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THE AWIBENGKOK CORE RESEARCH PROGRAM, pt. II – STRATIGRAPHY, VOLCANIC FACIES, AND HYDROTHERMAL ALTERATION

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ABSTRACT

More than 1 km of continuous core from well Awi 1-2, in the eastern part of the Awibengkok geothermal field, Indonesia, provides a clear record of the late Cenozoic volcanic succession as well as multiple episodes of fracturing, brecciation, and hydrothermal alteration. The core, spanning the depth range 762-1830 m, samples the main parts of two stratigraphic "packages" present throughout much of the field. The upper package comprises principally dacitic-composition flow-dome rocks, lahars, and tuffs. The deeper, andesitic package is made up of thinly interstratified flow rocks, tuffs, and lahars. The latter deposits dominate the upper portions of the packages, a relationship that in both cases could reflect declining volcanism coupled with erosion of initially constructive volcanic edifices.

The core samples the lower part of the geothermal system's clay-rich caprock as well as underlying propylitically altered volcanics which reach their shallowest levels in this part of the field. Abundant and pervasive smectite, illite/smectite, and chlorite in the caprock seal the geothermal system from incursion by overlying groundwaters. Some massively clay-altered tuff layers in the cap, particularly at its base, form "ductile lids" which appear to have resisted rupturing by flexing and shearing, thereby maintaining integrity of the hydrologic seal. Textural and mineralogical evidence indicates that much of the clay alteration affecting these tuffs occurred at and near the surface in response to weathering. Rocks of the propylitic zone are near-completely altered to various combinations of epidote, chlorite, illite, calcite, adularia, wairakite, titanite, and pyrite. The same minerals along with quartz and localized anhydrite and prehnite (1) abundantly fill and line dissolution vugs and high-angle fractures; and (2) tightly cement generally high-angle hydrothermal breccia bodies. The commonly spectacular breccias and fracture fillings/linings are not systematically related to modern thermal fluid entries. The single large and two minor hot water entries in the corehole are in recently fractured rocks, some mineralized and some not. The largest fluid entry is additionally distinctive in containing euhedral chalcopyrite crystals with abundant adularia, but without the otherwise ubiquitous vein epidote and chlorite.

1. INTRODUCTION

Late in 1995, Unocal Geothermal Indonesia (UGI) and the U.S. Department of Energy (DOE) collaborated to obtain 1085 m of continuous core from the eastern portion of the high-temperature, liquid-dominated, 330MWe Awibengkok geothermal field in West Java, Indonesia (Stimac and Sugiaman, pt. I, this volume, their Figure 1). This core is one of very few of such great length and continuity both retrieved from an active "andesitic" hydrothermal system and available for non-proprietary research. Under the terms of the UGI-DOE joint venture, a split of the core was shipped in 1998 to the USA, where, along with a voluminous accompanying database supplied by UGI (Anderson, 1996), it has since been the focus of the DOE-sponsored Awibengkok research project (Hulen and Anderson, 1998).

The project, coordinated by the Energy & Geoscience Institute (EGI) at the University of Utah, involves a multidisciplinary research team drawn from universities as well as U.S. governmental agencies and national laboratories. Even the project's preliminary results (GRC, 1999) have have shed new light on (1) the mechanisms by which andesitic geothermal systems originate, evolve, and ultimately wane; and (2) the means by which these systems can be found and profitably developed with minimal environmental impact. This paper details the fundamental aspects of the Awibengkok core – lithology, stratigraphy, fracturing and brecciation, hydrothermal alteration, and vein mineralization (Fig. 1) – as these variables pertain to past and present high-temperature thermal-fluid flow regimes. Supporting data from nearby wells strengthen inferences based on the core and applied to the broader Awibengkok geothermal system.

The core was retrieved from the so-called "ultimate corehole" completed as one of multiple and variably ramifying segments drilled from the Awi 1-2 well pad (Fig. 1). The near-vertical Awi 1-2 corehole segment spans the depth range 762-1830 m. Based on lost-circulation zones, temperature-pressure-spinner data, and temperature-gradient logs, the corehole penetrated only one major commercial-quality thermal-fluid entry, at a depth of 1676-1677 m.. A portion of our research effort has been aimed at discovering ways in which this entry differs from several of its noncommercial counterparts, and how all of these entries depart from similar yet impermeable intervening strata.

