Magma-Hydrothermal Activity in the Salton Sea Geothermal Field Imperial County, California

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Keywords

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ABSTRACT

The nature and intensity of hydrothermal activity in the Salton Sea geothermal field (SSGF) require energy release from a still-cooling igneous intrusion. Newly-integrated analyses of near-surface and wellbore thermal conditions, regional and local seismicity, chemistry of reservoir fluids, hydrothermal alteration of rocks, zoning of secondary minerals, and secondary-mineral zonation in the SSGF indicate that (**1**) active magma-hydrothermal processes here are dispersing energy from an igneous-intrusive complex, on the order of 20 km^2 in areal extent, emplaced to within ~5 km of the modern surface in the last 50,000 years; and (**2**) that these processes are still prograding, but are approaching a state of maturity. Our conclusions clearly imply that the commercially producible Salton Sea geothermal reservoir could be considerably larger than heretofore envisioned. Even with now-conventional technologies, production of this enormous resource could likely be sustained at 10^2 MW-year *per annum* levels for centuries into the future.

Introduction and Geologic Setting

This communication presents the results of our efforts over the past several years to document the current state of thermal, mechanical, and chemical processes in the Salton Sea Geothermal Field and vicinity (Figure 1). Our investigation has integrated data and conclusions from earlier work with new observations, measurements, and theoretical considerations of this remarkable domestic renewable-energy resource. Detailed petrologic and mineralogic observations and analyses—along with compilation of regional seismic data and thermal/

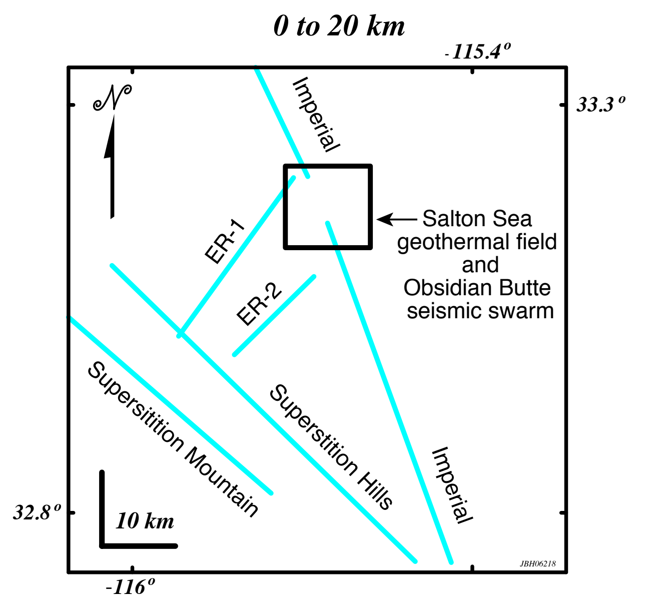


Figure 1. Relationship of major fault zones to epicenters for earthquakes occurring in the southern Imperial Valley during the period 1972-2005, and over the depth range 0-20 km (data, from the Southern California Earthquake Center [2006], include faults delineated by the U.S. Geological Survey). Epicenters are color-blended yellow to red, corresponding to M = 0.5-4.5, and are volume-blended, small to large. A northwest-oriented event grouping defines the Superstition Mountain and Hills fault zones, and a north-northwest trend defines the Imperial fault zone (herein considered to include the “Brawley seismic zone”). Two low-density epicentral bands trending northeast coincide with the Elmore Ranch fault (ER-1), and a subparallel unnamed zone (ER-2). These two features lack depth extent, and are possibly related to listric faults at the edges of a graben. The three blue dots in a row signify three of four exposed, Holocene rhyolite volcanic centers; the westernmost dot represents the Obsidian Butte rhyolite dome. The single blue dot, slightly to the east, marks the surface projection of a sediment-buried (to ~1.6 km depth), Pleistocene rhyolite volcanic and intrusive complex emplaced at about 0.4 Ma (Schmitt et al., 2006, this volume).

mechanical information from geothermal wells—have yielded fresh perspectives on the Salton Sea resource. Spatial and temporal data sets for the SSGF have revealed systematic distributions of alteration-mineral assemblages, microfractures, veins, breccia zones, temperatures, and chemistries that are similar to those found in the lithocaps (fundamentally, the rocks superjacent to a pluton when the igneous body is emplaced) of intrusion-linked fossil hydrothermal systems around the world. Interpretation of this information, in the context of magma-hydrothermal process theory (e.g., Norton, 1979, 1982, 1984), supports a space-time model that (**1**) describes the current dynamic state of the resource; (**2**) reconstructs natural development of the hydrothermal system over time; and (**3**) enables prediction of the system's ensuing evolution.

The Salton Sea geothermal resource is already the largest in the United States if not the world in terms of conventionally extractable, high-enthalpy geothermal energy for the production of electric power—up to at least 70,000 MW-years (Hulen et al., 2003b) and (as we will argue later in this paper) almost certainly a great deal more. However, even this vast resource is just the nearer-surface expression of a much larger magmatic-hydrothermal network—the "Greater Salton Sea Geothermal Cluster" (GSSC; Hulen, 2005)—with a surface projection exceeding 700 km^2 of the U.S. Salton Trough. An initial assessment of the GSSC (D.L. Norton, cited in Hulen, 2005) has indicated that the feature theoretically could yield close to 900,000 MW-years of electrical energy just from the 1-3 km depth range.

