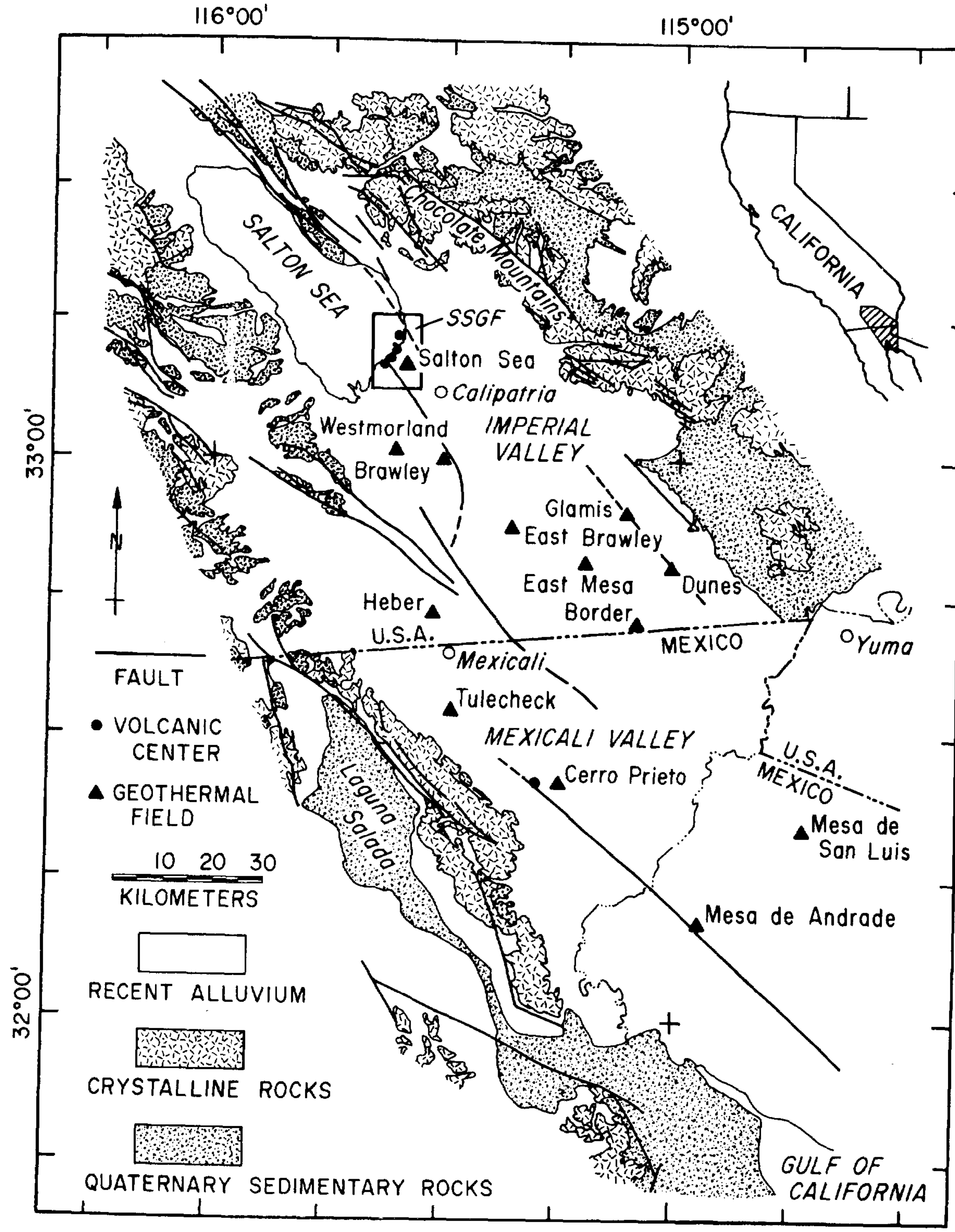
