PROCEEDINGS, Twenty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 29-31, 2001
SGP-TR-168

NEWLY-DISCOVERED, ANCIENT EXTRUSIVE RHYOLITE IN THE SALTON SEA GEOTHERMAL FIELD, IMPERIAL VALLEY, CALIFORNIA

Implications for Reservoir Characterization and Duration of Volcanism in the Salton Trough

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ABSTRACT

Thick (150-300 m), ancient rhyolites and tuffs unambiguously erupted onto a paleosurface have been discovered beneath 1.7 km of clastic sedimentary strata in the eastern part of the Salton Sea geothermal field. The rhyolites are aphyric and flow-banded, and consist entirely of micropoikilitically devitrified glass. The tuffs contain accretionary lapilli, blocky glass shards, and sedimentary debris; they are interpreted as phreatomagmatic.

Assuming an average sedimentation rate of 2.24 mm/yr for this part of the Salton trough (a figure based on occurrence of the petrographically distinctive, 0.76 Ma Bishop Tuff fallout deep in the nearby State 2-14 scientific borehole), the age of the new rhyolite is calculated to be about 0.73 Ma. A potentially valuable marker horizon, the new rhyolite is envisioned as part of a much larger buried dome field, perhaps analogous to the one now exposed above the Coso geothermal system about 390 km to the north.

INTRODUCTION

Two recently completed (1998, 1999) CalEnergy Operating Company (CEOC) injection wells in the eastern part of the Salton Sea geothermal field (Smith IW-2 and Vulcan IW-8; **Figs. 1 and 2**) penetrated thick (150 m and 300 m, respectively) intercepts of felsic igneous rock identified at the time of drilling by one of us (Pulka) as rhyolite. These newly discovered rhyolites greatly exceed in thickness any previously encountered at depth either in the Salton Sea field (maximum of 38 m in the bottom of well Elmore 1; **Fig. 2**) or the entire Salton trough (Reed, 1984; Robinson et al., 1976). The earlier-documented Salton Sea rhyolites were considered to be intrusives, possibly the subsurface equivalents of five small Pleistocene rhyolite domes (the Salton Buttes) at the southeastern margin of the Salton Sea (**Figs. 1 and 2**; Robinson et al., *op. cit.*). The Smith and Vulcan rhyolites were also thought initially to be intrusive, but as we demonstrate in this paper, there is more than ample evidence that these volcanics were erupted onto the contemporaneous surface.

This finding is significant for several reasons. First, these rhyolites are buried beneath about 1.7 km of Salton-trough fluviolacustrine clastic sediments (e.g., Muffler and Doe, 1968), so the volcanics must be considerably older than the ~10 ka (Herzig and Jacobs, 1994; Friedman and Obradovich, 1981) domes of the Salton Buttes. Secondly, the great thicknesses of the Smith IW-2 and Vulcan IW-8 intercepts imply that these rhyolites could be part of a much larger buried volcanic field. Thirdly, the rhyolites could constitute a useful time-stratigraphic marker horizon. If laterally extensive, this rhyolitic marker could enable geoscientists and reservoir engineers to constrain more accurately three-dimensional stratigraphic and structural models currently being refined for the entire Salton Sea geothermal field.

This paper provides the first detailed description of the thick, buried rhyolites in the eastern part of the Salton Sea field. Our focus is the rhyolitic interval penetrated in Smith IW-2; work in progress on the thicker Vulcan IW-8 intercept will be deferred for a future account. We first establish the extrusive nature of the rhyolite and associated tuff using a variety of compositional and textural criteria, then discuss the implications of this origin for the physical nature and volcanic history of the geothermal reservoir, as well as for the Quaternary volcanic evolution of the entire Salton trough.

GEOLOGIC SETTING

The Salton trough (**Fig. 1**) is the northern landward extension of the Gulf of California tectonic regime, within which oceanic crust is being formed at pull-aparts, or spreading centers, developed at the oversteps between major, *en echelon*, right-lateral strike-slip faults (Elders and Sass, 1988; Elders et al., 1972). On land as in the Gulf, these spreading centers are the sites of intense magmatism, volcanism, and high-temperature hydrothermal activity. The Salton Sea geothermal system (**Figs. 1 and 2**) is developed above the northernmost of the spreading centers, where interaction between the North American and Pacific plates changes from stretching and crustal extension to dominantly right-lateral slip along the San Andreas transform fault zone (*SAF*; **Fig. 1**).

Whereas the Gulf of California is a narrow new sea developed above fresh oceanic crust, its extension, the Salton trough, is filled by up to 6 km of Pliocene to Holocene deltaic fluviolacustrine clastic sediments supplied by the ancestral and modern Colorado River (Elders and Sass, 1988; van de Kamp, 1973; Muffler and Doe, 1968; Merriam and Bandy, 1965). These sediments serve as efficient thermal insulators above the continental spreading centers, enabling the formation of large, hot (up to at least 370^{o}C) hydrothermal systems like those at the Salton Sea and, to the south, Mexico's Cerro Prieto geothermal field (Reed, 1984; **Fig. 1**).

There are few volcanoes exposed in the Salton trough, and all are Quaternary (Herzig and Elders, 1988a, 1988b; Robinson et al., 1976). The age of a lone dacite dome near Cerro Prieto (**Fig. 1**) is estimated, based on paleomagnetic data, to be 100-10 ka (de Boer, 1980). Obsidian Butte, at the Salton Sea field (**Fig. 2**) yielded a K-Ar age of 16 ka $\pm$ 16 ky (Muffler and White, 1969). The Obsidian Butte and Red Island rhyolites (**Fig. 2**) also produced obsidian-hydration-rind ages of 2.5-8.4 ka (Friedman and Obrado-vich, 1981); we will show that the Smith IW-2 rhyolite is likely older by two orders of magnitude.

THE RHYOLITE OF SMITH IW-2

General – These rhyolitic rocks were penetrated in the injection well between drilled depths of 1646 m and 1801 m (**Figs. 2** and **3**). The rhyolites interrupt an otherwise compositionally consistent stack of clastic sedimentary rocks (see also the following paragraphs) in which Smith IW-2 was terminated at a depth of 2484 m (true vertical depth of 2464 m). Measured temperatures reach 360°C at total well depth, and range between 323°C and 333°C through the rhyolitic interval.

Like all Salton Sea wells, Smith IW-2 is dominated by late Cenozoic, fluviolacustrine sandstones, siltstones, mudstones, and probably marls. Since the trough first began to form about 4 m.y. ago (Herzig and Jacobs, 1994), the clastic source for these deposits has been the heavily sediment-laden Colorado River (**Fig. 1**).

