Proc. 5th NZ Geothermal Workshop 1983

ROCK GEOCHEMISTRY OF THE TONGONAN GEOTHERMAL FIELD, LEYTE, PHILIPPINES

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ABSTRACT

Major and trace element analyses of 52 whole rock core samples from 30 wells in the Tongonan geothermal field reveal broad geochemical trends that have been integrated into a hydrogeochemical model of the field. The early history of the entire field was thought to comprise periods of potassium then hydrogen metasomatism. Pyrophyllite-bearing veins and breccias cut biotite- and illite-bearing rocks which have been uplifted by at least 1 km and are exposed at or appear within a few hundred metres of the surface.

The mineralisation of the current system below about 3 km is conridered to consist of biotite, pyrophyllite, and other porphyry copper mineral assemblages. The present, shallow (less than 3 km) central part of the system appears to be undergoing sodium, and to a lesser extent magnesium and iron, metasomatism, these elements being derived from volcanic breccias and tuffs located mainly on the field margins. Heat and chemical transfer alro occurr from the pluton over a wide area from Mahiao to Malitbog, but vertically-upward fluid flow and permeability in the pluton is conridered to be greater in the Upper Mahiao area where the highest temperatures and greatert amount of mineralisation occurs. Massive withdrawal of fluid for approximately 300 MW may caure scaling in the Upper Mahiao wells and pipelines.

INTRODUCTION

The Tongonan Geothermal Field is located on the Visayan Island of Leyte, Republic of the Philippines. Exploration and development of the field has been progressing since 1973. A 112 MW(e) power station was commissioned earlier this year, and additional 112 MW(e) power stations are planned.

During drilling, commonly to about 25 km, of more than 50 vertical and deviated production wells, approximately 160 cores were cut for petrographic study. Twelve major and twelve trace elements have been analysed by XRF from 52 core samples comprising altered andesites, volcaniclastic sedimentary, and plutonic rockr. The object of this geochemical investigation is to distinguish parent fresh rock trends from alteration trends, then to develop a hydrogeochemical model which may have practical conrequences (e.g. scaling problems).

GEOLOGIC SETTING

The geology of the Tongonan region was first dercribed by Vasquez and Tolentino (1973) who recognised three rock units - the Bao Volcanic Complex, the North Central Leyte Formation, and the Janagdan Andesites which are not present in the drilled area. Since drilling operations began in 1973, additional rock units have been found in many wells. The bulk of the lithologies penetrated by wells consist of a pile of andesitic breccias, tuffs and lavas about 2 km thick with occasional intercalated limestone and shale beds and hornblende dacite dykes comprising the Bao Volcanic Complex (Ward, 1979). The shale layers are provisionally correlated with the Taog Formation, and the limestone unit with the Tagnocot Limestone (Woodward, 1964) which are upper Pliocene/lower Miocene and mid Miocene respectively. Most wells have penetrated a basement composed of quartz diorites, granodiorites and granites. Overlying the Bao Volcanic Complex, the loosely consolidated, unstratified volcanic sands and conglomerates forming alluvial terraces and lahar depoeits are correlated with the Nortb Central Leyte formation originally described from the Bao Valley Gorge.

The Leyte Formation appears to be the erosion product of a landmaee uplifted along the Philippine Fault which trends northwest-southeast through the island and indeed almost traverses the entire Philippine archipelago. Further evidence of uplift consists of the limestone beds which are elevated lese than about 600 metres above preeent rea level, displacement of the pluton surface by about 1.5 kilometres, and a high temperature (300°C) alteration mineral assemblage (pyrophyllite, diaspore) present near the surface. Uplift of more than 2 km in the Pliocene along the Philippine Fault has been recognised in Luzon (Divis, 1983). In Leyte, uplift is likely therefore to be tectonic and similar in extent allowing the cooling plutonic basement to be ultimately raised passively to a relatively high level in the earth's crust.

Lateral movements along the Philippine Fault have also occurred. In Mindinao, 30 km left-lateral displacement of Miocene sediments has been recognised by petroleum geologists (Gervasio, 1971). This extensive fault movement has created and elongate, trapezoid-shaped graben between two (the Central and West) of the three major branches of the Philippine Fault which split and join again in the centre of Leyte. Stepped uplift has occurred east of the Central Fault. Numerous nearly parallel splinter or synthetic faults occur off the major branches, particularly the prominent West Fault, along which hot springs often emerge at the surface. Under tension, the rynthetic and antithetic faults provide some of the permeability in the field itself which is located between the Central and Eart Faults directly over the pluton in the northern part of the large graben structure (Fig. 1). Current geothermal activity is related to Quaternary plutonism even though there was plutonism and volcanism in the Miocene.