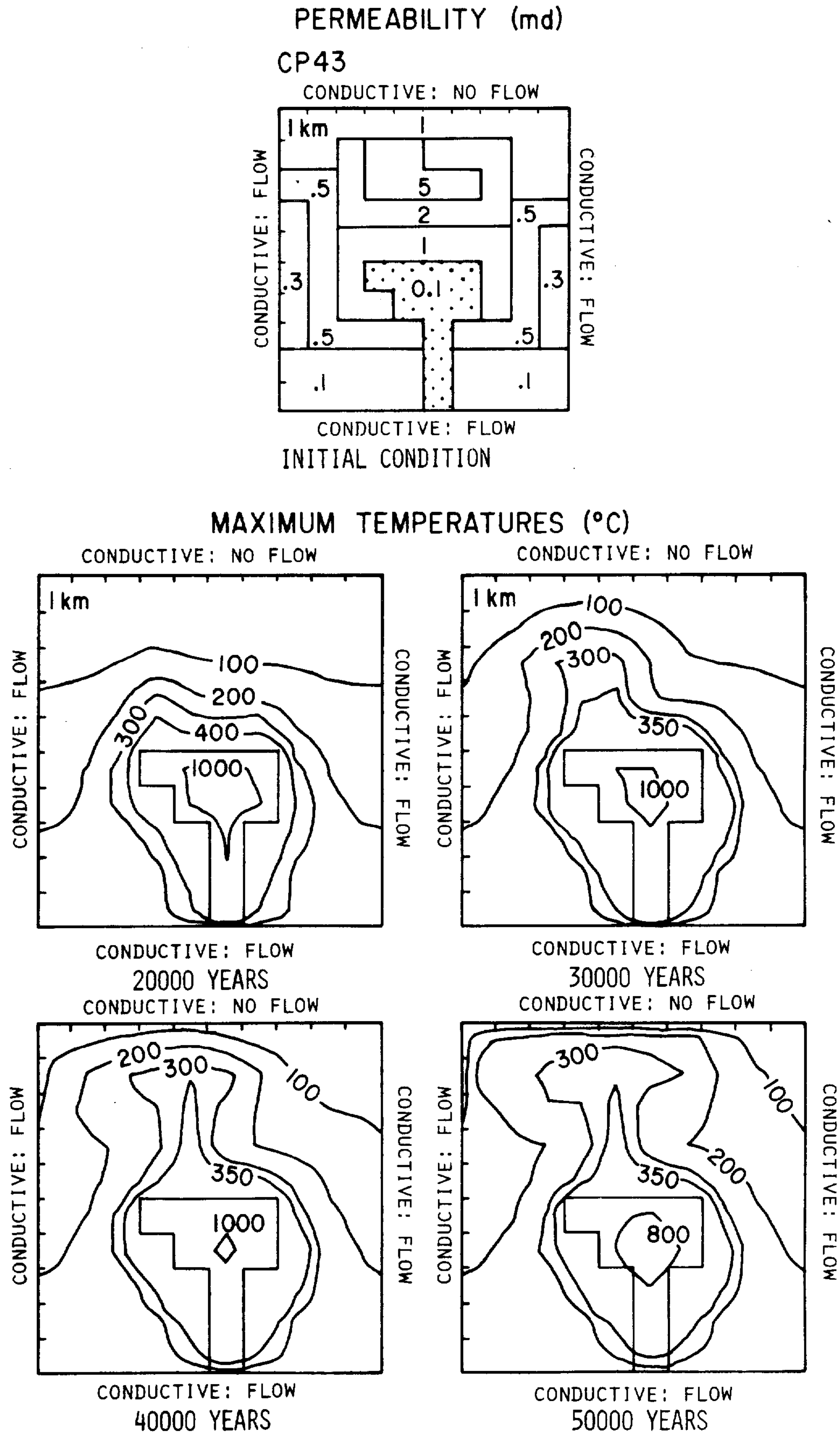