So much energy concentrated here requires correspondingly anomalous magmatic heating (Elders, 1979; Kasameyer et al., 1984), made possible in this case by active spreading of the Salton Trough and attendant, plate-juncture plutonism. The Trough is a major transtensional rift—between the Pacific plate, on the west, and the North American plate, on the east—that merges southward through Mexico into the long, narrow Gulf of California (Elders et al., 1972; Elders, 1979; Lachenbruch et al., 1988; Lonsdale, 1989). A chain of transform-segmented, oceanic spreading centers along the axis of the Gulf extends into southern California and the deeply-sedimented Trough as a succession of plate-bounding, right-stepping, right-lateral strike-slip faults connected by magmatically-active dilational jogs. The SSGF is situated in the northernmost of these jogs, the northeastern boundary of which is the southeastern terminus of the San Andreas transform.

The Salton Sea geothermal system is unusually hot (up to at least 390°C at 2 km depth; Hulen et al., 2003b), hypersaline (up to 26 wt.%), and metalliferous (Fe, Zn, Pb, Cu)(Helgeson, 1968; McKibben and Elders, 1985; McKibben and Hardie, 1997; Hulen et al., 2002, 2003b; Hulen and Moore, 2005). The system circulates in a permeable network of faults, stockwork fractures, breccias (hydrothermal and tectonic), and porous sandstones in the thick (~6 km) alluvial and lacustrine Salton Trough sedimentary sequence. The sequence comprises mostly sandstone, siltstone, and mudstone in various proportions, and (**1**) is locally intruded by Pleistocene to Holocene gabbroic, granitic, and rhyolitic (but not compositionally intervening) plutons; and (**2**) is interrupted at depth (about 1.6 km) by a buried rhyolite flow-dome-intrusive complex (Hulen and Pulka, 2001) emplaced about 400,000 years ago (Schmitt et al., 2006, this volume). Similar but smaller Holocene rhyolitic volcanic centers are exposed in a northeast-oriented, crescent-shaped, concave-northwest array at the northwestern margin of the developed SSGF (Robinson et al., 1976; Herzig and Jacobs, 1992; Schmitt et al., 2006).

The predominantly siliciclastic host rocks for the geothermal system have been intensely altered to form concentrically well-zoned assemblages of secondary minerals grading downward and inward from smectite to illite/smectite through illite-epidote-K-feldspar into muscovite-biotite-epidote-actinolite-K-feldspar (± garnet and clinopyroxene) domains (Helgeson, 1968; Hulen et al., 2002, 2003a, 2003b). A key feature of the alteration zoning is the paucity to absence of carbonate (whether clastic, diagenetic or hydrothermal) below the depth at which hydrothermal epidote appears in the geothermal reservoir. Another common feature is the co-location of many major thermal-fluid entries and abundant hydrothermal hematite. As a rule, sulfide minerals occur in only trace to minor amounts in the reservoir (McKibben and Hardie, 1997), a fact reflecting a reservoir brine relatively impoverished in H_2S. However, thick, brine-yielding epithermal veins in the shallow southwestern part of the Salton Sea resource boast grades of several wt.% Zn + Pb and 0.0X ounces per ton Ag over apparent fracture-zone widths ranging upward to 30 m (Hulen et al., 2004; Hulen and Moore, 2005)

The Salton Sea geothermal resource has remained remarkably robust since its initial development in the 1960s. Thermal brine from a single SSGF well (Vonderahe 1; not illustrated) steadily yields more electrical energy (over 40 MW-years *per annum*) than most geothermal *fields* elsewhere in the U.S. Moreover, in contrast with these other fields, the SSGF has experienced only minimal declines in reservoir temperature and pressure since the inception of development. One reason for the field's sustained high yield is almost certainly frequent rejuvenation of reservoir permeability by tectonic and hydrothermal rock rupture. Our analysis of tens of thousands of earthquakes recorded for the SSGF and vicinity by the Southern California Earthquake Center (SCEC, 2006) since 1972 has led to new concepts concerning the origin and distribution of the field's intriguingly configured seismicity.

Magmatic-Hydrothermal Activity

The processes that dissipate energy from magmas into their lithocaps result in rock-alteration patterns that are diagnostic of the state of the energy source (Norton, 1979, 1982, 1984). This fundamental concept is as true for active, high-temperature (say, >250°C) hydrothermal systems, including the one at the SSGF, as it is for fossil systems like those that formed the world's great porphyry copper deposits (Norton, 1984). Results of intensive drilling, mining, and geochemical/mineralogical analysis of these orebodies (along with the three-dimensional characterization required for their commercial success) have constrained numerical modeling of the coupled thermal, mechanical, and chemical processes responsible for the deposits' formation. Such models for the well-exposed but now-cold fossil systems provide the basis for modeling the modern ones—hot and still active but for the most part effectively hidden from view.

Mechanical—The current mechanical state of the southern U.S. Salton Trough, including the SSGF, has been deduced from a plot of recent (1972-1975) earthquake epicenters recorded for the area by SCEC (Figure 1). The region is clearly dominated by fracture failures generated in the prevailing right-lateral transtensional tectonic regime. The corresponding epicenters are clustered into quasi-linear failure belts associated with the Superstition Mountain, Superstition Hills, Elmore Ranch, and Imperial fault zones.