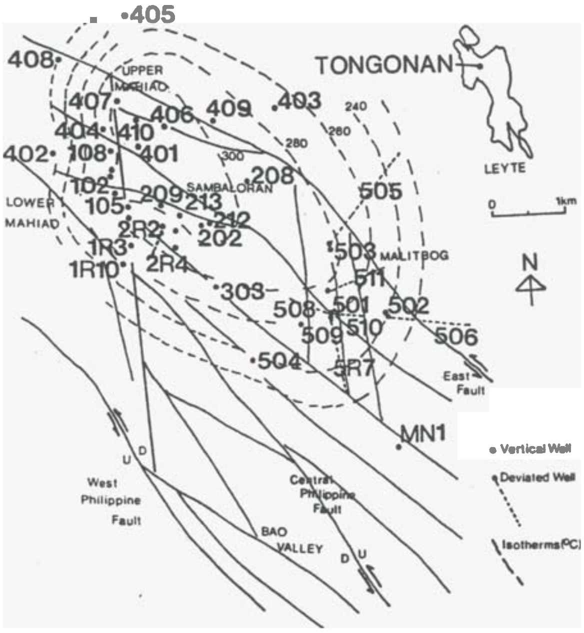

Fig. 1: Principal faults and isotherms (depth 900 m below sea level) of the Tongonan Geothermal Field.

HYDROLOGICAL MODELS

Four hydrological models for Tongonan have been proposed recently.

1. A fluid source from the extreme west between wells 402 and 408 with near-horizontal flow across the field to the Malitbog area (Leach, TM, pers. comm.).
2. A fluid source from the north between wells 405 and 403 and lateral flow onto the field over the dionite basement (Barnett, P.R., pers. comm.).
3. Vertical flw up the East and Central Faults and lateral flow onto the field (Hulston et al., 1982).
4. Fluid source in the Upper Mahiao region with lateral flow across the field to Malitbog mainly along the contact zone between the Bao Volcanic Complex and the plutonic basement (Lovelock et al. , 1982).

The first two models are conridered to be unrealistic although some aspects of models three and four are perhaps closest to the true situation.

Deep acidic fluids may be rising up the fractured zone immediately adjacent to the Central Fault, giving rise to the acidic waters in wells 402 and 1R3. It is possible that the acid waters in well 402 are due to superficial development of acid-sulphate waterr - such springs occur close by - but in well 1R3 pyrophyllite occurs which requires acid conditions and relatively high temperatures (350°C) and hence greater depth for its formation.

Lovelock et al. (1982) showed that the deep aquifer chloride concentrationr are greatest in the Upper Mahiao but the fluid chemical trends across the field do not necessarily indicate that there is lateral flow. Whittome and Smith (1979) demonstrated that there is little or no pressure gradient in single phase fluids across the field, which implies no lateral flow. In the light of the rock chemical data, an alternative hydrological model for the Tongonan field is presented in the discussion belw. Before the model and altered rock geochemistry is considered, the fresh rock geochemistry is examined.

FRESH ROCK GEOCHEMISTRY

The rock geochemistry of the Tongonan field is important because it provides a major constraint on the interpretation of the fluid chemistry and the source of its constituents as well as the fluid source and direction of flow. These interpretations in turn have important conrequences in terms of future production drilling and long-term field management.

Since virtually all of the samples analysed to date are altered, two of the least altered rocks have been used as references for interpreting the first approximation losses and gains of major and trace elements. The samples chosen are an andesite from well 505 (core 1) and a diorite from well 508 (core 4). The analyses of these two rocks have been compared with analyses published by Divis (1980, 1983) of fresh rocks from Philippine porphyry copper deposits and andesite volcanoes.

If all the major element data from the Tongonan field are plotted on Harker diagrams (Fig. 2), the resulting trends appear to indicate that the rockr sampled are not altered to any significant degree (this conclusion is supported by petrographic studies and semi-quantitative XRD data on six principal alteration minerals - total proportions seldom greater than 20%) and show the typical changer of differentiated andesites. Tongonan andesites are medium potassium, calc-alkaline rather than tholeiitic (Gill, 1981) and appear chemically (and temporally?) related to the dioriter. The following major element oxides give good linear correlation with silica: Fe_2O_3 (total), P, Mg, Ti, Al, Mn, and alro V which is known to substitute for ferric ion in pyroxenes, amphiboles and biotite but mainly magnetite (Wedepohl, 1970). These elements, as well as Zr and Y, would appear to be the least mobile; Y/Zr ratios that are very low are attributed to high-grade alteration (Fig. 3).