Mudstones dominate the upper 400 m of Smith IW-2, and help provide an effective caprock, or top seal, on the underlying, liquid-dominated hydrothermal system (**Fig. 3**; see also Moore and Adams, 1988; and Elders and Sass, 1988). Below the caprock, the proportion of mudstone to siltstone plus sandstone, averaged over 30-m intervals, is relatively constant at about 1:1 (**Fig. 3**).

Stratigraphy of the clastic rocks penetrated by Smith IW-2 is highlighted by a gamma-log trace (**Fig. 4**), on which potassium-rich shales show as highs, and intervening sandstones and siltstones as lows. The strongest gamma response in the well, however, closely corresponds to the rhyolitic interval.

A spontaneous-potential (SP) log also reveals the Smith rhyolite (**Fig. 5**). The reasons for this response remain to be determined, but the SP and gamma signals combined show great promise for tracking subsurface rhyolites in the Salton Sea field in the absence of drill cuttings, or where these volcanics are thin or otherwise difficult to recognize from borehole samples alone.

Petrology and Petrography – The Smith IW-2 rhyolitic interval comprises two distinct compositional and textural subzones: the main rhyolite, and an overlying tuff (**Fig. 6**). The rhyolite is massive, homogeneous, aphyric, microcrystalline, and commonly flow-banded. It is a micropoikilitically devitrified (criteria of Anderson, 1969; and McPhie et al., 1993) glass, characterized by interlocking to scattered, snowflake-textured quartz patches incorporating feldspar microlites along with bands and stringers of secondary chlorite. The turbid "snowflakes" account for 20-50% of the rock. The remainder is a microcrystalline (3-7 μm), massive to trachytic-textured mosaic of quartz, K-feldspar, and chlorite, along with accessory titanite and allanite. The latter is both a primary and an alteration phase, as well as a common constituent of hydrothermal veins in the rhyolite.

Cuttings of the tuff overlying the rhyolite reveal a chaotically-textured aggregate of silt- and sand-sized grains (quartz, feldspar, lithic fragments, and minor detrital mica) mixed with varying amounts of pumice, glass shards, and devitrified rhyolite fragments compositionally and texturally identical to the main rhyolite below. Glass shards up to 2 mm in diameter in the tuff are entirely altered to adularia and/or chlorite. These shards are blocky in outline, sparsely vesicular, and broken across the ovoid vesicles. Pumice shards and lapilli, mostly of the filamentous, or "tube" variety (McPhie et al., 1993), are also entirely chloritized and/or adularized.

Compaction-deformed accretionary lapilli are common throughout the tuff interval. These lapilli, of the massive "core-type" (Schumacher, 1989), are crudely ovoid, agglutinated masses of fine ash and sedimentary clastic debris. Along with the blocky glass shards noted above, these accretionary lapilli indicate significant groundwater involvement in the causative eruption(s) (e.g. Sheridan and Wohletz, 1983).

The Smith IW-2 rhyolite is not only texturally but mineralogically distinct from overlying and underlying clastic strata (**Fig. 6**). Whereas the clastic beds contain appreciable illite and plagioclase, the rhyolite is devoid of these phases. Chlorite and quartz are each about equally abundant in the sediments and the rhyolite.

The tuff overlying the rhyolite contains large amounts of sedimentary debris, and is mineralogically intermediate between the rhyolite and the clastic rocks (**Fig. 6**). A noteworthy compositional feature of the tuff is its locally abundant chlorite (up to one third by weight). This enrichment reflects massive hydrothermal chloritization of glass shards and pumice.

Internal Structure – As revealed by Formation MicroScanner (FMS) data (Schlumberger, 1998), the Smith IW-2 rhyolite and tuff also have different internal structures than the enclosing sediments (**Fig. 7**). On dip vs azimuth plots of the FMS data, clastic rocks above and below the rhyolitic interval show quite consistent shallow southerly dips, mostly between 15^o and 25^o. By contrast, the intervening tuff and rhyolite show a wide range of shallow to moderately steep dips spanning a broad range of bearings. Dips in the tuff are predominantly southward and eastward, whereas dips in the rhyolite have no preferred orientation (**Fig. 7**).

INTERPRETATION, DISCUSSION, AND CONCLUSIONS

Discovery and petrographic confirmation of the thick rhyolitic interval penetrated by Salton Sea well Smith IW-2, and the even thicker allied volcanic sequence of Vulcan IW-8 (study in progress), calls for modification of earlier interpretations of Quaternary volcanism in the Salton trough. This buried rhyolite interval may also provide an important marker horizon to help constrain detailed three-dimensional geologic models currently being prepared by the authors for the entire geothermal field.

Mode of Emplacement -- We believe that the evidence presented above argues strongly for eruption of the Smith IW-2 rhyolite onto a paleosurface. The volcanic rock is entirely devitrified glass, homogeneous, and of considerable thickness (119 m), so it was not emplaced as a pluton even at then-subvolcanic levels. If the rhyolite had been emplaced at greater depth, it would have cooled more slowly and developed primary holocrystalline rather than devitrification textures (except perhaps for thin glassy chilled borders). Moreover, there is no mineralogic or textural indication of baking or metamorphism of the clastic strata in contact with the rhyolite.

The tuff above the rhyolite could *only* have been emplaced at the contemporaneous paleosurface. The tuff contains abundant shards, pumice, and accretionary lapilli, as well as devitrified rhyolite lithic clasts identical to the underlying massive rhyolite. These features, along with position of the tuff immediately above the rhyolite, are consistent with phreatomagmatic eruption through a previously emplaced flow rock. The abundant clastic component of the tuff means that the eruption also encompassed a substantial thickness of water-saturated Salton-trough sediments.

A conceptual model for the current configuration of the Smith IW-2 rhyolite and tuff is presented as **Figure 8**. The volcanics are shown as being enclosed by Salton-trough clastic strata that dip gently southward (deduced from the simulated dipmeter presentation; **Fig. 7**). We interpret the consistent shallow dip of the initially sub-horizontal fluviolacustrine sediments as likely resulting from post-depositional tilting.

