GEOCHEMICAL EVOLUTION OF THE VAPOR-DOMINATED REGIME AT KARAHA-TELAGA BODAS, INDONESIA: INSIGHTS FROM FLUID INCLUSION GAS COMPOSITIONS

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SUMMARY – Karaha-Telaga Bodas is a partially vapor-dominated geothermal system related to Galunggung Volcano. The gas compositions of fluid inclusions trapped during the evolution of the vapor-dominated regime were analyzed to determine their sources and the processes that have affected the fluids. Minerals from three core holes were analyzed. Core holes T-2 and T-8, drilled near an active thermal area, penetrated several hundred meters of the vapor-dominated regime. The third well, K-33, is located in the central part of the field, where the steam zone is thin.

N_2/Ar ratios of quartz-hosted inclusions in all three wells record the flux of magmatic gases during the initial development of the vapor-dominated regime. The trapping of magmatic gases suggests that the emplacement of a high level intrusion triggered the depressurization that led to the boiling off of an early liquid-dominated system. Fluids trapped in younger minerals in T-2 and T-8, and the presence of tourmaline, fluorite and native sulfur in T-2, document the continued flux of magmatic volatiles in the southern part of the field. Younger inclusions in K-33, however, contain gases that were dominantly meteoric in origin. Gas concentrations in T-2 and T-8 commonly range from >1.5 to 10 mole percent, although values in excess of 20 mole percent were obtained. These gas concentrations can be related to boiling and the accumulation of externally derived volatiles within an expanding vapor-dominated regime. Variations in the gas contents of quartz-, pyrite- and anhydrite-hosted inclusions record the progressive growth of the vapor-dominated regime.

1. INTRODUCTION

Vapor-dominated geothermal regimes are an important, but still poorly understood environment within volcanic terrains. Ongoing investigations of Karaha-Telaga Bodas, located on the flanks of Galunggung Volcano in western Java, have demonstrated that vapor-dominated conditions can form and evolve very rapidly (Allis et al., 2000; Moore et al., 2002a, b,). At Karaha-Telaga Bodas, the evolution of the vapor-dominated regime is represented by a unique sequence of mineral and fluid inclusion assemblages that formed within the last 4000 years. In this paper, we combine petrologic relationships with the gas compositions of the inclusion fluids from three core holes, T-2, T-8 and K-33, to characterize the compositions and behavior of the fluids that were present during the evolution of the vapor-dominated regime. One of the goals of this work is to identify the petrologic relationships that characterize vapor-dominated systems.

2. GEOLOGIC SETTING

Karaha-Telaga Bodas is located beneath a north-trending volcanic ridge extending from Kawah Galunggung, Galunggung Volcano's main eruptive center. Between 1822 and 1984, the volcano erupted five times. During the 1990s, the Karaha Bodas Co., LLC, drilled more than two dozen wells, some to depths of 3 km. Allis et al. (2000) presented a conceptual model of the geothermal system based on the down hole temperatures and pressures (Fig. 1). They demonstrated that the vapor-dominated regime extends laterally for more than 10 km and to depths below sea level. It is underlain by a liquid-dominated reservoir with salinities of 1-2 weight percent and temperatures of at least 350°C. Fluids in the overlying cap rock are dominated by steam condensate. Surface discharges occur at the southern and northern ends of the prospect. At the southern end, the thermal features include the fumaroles at Kawah Saat, an acidic lake (Telaga Bodas), and chloride-sulfate-bicarbonate springs that discharge neutral to acidic waters. Elevated F and Cl in Telaga Bodas and nearby wells suggest that magmatic gases are modifying the lake-s composition. Kawah Karaha, a smaller fumarole field, is located at the northern end.

The geothermal reservoir at Karaha-Telaga Bodas is developed in andesitic to basaltic flows and pyroclastics that were intruded by granodiorite. Gravity data suggests the intrusion is shallowest beneath the Telaga Bodas thermal area (Tripp et al., 2002). Emplacement of the granodiorite resulted in the development of an extensive liquid-dominated geothermal system (Moore et al. 2002a). Carbonate veins were deposited at shallow depths. In the deeper parts of the system, propylitic and potassic

