Geothermal Resources Council, TRANSACTIONS, Vol. 8, August 1984

MINERALOGICAL EVOLUTION OF A HYDROTHERMAL SYSTEM

II. HEAT SOURCES - FLUID INTERACTIONS.

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ABSTRACT

Interaction between hot intrusive rocks and hydrous fluids establish and maintain high-temperature hydrothermal activity. Mineralogical evidence from the Geitafell Central Volcano SE-Iceland shows that heat extraction from hot intrusive rocks may proceed via supercritical and/or superheated fluid layers into the hydrostatically controlled hydrothermal system hosted by the basaltic volcanics. In the case example two types of metamorphic and hydrothermal mineral assemblages resulted:
A. The development of an inner aureole of hornfels and an outer aureole of skarn minerals at the contacts of large intrusive bodies (gabbros); the skarn minerals being produced from supercritical fluid ($T \geq 400°C$, $P_{fluid} \cong P_{load} \leq 0.3$ Kbar) and,
B. The development of secondary mineral assemblages within shallow level intrusives, of higher grade than those existing within the host rocks at the same depths; apparently produced from superheated steam within the intrusive rocks ($T \geq 300°C$, $P_{fluid} < 0.1$ Kbar).

INTRODUCTION

Magma is generally assumed to be the source of heat in high-T hydrothermal systems, while discussions on the actual heat transfer processes extend over a few decades (review in Stefansson, 1984,(1)). One of the heat transfer mechanisms originally proposed in 1951 (2) assumes a convective downward migration of water into a hot intrusive body (3,4), referred to below as "water-penetration" process. The process results in a much faster heat transfer than is possible by assuming a thermal conduction from a magma body into a hydrothermal system. The high thermal output of some of the Icelandic high-T systems has convincingly been accounted for by assuming the "water-penetration" process effective (1,2,5). Hitherto, supporting field or drillhole evidence from the Icelandic high-T geothermal systems has not been available, while an experimental "lava-watering" project in Heimaey, since 1973, enlightened the "convective downward migration" model (1,5). In a recent study of the Geitafell Central Volcano in SE-Iceland (6,7) both field and mineralogical evidence for hot-rock/fluid interactions is available, part of which is described in the present paper.

THE GEITAFELL HIGH-TEMPERATURE SYSTEM

The Tertiary Geitafell Central Volcano was formed within the eastern-Iceland rift zone some 6-5 m.y. ago. Thus, by assuming spreading, its palaeoposition was within the Grimsvotn-Kverkfjoll region (6), presently nesting two of Iceland's most active central volcanoes and covered by the Vatnajokull ice-sheet (figure 1). The geothermal area within the Grimsvotn volcano, for instance, yields a heat flow of some 5000 MW thermal, this exceptionally high thermal output being explained by the "water-penetration" process (5). Of a figurative interest is the similar setting of the extinct Geitafell volcano to the presently active volcanoes. Two subglacially formed hyaloclastite units within the Geitafell volcano were emplaced in a similar regime that now reigns water the Vatnajokull ice-sheet. A part of the younger hyaloclastite is considered to be fed by dykes, slightly post-dating the major gabbro intrusive event (IP.2) discussed below.

In a combined study of the magmatic- and hydrothermal evolution of the Tertiary volcano, it has been shown that a high-temperature hydrothermal system was established in the wake of a major gabbro intrusion (IP.2) emplaced in the centre of the volcano at approximately 1 km depth (6,7). The high-T geothermal system is estimated to have lasted some 2-3 x 10^5 yrs, or the last quarter of the volcano's lifetime. Thermal energy was supplied by vigorous intrusive activity, the intensity of intrusive rocks ranging from approximately 10 - 100% within the exposed part of the volcano and extending some 2 km down from the palaeosurface (6,7). Twelve intrusive phases (IP. 1-12) are distinguished in the volcano, ten of which were emplaced during the active lifetime of the high-T hydrothermal system. Distinctive evidence for hot-rock/fluid interaction is found attached to IP. 2,5,6 and 10.