The thick, Smith IW-2 rhyolite is shown as part of a flow or dome edge, based on the rock's textural homogeneity and lack of apparent dips greater than about 50^o (**Figs. 7** and **8**). The overlying tuff, also with moderate dips (but with a smaller spread of bearings), is definitely of phreatomagmatic origin (Woh-letz and Heiken, 1992; Wohletz, 1986, 1983; Heiken and Wohletz, 1985; Sheridan and Wohletz, 1983; Heiken, 1971). Pyroclastic eruptions of this type arise from the interaction of magma with aquifer-confined or surficial meteoric water. The typical pyroclast-dispersal mechanisms in these eruptions are pyroclastic surges and fallouts, with pyroclastic flows and lahars attending eruptions involving deeper and more copious water supplies. The latter eruption type tends to produce moderately steep-sided but poorly-bedded tuff cones, which can reach at least 100 m in height (Fisher and Schmincke, 1984).

The dip vs. azimuth display for the Smith IW-2 tuff shows few but moderate dips with azimuths confined to a 180^o spread. These attitudes, along with the tuff's blocky shard morpho-logies and common accretionary lapilli, lead us to interpret the unit as part of a tuff cone. Such landforms have primary bedding dips of no more than about 30^o (Fisher and Schmincke, 1984), so the steeper inclina-tions shown by the Smith IW-2 dipmeter plot (**Fig. 7**) could reflect post-depositional slumping. Preservation of accretionary lapilli in the tuff means that the erupted pyroclasts accumulated subaerially. How-ever, it is entirely possible that the water-rich eruption was initiated beneath or through a contemporaneous lake.

Age -- As deeply-buried paleosurficial deposits, the Smith rhyolite and tuff are clearly older than Obsidian Dome and other young (~10 ka) rhyolites of the Salton Buttes (**Fig. 2**). Massively adularized, the Smith volcanics are not readily amenable to radiometric dating methods. Nonetheless, they are likely comparable in age to the 0.76 Ma (van den Bogaard and Schirnick, 1995) Bishop Tuff fallout probably penetrated at 1.7 km depth in borehole State 2-14, about 4 km to the north (**Fig. 2**; Herzig and Elders, 1988a, 1988b). The State 2-14 tuff has has the same trace-element signature and phenocryst mineralogy as massive proximal early Bishop ash-flow tuffs (Hildreth, 1979) and distal Bishop fallout layers deposited hundreds of kilometers away from the Long Valley caldera (e.g. Izett et al., 1970).

It should be noted that even though occurring at about the same depth below the modern surface, the Smith IW-2 rhyolite and the State 2-14 Bishop Tuff are petrographically distinct. The principal difference is that, whereas the presumed Bishop Tuff is rich in broken phenocrysts (in particular fragmental quartz bipyramids; Herzig and Elders, 1988a), the Smith rhyolite is conspicuously aphyric. Nonetheless, the occurrence of the 0.76 Ma Bishop Tuff at a true vertical depth of 1704 m in the State 2-14 well does constrain the average sedimentation rate for this part of the Salton trough at about 2.24 mm/yr (Herzig and Elders, 1988a, 1988b). Combining this rate with the 1646 m drilled depth (true vertical depth of 1635 m) to the top of the Smith rhyolite flow yields an approximate age of 0.73 Ma.

This indirectly estimated age must be tested if possible by radiometric or other dating methods. Even at this juncture, however, we feel confident in stating that the Smith rhyolite must be older than the domes of the Salton Buttes (**Fig. 2**) by several hundred thousand years.

Implications for Geologic Modeling -- There are few field-wide marker beds in the Salton Sea geothermal field. Here as elsewhere in the Salton trough (e.g., Herzig et al., 1988), the fluviolacustrine clastic sequence can show only minor lithologic variation over kilometers of thickness. The Smith IW-2 rhyolite promises to address this shortcoming by providing an extensive and reliable time-stratigraphic volcanic marker horizon. The Smith rhyolite is readily identifiable visually, petrographically, and on geophysical logs, and as a marker would be very valuable for helping to constrain evolving 3-D stratigraphic and structural models for the entire Salton Sea geothermal system.

At 155 m thick, the Smith rhyolite-tuff interval is unlikely to occur only in the vicinity of the borehole. Indeed, the Vulcan IW-8 (Fig. 2) rhyolite is apparently about twice as thick as its counterpart in the Smith Well. Even if these buried rhyolitic lavas were particularly viscous when erupted (unlikely, as they are aphyric), at these thicknesses they could easily be several km^2 in extent. In fact, they could be analogous to the volcanic rocks of the Coso rhyolite dome field (Bacon et al., 1980; Duffield et al., 1980), 390 km to the north-northwest

Of course, it would be risky to assume *a priori* that voluminous felsic volcanic eruptions like those represented by the Smith IW-2 rhyolite occurred at only one stage above the Salton Sea spreading center. Extreme care must be taken, using multiple compositional and textural criteria, to ensure that all penetrations of this potential marker horizon do in fact represent the same volcanic deposit.

Even so, the Coso analogy may be especially apt for the Smith and Vulcan rhyolites, since Coso's large and abundant tuff rings and cones are in part phreatomagmatic in origin (Bacon et al., 1980). We therefore conclude by asserting that a buried rhyolite dome field up to the size and volume of the one at Coso is by no means unlikely to be found at depth in the eastern Salton Sea geothermal system.

ACKNOWLEDGEMENTS

This study is part of a comprehensive new geologic modeling effort for the Salton Sea geothermal field being carried out jointly by CEOC and EGI. EGI's part of the study is being funded by the U.S. Department of Energy, Office of Geothermal and Wind Technologies, Grant No. DE-FG07-00ID123891). Said support does not necessarily constitute an endorsement of the views expressed in this paper.

Steve Harner, of Epoch Well Logging, Inc., is acknowledged for immediately and perceptively recognizing at the drill site that the Smith IW-2 cuttings later identified as rhyolite were conspicuously anomalous for the Salton Sea geothermal field.

We are grateful to CalEnergy for making this study possible, for essential access to key subsurface samples and data sets, and for permission to publish this paper. We thank Denis Norton, Pat Browne, and Joe Moore for carefully reviewing the manuscript on very short notice, and for their many helpful suggestions for improvement. Discussions with Pat Dobson were especially valuable for placing the new rhyolites in the appropriate regional volcanotectonic framework. Illustrations are the work of graphic artist Doug Jensen.

