CHARACTERIZATION AND CONCEPTUAL MODELING OF MAGMATICALLY-HEATED AND DEEP-CIRCULATION, HIGH-TEMPERATURE HYDROTHERMAL SYSTEMS IN THE BASIN AND RANGE AND CORDILLERAN USA

Principal Investigator – Jeffrey B. Hulen
Energy & Geoscience Institute, University of Utah
423 Wakara Way, Suite 300, Salt Lake City, UT 84108
801-581-8497 jhulen@egi.utah.edu

Collaborating Investigators – Joseph N. Moore, Michael C. Adams, Susan J. Lutz (all at the Energy & Geoscience Institute) and Denis L. Norton, School of Thought, P.O. Box 310, Stanley, ID 83278

Key Words – The Geysers; Dixie Valley; Glass Mountain; Salton Sea; hydrothermal system; conceptual model; igneous intrusion; granitoid; granite; rhyolite; faults; fractures; analysis, breccias; permeability; porosity; mineralization; hydrothermal alteration

Project Background and Status

The western USA is one of the world's richest geothermal provinces. This tectonically and thermally active region has an installed geothermal electric-power production capacity of ~2500 MWe, with the solid promise of several times that amount still to be developed.

Examples of this great potential can be found throughout the West. The Salton Sea geothermal system, in California's Imperial Valley (a part of the Basin and Range), has a current capacity of 335 MWe, but can likely support seven times that value. In other words, just this one system may one day supply enough electricity for ~9,000,000 people. The Glass Mountain system, at Medicine Lake volcano in the southern Cascade Range of northern California, is the biggest known, wholly undeveloped, high-temperature geothermal system in the contiguous 48 states. Nevada's current 260 MWe capacity scarcely hints at the hidden systems surely yet to be found in the state.

The West's geothermal wealth and the nation's ever-expanding need for clean, renewable energy sources underpin the Department of Energy's stated aim for geothermal energy to provide 10% of the region's electric power by the year 2020. Achieving this ambitious goal requires continuing support for mission-oriented geothermal research at National Laboratories, the U.S. Geological Survey and other agencies, and geoscience-oriented Universities.

Not only are geothermal reservoirs exceptionally complex natural phenomena, they are also concealed from direct observation. Transforming them from raw prospects into profitable, long-lived producers of electrical energy is therefore arduous, risky, and expensive. We can help geothermal companies ease this process, while reducing costs and improving the odds for success, by maintaining a robust national geothermal research program. The more that we know about these systems, the more readily and cost-effectively they can be found, developed, and managed.

Governed by the foregoing philosophy, we have undertaken to obtain greater insight into the intricate and interlinked geological, geochemical, thermal, and mechanical controls on the inception, evolution, and 3-D geometry of the two types of high-temperature hydrothermal system found in the western United States. The first type is distinguished by having an obvious igneous heat source. Examples include systems at The Geysers, the Salton Sea, and Glass Mountain. The second type is ostensibly heated entirely in response to circulation along deeply-penetrating faults and fractures in regions of thinned crust and elevated heat flow. This is the dominant type of system in Nevada, and the prime example is the Dixie Valley field in Churchill County

At the close of FY 2001, we were well underway in constructing conceptual geological and geochemical models for the study systems noted above. The Geysers field has received most of our attention to date. We have modeled the northern Geysers, with emphasis on a transect through Geysers Coring Project corehole SB-15-D (*Hulen, 2001; Norton and Hulen, 2001*), and on the high-temperature Aidlin sub-reservoir in the extreme northwestern part of the field (*Hulen et al., 2001*). The Salton Sea system modeling effort began in earnest only in late FY 2001, when a full suite of subsurface data and borehole samples was finally made available. Even so, we have already made an exciting volcanological discovery that has changed concepts about geothermal heat sources and hydrology throughout the Salton Trough (*Hulen and Pulka, 2001*). We have completed several interesting ancillary studies at Dixie Valley, but have really just begun our field-wide modeling work there. Redoubled efforts on this exemplary deep-circulation system are planned for FY 2002. The Glass Mountain modeling study has been temporarily deferred because of DOE funding limitations.

Project Objectives

(1) Working closely with our counterparts in the U.S. geothermal industry, refine and develop new conceptual, geological, and geochemical models for western U.S. high-temperature hydrothermal systems, including new ones certain to be found in the Cascades and adjoining Basin and Range.