> ***Note***: *For this report, the "Imperial fault zone" is considered to be the locus of earthquake epicenters that incorporates (**1**) the northwest-trending Imperial fault (south of the SSGF) in the traditional sense (e.g., Elders, 1979); and (**2**) the north-northwest-trending "Brawley seismic zone," which departs northerly from the northern end of the Imperial fault and transects the SSGF from the south.*

Within the SSGF, a northeast-southwest-trending but relatively diffuse cluster of 1972-2005 epicenters, with a comparatively abrupt and shallow cluster "floor" (~6 km depth), has been designated the Obsidian Butte seismic swarm (OBS; Figure 1). The OBS is roughly coaxial with the crescent-shaped array of Holocene rhyolitic volcanic centers that includes Obsidian Butte itself. The diffuse configuration and seismic character of the OBS have merited special classification in the U.S. Geological Survey's California Hazards Assessment database (USGS, 2006). The feature is noted for unusually frequent seismicity, particularly prevalent during fall 2005, when 1900 events occurred within a few weeks (SCEC, 2006).

In 3D, the OBS clusters into two "chimney"-like hypocentral forms extending from near-surface to about 6 km depth (Figure 2). The events are dispersed within a volume of ~124 km^3. The "chimneys," roughly cylindrical, mirror one another on either side of and close to the Imperial fault zone (Figure 1). Hypocenters within the chimneys display irregular patterns in both spatial location and magnitude, and their "b" ("binned" frequency vs. magnitude) values deviate slightly from those prevailing regionally. The patterns do not show the coplanar distributions typical of those associated with major faults.

Two clusters of seismic hypocenters are apparent within the OBS. A shallow cluster at 1-2 km depth (Figure 3) in the southwestern half of the swarm coincides with the top of the SSGF "carbonate-destruction" zone delineated by Hulen et al. (2002, 2003b). A deeper (5-6 km; Figure 4, overleaf) cluster just to the northeast may signal the contact between a concealed young plutonic complex and its lithocap.

Microearthquakes recorded in the southwestern, shallower seismic cluster in the OBS actually may have been abetted by destruction of reservoir carbonate. The logic behind this contention can be summarized as follows:

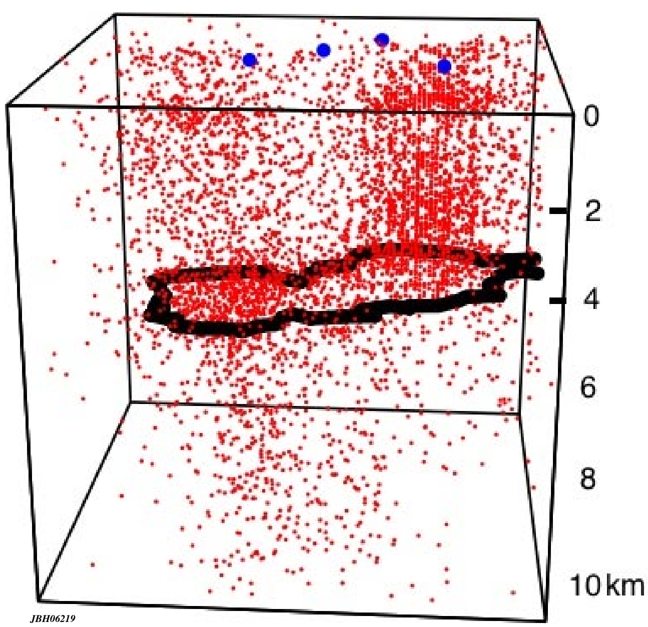


Figure 2. Three-dimensional portrayal of the Obsidian Butte seismic swarm (OBS), comprising earthquake hypocenters (distributed irregularly over a mean M = 1.5) for the period 1972-2005 in the Salton Sea geothermal field. Horizontal plane at the top of this diagram corresponds to the bold black box shown on Figure 1. Front and back vertical planes are oriented east-west, and corresponding side planes are north-south. The four blue dots are the Quaternary rhyolite volcanic centers noted for the previous figure (recall that the easternmost dot is a surface projection). The horizontal black contour, at 5.5 km depth, marks the approximate base of overlying, chimney-like, seismic-event concentrations; there are few hypocenters below this depth. This configuration is atypical for the Imperial Valley, where major-fault-related hypocentral clusters have a much greater depth range. Because of its spatial correlation with a huge and very high-temperature geothermal system, the uniquely-configured OBS seismic swarm is likely linked to active magmatic-hydrothermal processes.