Figure 1. Geothermal Fields of the Salton Trough

Figure 2. Two-dimensional Heat Transfer Model for the Cerro Prieto Geothermal Field. Initial condition at time of intrusion (stippled) and isotherms at four successive time steps. The 50,000 year isotherms closely match those observed in the geothermal field. (Source: Elders et al., 1982, Figure 15).



source for the Cerro Prieto field is probably a funnel-shaped gabbroic intrusion, at least 5 km in diameter, with its top at a depth of no more than 6 km and a sheeted dike swarm above it (Elders et al., 1984). Supporting evidence for this model comes from an interpretation of the magnetic anomaly associated with the field (Goldstein et al., 1984). These authors interpret the magnetic source to be a magnetite-rich peridotite-gabbro pluton. They infer that the bottom of the magnetic source body is the Curie isotherm for magnetite (575°C) at a depth of about 6 km. This is consistent with our cooling model (Elders et al., 1982), which shows that the upper 1 km of the postulated gabbro intrusion should be crystallized. To make the model isotherms fit the observed thermal structure of the Cerro Prieto field requires that the gabbro was emplaced as recently as 0.05 Myr ago (Figure 2).

It is also suggested that this kind of igneous activity is not merely restricted to the present geothermal fields but was much more widespread at depth. A very extensive seismic refraction study by the USGS has generated a new detailed crustal model for the Imperial Valley (Fuis et al., 1984). These workers infer that the central third of the Imperial Valley is underlain by a sedimentary layer (V_p = 1.8-5.0 km/s), a "transitional zone" (V_p = 5.0-5.5 km/s), a basement (V_p = 5.65 km/s), and a sub-basement (V_p = 7.2 km/s). The deepest part of the sedimentary section is 5.7 km thick at the Salton Sea and 4.8 km thick at the international border. It coincides approximately with the zone of highest seismicity in the center of the valley, presumably the location of present-day rifting (Fuis et al., 1984). According to Fuis et al., the Trough has two different types of basement. Although variable in thickness, the sediments on the mesas toward the sides of the basin lie with a sharp seismic discontinuity upon a basement of granitic and crystalline metamorphic rocks (V_p = 5.9 km/s). In the central zone, where the sedimentary section is thicker, a transitional zone about 1 km thick grades downward into the upper basement. This upper basement is believed to be the metamorphic equivalent of the sedimentary rocks above and is probably similar to the greenschist facies rocks encountered in the geothermal fields at much shallower depth (Muffler and White, 1969). Fuis's model suggests that the total section of sedimentary rocks (including their metamorphic equivalents) could be up to 10 to 16 km thick on the central axis of the Trough. Beneath this is thought to be a mafic intrusive complex (V_p > 7.2 km/s) (Fuis et al., 1984). The implications of this model are that the central portion of the Imperial Valley has a seismic basement similar to layer 3 in the oceans, and that intrusions associated with the emplacement of this oceanic-type crust have metamorphosed the overlying sediments. The inferred geology of the basement is similar to models of middle oceanic crust based on the study of ophiolites (Fuis et al., 1984).

This sub-basement compensates gravitationally for the great thickness of overlying sedimentary rocks. As the continental crust rifted apart, the Trough was filled by sediments from the Colorado River delta from above, and by mafic intrusions from below (Elders et al., 1984). Thus processes analogous to those now going on at shallow depth in the modern geothermal fields may have been going on for at least the past 4.5 million years as the Salton Trough evolved (Elders et al., 1972).

Geophysical anomalies associated with the field are probably only partly due to hydrothermal alteration of the sediments. A local gravity maximum with a Bouguer residual of +23 mgal is centered on Red Island rhyolite dome and is attributed to both the increase in density of the sediments and the presence of igneous intrusions (Elders et al., 1972).

Magnetic surveys reveal the presence of material with relatively high magnetic susceptibility and remnant magnetization near the surface. Griscom and Muffler (1971) suggest that a large wavelength anomaly is caused by intrusive rocks at depths greater than 2 km, and that smaller elliptical anomalies result from dike or sill clusters at depths of approximately 1 km. Also indicative of relatively shallow intrusive is a seismic refraction study across the center of the field that revealed high-velocity zones at shallow depth -- 4.05 km/s at 0.8 km and 4.51 km/s at 1.8 km (Frith, 1978). These velocities, significantly higher than those expected for sedimentary rocks, probably result from intrusion of basaltic material, which caused intense induration of the sediments.