(2) Assist domestic geothermal companies in application of the new models for risk-reduced and more cost-effective exploration, development, expansion, and maintenance of these systems. Better resource knowledge through conceptual modeling will mean fewer million-dollar "dry holes" and more successful high-temperature wells.

(3) Maintain and augment the EGI Geothermal Sample Laboratory as a unique western U.S. and international research collection of geothermal cores, cuttings, and resource information.

Approach

There are several ways to stimulate development of known U.S. geothermal systems, and to enhance the likelihood of locating and producing the new ones that remain to be found in the region: (1) increasing access to public lands for responsible resource development; (2) extending production-tax credits to geothermal energy as well as wind and other renewables; (3) refining drilling and production technologies; and (4) simply improving basic knowledge of the resource itself.

Of these four approaches, the first two are political concerns beyond the scope of this report. The second two are both germane, but (4) is fundamental. Even the most sophisticated drilling system can cleanly miss, at enormous expense, an incompletely understood resource target.

Accordingly, we are in the midst of formulating the next generation of conceptual, geological, and geochemical models for high-temperature western U.S. geothermal resources. The models will help provide answers to the following key questions not only about these systems, but by extension their analogues abroad.

- What are the characteristics and 3-D configurations of the large-fracture networks that control most high-temperature fluid flow? . . . of the small-fracture stockworks and primary pore volumes that are not major flow channels but are important for thermal-fluid storage? Improving knowledge of these features will be important not only for more efficient extraction of indigenous reservoir fluids, but for planning and executing long-term injection strategies.

- In what ways do primary lithologic variables influence the creation of fracture permeability by tectonic and hydrothermal disruption? . . . of other types of porosity and permeability (e.g., dissolution)?

- How do igneous intrusions interact with the rock and fluid regimes they intrude to create, enhance, or occlude porosity and permeability? Can the relevant processes be modeled to predict permeability "sweet spots" in hydrothermal systems, or, conversely, to identify and avoid nonproductive reservoir sectors?

- How can broad-scale and local alteration mineralogy and zoning be used to help deduce a system's hydrothermal history, and to provide vectors toward productive thermal-fluid channels and reservoir volumes?

- How can the compositions and crosscutting relationships of hydrothermal veins and breccias be better utilized to (1) decipher a system's thermal and chemical evolution; and (2) to narrow the search for fluid conduits?

- How do "blind" hydrothermal systems differ from their surficially expressed counterparts? Are there subtle surface clues, not yet recognized, that point to these systems' subsurface presence?

Meeting these goals requires a mix of traditional and innovative research techniques judiciously applied by a research group with a balanced blend of skills, talents, backgrounds, and viewpoints.

Our research program for the full five-year performance period of this grant has been organized into the following tasks:

- Generation of refined conceptual, exploration, and production models for The Geysers geothermal system (industry partner Calpine Corporation), with emphasis on the northern, high-temperature part of the field. Among research methods applied to this Task are (1) field-wide, four-dimensional (three spatial plus temporal), geological and geochemical mapping and reservoir characterization; (2) petrologic studies of cuttings and cores, with emphasis on tracing fluid sources and evolutionary histories, and on characterization of alteration mineralogy and zoning as these features relate to a field's overall geologic framework; (3) organic-geochemical studies, principally to define independent paleotemperature measurements for reservoir rocks; (4) radiometric age-dating; and (5) numerical hydrothermal-history modeling.

- Generation of refined conceptual and geological/geochemical models for the Salton Sea geothermal field (industry partner CalEnergy Operating Company; CEOC), where a major expansion is underway. Same approach as for The Geysers, but tailored to the unique geologic setting and tectonomagmatic history of the Salton Trough.

- Generation of refined exploration and production models for the Glass Mountain geothermal system (industry partner Calpine Corporation). Same approach as above, but modified to fit a southern Cascade Range composite volcano. Knowledge gained from this study will help narrow the search for similar such systems concealed beneath cool-water "rain curtains" along the full length of the Cascade arc and its eastern flank.

- Generation of refined exploration and conceptual models for western Great Basin "deep-circulation" geothermal systems (various corporate partners, but principally Caithness Energy). Limited work focused to date on the Dixie Valley geothermal system.