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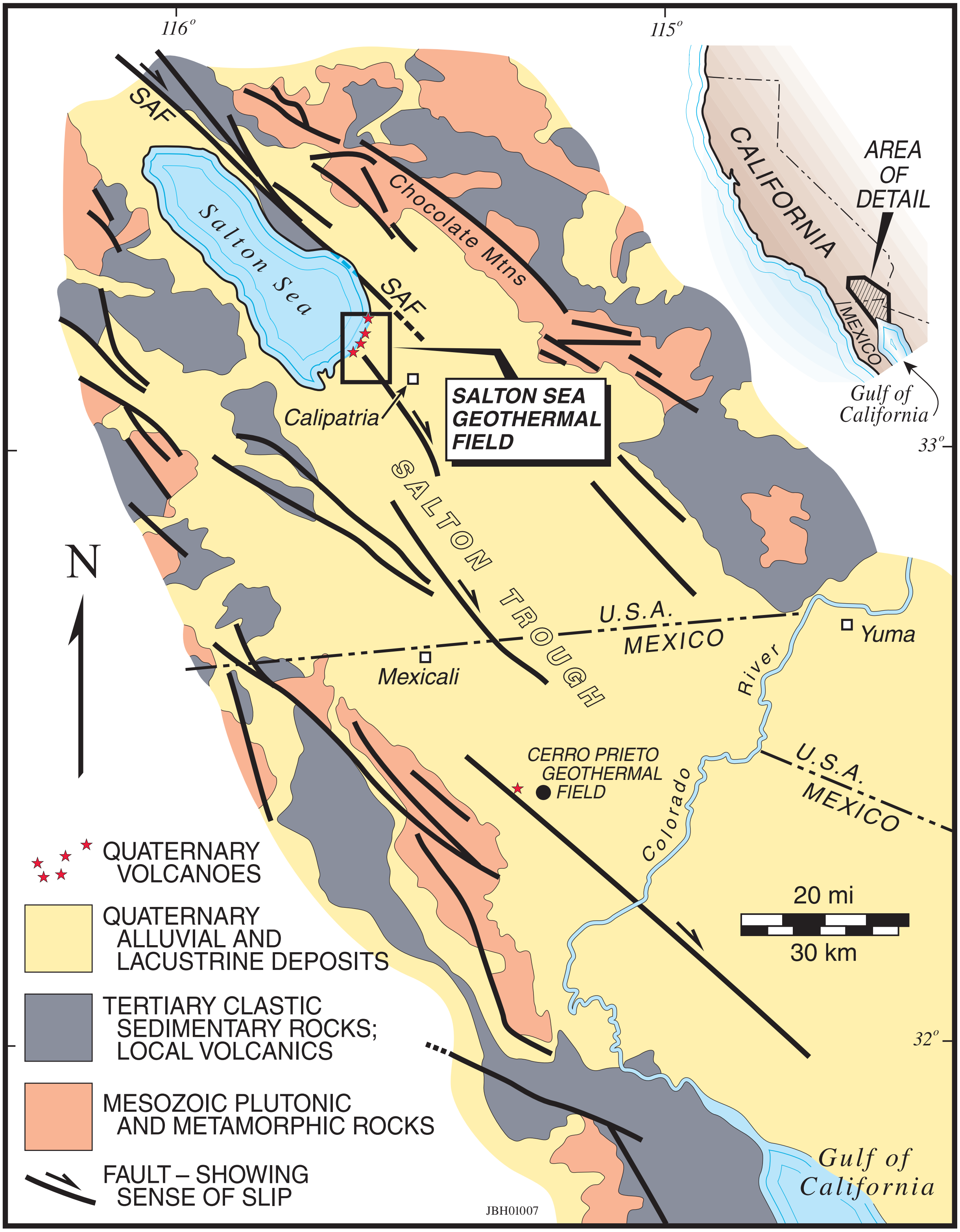

From Elders and Sass, 1988

Figure 1. Location and generalized geologic map of the Salton trough. Note the rarity of Quaternary volcanoes in this vigorously active tectonomagmatic regime; and the close association of these volcanoes with the Salton Sea and Cerro Prieto high-temperature geothermal systems.