HOT-ROCK/HYDROUS FLUID INTERACTIONS

A contact aureole attached to the IP.2 gabbro in Geitafell consists of an inner aureole of sanidinite facies basaltic lava hornfels enveloped by an outer aureole of skarn deposits, formed in amygdales within hydrothermally altered actinolite -bearing lavas. Of importance, while not discussed

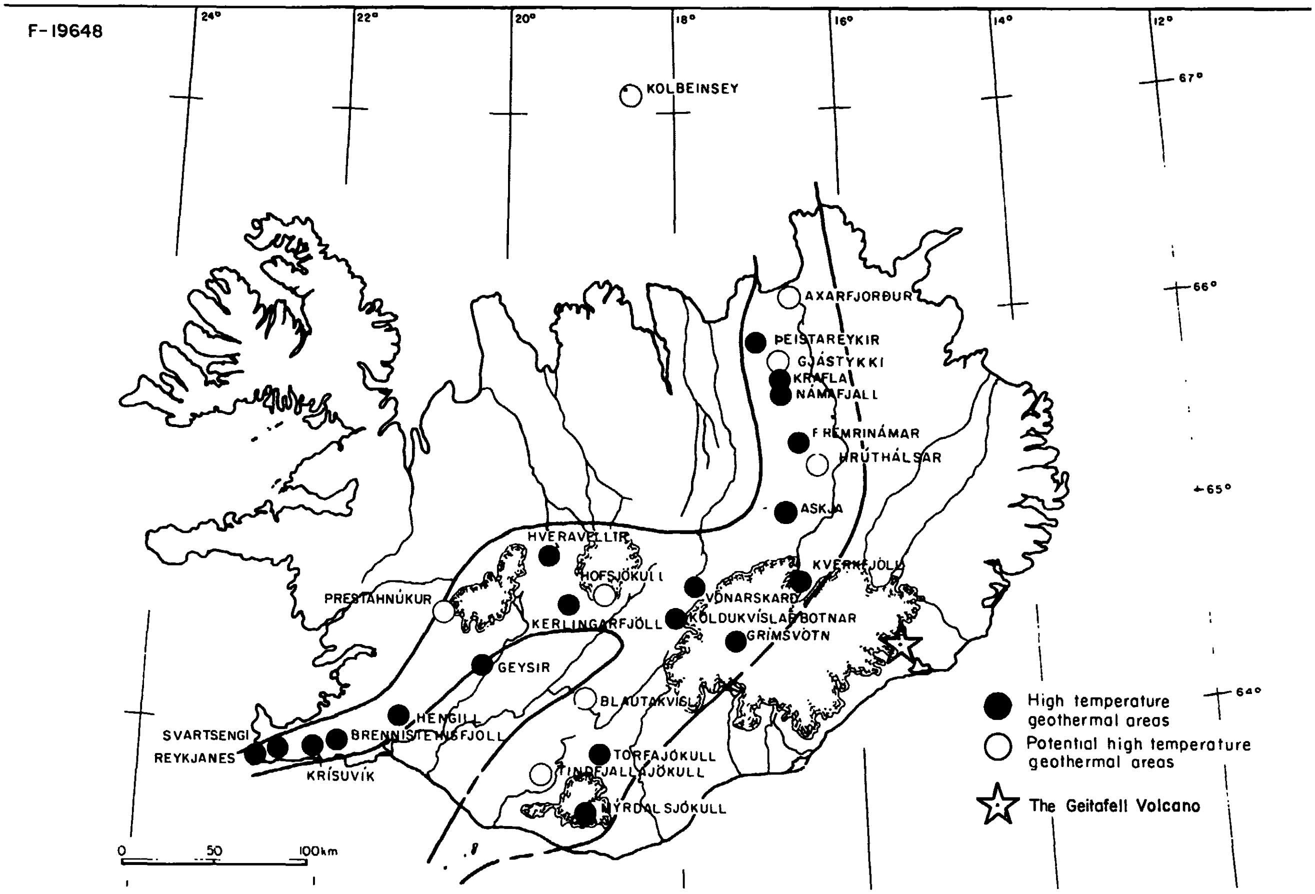

Figure 1. Location of high temperature geothermal areas in Iceland, also showing the location of the Geitafell Central Volcano, Southeast Iceland.

much further, are the exceptionally well-developed chlorite-albite amygdale halo zones formed within the outer aureole lavas, basically implying a "massive" Ca^{2+} - leaching from the contact aureole rocks. The secondary minerals discussed below have all been chemically analysed by an electron microprobe (6).