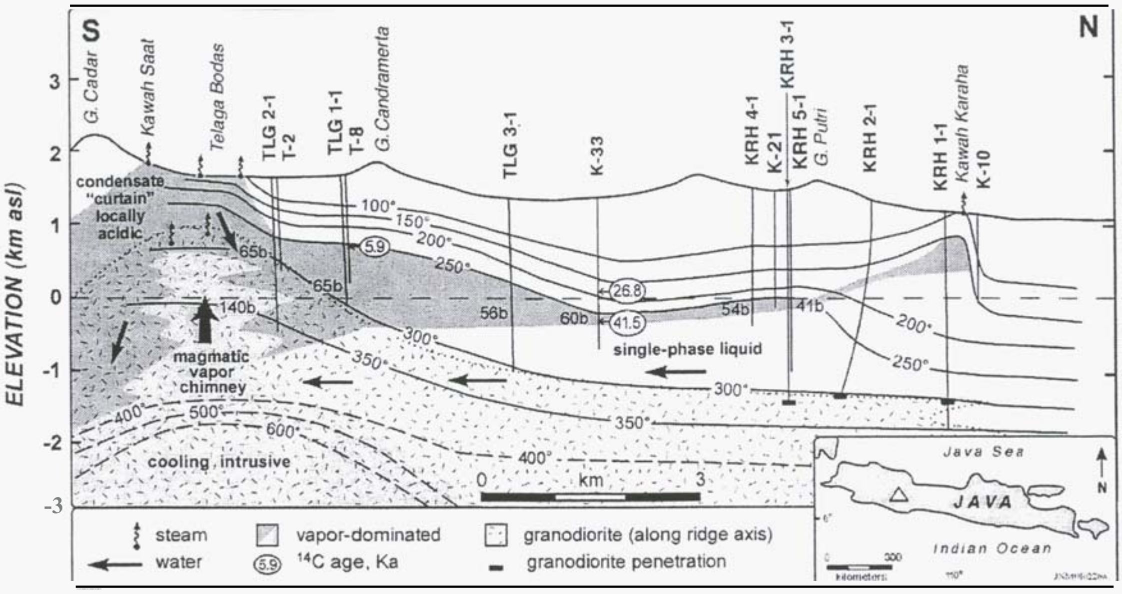


Figure 1. North-south cross section through the Karaha-Telaga Bodas geothermal system. Temperatures ("C), spot pressure measurements (bars) within the vapor zone and fluid state are shown. The triangle on the inset map shows the location of the project area. Modified from Allis et al. (2000).

assemblages formed. The intrusion is only weakly altered and may provide the heat that drives the system.

The transition to vapor-dominated conditions was marked by the precipitation of chalcedony and quartz. The quartz occurs as overgrowths on chalcedony cores without any apparent hiatus. Chalcedony was deposited directly on actinolite and epidote in core holes T-2 and T-8. In contrast, prehnite was deposited after actinolite and epidote but before quartz in K-33. These parageneses suggest that temperatures had begun to wane in the central part of the field (C. Bruton, pers. comm.) but were still very high in the south prior to the initiation of the vapor-dominated regime.

Fluid inclusions trapped in quartz suggest that chalcedony was deposited at temperatures ranging from 235° to –350°C. Salinities ranging from >3 weight percent NaCl equivalent to –24 weight percent NaCl-$CaCl_2$ equivalent are common in quartz-hosted inclusions from **T-8.** Both low and high salinities (<3.3, >11 weight percent NaCl equivalent) are found in T-2. However, only low salinity fluids (<2.1 weight percent NaCl equivalent) have been found in quartz from K-33.

At the temperatures indicated by the fluid inclusions, extreme supersaturation of silica with respect to quartz is required to precipitate chalcedony. Fluid pressures inferred from the temperature measurements show that the system was greatly over-pressured compared to the elevation of the volcano flanks. Moore et al. (2002a) concluded that the high pressures could have contributed to the flank collapse that produced Galunggung's crater, Kawah Galunggung -4200 years ago (Bronto, 1989). They also suggested that this slope failure triggered depressurization and the boiling off of the liquid system, leading to silica supersaturation and the high inclusion salinities.