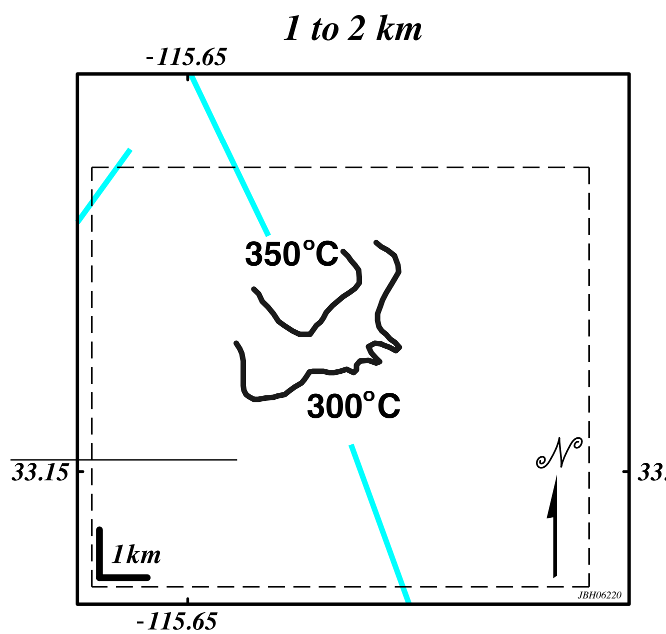


Figure 3. Earthquake epicenters for the period 1972-2005 in the depth range 1-2 km in the Obsidian Butte seismic swarm (box encloses a 1 km-thick, horizontal slab of the volume shown as Figure 2). Blue dots are the vertical projections, onto this slice, of the rhyolitic volcanic centers depicted on the former figure. Black contours are the 300°C and 350°C isotherms (from static temperatures in geothermal wells) at 1.5 km depth. Blue lines depict the trends of the Imperial fault zone (northwest) and the Elmore Ranch cross faults (northeast; Figure 1). Dashed line encloses the area of Figure 4.

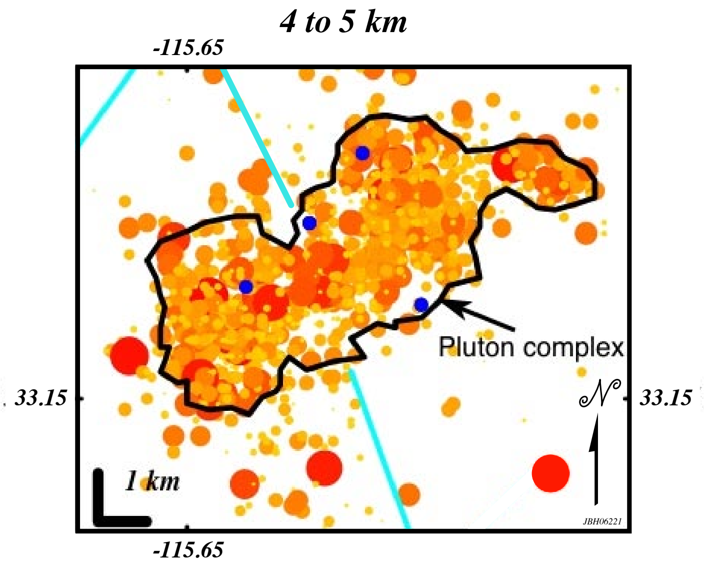


Figure 4. Earthquake epicenters for the period 1972-2005 in the depth range 5-6 km in the Obsidian Butte seismic swarm. Note slightly smaller area and larger scale of this figure (see also Figure 3). Events are color- and size-blended as in Figure 1. As in Figure 3, blue dots are rhyolite volcanic centers and blue lines are fault trends. Black contour encloses the horizontal extent of a postulated, still-cooling, <0.05 Ma plutonic complex emplaced to within ~5.5 km of the modern surface. Such a plutonic complex essentially is required to explain the shallow, very high temperatures (up to 390°C at 2 km depth) of the SSGF. Most earthquakes in the illustrated 5-6 km depth slice are likely caused by (**1**) the transfer of mechanical energy into the lithocap from the cooling pluton in response to magmatic-volatile exsolution; and (2) the bursting of initially sealed, brine-filled cavities as a result of heating-induced overpressuring in thermally-prograding hydrothermal upflow zones.

(1) The carbonate destruction is a hydrothermal process, since the top of the carbonate-removal zone (typically 1-2 km beneath the modern surface) coincides in every instance with the appearance of hydrothermal epidote.

(2) Carbonate removal accompanies upward and outward, thermally-driven, natural-hydraulic fracture propagation. Evidence for this fracture mechanism is provided, in drill cuttings, by myriad high-temperature-hydrothermal microveinlets lacking any indication of cataclasis (Hulen et al., 2003), and by spatially associated "jigsaw-puzzle" textures (which can also form as a result of tectonically-induced implosion).

(3) As Knapp and Knight (1977) demonstrate, the overpressures that stimulate this type of hydraulic fracturing are the result of progressive heating of sealed, fluid-filled cavities in a prograding thermal regime above a cooling pluton.