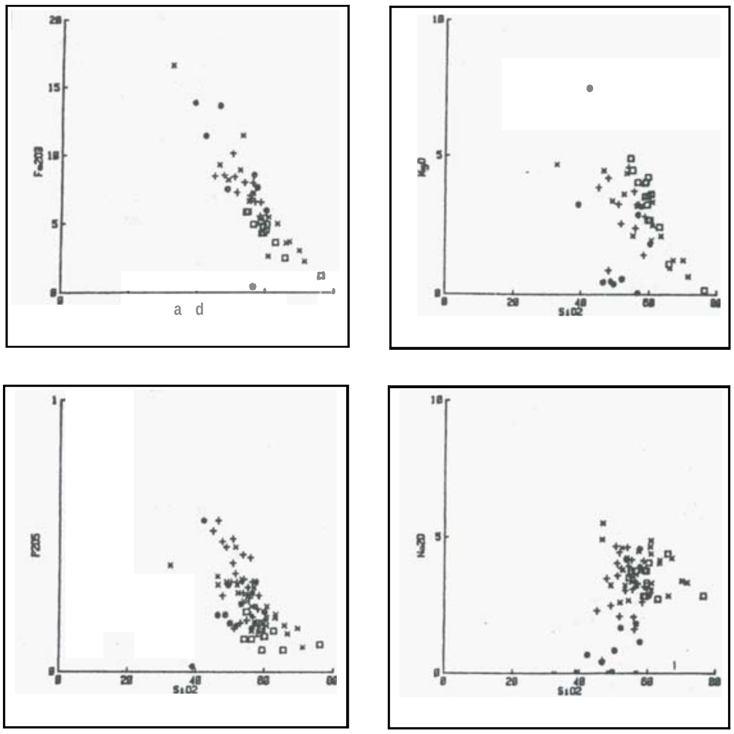

Fig. 2: Harker diagrams for Fe_2O_3 (total), MgO, P_2O_5 and Na_2O.
Symbols represent: x diorite,
+ andesite,
* volcaniclastic breccias and tuffs,
□ fresh andesite.

(Divis, 1980)

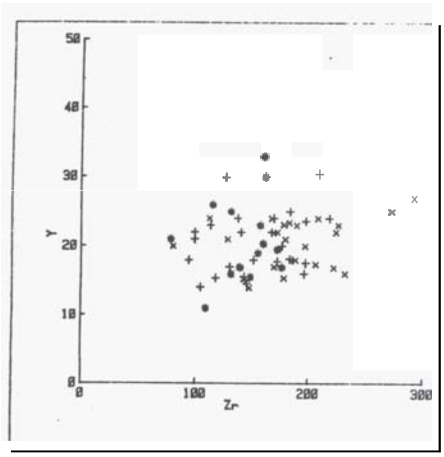

Fig. 3: Y/Zr plot of all altered Tongonan rock samples.

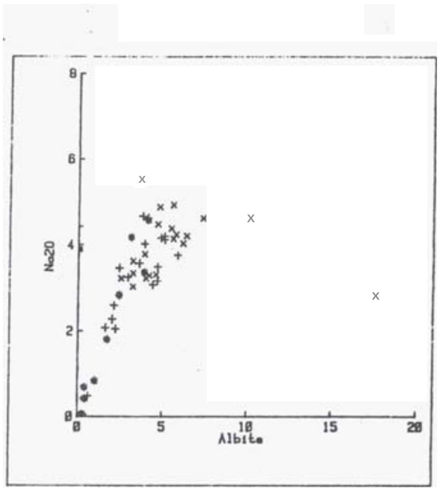

Fig. 4: Na versus albite. Points off straight line are orthoclases.

ALTERATION GEOCHEMISTRY

Relative to the least altered reference samples (from wells 505, 508), the most significant chemical changes from the diorites are a depletion in Si, K, Rb, Ba, Cr, and an enrichment in Fe_2O_3 (total), Mg, Ca, Ti, P, Sr, S, V, Ni, Cs, Pb, Zn, Th. In the andesites the pattern is not as simple but generally there is a depletion in Si, Fe_2O_3 (total), Ti, Ca, Na, Mg, V, Sr, Cu and enrichment in K, Rb, Ba, Ba, Ni, Zn, Pb, Th, Cr in most of the samples.

The most interesting change is the depletion of Cu from the andesites but this assumes that the original concentration was 127 mg/kg which is high relative to all other samples including the fresh reference ones. There seems to be a transfer of Si, K, Rb, Ba, Cr from the diorites to the andesites and a transfer of iron, magnesium and sodium from andesites to diorites. As indicated in the previous section, most major elements show a linear decrease with increasing silica, except some breccia and tuff samples and the alkalis and lime, suggesting that the latter elements are the most mobile.