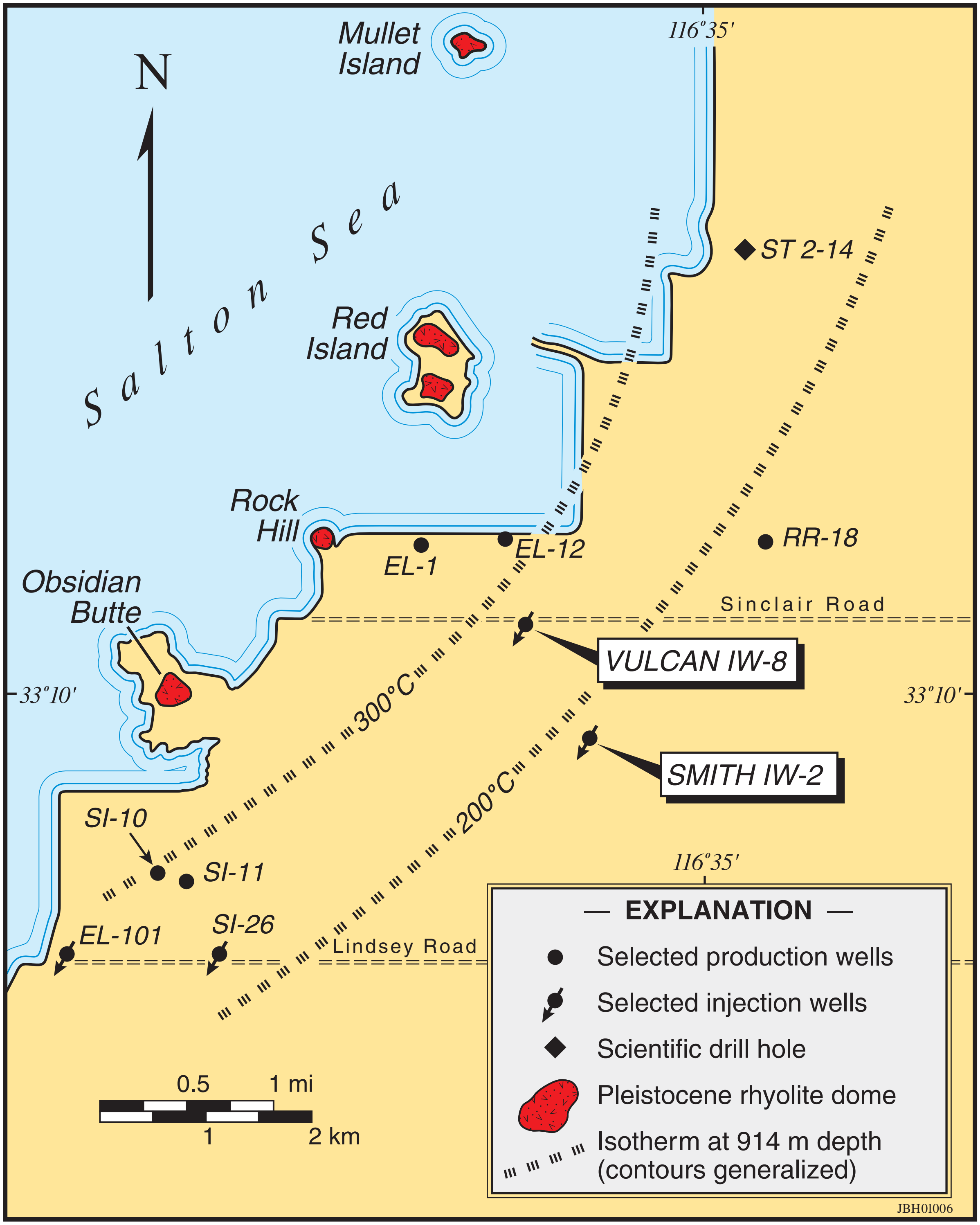

Figure 2. Map of the Salton Sea geothermal field (refer to Figure 1 for location). Quaternary rhyolite flow/dome locations and isotherms at 914 m depth are modified from Elders and Sass (1988). Salton Sea shoreline from a 1989 Unocal Corporation photomosaic. EL = Elmore; IW = injection well; SI = Sinclair; ST = State; RR = River Ranch.

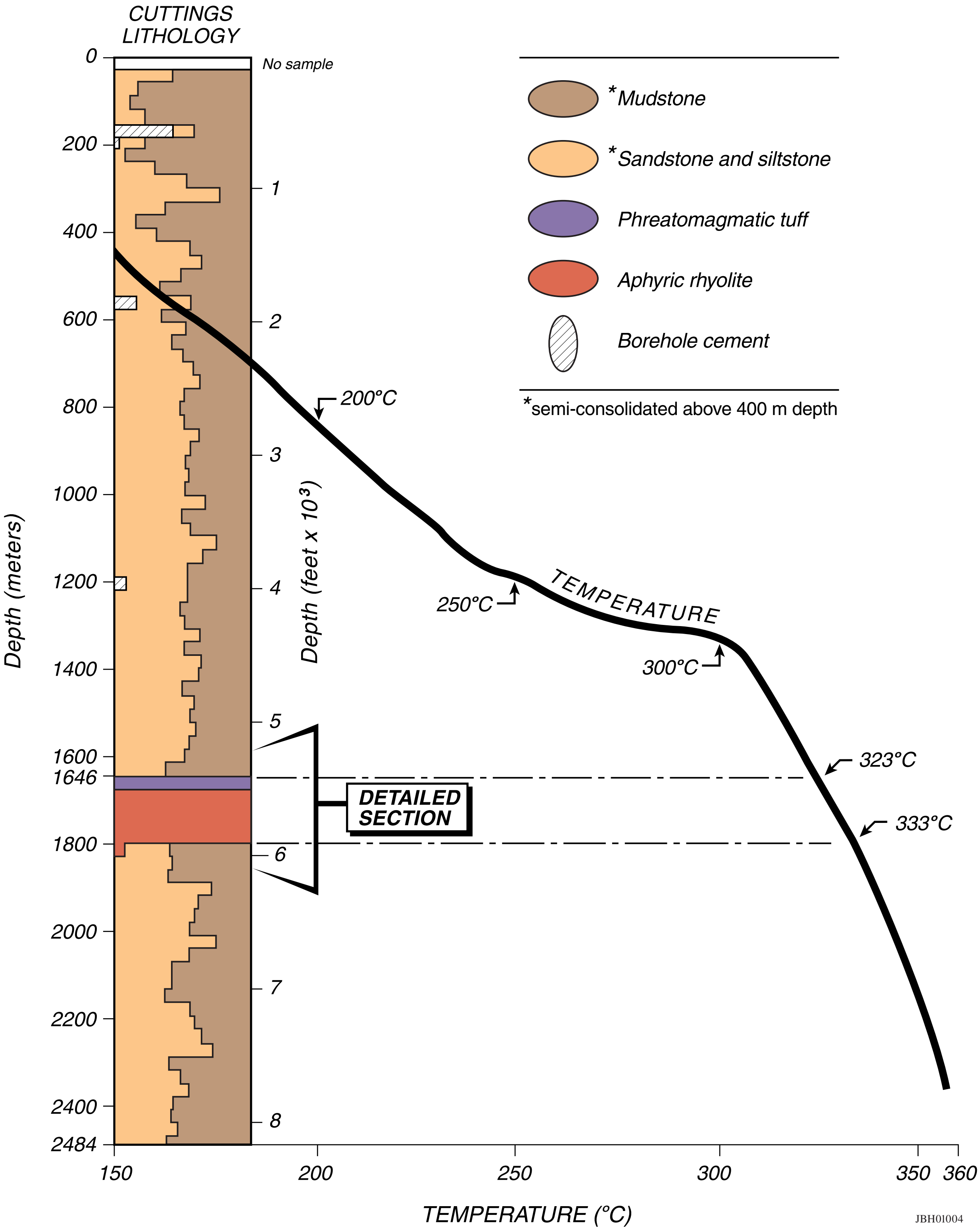

Figure 3. Generalized lithologic and temperature log for well Smith IW-2 (refer to Figure 2 for location), showing position of rhyolite flow/dome and tuff interval. Depths shown are as-drilled, but close to true vertical depths. The well is inclined generally northeastward at 6-11°; total drilled depth at 2484 m = true vertical depth of 2464 m. Data from Epoch Well Logging (1998) and this study.