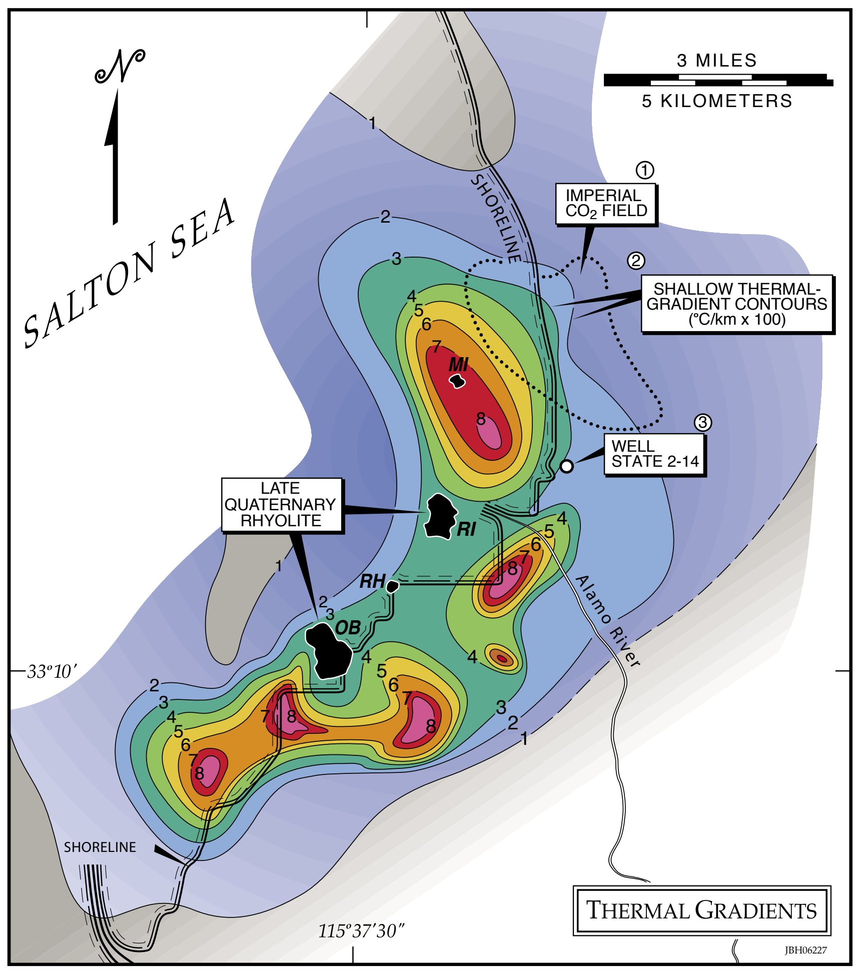
(4) The newly-created hydraulic fractures permit hot brine invasion into the sparingly permeable (in part because of the carbonate itself) calcareous-siliciclastic host rocks.

(5) Before the newly-formed hydraulic fractures are eventually sealed by precipitation of hydrothermal minerals, the attendant pulse of formation-invading brine both dissolves carbonate and causes its metasomatic replacement.

(6) The carbonate-replacement phases are epidote and other calc-silicates. The relatively low calc-silicate to removed-carbonate ratio (typically <0.3) indicates that simple replacement cannot fully account for the carbonate's disappearance.

(7) Carbonate dissolution by the hot acid brine at depth, along with alteration of the carbonate to calc-silicate phases, inevitably release carbon dioxide. In the past, these processes yielded the CO_2 that charged the shallow, sandstone-hosted gas reservoirs once exploited in the Imperial carbon dioxide field (Rook and Williams, 1942; Muffler and White, 1968, 1969).

(8) At greater depth, the liberated CO_2 is trapped initially beneath a cap of unaltered, calcareous siliciclastics. The gas therefore adds its own partial pressure to that gener-



① Rook and Williams, 1942; Muffler and White, 1968 ② 30-80m depth; this document; modified and updated from Newmark et al. (1988) ③ Salton Sea Scientific Drilling Project (Elders and Sass, 1988)

Figure 5. Shallow static thermal-gradient anomaly for the Salton Sea geothermal field, with contour values in °C/km. Refined and updated from Newmark *et al.* (1988) by Hulen et *al.* (2002).

ated by thermally prograding brines behind the expanding fracture-propagation front. The net effects are more rapid overpressuring and, as a consequence, more frequent hydraulic-fracturing events and more rapid advection of the magmatically heated fluids toward the surface.

(9) This concentrated seismicity is expressed over time (in this case, 34 years) as the diffuse, shallower "cloud" of earthquake hypocenters observed in the southwestern OBS seismic chimney.

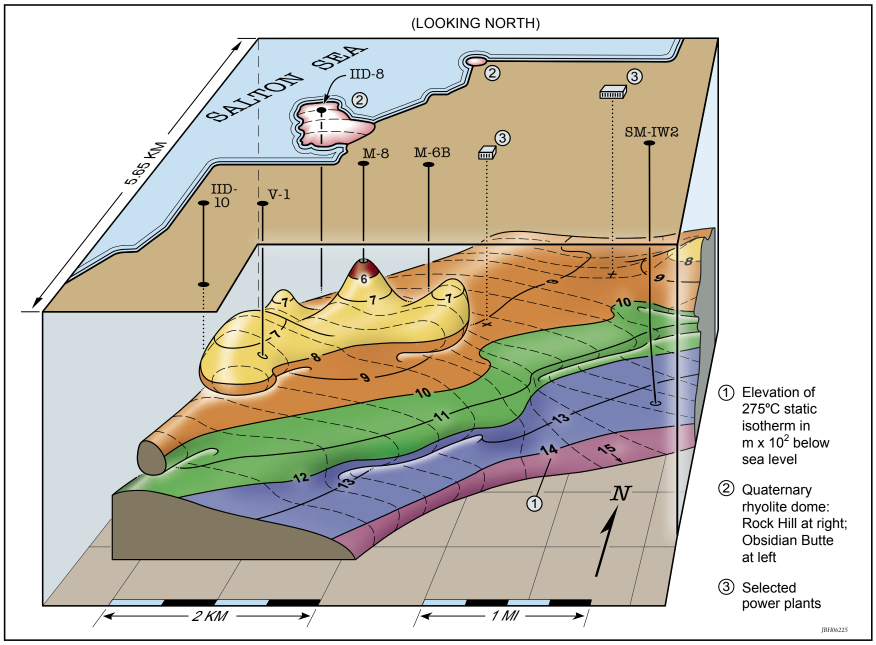


Figure 6. Three-dimensional hull of static temperature = 275°C in the Salton Sea geothermal reservoir. Contours on the hull are elevations, in meters x 100 below sea level. Vertical exaggeration is 2X. East-west grid lines on the hull are 250 m apart. Note the intricate irregularity of this surface, likely due to prograde thermal-brine flow along fracture-controlled percolation pathways.