Methods for implementing each of these tasks are as follows:

- Lithologic, stratigraphic, structural, alteration, and mineralization mapping at each system, at various levels of detail depending upon the resource. Where data density permits, 3-D maps and block diagrams are prepared, as these can be superior to 2-D sections for understanding the true character of a subsurface resource.

- Petrologic studies, including standard petrographic characterization, whole-rock geochemical analysis, microchemical analysis of selected secondary phases, fluid-inclusion microthermometry and gas analysis.

- Organic geochemistry, for mapping fluid-flow paths and monitoring both natural and production-induced reservoir processes.

- $^{40}Ar/^{39}Ar$ age-spectrum dating and thermal-history modeling.

- Numerical pluton-cooling and hydrothermal-history modeling by D.L. Norton, who is separately funded but working closely with the PI on this project.

Results to Date

A partial list of major accomplishments through FY 2001 for this project (Grant DE-FG07-00ID13891, Task I) is as follows:

- Determined the sealing mechanism and mineralogy inhibiting thermal-fluid escape and groundwater incursion at the Glass Mountain system (*Hulen and Lutz, 1999*).

- Worked closely with D.L. Norton to complete numerical igneous-intrusion and thermal-history models for the north-central Geysers steam field, California, with emphasis on a transect through Geysers Coring Project corehole SB-15-D (*Hulen, 2001; Norton and Hulen, 2001*).

- Examined the role of strike-slip fault tectonics in guiding intrusion of the Geysers felsite (*Hulen and Norton, 2000*). Determined that the pluton likely was emplaced sequentially in pull-aparts developed between right-stepping, right-lateral wrench-fault zones.

- Completed preliminary work on the use of indigenous bitumens as thermal-history indicators in The Geysers and other high-temperature hydrothermal systems.

- With CEOC, characterized scaling mechanisms and scale compositions for selected production and injection wells at the Salton Sea geothermal field (*Lutz et al., 2000, 2001*).

- Also with CEOC, discovered and characterized an ancient (~0.65 Ma), buried, rhyolite dome complex at the Salton Sea field (**Figs. 1 and 2; *Hulen and Pulka, 2001*). Developed a working model incorporating the influence of this igneous body and implied granitic plutons on past, present, and future hydrothermal fluid flow at the Salton Sea and elsewhere in the Salton Trough (Fig. 3).

- Investigated, with Pat Dobson and Tim Kneafsy of LBL, the nature of porosity and permeability at shallow levels in a portion of the Yellowstone hydrothermal system (*Dobson et al., 2000, 2001*).

- Completed a detailed study of the Aidlin sector of The Geysers (*Hulen et al., 2001*), and determined the following: (a) Unlike the rest of the field, Aidlin produces exclusively from a "high-temperature" reservoir (Fig. 4); (b) the reservoir has cooled ~100^{o}C from its thermal maximum;
 (c) atypically for The Geysers, the reservoir is hosted principally by "normal" reservoir rocks, that is,
 non-hornfelsic lithologies containing only small amounts of hydrothermal or metamorphic biotite; (d) like the rest of The Geysers, the top of the Aidlin reservoir closely coincides with the upper limit of pervasive hydrothermal epidote (Fig. 4).

Plans

At the close of FY 2001, 40% of our five-year project has been completed, and most of the project's stated interim goals to this point have been met. Work on the important Geysers system will continue into year 3, with a focus on the high-temperature reservoir slated for deep injection.

The Salton Sea geologic model is still in the early stages of preparation, and we anticipate that its completion will involve a large effort each year for the remaining duration of the grant.

Because of DOE budget cuts for FY 2002, we have reluctantly sidelined work on the Glass Mountain geothermal system pending restoration of funding for this project.

Thus far in our research program, we have emphasized magmatically-heated western U.S. geothermal systems. During ensuing years of the grant, we will transfer some of that emphasis to the deep-circulation systems, a type which will account for many new discoveries in the Great Basin. We have completed alteration mapping, lithologic logging of cuttings, and the study of hot-spring deposits at the Dixie Valley field, but will strive during the coming year to place disparate data from these investigations into a coherent 3-D geologic context.

Technology Transfer; References

The following publications through FY 2001 have been supported, wholly or in part, by this grant. Citations for the present document are highlighted in bold text.