Sodium correlates quite well with the proportions of albite in the whole rock samples (Fig. 4), i.e. albite is the only sodium mineral in the cores - a conclusion substantiated by petrographic studies. Albite commonly replaces plagioclase, but it also rarely occurs in veins (e.g. in well 209, core 9) (Leach, 1980). Samples with the highest amount of sodium occur mainly in the Upper Mahiao region in wells 410, 407, 401 and 510, whereas those samples with the lowest sodium are almost entirely breccias and tuffs located mainly on the field margins (Fig. 5).

Variations in Ca can be explained by exchange of the anorthite component in plagioclase for Na in Ca-depleted rocks (albitization), and addition of calcite, anhydrite, wairakite and/or epidote in Ca-rich rocks. K is more interesting because some samples (e.g. 407, 102, 202, 105) that are enriched were considered to be relicts of an earlier episode of K-metasomatism (Leach and Bogie, 1982) that commonly occurs early in the development of porphyry copper deposits usually by mineralised, slightly acidic, magmatic-hydrothermal fluids emanating from intrusive stocks (Ford, 1978; Henley and McNabb, 1978). All other samples (from 303, 403, 405, 503, 504, 505, 507, 511, MN1) with moderate amounts of K but some with high Rb contents (Fig. 5) are located in volcanics on the field margins. Samples high in Ba relative to Sr are nearly all diorites; Ba is probably contained in the feldspars (Wedepohl, 1970). The diorites from the central wells (410, 401, 407, 209) have the highest K/Rb and lowest Rb/Sr ratios, implying that the greatest amount of chemical alteration has occurred in that region. Samples high in K usually contain illite and/or biotite, and occasionally (e.g. well 407) have pyrophyllite-anhydrite veins crosscutting the matrix (Wood, 1977). Pyrophyllite is considered by Burnham (1979) to be the low pressure source of a magmatic aqueous phase which penetrates wall rock without extensive reaction, but he also maintains that acidic fluids could be derived by hydrolysis of sulphur dioxide which reacts with calcium chloride to produce anhydrite. The latter interpretation may explain why pyrophyllite-anhydrite veins occur in well 407 and why acidic waters occur in wells 402 and 1R3.

On the CaO, MgO, FeO plot (Fig. 5), samples from most high temperature central wells were relatively rich in MgO and FeO. Analyses of a few chlorites in central well 108 are Mg-rich whereas in peripheral well *504* chlorites are Mg-poor. More analyses from samples in different wells are needed to confirm this trend. The iron content in samples from central wells tend to be more reduced, substantiating the general observation that with increasing metamorphic grade there is a tendency for reduction of ferric to ferrous ion. Furthermore, on Fig. 2, there is a superposition of an unaltered rock differentiation trend on an alteration trend. Samples mostly from central wells containing less than about 50 per cent silica are enriched in total iron whereas samples from peripheral wells with higher silica are generally depleted in iron.

On the Cu-Pb-Zn plot (Fig. 5), samples with high proportions of Cu relative to Zn are also usually high in K, Rb, Y, Th and Cr. These samples are very similar to K-silicate assemblages in porphyry copper deposits. In addition, all diorite samples have high alumina to alkali plus lime ratios which are usually porphyry copper bearing (Mason and Feiss, 1979). Those samples with high Zn relative to Cu, as well as having high absolute Ni and Pb, are present mainly in marginal wells, again a situation similar to porphyry copper deposits.

DISCUSSION

The present Tongonan Geothermal Field to drilled depths seems to be undergoing Na and, to a lesser extent, Mg and Fe metasomation, the former exchanging with K. These elements are derived from rocks on the field margin, and they make their way with meteoric fluids to the hotter plutonic centre of the field where presumably supersaturated conditions have prevailed, enabling albite, Mg-rich chlorite, actinolite, hydrogarnets and talc to precipitate. The K-rich samples are considered to be the preserved remnants of rocks that underwent K-metasomatism by earlier hydrothermal fluids at a deeper level in the geothermal system but have been uplifted closer to the surface and subsequently exposed to a lower temperature environment. Bwever, K-metasomatism and porphyry copper deposition may still be occurring deep within or around the margins of the pluton. Meat and chemical transfer from the pluton also occurs (since the hottest area' on isotherm diagrams drawn at several horizontal levels matches the surface configuration of the pluton and remains centred over the Upper Mahiao-Sambaloran area (Lovelock et al., 1982)) but vertically-upward fluid flw, hydrothermal chemical alteration and mineralisation are greater in the Upper Mahiao