2. STRATIGRAPHY AND VOLCANIC-FACIES INTERPRETATION

The volcanic succession hosting the Awibengkok geothermal reservoir is several km thick and comprises flow rocks, tuffs, lahars, epiclastic sediments, and hypabyssal intrusives ranging in composition from rhyolite to basalt and in age from Miocene to Recent (Stimac and Sugiaman, this volume, their Table 1). This accumulation has been divided into three formations, only the middle of which was penetrated by the Awi 1-2 corehole. The middle formation consists of andesitic and dacitic volcanics representing "pre-modern and early-modern cone construction (Stimac and Sugiaman, *ibid.*)"; the age is probably 1-2 Ma.

On the basis of compositional and textural criteria, the portion of the middle volcanic formation penetrated by the Awi 1-2 corehole can be subdivided into two informal "packages" and five stratigraphic zones (Fig. 2). The upper package consists of a thick dacite unit encased above and below by andesitic lahars (zones 1-3). The lower package consists of a massively layer-silicate altered andesitic tuff (zone 4) and an underlying sequence of interstratified andesitic flows, tuffs, and lahars.

Zones 1 and 3, consisting of andesitic lahars, enclose the thick, Zone 2 quartz-, plagioclase-, and biotite-phyric dacite lahars, flow rocks, autobreccias, and tuffs (both fallout and ash-flow). The sequence is intrepreted as a flow-dome complex and associated tephra with related erosional products. Zone 2 defines the so-called "middle dacite", an important marker horizon in this part of the field (Stimac and Sugiaman, this volume). As mapped in Awi 1-2 and nearby wells, the unit has an irregular and steeply convex upper surface, and is probably a flow-dome comnplex. Based on Formation MicroScanner (FMS) interpretations (Shemeta, 1995), tuffs in the Awi 1-2 middle dacite have the steepest average dips (10-25^{o} SW) in the corehole. This could reflect deposition of the tuffs on steep domal flanks.

Zone 4 is a gray-green to maroon, entirely layer-silicate-altered (see ensuing section), andesitic tuff horizon. Core freshly retrieved from this unit was disrupted by myriad microfractures of unknown origin and with highly convoluted surfaces. These ruptures caused the rock to break up into 2-3 cm chunks upon liberation from the core tube. Although this zone is thin (21 m), it serves as a significant barrier to thermal fluid ascent.

Most rocks in the zone 4 tuff sequence are now >95% massive microcrystalline layer silicate – mixed-layer clays and chlorite for the most part (more details below). Relict textures including abundant, flattened pumice lapilli indicate that the rocks are either fused fallout tuffs or ignimbrites. We favor the latter origin, as the lapilli in general are matrix-supported and are not in contact with one another as they would likely be in a fused deposit.

The zone 4 tuff has clearly served as a "ductile lid" on the more brittle volcanics hosting the underlying commercial geothermal reservoir. It is disrupted by bedding-parallel shears and tight gouge zones, the presence of which indicates that applied stresses have been accomodated mostly by flexure and slip.

Propylitically altered Zone 5 andesitic volcanic rocks host the upper portion of the commercially productive Awibengkok geothermal system. Relatively thick lahars predominate in the upper one-third of the zone. The lower two thirds comprises literally hundreds of thinly interstratified flow rocks, autobreccias, lahars, very rare sandstones, and tuffs of both fallout and ash-flow origin. FMS log interpretation indicates that the beds of this unit dip mostly to the west and northwest at <10^{o}. The foregoing relationships suggest that the zone 5 units accumulated in a setting distal to a stratocone or composite volcanic center.

Microdiorite Porphyry – Spanning the depth range 1690-1733 m is the only significant and unambiguous intrusive rock encountered in the Awi 1-2 corehole. The rock is a microdiorite to fine-grained diorite porphyry with large, euhedral pyroxene phenocrysts in a microcrystalline matrix of plagioclase, pyroxene, and minor primary quartz with accessory titanite. The upper and lower contacts of the microdiorite are subhorizontal and subparallel with enclosing volcanic units. There are subtle but apparent chill zones at the top and bottom of this interval, and we interpret it to be a thick sill. It is probably a subvolcanic counterpart of the many surficially emplaced andesitic units found in the Awibengkok volcanic sequence. The sill probably intruded and wedged open a particularly ductile tuff horizon, as that lithology, sheared, deformed, and attenuated, is present at the pluton's top and bottom contacts alike.