1. Adams, M.C., Moore, J.N., Bjornstad, S., and Norman, D.I., 2000, Geologic history of the Coso geothermal system: Japan, World Geothermal Congress, Proceedings.

2. Allis, R.G., Johnson, S., Nash, G.D., and Benoit, R., 2000, Mapping changes in surface thermal activity at Dixie Valley geothermal field, Nevada: *Geoth. Resourc. Counc.*, Trans., v. 23, p. 499-504.

3. **Dobson, P., Hulen, J., Kneafsy, T.J., and Simmons, A., 2000, The role of lithology and alteration on permeability and fluid flow at the Yellowstone geothermal system, Wyoming: *Stanford University*, 25th Wkshp. on Geoth. Res. Eng., Proc.**

4. **Dobson, P., Hulen, J., Kneafsy, T.J., and Simmons, A., 2001, Permeability at Yellowstone – A natural analogue for Yucca Mountain processes: Las Vegas, Nevada, 9th International High-Level Radioactive Waste Management Conference (April 29-May 1, 2001.**

5. Gruszkiewicz, M.S., Horita, J., Simonson, J.M., Mesmer, R.E., and Hulen, J.B., 2001, Water adsorption at high temperature on core samples from The Geysers geothermal field, California: *Geothermics*, v. 30, p. 269-302.

**Figures follow references

6. **Hulen, J.B. (Guest Editor), 2001, The Geysers Coring Project and the Geysers-Clear Lake igneous-geothermal domain (special issue): *Geothermics*, v. 30, p. 165-394.**

7. Hulen, J.B., and Wright, P.M., 2001, Geothermal energy – Clean, sustainable energy for the benefit of humanity and the environment: *U.S. Department of Energy* Brochure (May 2001), 8 p.

8. Hulen, J.B., and Collister, J.W., 1999 (issued February 2000), The oil-bearing, Carlin-type gold deposits of Yankee basin, Alligator Ridge district, Nevada: *Econ. Geol.*, v. 94, p. 1029-1051.

9. Hulen, J.B., and Langton, D., 2001, The EGI Geothermal Sample Laboratory – A western U.S. and international geothermal research collection and study center: *Univ. of Utah*, Energy & Geosci. Inst. Rpt., 202 p.

10. **Hulen, J.B., and Lutz, S.J., 1999 (October), Altered volcanic rocks as hydrologic seals on the geothermal system of Med. Lake volcano, Calif.: *Geoth. Resourc. Counc.* Bull., v. 28, p. 217-222.**

11. **Hulen, J.B., and Norton, D.L., 2000, Wrench-fault tectonics and emplacement of The Geysers felsite: *Geoth. Resourc. Counc.*, Trans., v. 24, p. 289-298.**

12. **Hulen, J.B., and Pulka, F.S., 2000, Deeply concealed rhyolite and associated phreatomagmatic tuff in the southeastern Salton Sea geothermal field, California: *Stanford Univ.*, 26th Wkshp. on Geoth. Res. Eng., Proc.**

13. **Hulen, J.B., Norton, D.L., Moore, J.N., Beall, J.J., and Walters, M.A., 2001, Initial insights into the origin, configuration, and thermal-chemical evolution of the Aidlin steam reservoir, northwest Geysers geothermal system, California: *Geoth. Resourc. Counc.*, Trans., v. 25, 10 p.**

14. Lutz, S.J., and Hulen, J.B., 2000, Depositional setting for nickel mineralization in the Jurassic Boyer Ranch Formation and the Humboldt igneous complex, Bolivia area, northern Stillwater Range, Nevada (abstract): *GSA*, 2000 Ann. Mtng. (Reno, Nevada), Progr. with Abstr.

15. **Lutz, S.J., Hulen, J.B., and Osborn, W., 2000, Production-well scales from the Salton Sea geothermal field, California: *Stanford Univ.*, 25th Wkshp. on Geoth. Res. Engineering, Proc..**

16. **Lutz, S.J., Hulen, J.B., and Osborn, W.L., 2001, Chemical, mineralogical, and textural characterization of production-well scales from Salton Sea geothermal wells: *Stanford Univ.,* 26th Wkshp. on Geoth. Res. Eng., Proc.**

17. Lutz, S.J., Hulen, J.B., and Schriener, A., Jr., 2000, Alteration, geothermometry, and granitoid intrusions in well 31-17, Medicine Lake volcano geothermal system, California: *Stanford Univ.,* 25th Wkshp on Geoth. Res. Eng., Proc., p. 289-295.