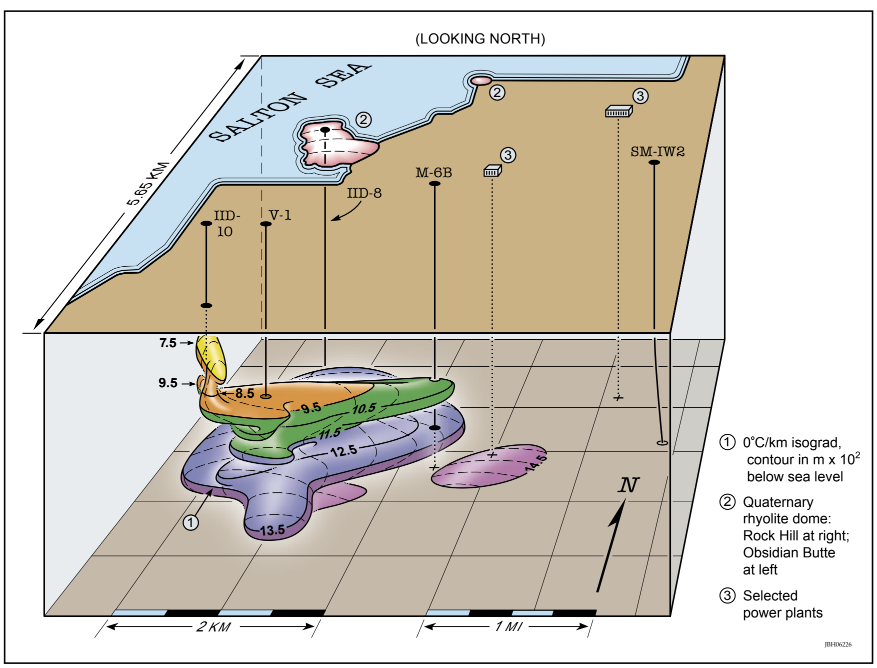


Figure 7. Three-dimensional hull for thermal gradient (TG) = 0°C/km in the Salton Sea geothermal reservoir. Diagram shows the same volume as Figure 6. Contours on the hull are elevations, in meters x 100 below sea level. Vertical exaggeration is 2X. East-west grid lines are spaced 250 m apart. The TG = 0°C/km surface is surrounded in three dimensions by exclusively positive gradients, locally up to several hundred °C/km. This disparity suggests that the null-gradient hull encloses a zone of especially vigorous thermal-fluid upflow with correspondingly accelerated convective transport processes.

The northeastern OBS hypocentral cluster, 5-6 km deep, has the same diffuse seismic-event distribution as its shallower counterpart. However, the deeper cluster is situated 3-4 km below the top of the carbonate-destruction zone, so increased partial pressure due to CO_2 liberation cannot be invoked to help explain the concentrated seismicity. The deeper cluster *is* in an appropriate depth range to emanate from the contact region between a sizable igneous intrusion and its proximal lithocap. The presence of such a pluton is mandated by the very high shallow temperatures of the SSGF (Norton, 1984; see also Kasameyer et al., 1984). Therefore, the deeper earthquakes could be due in part—in addition to the thermally-driven bursting of sealed, fluid-filled cavities—to overpressuring of the lithocap (exceeding its rock strength) in response to intermittent magmatic-volatile exsolution at the top of the pluton (Knapp and Norton, 1981; Burnham, 1985).

Thermal—Not surprisingly, the SSGF (and vicinity) is a region of anomalous heat flow and localized surface thermal phenomena (Elders, 1979; Kasameyer et al., 1984). Steaming ground, thermal springs, and mud pots were common when Sea level was lower, and a few mud volcanoes can still be found in the flats to the east of the shore. Shallow thermal gradients in boreholes throughout the SSGF define a large (72 km^2), boomerang-shaped, static thermal-gradient anomaly of >200°C/km (Figure 5). Within this feature are numerous "short-wave-length" anomalies with extremely high shallow (30-80 m) thermal gradients commonly in excess of 600°C/km (Figure 5). These hot spots likely occur above focused, high-velocity, thermal-fluid upflow zones in fracture networks and tectonic or magmatic-hydrothermal breccia pipes (Hulen et al., 2003a, 2003b). The broader anomaly is unquestionably linked to a deeply-underlying late Quaternary igneous intrusive complex.

Three-dimensional mapping of static temperatures and temperature gradients in the SSGF has defined complex, three-dimensional, high-temperature (>225°C) isothermal surfaces, exemplified by the one for T = 275°C (Figure 6). Spatially, these isothermal "hulls" closely match the seismic-event chimneys described above (Figure 3).