Volcanic Facies Analysis – The Awi 1-2 corehole provides nearly complete sections of two related packages of volcanic rocks, each thought to represent an eruption-erosion cycle. The dominantly andesitic lower package (Fig. 1) contains principally lahars in its upper third, and thinly interstratified flow rocks, lahars, and tuffs in it lower two thirds. This rock composition and assemblage is consistent with a subaerial depositional environment on the outer flank of an andesitic stratocone or multi-vent center (Cas and Wright, 1987). In such an environment, thinly bedded lavas, tuffs, and lahars would dominate the constructional phase of the edifice. With the waning of volcanism, erosion would prevail, and deposition of reworked debris in the form of lahars would become the norm. The shallow north and northwest bedding dips inferred from FMS imagery for the lower package are consistent with location on the outer flank of a stratocone or composite center located to the south-southeast. The few steeper dips recorded for lower-package tuffs may reflect fallout mantling local topographic irregularities.

3. FAULTS, FRACTURES, AND BRECCIAS

All thermal-fluid entry zones encountered by the Awi 1-2 corehole (Figs. 1 and 2) show evidence of relatively recent fracturing. None of these zones is remarkable in terms of intensity of hydrothermal alteration or vein mineralization. The entire core is more or less altered and veined, and numerous intervals are far more dramatic in this regard than the fluid conduits themselves. It is apparent that even though commonly open and porous where cut by Awi 1-2, these veins are actually tightly sealed fractures at larger than core scale. Reactivation of the veins by fracturing appears required for throughgoing permeability development.

Shemeta (1995) has interpreted, from FMS imagery, the orientations of large, "open fractures" penetrated by the Awi 1-2 corehole and production sidetrack (Fig. 1). Implicitly included in this set of structures are rare, unmineralized fractures as well as the more common, strongly mineralized, vuggy open veins. Virtually all of these features are steeply dipping, and most strike clearly north to north-northeast. From the foregoing relatioships it can be inferred tentatively that the tectonic stress regime controlling fracturing and fluid flow today is essentially the same which has prevailed since inception of the Awibengkok hydrothermal system.

Hydrothermal Breccias are also common throughout the core (Fig. 2; Hulen et al., 1999**)**. Like the veins, many of these breccias are high-angle features, but some are subhorizontal. The latter may represent aprons of debris accumulated around hydrothermal eruption vents. The full range of classical hydrothermal breccia textures are represented in the core – for example, rounded clasts in rock-flour matrices; jigsaw-puzzle aggregates; sheeted fractures. All of these breccias are intensely mineralized and altered, and like the veins with which they occur, they are tightly sealed by secondary phases at scales larger than the corehole diameter.

4. HYDROTHERMAL ALTERATION AND MINE-RALIZATION

The entire volcanic sequence penetrated by Awi 1-2 is intensely hydrothermally altered. Based on data from existing wells, the corehole targeted and penetrated three of the Awibengkok geothermal system's major alteration zones – argillic, argillic-phyllic, and propylitic.

The corehole penetrated only the base of the thick argillic alteration zone (Fig. 2), dominated by smectite, chlorite, calcite, and microcrystalline titanite, the latter developed by reaction of groundmass plagioclase and ilmenite or titanian magnetite. X-ray diffraction (XRD) analysis of the smectite indicates that it is free of illite interlayers, and that it has a basal spacing (air-dried) of 14-15A. Thus, calcium and magnesium are the likely principal interlayer cations (Hulen and Lutz, 1999). Primary mafic minerals have been completely chloritized, but much of the primary phenocryst plagioclase survives as "islands" in the argillic matrix.

The uppermost dacitic ash-flow tuff in zone 2 (Fig. 2) preserves important evidence about the means by which most tuffs in the Awibengkok volcanic succession may initially be converted to secondary layer silicates. The tuff's large biotite phenocrysts have been altered to vermiculite, which displays a characteristic curved and highly-expanded book texture. The matrix surrounding these accordion like vermiculite books is undeformed, so their expansion could only have occurred in the absence of significant confining pressures (certainly the pressures likely to prevail at the modern burial depth of this unit). We conclude that the vermiculite formed in the weathering environment soon after this tuff was erupted. Smectites and perhaps kaolin could readily have developed at the same time. A suggested modern analog is the Holocene "Orange Tuff" blanketing the surface at Awibengkok (Stimac and Sugiaman, this volume). This tuff, a coarse pumice fallout deposit, is already extensively clay-altered. One can readily imagine these tuffs in the future as buried blankets of clay. Progressively deeper burial with rising temperature will, depending upon water chemistry, induce pure smectites to alter to mixed-layer illite/smectites (I/S; e.g. Reyes, 1990). Conceptually, however, at some point the sparingly permeable layer-silicate horizons will compact and alter to the point that no further illitization of smectite can occur (fluids can no longer access the I/S to effect the smectite-to-illite transformation. This gives rise to deep layer-silicate assemblages which are slightly to dramatically out of equilibrium with respect to corresponding modern temperatures.