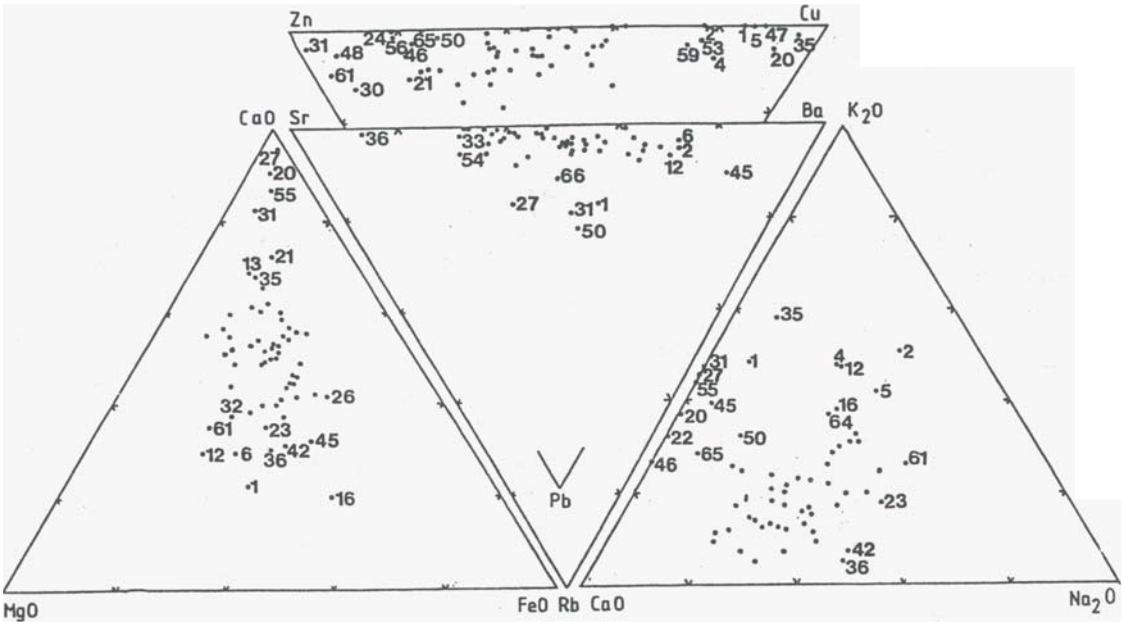

Fig. 5: Tripartite plote of major oxide and trace element relative proportions. Sample numbers refer to chemical analyses of altered rock (available from author upon request) - the ones labelled are from the following vellr:

1 - well 102/core 1, 2 - 102/2, 4 - 105/2, 5 - 105/3,
6 - 108/2, 12 - 202/5, 20 - 303/5, 21 - 303/6, 22 - 401/1,
23 - 401/7, 24 - 401/8, 26 - 403/1, 27 - 403/2, 31 - 405/1,
32 - 405/4, 35 - 407/2, 36 - 407/3, 42 - 410/1, 45 - 503/3,
46 - 506/3, 47 - 504/1, 48 - 504/2, 50 - 505/3, 53 - 506/3,
55 - 507/1, 59 - 509/3, 60 - 509/5, 61 - 510/1, 64 - 511/5,
65 - MN1/2.

becauee of the greater permeability of the pluton in that region. This permeability is related to deeply penetrating, intersecting rynthetic and antithetic faults and associated fractures which allow the release of volatiles (e.g. SO_2, CO_2, Cl, H_2O) from a water-saturated carapace deep (4-5 km) within the cooling pluton to mix with ehallwer meteoric water. Acidic, volatile-enriched fluids which are perhaps tapped by wells 402 and 1R3 may continue to escape from this carapace to the Upper Mahiao region, particularly in the event of fault movement, depositing pyrophyllite assemblages in fractures as they have done so in the part. Furthermore, the development of an expanded steam zone upon exploitation may lead to euperraturation of certain minerals (e.g. silica, halite, calcite, anhydrite) in the remaining single-phase fluid. Hence, scaling could occur in Upper Mahiao wells and pipelines during long-term exploitation of the reservoir.

ACKNOWLEDGEMENTS

I would like to acknowledge the assistance of Drs P.R.L. Browne and F.E. Goff and Mr G. Caldwell, (Geothermal Institute); Aeeociate-Professor P.M. Black, Dre R.J. Parker and I.E.M. Smith (Geology Department); and Mr T.M. Leach (KRTA) for various aspects of this research work. I am aleo grateful to the Philippine National Oil Company - Energy Development Corporation for permission to uee the core samples for this study.

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