The lava hornfels consists of secondary augite-andesine-ore, which replaces the primary lava matrix, with the augite and andesine additionally forming amygdales. The metamorphic hornfels is cross-cut by igneous rocks belonging to IP.3 (basaltic dykes) and IP.4 (felsite intrusions). The igneous veins of IP.4 are not chilled against the metamorphic hornfels. This is taken to imply that the metamorphic temperature were close to magmatic, and the hornfels, accordingly, grouped within the sanidinite facies, formed at temperatures above approximately 800°C.

Information suggesting that a metamorphic fluid, rich in gases, was moving within the inner aureole appears to be preserved by rather unusual mineral veins which occur within an unmetamorphosed dyke (IP.3) cross-cutting the hornfels. The veins, which look like trails of elongated amygdales connected by narrow channels, strike nearly perpendicular to the dyke walls. Narrow wall-rock zones are found alongside the mineral veins composed of andesine and salitic pyroxene (Wo_{45-47} En_{30-34} Fs_{21-23}) whose composition suggests a genetic relation to those of the hornfelses. Closer to the vein centre the pyroxene composition ranges from salite via ferroaugite, ferrohedenbergite to hedenbergite in the vein centre. Additional minerals in the vein-wall-rock zones include garnet, actinolite, sphene and apatite, with the further addition of quartz, epidote, albite, K.feldspar, prehnite, and stilbite in the vein centre. Part of this multimineralic assemblage relates to superimposition by later hydrothermal events (6).

Not the less interesting is the outer contact aureole. By the study of amygdale infilling sequences and mineral vein systems (6,7) it is clear that prior to the IP.2 gabbro emplacement, the lava host had only suffered patchy, low-grade mineral infillings, including limonite, mud-deposits, silica, and clays. The limonite, in particular, was involved in an interesting metamorphic reaction sequence, informative on the thermodynamic conditions within the metamorphic aureole. In short, the vesicle limonite was metamorphosed via hematite to magnetite, which further reacted to produce a typical skarn mineral assemblage, namely hedenbergite$_{ss}$ - andradite. Following retrograde conditions the hedenbergite was partly replaced by andradite, which contains