Good examples of the above-described phenomenon are represented in the argillic-phyllic zone, which extends from the base of the argillic zone to the top of the propylitic (Fig. 2). Tuffs in this zone contain, in addition to chlorite, abundant I/S (from 10-80%). The tuff at the base of this zone contains up to 45% interlayer smectite, a figure which according to modern clay-mineral geothermometry (e.g. Reyes, 1990) corresponds to a formation temperature of about 150^{o}C. This is roughly 100^{o}C less than the modern temperature at the depth of this tuff. Such a profound discrepancy can only be due to the tuff having acquired its I/S composition at the lower temperature, then having been tightly sealed against further fluid incursion as the temperature subsequently and dramatically increased. Above the basal tuff, the argillic-phyllic zone rocks are altered to I/S with interlayer smectite contents (10-30%) more appropriate for the corresponding formation temperatures.

In sharp contact with the argillic-phyllic zone is the propylitic alteration zone, which extends from there to total depth at 1830 m and includes the hole's major thermal fluid entry at 1677 m (Fig. 2). Typical for this style of alteration, the Awi 1-2 propylitic zone (which encompasses all of zone 5) is characterized by the secondary-mineral assemblage chlorite-epidote-calcite-illite-pyrite with variable amounts of wairakite, hematite, anhydrite, and adularia, with localized minor prehnite. Chlorite is concentrated at the sites of original mafic minerals. Epidote occurs mostly at these sites and, along with illite, in phenocrystal plagioclase phenocrysts. The latter is the most refractory primary mineral in the propylitic zone, and commonly is preserved as "islands" in the otherwise altered crystals. Adularia is erratically distributed, occurring principally as selvages flanking veinlets of the same mineral intergrown with quartz, wairakite, epidote, titanite, chlorite, and calcite in various combinations. This is a very typical propylitic zone in all aspects but one: it is locally and extensively pocked with prominent, secondary-mineral-lined dissolution cavities, some of which reach several cm in diameter. The cavities are characteristically lined with prismatic epidote and quartz, and many are filled with late-stage, coarse rhombic calcite crystals.

The microdiorite porphyry sill of zone 5 (Fig. 2) is the propylitic regime's least altered rock body. Large pyroxene phenocrysts in the zone are only weakly altered (mostly to chlorite). The less altered portions of the sill are toward its interior, suggesting that hot fluids simply could not penetrate effectively into the heart of the pluton. In general, dikes and sills in the Awibengkok geothermal system are thought to act as local barriers to fluid flow, dividing the reservoir into discete sectors.

5. VEIN AND BRECCIA MINERALIZATION AND PARAGENESIS

The entire rock column represented by the Awi 1-2 core is laced with high-angle hydrothermal veins and cemented hydrothermal breccias, many of which as we have noted are vuggy and conspicuously open at the scale of the core, but few of which (and only where recently fractured) correspond to modern thermal-fluid channels. The veins range from nearly invisible megascopically to 5 cm in true width, although the majority are <5 mm wide. Their secondary-mineral paragenesis is complex and repetitive and can be characterized only in general terms, since exceptions to the prevailing sequence of mineralization are by no means uncommon occurrences.

Based on fracture- and vug-filling and cross-cutting textures, the earliest secondary minerals precipitated in the Awi 1-2 rocks were calcite and anhydrite, probably representing precipitation from formation fluids in response to heating (the two phases have retrograde solubilities; Moore and Norman, 1999). The carbonate and sulfate were succeeded by a much more abundant assemblage comprising quartz, epidote, adularia, pyrite, and sericite in various combinations with local traces of actinolite and grossular. Calcite-wairakite veins were then emplaced in newly created fractures and remaining voids, only to be superceded by quartz-epidote-sulfide veins and vug-linings. Wairakite was again deposited, then still younger quartz-epidote veins, and, finally, the coarse, blocky, rhombic calcite described above. Fluid-inclusion evidence indicates that some of the early calcite was precipitated at about 270^{o}C from highly saline (16-18 equivalent weight % NaCl) fluids, possibly magmatic in origin and derived from the microdiorite sill (Moore and Norman, 1999). Later inclusions in quartz, epidote, and wairakite have lower salinities, up to 3.5%, more typical of the modern hydrothermal fluid regime; they exhibit a range of temperatures and gas ratios indicating mixing of geothermal brine and steam-heated meteoric water. Hydrothermal breccias previously described in this paper are cemented by various combinations of quartz, wairakite, epidote, chlorite, pyrite, and other minor phases. Wairakite is particularly abundant in these breccia cements and appears to be largely responsible for their present impermeability (Hulen and Lutz, 1999). .