18. Klusman, R.W., Moore, J.N., and LeRoy, M.P., 2000, Potential for surface gas-flux measurements in exploration and surface evaluation of geothermal resources: *Geothermics*, v. 29, p. 637-670.

19. Moore, J.N., Adams, M.C., Sperry, T.L., Bloomfield, K.K., and Kunzman, R., 2000, Preliminary results of geochemical monitoring and tracer tests at the Cove Fort-Sulphurdale geothermal system, Utah: *Stanford Univ.*, 25th Wkshp. on Geoth. Res. Eng., Proc.

20. **Norton, D.L., and Hulen, J.B., 2001, Preliminary numerical analysis of the magma-hydrothermal history of The Geysers geothermal system, California, USA: *Geothermics*, v. 30, p. 211-234.**

21. Persoff, P., and Hulen, J.B., 2001, Hydrologic characterization of reservoir metagraywacke from shallow and deep levels of The Geysers vapor-dominated geothermal system, California, USA: *Geothermics*, v. 30, p.169-192.

22. Wannamaker, P.E., Hulen, J.B., and Heizler, M.T., 2000, Early Miocene lamproite from the Colorado Plateau tectonic province, Utah: *J. Volc. Geoth. Res.*, v. 24, p. 637-640.

**Figures follow references

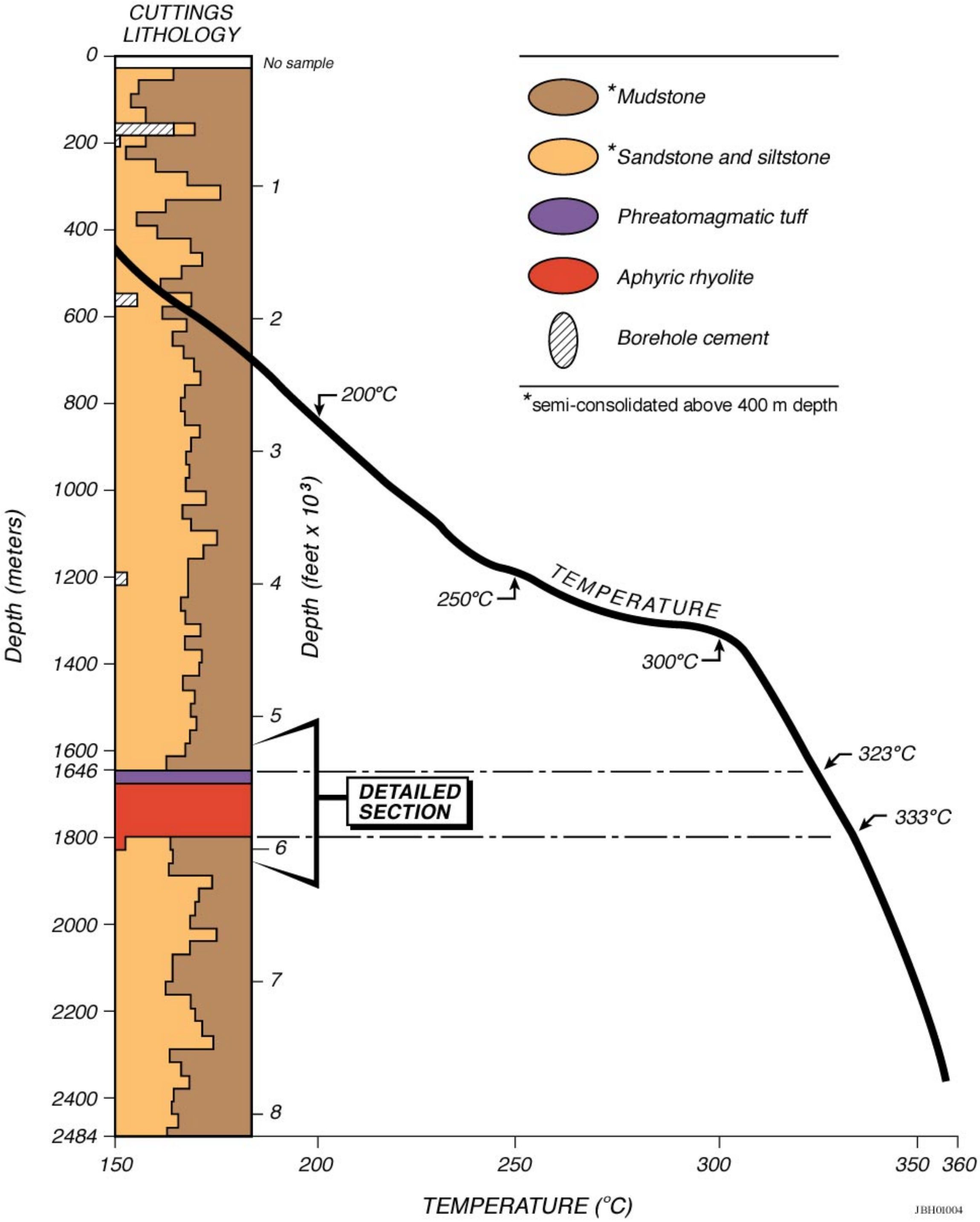

Figure 1. Generalized lithologic and temperature log for well Smith IW-2, in the Salton Sea geothermal field, showing position of rhyolite flow/dome and tuff interval. Depths shown are as drilled, but close to true vertical depths. The well is inclined generally northeastward at 6-11°; total drilled depth at 2484 m = true vertical depth of 2464 m. Data from Epoch Well Logging (1998) and this study.

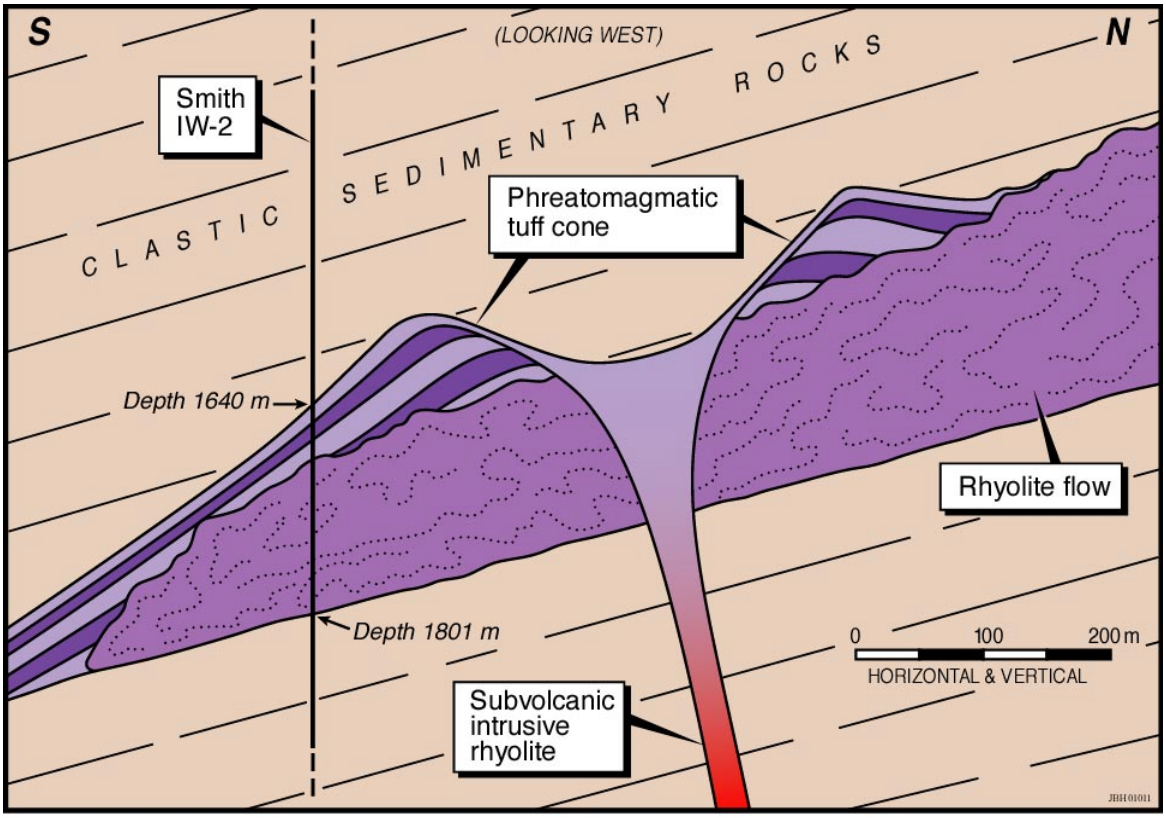

Figure 2. Geologic interpretation of the Smith IW-2 rhyolite and tuff interval.