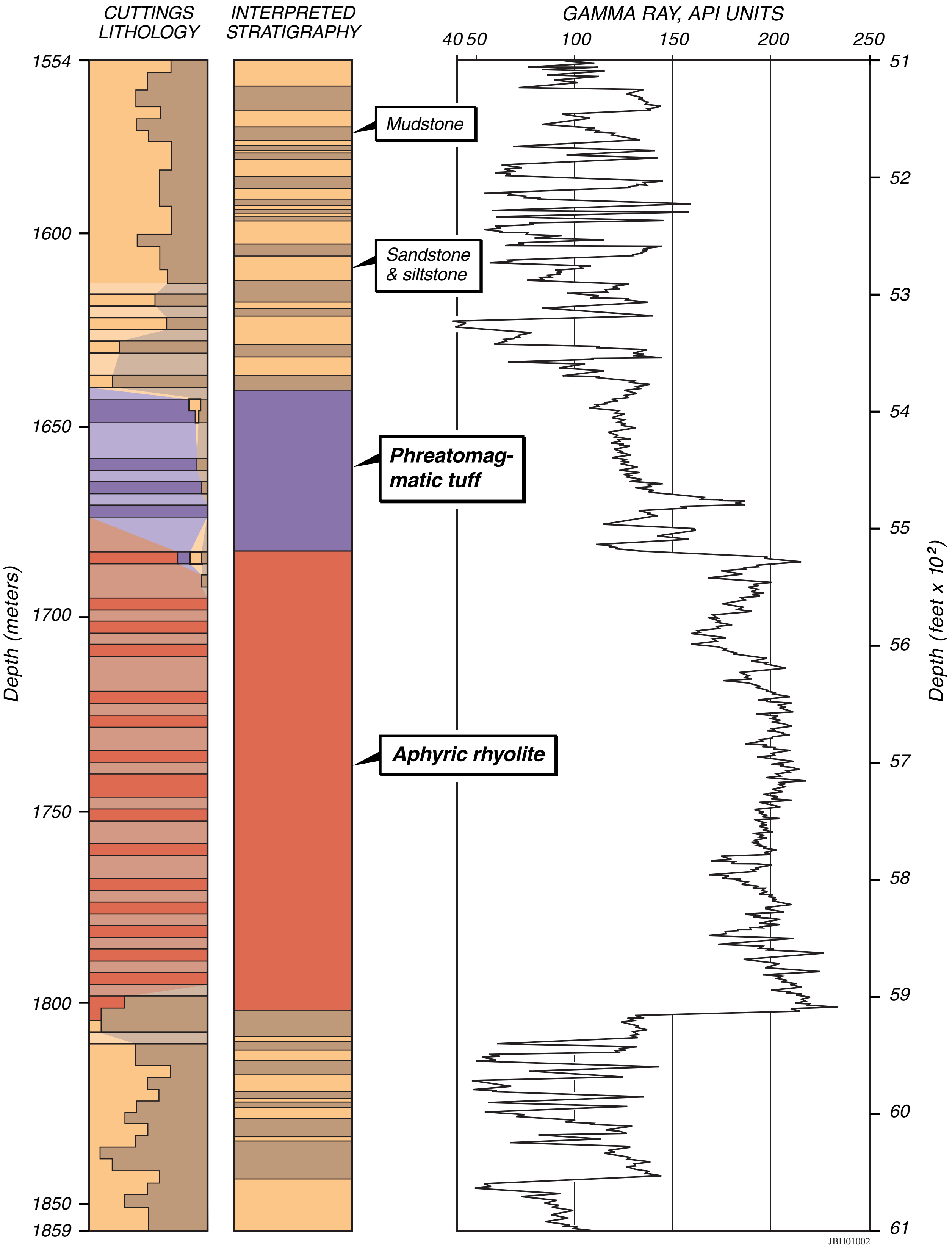

Figure 4. Cuttings lithology, interpreted stratigraphy, and gamma ray log for the Smith IW-2 rhyolitic interval and enclosing clastic strata. On column at left: thick solid intervals at top and bottom are from Epoch Well Logging (1998) geologic mud logs; and thin horizontal bars and intervening interpolations (pale patterns) are based on detailed petrographic analysis (this study).