A potentially important finding of our alteration and vein-mineral investigation is the fact that the major fluid entry at 1677 m (Fig. 1) is the only interval in which the veins are dominantly quartz-adularia-pyrite without many of the other pore-filling phases discussed above. The abundant (Fig. 2) adularia is coarse (up to 2 mm), and the quartz distinctly acicular. Another mineral confined to this particular zone is chalcopyrite, deposited locally in equilibrium with the pyrite. The chalcopyrite forms euhedral tetrahedra up to several mm in diameter. Fluid-inclusion gas compositions for this sulfide indicate that it was precipitated from an evolved meteoric fluid (Moore and Norman, 1999). The field-wide significance of the quartz-adularia-sulfide vein assemblage confined to the large entry is still under investigation.

DISCUSSION AND CONCLUSIONS

The Awibengkok geothermal field, although at 330 Mwe larger than most, produces power from a very typical island arc hydrothermal system. The alteration zoning is classical, with more ductile, layer-silicate-rich caprocks above deeper, brittler, propylitically altered volcanic packages. The presence of surficially "pre-altered"clay-rich tuff horizons serving as hydrologic barriers has to our knowledge not been previously reported. We believe that this mechanism, however, is of crucial importance in other tropical geothermal systems around the world.

Another significant (and to us initially counterintuitive) finding of this study, is that the spectacular veins and hydrothermal breccias penetrated by the corehole are in fact anti-correlated with modern-day thermal fluid channels. Upon reflection, this should probably not have been a surprise, since the vein-lining minerals themselves signal good potential for total sealing of a fracture at "choke points" or constrictions along the controlling fractures. For the most part, it is only when such veins are extensively refractured that they can serve once again as throughgoing hot-water conduits.

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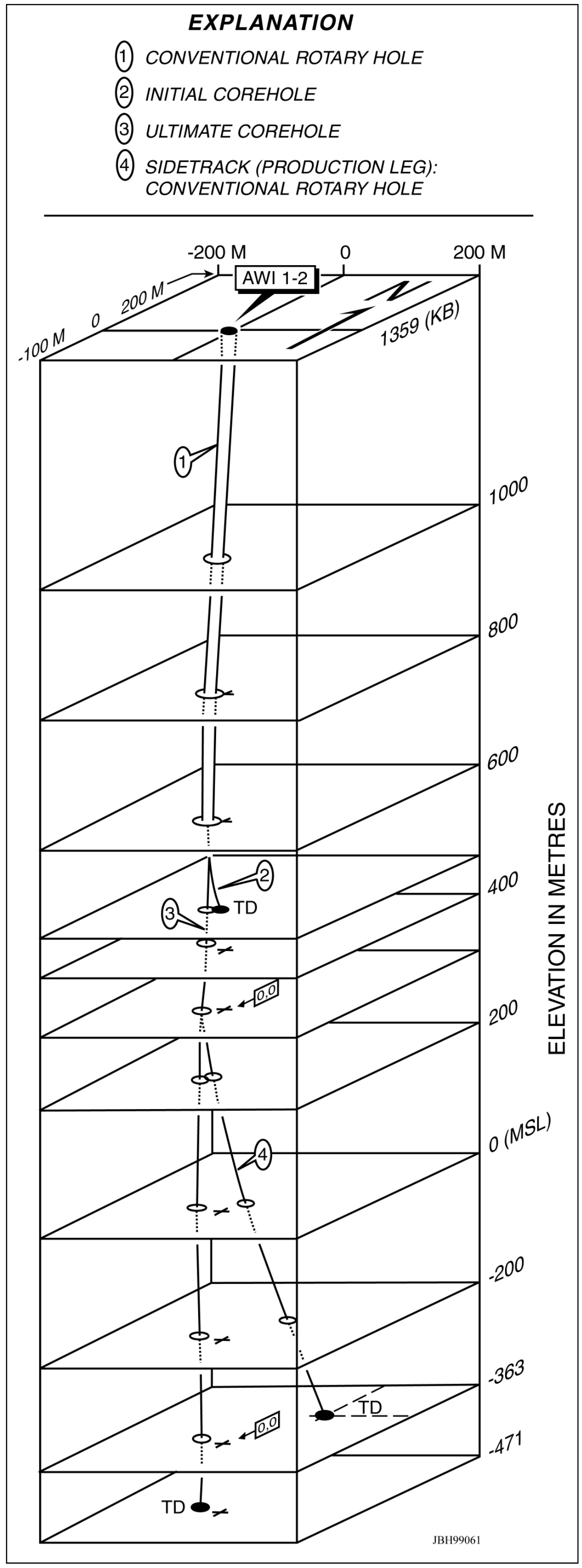