As pressures declined and the vapor dominated regime developed, steam condensate percolated downward. Interactions between the condensate and wall rocks produced advanced argillic alteration assemblages and veins dominated by anhydrite, pyrite or carbonates (siderite, dolomite and calcite). Throughout the field, the carbonates postdate both the pyrite and anhydrite veins, which display mutually crosscutting relationships. In T-2, late tourmaline, fluorite and native sulfur are also found, but these minerals are generally absent in other wells. Their presence suggests episodic contributions of magmatic gases containing H_3BO_3, HF and SO_2. In the deeper parts of the system, pyrite, wairakite and chlorite postdate quartz. Fluid inclusions trapped in anhydrite, calcite and fluorite record the evolution of these descending fluids. At elevations shallower than **900** m above sea level (masl) the fluid salinities decrease, as temperatures increase from 160"-205°C due to the uptake of SO_4 by newly formed minerals. At greater depths, where homogenization temperatures range from 235" **to** 300°C, the salinities increase dramatically with increasing temperature. Fluid inclusions in the deepest crystals of anhydrite are dominantly vapor-rich, although a few hypersaline liquid-rich inclusions containing daughter crystals of halite (31 weight percent NaCl equivalent) are present. Moore et al. (2002b) concluded that the increase in salinity could only be caused by concentration of salts as the fluids boiled toward dryness.

The youngest stage of hydrothermal activity is represented by the deposition of NaCl, KCl, $FeCl_x$ and Ti-Si-Fe precipitates on the hydrothermal minerals. The presence of these scales suggests that portions of the system had dried out completely prior to drilling.

The low salinities of the waters encountered beneath the vapor-dominated region preclude the possibility that these fluids represent the residual liquids left after the liquid-dominated system boiled off. Instead, these waters must represent mixtures of inflowing meteoric recharge and downward percolating condensate. The present under-pressured state of the system is assumed to be sustained by rapid boiling and steam loss as the waters enter a magmatic chimney beneath the Telaga Bodas area (Allis and Moore, 2000).

3. FLUID INCLUSION GAS ANALYSES

Fluid inclusion gases trapped in quartz, pyrite, anhydrite, calcite, wairakite and epidote from T-2, T-8 and K-33 (Fig. 1) were analyzed by quadrupole mass spectrometry (see Norman et al. (2002 and references therein). The samples were crushed under vacuum and analyzed for H_2, He, CH_4, H_2O, N_2, O_2, H_2S, Ar, CO_2, SO_2 and hydrocarbons (C_2-C_7). Typically, each crush yields an analysis of ~6 to 12 inclusions, although the number depends on their size and gas contents. H_2O was the dominant species, accounting for 99.9 to –90 mole percent in most analyses (Fig. 2). However, H_2O contents as low as 31 mole percent were recorded. CO_2 was the dominant noncondensible species.

4. DISCUSSION

4.1 Abundances of Gaseous Species

Variations in the gas abundances and ratios are a unique source of information on the origins and behavior of the fluids. Figure 2 shows that the gas concentrations in T-2 and T-8 vary systematically with depth and age of the host mineral. Quartz-hosted inclusions at the shallowest depths in T-2 (>900 masl) and T-8 are dominantly liquid-rich with gas contents <1.5 mole percent. At greater depths in T-2 and at elevations <600 masl in T-8, gas concentrations exceeding several mole percent dominate but low gas inclusions are still present. Concentrations >1.5 mole percent indicate that at least some of the inclusions trapped a vapor phase while multiple analyses with concentrations >~20 mole percent suggest the presence of a gas cap and vapor-dominated conditions (Norman et al., 2002).

The distribution of gas contents in pyrite and anhydrite from T-2 and T-8 parallels the trends in the earlier deposited quartz. Analyses from shallow depths record the dominance of gas-poor liquid-rich inclusions whereas the compositions of the deep samples document the presence of abundant vapor-rich inclusions. However, unlike the pyrite-hosted inclusions, all of the analyses of inclusions trapped in anhydrite at intermediate depths are gas rich. The highest gas contents in T-8 (>20 mole percent) are from the sample containing vapor-and hypersaline inclusions. These inclusions must have formed within a vapor-dominated regime. We interpret the progressive decrease in the depth of significant liquid circulation, as indicated by the presence of gas-poor liquid-rich inclusions in quartz, pyrite and anhydrite, as a measure of the vapor-dominated regime's growth during the boiling off of the early liquid-dominated system.

Evidence of extensive boiling in K-33 is found between elevations of 400 and -200 masl. This region is currently located in the conductively heated cap rock above a thin steam zone. Anhydrite- and quartz- hosted fluid inclusions from depths below this zone, between –130 and –435 masl, yielded only low salinity waters (<~2 weight percent NaCl equivalent). These salinities are typical of the deep waters currently circulating below the vapor-dominated regime.