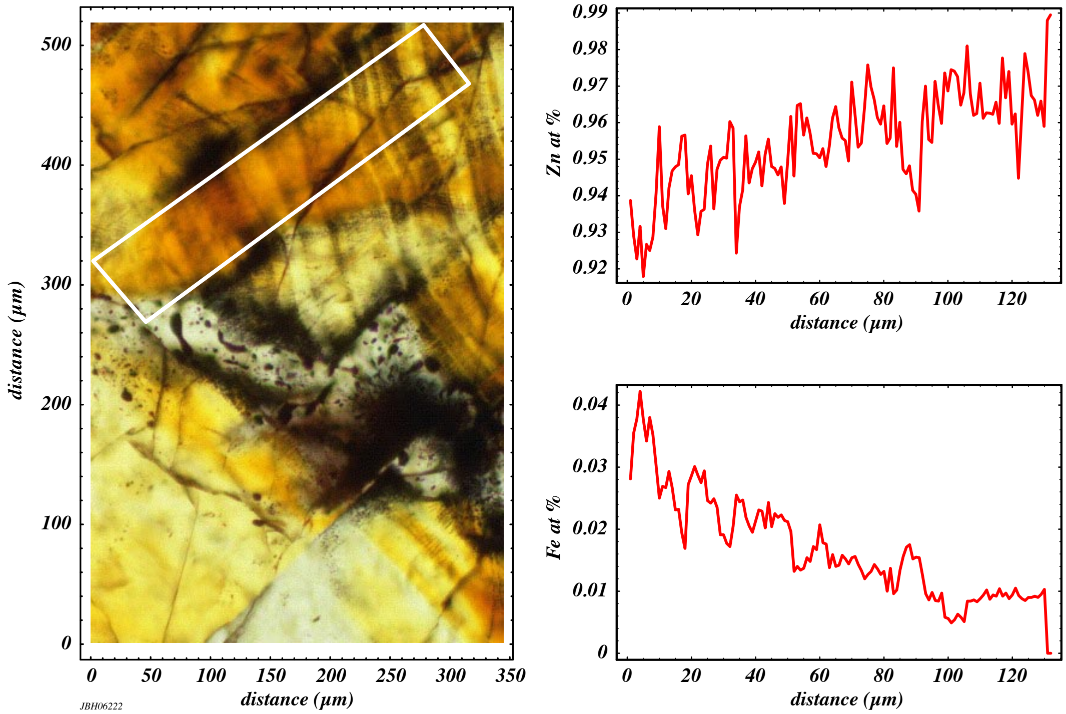


Figure 8. Photomicrograph (plane polarized light) of a portion of a sphalerite crystal from an ore-grade (up to 7% over 10-m apparent widths), epithermal Zn-Pb vein penetrated in geothermal well IID-10 (Figures 6 and 7). Core of the crystal is out of view beyond top right of the image. Jagged white-and-black central band is late-stage, iron-poor sphalerite (transparent white) encapsulating exsolved chalcopyrite. Diagonal rectangle in the upper half of the image outlines electron-microprobe traverse (left to right) used to determine atomic per cent zinc in sphalerite (upper sub-diagram to the right of the image) and atomic per cent iron in sphalerite (lower sub-diagram). The irregular patterns of the values for both parameters reflect similarly oscillating thermal-fluid compositions and flow rates as well as alternating fracture propagation and hydrothermal sealing during mineralization. Electron-microprobe microchemical analyses completed by Professor Barbara L. Dutrow, Department of Geology, Louisiana State University.

A corresponding and even more intricate three-dimensional map is the (static) ≤ 0°C/km Salton Sea geothermal-reservoir volume shown as Figure 7. This null-gradient hull almost certainly encloses those portions of the reservoir with the most vigorous thermal-fluid upflow and consequently accelerated advective-transport processes. The narrow part of the hull in closest proximity to the surface (Figure 7) corresponds to the fracture zone within which the Zn-Pb-Ag veins noted above were localized and may still be developing today.

Chemical—These rich Zn-Pb-Ag veins (Hulen et al., 2004; Hulen and Moore, 2005), exemplified by those penetrated in well IID-10 (Figure 7), contain relatively coarse-crystalline (up to several mm) sphalerite, which in thin section displays delicate textural and compositional zoning (Figure 8). Zoning of this type reflects comparatively rapid oscillations in fluid composition and crystal-growth rate that are diagnostic of pulsed fracture propagation and brine flow at near-critical conditions (as in the lithocap region of the granitoid pluton underlying The Geysers steam field in northwest-central California; Norton and Hulen, 2001; Norton and Dutrow, 2001).

Within and below the Zn-Pb-Ag veins, local equilibrium amongst hydrothermal minerals and the hot brines with which the minerals are now in contact (chemically analyzed geothermal-production fluids) requires chemical topologies for the sphalerite-hematite-anhydrite assemblage as shown in Figure 9. Although considerable literature exists on the SSGF brines and their equilibrium secondary-mineral assemblages (McKibben and Elders, 1985; McKibben et al., 1989; McKibben and Hardie, 1997), our work strongly suggests that these thermal brines, including those responsible for the sphalerite mineralization, must have been considerably more acidic than the pH ~5.5 previously envisioned. Brine pH in the approximate range 4-4.5 is more consistent with: (**1**) irreversible reaction paths that lead to the formation of epidote (Helgeson, 1967); (**2**) measured concentrations of zinc (up to at least 500 ppm) in the modern production fluids; and (**3**) the enormous amount of hydrogen ion requisite for the documented hydrothermal removal of literally cubic kilometers of carbonate from the geothermal reservoir.