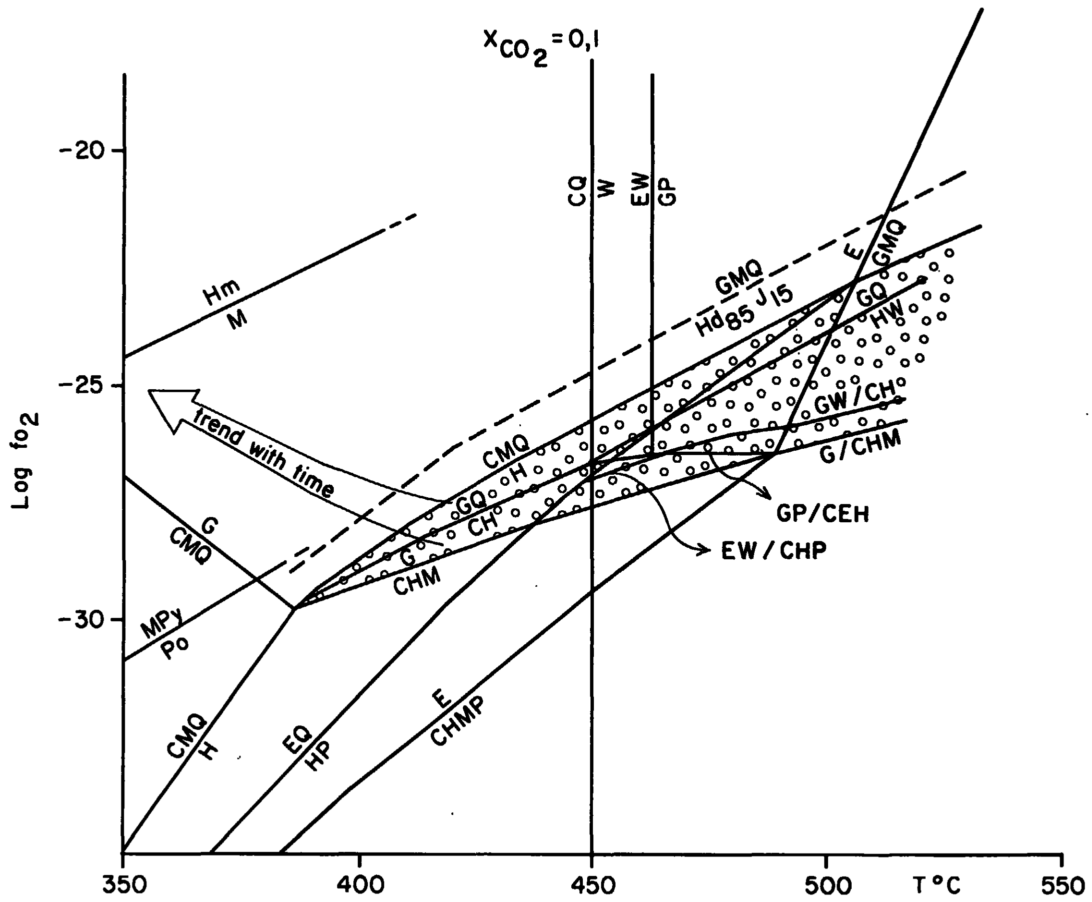

Figure 2. Temperature - oxygen diagram in the system CaO - FeO - Fe_2O_3 - Al_2O_3 - SiO_2 - H_2O - CO_2 at X_{CO_2} = 0,1 and P = 0,3 Kbar, depicted by Shimizu and Hyama (8). The position of the broken curve is shown approximately from data provided by Burton et al. (9). Abbreviations: C: calcite, E: epidote, G: andradite, H: hedenbergite, Hm: hematite, J: johannesite, M: magnetite, P: plagioclase, Po: pyrrhotite, Py: pyrite, Q: quartz, W: wollastonite. Stippled field: see text.

minute inclusions of calcite (which did not thrive elsewhere in the aureole) and Mn-enriched hedenbergite. These minerals form assemblages with wairakite, quartz,and epidote.

The fluid pressure within the gabbro contact aureole is estimated, from a lithostatic load of near 1 km and an uplifting episode that accompanied the gabbro emplacement, to have been close to 0.3 Kbar (6). Figure 2 shows a T-f_{O_2} diagram for the skarn minerals discussed above, depicted at 0.3 Kbar and X_{CO_2} = 0.1 by Shimizu and Hyama (8). The effect of increased Mn-content in hedenbergite on the univariant equilibria involved is also shown (9). The stippled area in fig. 2 shows the field of coexistence of andradite and hedenbergite, which accordingly may have formed at temperatures below 400°C at f_{O_2} -value as low as 10^{-30}, and evidently at higher temperatures and oxygen fugacities within the stippled field. Of significance is the recognition of a former supercritical fluid within the extinct hydrothermal system, as the P-T estimates are both above the critical point value.

Within the IP.2 gabbro itself, the earliest hydrothermal mineral veins consist of an actinolite-sphene assemblage, deposited within early shrinkage joints in the gabbro, and also formed in vein-wall-rock zones at the expense of augite and ilmenite respectively. The thickness of the actinolite-sphene veins is usually ≤ 1.0 mm, and often irregular micro-veins (<0.1 mm) branch the veins. Elsewhere in the gabbro, the primary augite is either unaltered or marginally replaced by actinolite. The actinolitization (+ sphene) within the gabbro contrasts markedly with the development of other secondary minerals, which is more restricted to the wall-rock zones associated with later hydrothermal vein systems. The earliest hydrothermal fluid affecting the gabbro thus appears to have fluxed the gabbro body via major- and micro-joints and along crystal boundaries. The actinolite-sphene veins slightly post-date the IP.4 felsite veins, discussed above, but were formed during the cooling period of the gabbro (6). While the P-T condition of their formation is not known, the actinolite-sphene veins may relate to an effective "water-penetration" process, discussed earlier.