4.2 Fluid Sources

Ratios of N_2, *Ar* and He in fluid inclusions have proven to be particularly useful for tracing fluid sources (e.g. Norman and Musgrave, 1993). Figure 3 compares the N_2/Ar and Ar/He ratios of the inclusions with the range of volcanic gas compositions reported by Giggenbach (1997) (Blamey et al., 2002). The quartz-hosted fluid inclusions, which record the initial development of the vapor-dominated regime, display a similar range of compositions in each well. The lowest N_2/Ar ratios are typical of air-saturated water (38) and indicate that these inclusions trapped meteoric fluids. The highest values (100 to –110) are indicative of a magmatic origin. These ratios suggest that depressurization of the early, over-pressured liquid-dominated geothermal system may have been contemporaneous with the emplacement of a shallow intrusion beneath Galunggung Volcano.

The N_2/Ar ratios of inclusions trapped in anhydrite, calcite and wairakite in K-33 are different than those in T-2 and T-8. In K-33, the fluids were dominantly meteoric in origin, whereas the compositions of the inclusions in the southern wells were strongly influenced by magmatic contributions. Cooling of the rocks in K-33, perhaps resulting from sealing of the shallow fractures by meteoric waters, may have inhibited the upward growth of the vapor zone in the central part of the field.

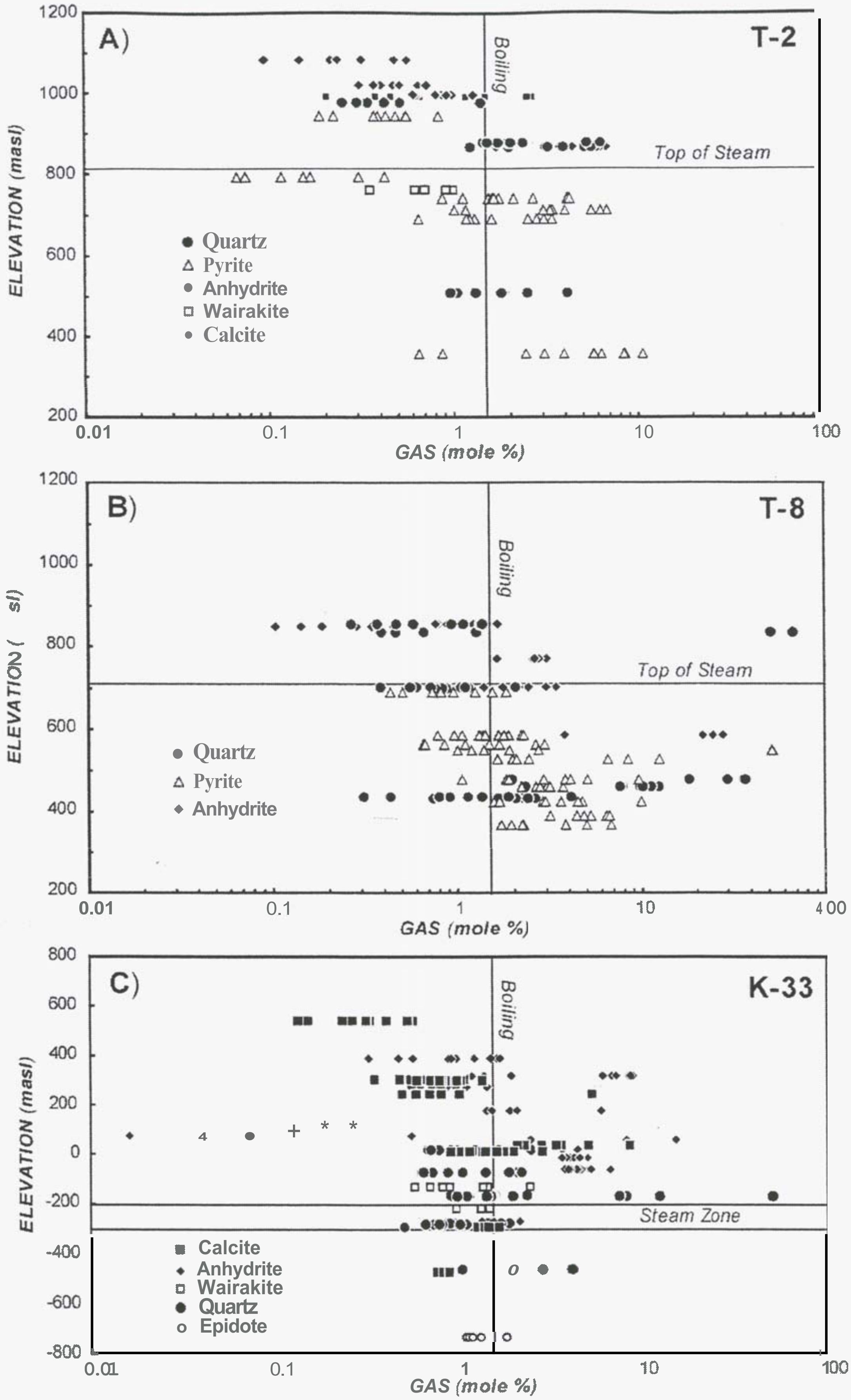
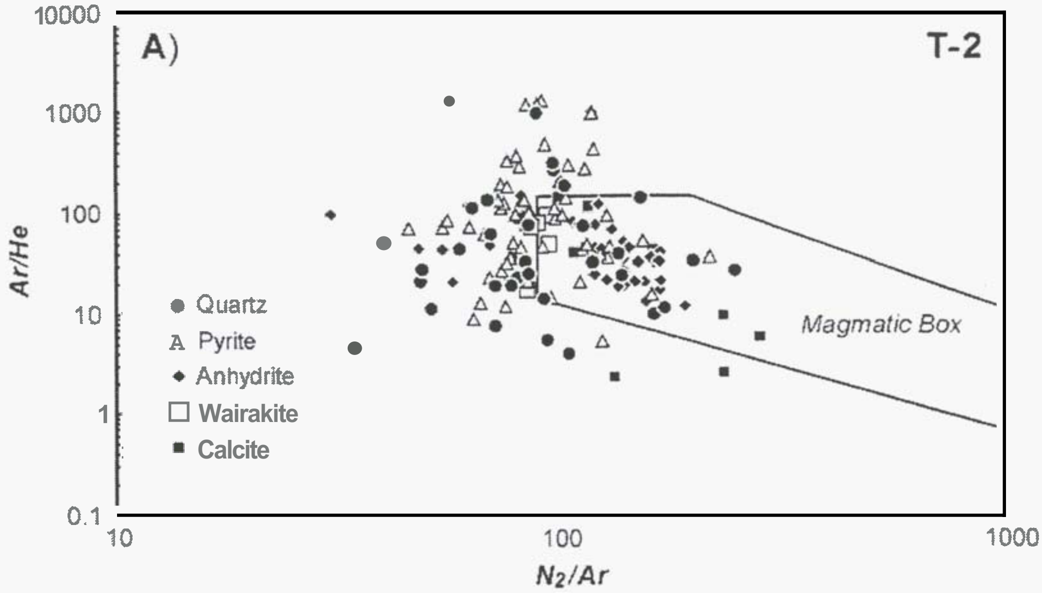
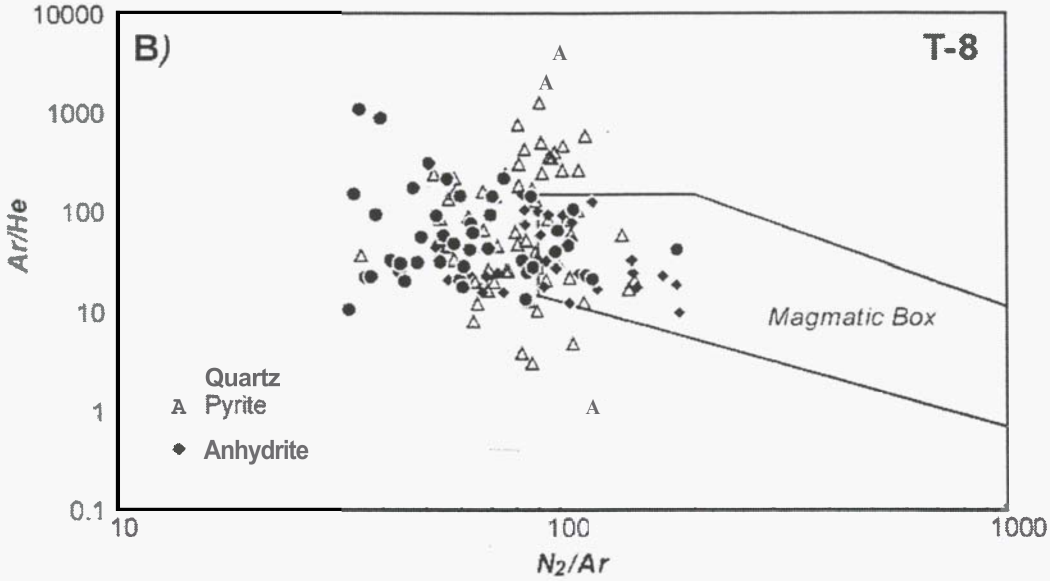


Figure 2. Distribution of gas contents (in mole percent) in fluid inclusions from T-2 **(A)**, T-8 (B) and **K**-33 (C). Gas contents >1.5 mole percent (vertical line) indicate trapping of a gas-rich vapor phase. Vapor-dominated conditions extend below 200 masl in **A** and B but are restricted to a narrow depth interval in K-33.