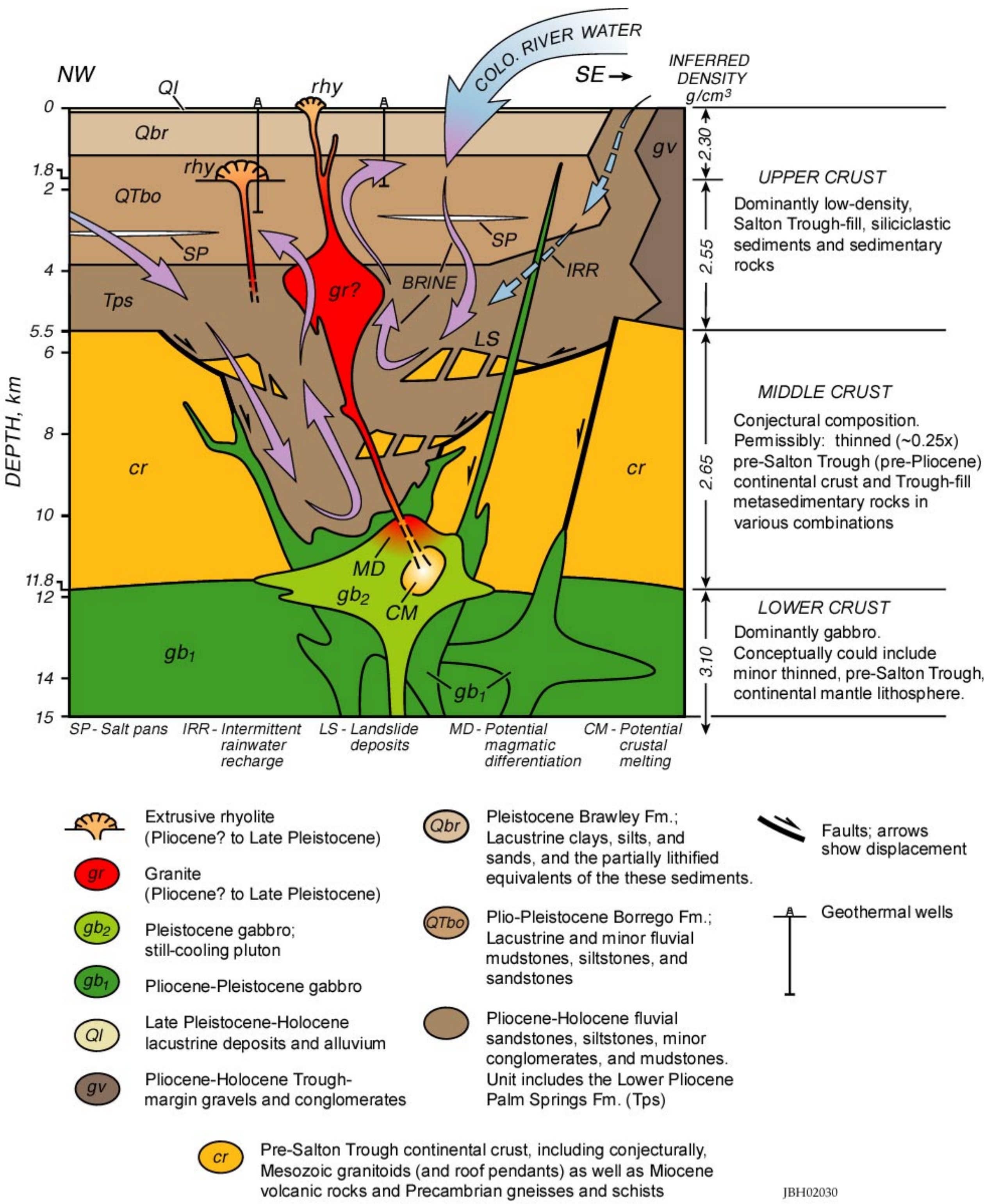

Figure 3. Conceptual lithostratigraphic section through the western Salton Trough and the Salton Sea pull-apart zone. Based on the landmark studies of Wilfred Elders, Arthur Lachenbruch, Michael McKibben, and others, and modified on the basis of new deep-drilling information from the Salton Sea geothermal field. Synthesis by J. Hulen and D. Norton.