Briefly summarized, the physico-chemical implications from the Geitafell gabbro contact aureole include:

A: P_{fluid} in the contact aureole approached $P_{lithostatic}$ ($\leq$ 0.3 Kbar).

B: Supercritical fluid existed in the vicinity of the cooling magma for an unknown length of time.

C: The supercritical fluid was CO_2 - poor and reducing, the f_{O2} - values ranged between 10^{-30} to 10^{-15} (fig.2).

D: Within the contact aureole well-developed fluid-rock reaction zones formed in environments of high fluid/rock ratio, driving Ca^{+2} and all other elements not participating in the rock replacement by chlorite-albite into solution. Apart from Ca^{2+}, this would include Ti^{2+} amongst other elements, the two mentioned being essential for sphene development which coincidently (?) took part in the construction of the earliest hydrothermal veins within the gabbro.

E: Upon the intrusive event, prevailing hydrous fluid within the contact aureole must have undergone boiling and phase separation, driving gases (CO_2, SO_2) out of the contact aureole system. The boiling, necessarily, would have proceeded outwards from the heat-source and subsequently inwards upon cooling. A few hundred meters up- and outwards from the IP.2 heat source, and time-related to the intrusive event, extensively carbonatized rocks are found which are tentatively related to a boiling zone doming the IP.2 gabbro (6).

F: Upon cooling the hydrothermal fluid in the contact aureole oxidized and f_{O2} -values crossed the HmM-buffer curve as the fluid adjusted to ambient hydrostatic P-T values.

Contemporaneously or not, D and E above imply that a two directional fluid flow took place within the contact aureole, i.e. towards the heat source, and away from it. Temporarily also, the fluid is proposed to have been at supercritical conditions. Questionable as supercritical pressures thriving within hydrothermal systems may be, the indirect evidence provided relates to a major uplifting event accompanying the IP.2 gabbro (6,7). The periodic uplifting/subsidence events within the active Krafla volcano (10) may be comparable, though at different scale. An important alternative, that a part of the high-T mineral assemblages described above might be produced from superheated steam, is discussed below.

Circumstantial evidence from the IP.5 and 6 basaltic cone-sheets of the Geitafell volcanic system implies that superheated steam may indeed be quite common inside cooling intrusive bodies. While actinolite is absent from the host rocks of the epidote zone in the Geitafell volcano (6,7), extensive pyroxene replacement by actinolite is common within the cone-sheets inside the epidote zone, even at depths of only 100-200 m below the palaeosurface (6). The low-temperature limit for actinolite development in the Icelandic active high-T systems appears to be above 280°C (11). Assuming the near 300°C to be close to the minimum temperature, the actinolite development within the intrusive rocks at depths less than approximately 1 km must have arisen from superheated steam - unless an ice-cap, several hundered metre thick was added on top of the volcano. Yet, one would be left with explaining the actinolite confinement to the intrusive rocks. Therefore, a model of hot-rock actinolitization from superheated steam is favoured, assuming the P-T estimates valid (6). Once the hydrostatic P-T control is off, an upper thermal barrier for a hydrous fluid ceases to exist. Quite likely the fluids in the Geitafell gabbro and its contact aureole may thus have passed through both the supercritical and superheated fluid regions, eventually adjusting to hydrostatic values.

PRACTICAL APPLICATION

The idea has been forwarded, that drilling of water-injection wells into hot- rock boundaries in water-deficient systems could be a possible aid in steam generation (5). Due to the thermal effect of boiling within reservoirs and cooling by circulation fluid in conventional geothermal drilling, however, problems may arise in recognizing such potential hot- rock zones, particularly in the case of thin tabular intrusive bodies at economic depths (e.g. sheets similar to those of IP.5 and 6). One plausible method, however, would involve a detailed study of mineral veins and amygdale time-relationships in core samples, providing similar evidence as discussed in this paper.

ACKNOWLEDGEMENTS

Thanks are due to Prof. S. Bjornsson, Dr. I.B. Fridleifsson and Dr. H. Franzson for critical reading of the manuscript and inspiring discussions, and S. Asbjornsson for assistance in computer editing the paper.

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