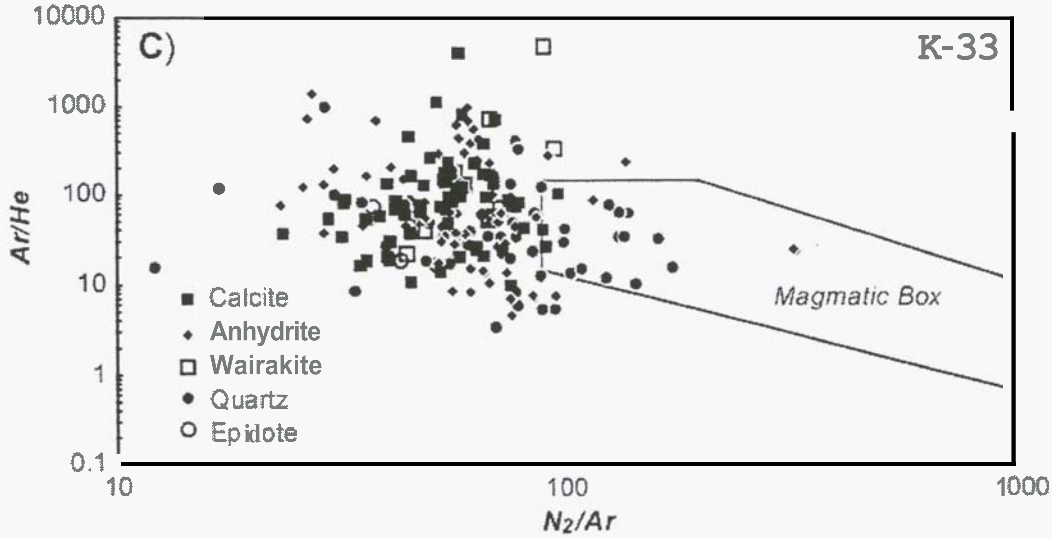


Figure 3. Relationship between N_2/Ar and Ar/He ratios in fluid inclusions from **T-2** (A), **T-8** (B) and K-33 (C). **The** magmatic **box** represents the compositions of magmatic gases compiled by Giggenbach (1997). Air-saturated water **has a** N_2/Ar ratio of **38** (modified from Blamey and Norman, **2002).**

5. CONCLUSIONS

Karaha-Telaga Bodas is a young, partially vapor-dominated geothermal system on the flanks of Galunggung Volcano. Chemical and mineralogic data show that the vapor-dominated regime evolved rapidly since its inception 4200 years ago. The gas compositions of fluid inclusions from core holes, T-2, T-8 and K-33, representing different but contemporaneous hydrothermal environments within the geothermal system were studied.

The fluid inclusion data indicate that development of vapor-dominated conditions may have accompanied emplacement of a high level intrusion that produced an over-pressured liquid-dominated geothermal system within the volcanic edifice. Gases and liquids trapped in quartz as the vapor-dominated system began to form suggest that the early liquids were low salinity meteoric waters.

T-2 is located within a magmatic vapor chimney. Hydrothermal alteration was strongly influenced by magmatic volatiles, which contributed to the deposition of anhydrite, tourmaline, fluorite, native sulfur, pyrite and advanced argillic alteration assemblages. Fluid inclusions are typically gas rich, and analyses of their compositions are dominated by vapor-rich inclusions. N_2/Ar ratios indicate that the volatile contents of the inclusions are mixtures of gases derived from magmatic and meteoric sources. T-8 is located on the fringe of the vapor chimney. Temperatures are several tens of degrees lower than in T-2, and the mineral assemblages display less evidence of direct magmatic contributions. However, N_2/Ar ratios still indicate a strong magmatic contribution. K-33 is located well outside the chimney. Temperatures are lower still, and there is mineralogic evidence of cooling before vapor-dominated conditions started to develop. Magmatic contributions and boiling are much less significant in this part of the field. Cooling and mineral deposition by recharging meteoric waters may have quenched growth of the vapor-dominated regime after boiling began.

6. ACKNOWLEDGEMENTS

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