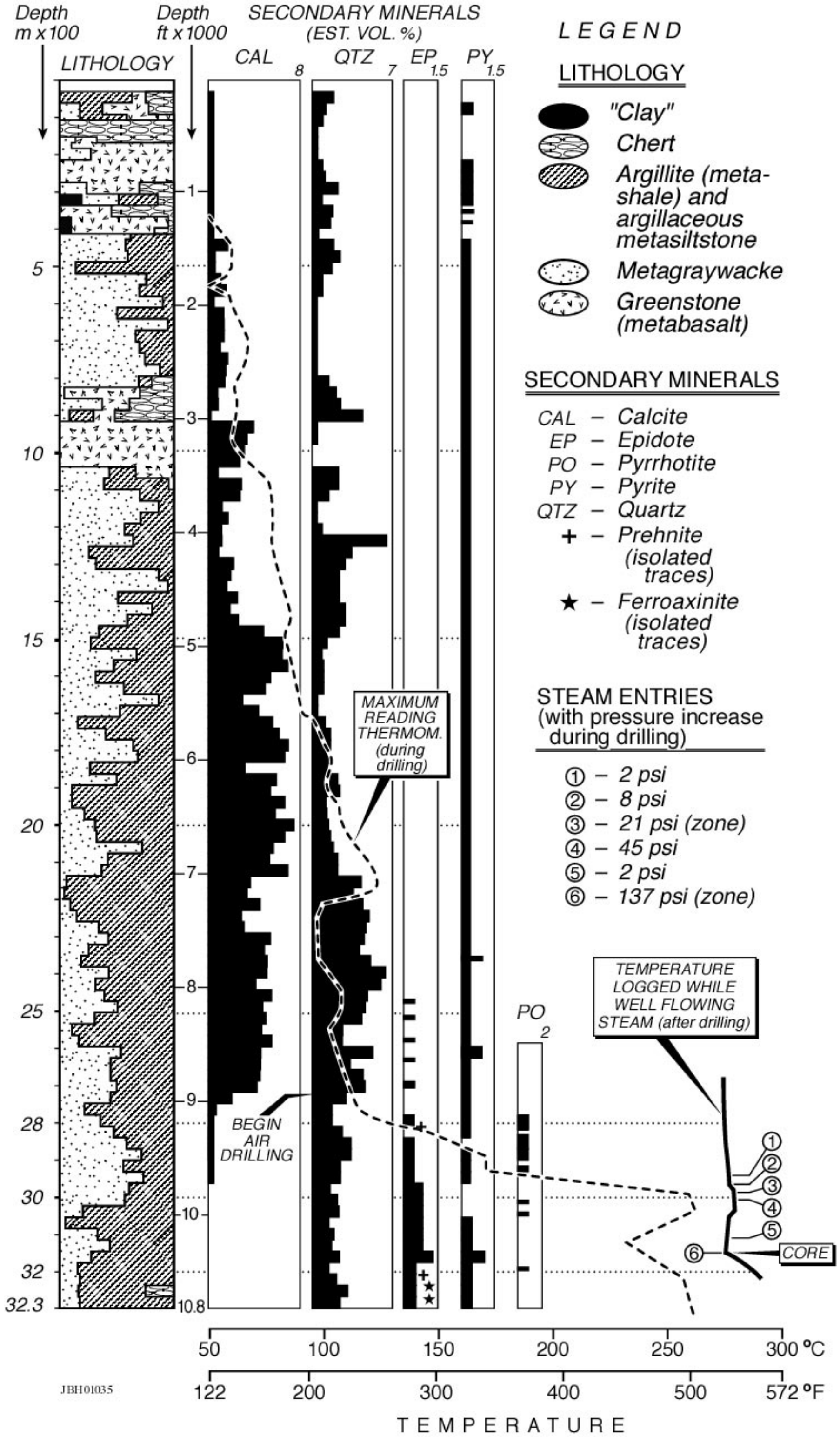

Figure 4. Generalized lithologic, temperature, and secondary-mineral log for geothermal well Aidlin-8, in the northeastern Geysers steam field, California.