Figure 1. Diagram showing configuration of corehole Awi 1-2 relative to other "legs" completed from the Awi 1-2 well pad.

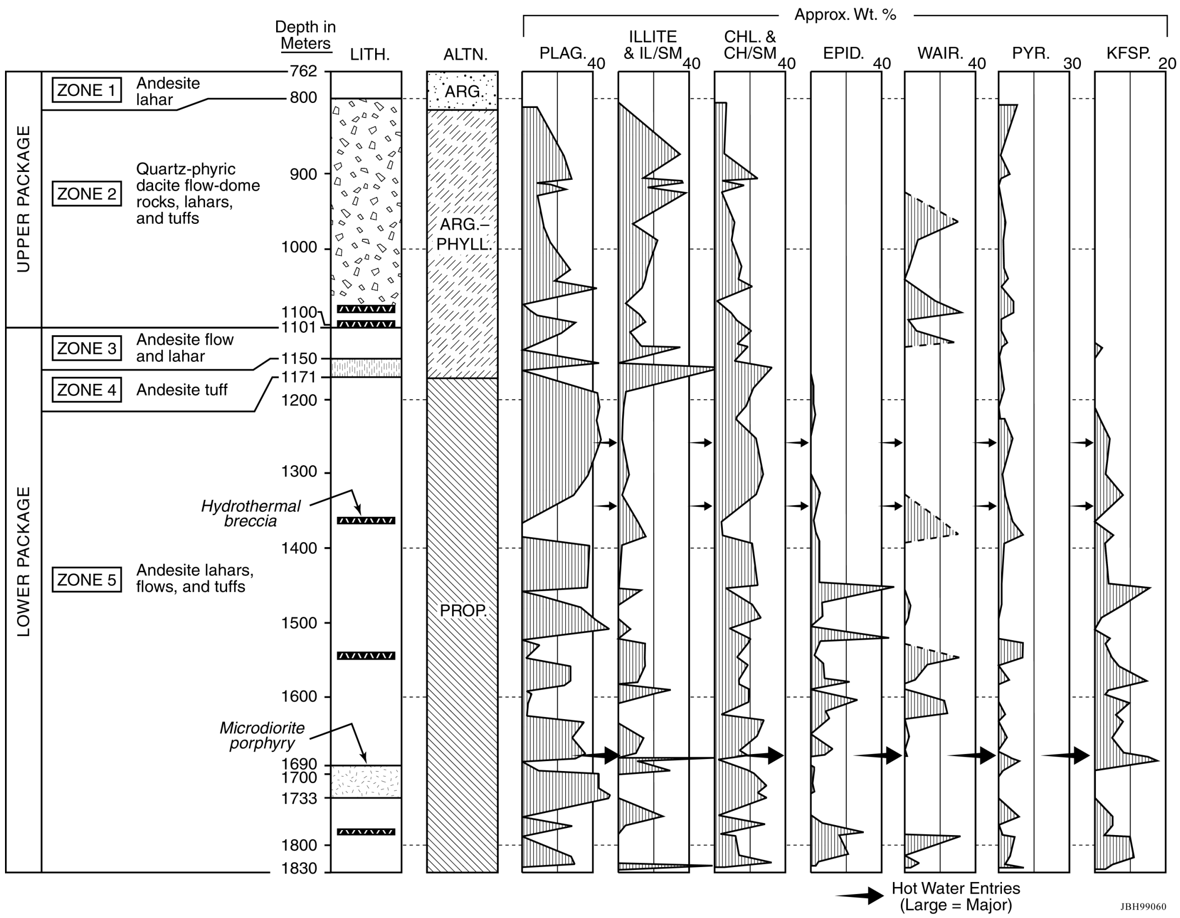

Figure 2. Summary stratigraphic, lithologic, fluid-entry, and alteration log for corehole Awi 1-2.