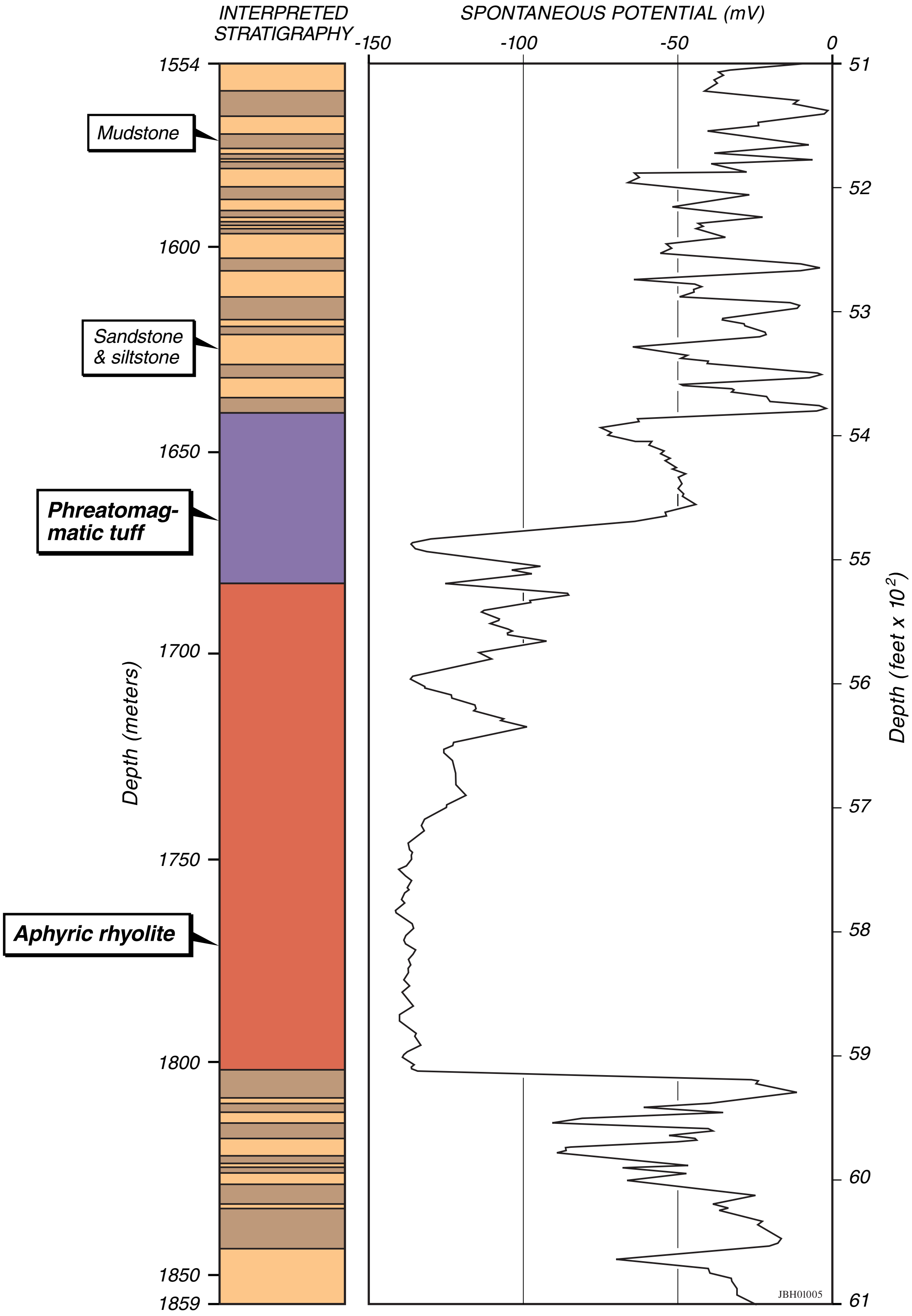

Figure 5. Interpreted stratigraphy (refer to Figure 4) and spontaneous potential log response through the Smith IW-2 rhyolitic interval.

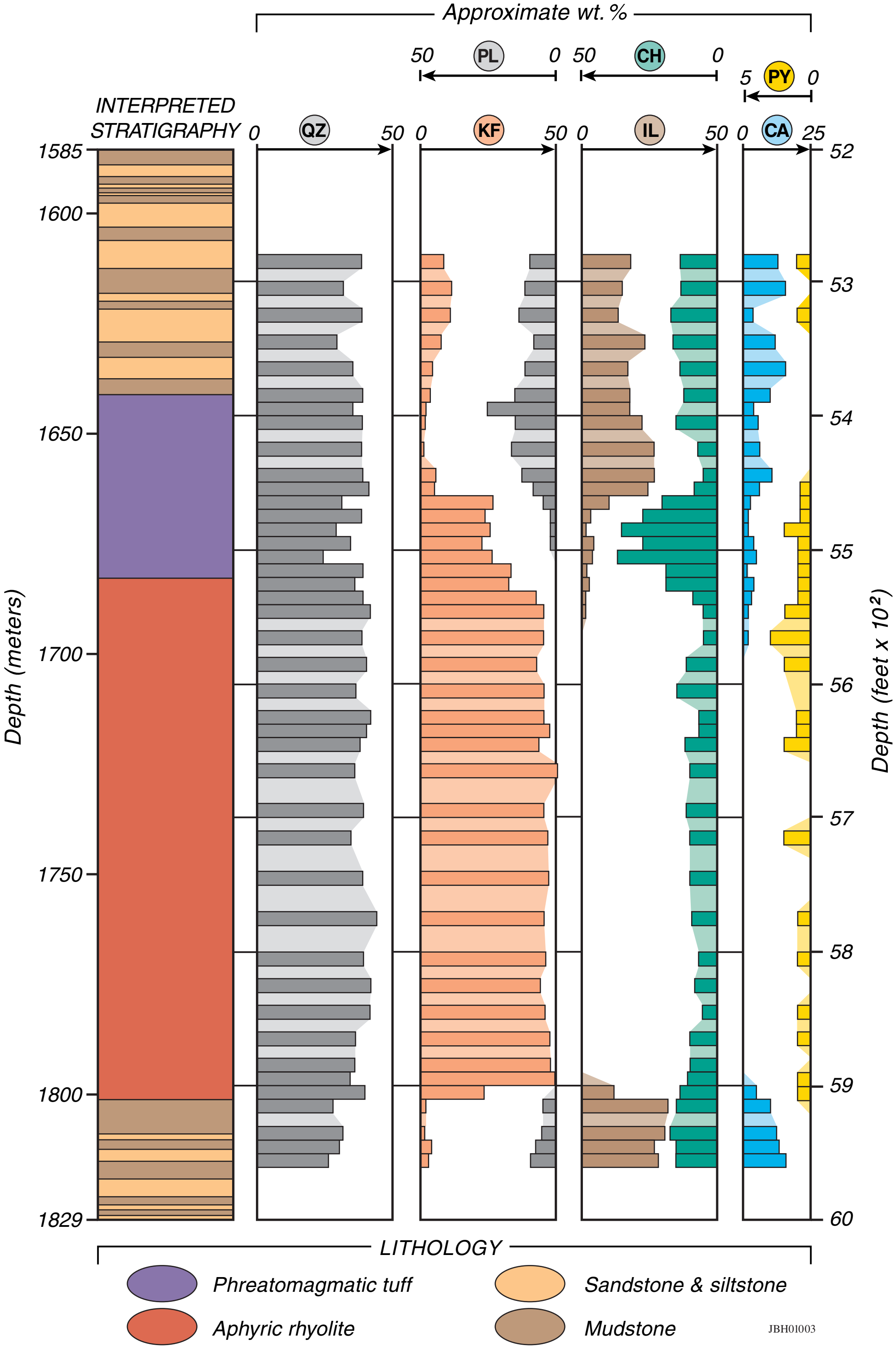

Figure 6. Mineralogy of the Smith IW-2 rhyolitic interval and enclosing clastic strata, from X-ray diffraction and petrographic analysis. Abbreviations as follows: CA = calcite. CH = chlorite. IL = illite. KF = potassium feldspar (dominantly secondary adularia through the rhyolitic interval). PL = plagioclase. PY = pyrite. QZ = quartz.