We believe that the thermal, gravity, magnetic, and seismic velocity anomalies associated with the SSGF are consistent with the presence of sheeted dike swarms that pass downward into a gabbroic pluton. By analogy with our model of Cerro Prieto, the top of this pluton may be as shallow as 6 km.

VOLCANISM IN THE SALTON TROUGH

The Cenozoic record of volcanism around the Gulf of California has been described by Gastil et al. (1979). However, as yet there exists no comprehensive study of the igneous activity in the northern prolongation of the Gulf, i.e., the Salton Trough. Understanding these igneous processes has an important bearing on models for the tectonic evolution of the basin and upon models for the origin of its geothermal systems.

Within the Trough only two relatively small expressions of surface volcanic activity are known: the 235-m high Cerro Prieto dacite volcano, which lies 10 kilometers northwest of the Cerro Prieto geothermal field, and five small rhyolite domes at the south end of the Salton Sea, within the Salton Sea Geothermal Field. There are no surface volcanic rocks, hot springs, or vents associated with Brawley, East Brawley, Heber, East Mesa, or Dunes geothermal fields of the Imperial Valley, nor with the Tulecheck, Mesa de Andrade, and Mesa de San Luis geothermal fields of the Mexicali Valley (Elders, 1979).

The Cerro Prieto Volcano, which gives its name to the adjacent geothermal field, consists of a lithoidal dacite containing a few percent of andesine, hypersthene, and opaques, and a few percent of glass. It contains up to 68% SiO_2 by weight, about 5.5% Na_2O, and 1.7% K_2O, (Elders et al., 1978; Reed, 1984). Based upon the similarity of its major and minor element chemistry to that of the adjacent granodiorite outcrops, Reed concluded that its parental magma formed by remelting of Mesozoic basement rocks. This hypothesis is also supported by the single $^{87}Sr/^{86}Sr$ ratio value of 0.7056 he reported for the dacite.

This Sr isotope value is close to the lower end of the range of values, (i.e. 0.706) reported by Silver (1979) for granodiorites in the Peninsular Ranges, to the west of the Salton Trough. However there is an as yet unexplained discrepancy with a $^{87}Sr/^{86}Sr$ value of 0.703 for a sample of Cerro Prieto dacite published earlier by Elders et al. (1978). If correct, this suggests that the volcano is chemically heterogeneous and that its magma ultimately derived from a more primitive mantle source. The age of Cerro Prieto is not yet well constrained. Most of the volcano has normal magnetic polarity, but according to de Boer (1980), an early pyroclastic phase apparently erupted during a reverse polarity event 100,000 years ago. On the other hand, studies of the thermal annealing of spontaneous fission tracks in detrital apatites in sandstones from a deep well in the field shows that it reached a temperature of 175°C about 50,000 years ago (Sanford and Elders, 1981).

The five alkalic rhyolite domes in the SSGF are smaller than Cerro Prieto and have very different chemistry from it (Robinson et al., 1976). They are glassy to lithoidal rhyolites with only 1 to 2% crystals, containing up to 74.5% SiO_2, 4.7% Na_2O and 4.2% K_2O and low CaO. This is both more silicic and more alkalic than the Mesozoic granites which crop out on the margins of the valley and also occur as partly melted xenoliths in the rhyolites (Robinson et al., 1976). Rhyolite from Obsidian Butte has a $^{87}Sr/^{86}Sr$ ratio of 0.704, whereas a granitic xenolith gave a value of 0.712. Based upon this and upon differences in the chemistry of these rhyolites and that of the Mesozoic granites it was concluded that the parental magma was derived from the mantle and was only slightly contaminated by crustal material.