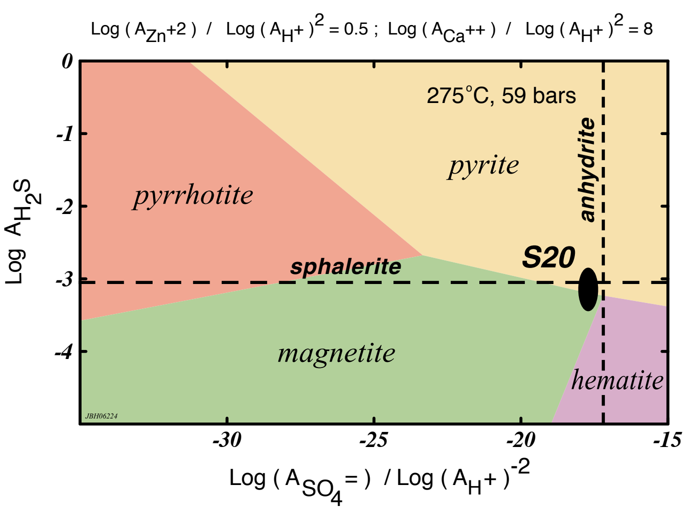


Figure 9. Germane to precipitation of sphalerite in the IID-10 Zn-Pb vein (Figure 8), this phase-equilibrium diagram corresponds to a portion of the Fe-Zn-Ca-O-S system and relationships amongst sphalerite, hematite, pyrite, pyrrhotite, and anhydrite. $Log A_{Fe2+}/Log A^2_{H+}$ conserved among solid phases. Filled ellipse portrays the approximate equilibrium value for geothermal production brine from well Sinclair 20 (near IID-10; Figures 6 and 7). A very similar brine must have provided the large amounts of dissolved zinc (~ 270 ppm in the Sinclair 20 fluid) requisite for the sphalerite mineralization.

Discussion and Conclusions

We propose that the combined thermal, mechanical, and chemical data sets for the SSGF depict prograde energy transport through the lithocap above a still-cooling young igneous-intrusive complex. The data are consistent with emplacement of the complex into the lower reaches of the Salton Trough sedimentary sequence, and with pluton tops in the approximate depth range 5-6 km. From numerical modeling of heat and mass transport in the Salton Sea geothermal system (to be discussed in much more detail in a forthcoming manuscript by the authors), we estimate that individual plutons of the complex are a few kilometers in diameter, at least two kilometers thick, and have progressed from 10,000 to 50,000 years into their crystallization and cooling histories. This finding is in harmony with Kasameyer et al.'s [1984] modeled age of 20,000 years for the present manifestation of the geothermal system.

Energy from the postulated deep SSGF plutonic complex is dispersed into the sedimentary host rocks, causing upward and outward, natural hydraulic-fracture propagation with affiliated, intermittent surging of hot acid brine. The brine at first floods into and alters the initially calcareous siliciclastic host rock—in the process dissolving carbonate and liberating CO_2—but eventually seals the newly-developed cracks with hydrothermal minerals. This process sets the stage for the next pulse of rock rupture and fluid surge. Brine trapped beneath the hydrothermally healed fractures becomes critically re-pressurized—in response to continued magmatic heating augmented by carbon dioxide buildup—and bursts the sealed cracks while forming new ones, sustaining chaotic but geologically rapid fracture propagation and heat transport toward the surface.

Considering (**1**) the likely ~5.5 km depth to the plutonic heat source; (**2**) numerically modeled rates for magmatic-hydrothermal energy dispersal (Norton, 1984), and (**3**) a well-developed near-surface heat-flow anomaly with localized "hot spots," then the processes outlined above have probably been ongoing for tens of thousands of years. The occurrence of steeply "concave-upward" shallow static thermal gradients in geothermal wells within a broad region of high but convex-upward such gradients (Hulen et al., 2002) indicates in the first instance that parts of the field are still undergoing vigorous thermal progradation, and in the second case that other sectors are nearing thermal maturity. Both of these thermal-gradient signatures are associated with frequent seismicity, and all of these phenomena support the concept that truly vast energy reserves remain in the Salton Sea hydrothermal system below currently drilled depths

The distributions of fracture failures and the measured thermal state of the SSGF indicate that in the causative hydrothermal system, the 350°C isotherm has moved upward from the plutonic heat source at a rate of tens of centimeters per year within highly permeable pipe-like volumes characterized by frequent seismicity. The prevailing temperature at depth in these volumes is in the range 400-500°C, but is closely locked to the locus of extrema in the NaCl-H_2O system, such that corresponding thermal gradients may be quite low within the features themselves.

These conclusions are hypothetical, but are strongly supported by geologic observation and hydrothermal transport theory. Results of the present study will lead inevitably to refinement of methods—and creation of new ones—not only for gauging the resource potential of the SSGF, but for geothermal exploration, development, and assessment throughout the greater Salton Trough.

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