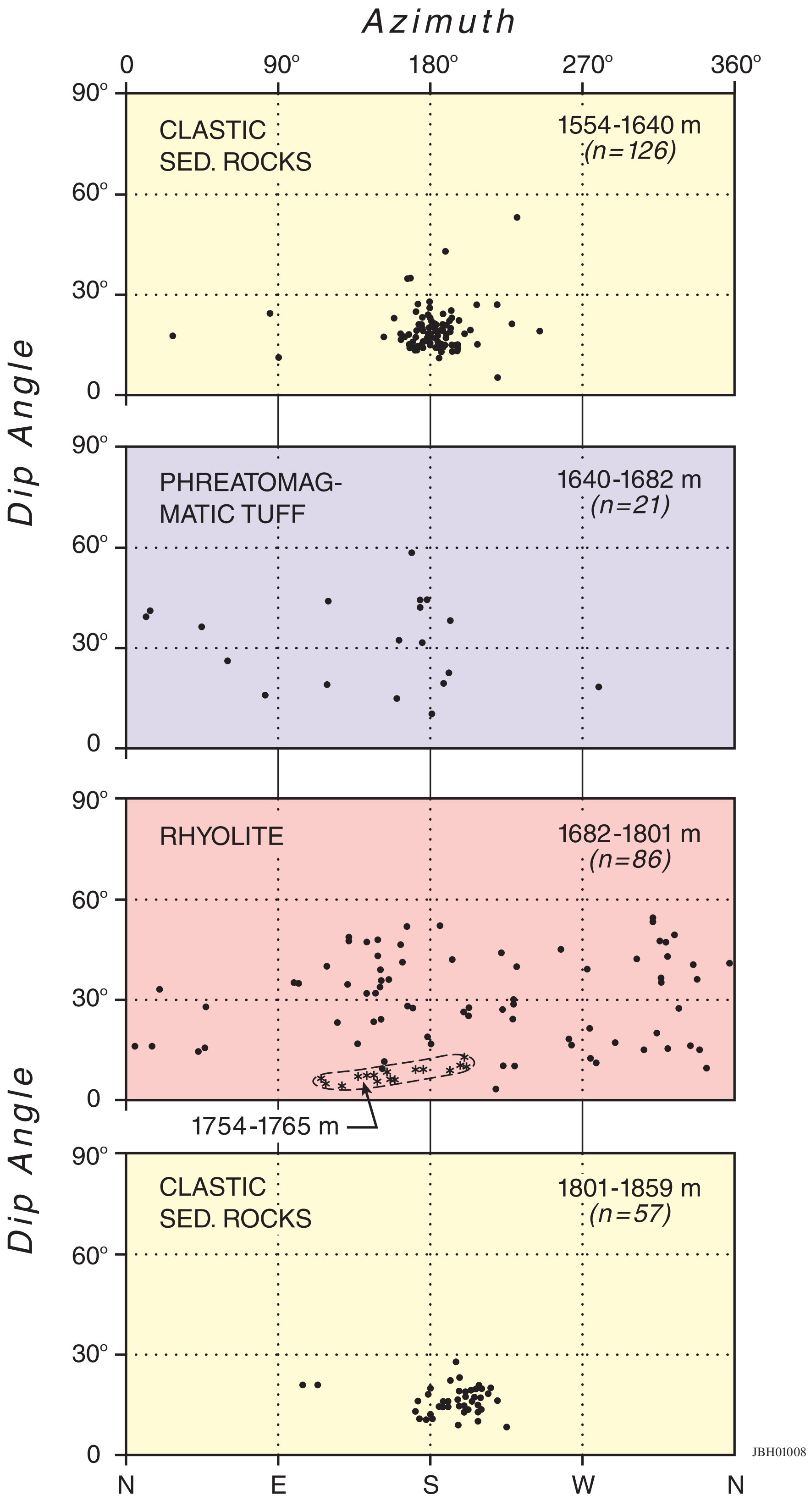

Figure 7. Dip vs azimuth plots for the Smith IW-2 rhyolite and tuff interval as well as enclosing clastic strata, as taken from Schlumberger (1998) fullbore microscanner (dipmeter presentation).

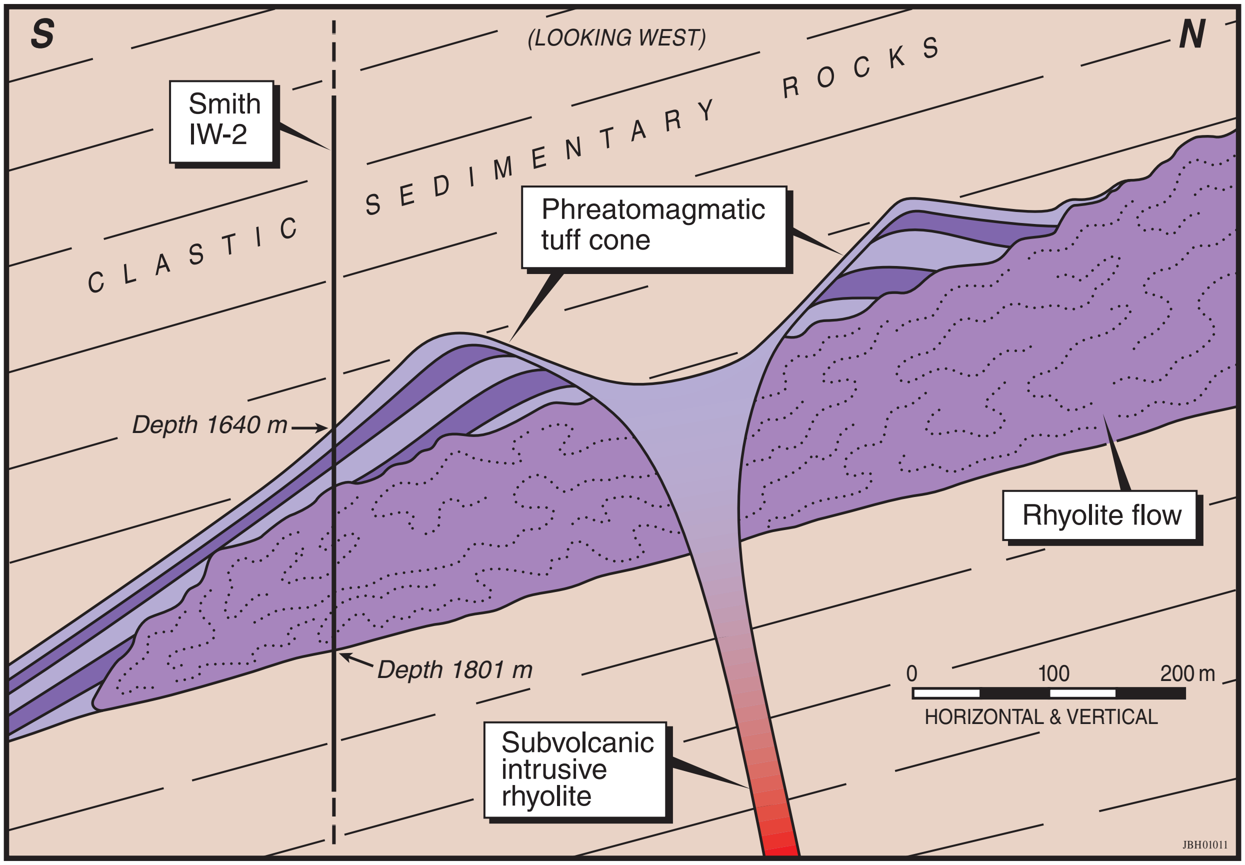

Figure 8. Geologic interpretation of the Smith IW-2 rhyolite and tuff interval.