This interpretation is supported by the occurrence of numerous basaltic and gabbroic xenoliths in these volcanoes. The basaltic xenoliths are low potassium tholeiites containing normative hypersthene and olivine and are similar to oceanic tholeiites erupted on the crest of the East Pacific Rise (Robinson et al., 1976). We might therefore conclude that we are dealing with a genetically related bimodal rhyolite-basalt assemblage typical in many tectonic environments of rifting and extension. Preliminary studies of the compositions of clino-pyroxenes in the mafic xenoliths are, however, puzzling. Xenoliths from Rock Hill and Obsidian Butte have clinopyroxenes similar to those in mid-ocean ridge basalts, whereas those from Red Island volcano are more like pyroxenes from orogenic basalts (Hull and Elders, 1982). Possibly a composite layered gabbro/granite body exists at depth. More work is necessary on these rocks in order to answer the questions surrounding the nature and origin of the parental magmas in the SSGF.

The age of these volcanoes has been reported to be less than that of Cerro Prieto, based on a single K-Ar measurement, which gave a cooling age of only 16,0000 years (Muffler and White, 1969). However, the much larger positive magnetic and gravity anomalies here than at Cerro Prieto suggest that the intrusion responsible is both larger and more crystallized than that responsible for the Cerro Prieto geothermal field.

Additional important information on these questions comes from the frequent occurrence of sills (or dikes) in boreholes in the field. Robinson et al., (1976) described examples from the Magmamax No. 2, Magmamax No. 3, Elmore

No. 1 and IID No. 2 wells (figure 3). In addition we have recently acquired drill cuttings of intrusive rocks from Fee No. 1 and Fee No. 5 wells, and from the Salton Sea Scientific Drilling Project's California State 2-14 well (Herzig & Mehegan, 1986a, b; Mehegan et al., 1986; Lilje & Mehegan, 1986). Sill or dike intrusion may still be continuing. The frequent intense earthquake swarms that occur in the Salton Sea and Brawley geothermal fields have been attributed by some authors to the emplacement of minor intrusions (Hill, 1977; Johnson and Hill, 1982).

The subsurface igneous rocks recovered from the SSGF consist of both rhyolites and basalts, all of which show greater or lesser degrees of hydrothermal alteration, consistent with their being emplaced into an active hydrothermal system. Multiple intrusions up to 3 m thick can be recognized, both in the cuttings and from their characteristic signatures on wireline logs (Muramoto and Elders, 1984).

A similar silicic-mafic bimodal assemblage also occurs in several deep wells in the eastern part of the Cerro Prieto field (Elders, et al., 1984). These also exhibit various stages of hydrothermal alteration. Fresh diabase was also encountered in a recent exploration well at Riito, 45 km southeast of Cerro Prieto (unpublished information at UCR).

Keskinen and Sternfeld (1982) reported the occurrence of fairly abundant dike rocks described as "meta-andesites" from two wells in the East Brawley field. they also report a spread of K-Ar ages for these rocks of from 8 to 11 million years before the present. This last result is surprising as the apparent ages reported exceed the assumed age of the enclosing sediments. This implies that there are problems in dating these hydrothermally altered rocks by this method (Keskinen, personal communication, 1984).

The largest subsurface intrusion yet reported from the Salton Trough occurs in the Heber geothermal field, where a well penetrated a thickness of 31 m of microgabbro with cumulate textures. Its essential primary minerals are augite, labradorite, olivine, and orthopyroxene (Browne and Elders, 1976; Browne, 1977). Although the ambient temperatures in this field are less than 200°C, this gabbro is partially altered to chlorite, prehnite, calcite, and albite.

In addition to intrusive igneous rocks, Plio-Pleistocene tuffaceous units have been identified in the Durmid Hills section (Randall, 1964) and in recent SSGF exploration and research wells (unpublished studies at UCR).

Apart from the published study of the volcanic rocks in the SSGF (Robinson et al., 1976) all of the studies of igneous rocks in the Salton Trough must be regarded as preliminary. The opportunity to obtain much new information and new samples from the SSSDP well has stimulated us to return to these issues, as to date there has been no systematic study of the subsurface igneous rocks and their significance for questions of geothermics and crustal rifting.

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