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THE RELATIONSHIP BETWEEN VOLCANIC CENTRES AND ACTIVE HYDROTHERMAL SYSTEMS OF THE BICOL PENINSULA, LUZON, PHILIPPINES

I. BOGIE and J.V. LAWLESS

KRTA Limited, P.O. Box 4498, Auckland

ABSTRACT

The Bicol Peninsula is the setting for a chain of andesitic volcanic centres related to the subduction of the Philippine Plate along the Philippines trench. Two of these volcanic centres are currently active and there is evidence that at least five of them host large hydrothermal systems. The area was first evaluated by Dr G.W. Grindley for geothermal development in. 1963-64 and constitutes a major geothermal province with 330 MW(e) already installed and a further 110 MW(e) under development. Volcanic centres which are known to host hydrothermal systems are geomorphically complex with domes and collapse features, and produce differentiated rock types reflecting the presence of shallow subvolcanic magma chambers. In contrast simple andesitic stratovolcanoes tend to produce perfect cones, little variation in rock chemistry and do not appear to host hydrothermal systems.

LOCATION, REGIONAL TECTONICS AND GEOLOGY

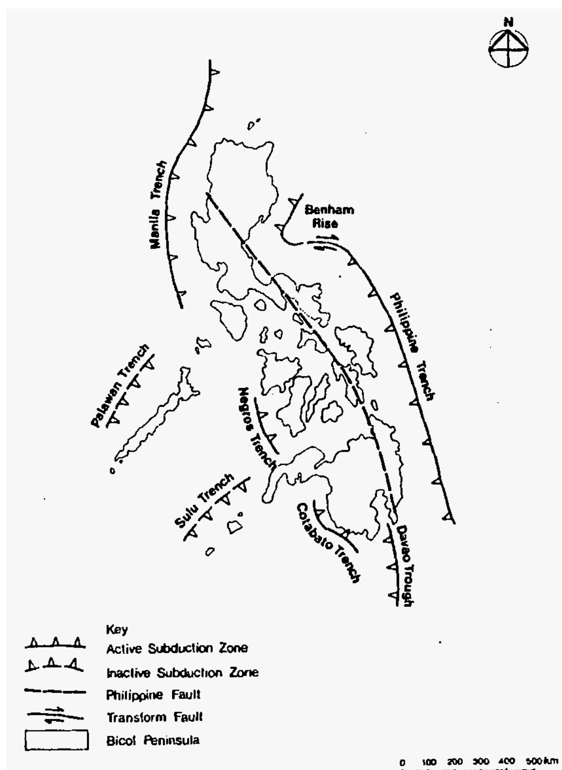
The Bicol Peninsula constitutes the southern-most part of the island of Luzon within the Philippine archipelago (Figure 1). A slightly arcuate chain of andesitic volcanic centres runs along the peninsula. For the purposes of this paper they are referred to as the Bicol Volcanics, although the PBMG (1982) has divided them into a number of separate formations. This volcanic arc parallels the Philippine Trench 100 km to the east. In the southern half of the chain a Wadati-Benioff zone of earthquake hypocentres lies approximately 100km below the volcanoes (Acharya and Aggarwal 1980). This activity is related to the westward subduction of the Philippine plate along the Philippine trench (Cardwell et al. 1980).

The lack of a Wadati-Benioff zone in the northern part of the arc is related to an overall change in the tectonics of the Philippine region. Activity along the Manila subduction zone to the west of Luzon has ceased due to the Palawan continental block entering the subduction zone (Hamilton 1981). This has resulted in a change of polarity of subduction to the eastern side of Luzon, manifested by incipient subduction of the Benham Rise (Lewis and Hayes 1983). This has produced a change in the nature of the plate boundary associated with the northern part of the Philippine Trench, from a subduction zone to a transform fault (Hamburger et al. 1983). Hence subduction has also ceased beneath the northern Bicol Volcanics.

Volcanic activity in the Bicol Peninsula associated with subduction along the Philippine trench has taken place since late Miocene times (PBMG 1982). Individual volcanic centres sit on substantial volcanic piles. The basal portions of these piles are probably submarine and the older volcanic rocks may be intercalated with early-to middle-Miocene sediments deposited in fore- and back-arc basins. The underlying basement rocks consist of pre-Tertiary schists and ultramafics intruded by upper-Tertiary diorite and granodiorite (PBMG 1982).

The major structural feature of the area is the Philippine fault (Allen 1962) which lies to the west of the Bicol peninsula. A number of second order shears run off the Philippine fault and divide the peninsula into a series of grabens and horsts. This overall tensional tectonic regime is a result of the coupled rotation of the area west of the Philippine trench produced by the portion of the northwest vector of movement of the Philippine plate which is not fully taken up by subduction in a southwest direction.

Along the western part of the peninsula is a series of fold belts, the most prominent of which has been called the Albay Syncline. This deformation appears to predate volcanism and reflects an early compressive tectonic environment.



MAJOR TECTONIC FEATURES OF THE PHILIPPINES
Fig1

VOLCANIC CENTRES AND HYDROTHERMAL ACTIVITY

Hydrothermal activity on the Bicol Peninsula was noted in the earliest geologic reports (Becker 1901). The first inventory of hydrothermal activity, which included a review of regional volcanism, was made by Grindley (1964) as a United Nations project. He identified the Tiwi area as the prime geothermal prospect in the region. He also commented on relative ages of the volcanic centres based on the degree of dissection. This section reviews data on each of the volcanic centres in the Bicol chain, and is followed by a generalised model summarising the geology and associated thermal features of the volcanic centres. Sources in addition to Grindley (1964) are Pelaez (1953). (PBM 1963), Waring (1965). Alcaraz (1976) Newhall (1977). Divis (1980) and PBMG (1982).

The Bicol volcanic chain can be divided into a series of recognisable major eruptive centres. Going from north to south they are: Mt Labo, Mt Colasi, Mt Isarog, Mt Iriga, Mt Malinao, Mt Masaraga, Mt Mayon, Pocdol Mts, Mt Juban, Mt Bulasan and the Gate Mts (Figure 2). The Pocdol and the Gate Mts each consist of a number of smaller coalescing volcanic centres rather than one central edifice.

Calc-alkaline andesites are the predominant rock type of the Bicol Volcanics, although basalts and basaltic andesites are found along with dacites, particularly as late stage domes. Rare rhyolites have also been reported occurring as perlitic domes south of Legazpi (Newhall 1977) and as an ignimbrite in the Gate Mts. (Divis 1980).

Mt Labo is an early-to-mid-Pleistocene compound volcano consisting of interlayered andesite and dacite flows and pyroclastics. The summit is a steep conical protrusion which overshadows a number of surrounding dacitic domes which are in turn surrounded by extensive pyroclastic flow deposits. Thermal springs are reported to occur at three separate localities on the lower slopes and areas of hydrothermal alteration are associated with major faults (PBMG 1982). To the north of Mt Labo, eroded Pliocene volcanics make up Mt Bagacay; they conformably underlie the Labo Volcanics.

Mt Colasi and an associated plug dome, Mt Cone, lie to the southeast of Mt Labo and the aprons of volcanic material of Mt Labo and Mt Colasi overlap. Mt Colasi appears to be more dissected and hence older than Mt Labo but younger than Mt Bagacay. Warm springs are found at low elevations to the southeast of the volcanic centre.

Mt Isarog is a large stratovolcano which is regarded as having been dormant since the Pleistocene. It has a summit caldera and consists of a sequence of hornblende andesite flows and pyroclastics of Pliocene to Pleistocene age. A solfatara occurs on the upper eastern slopes of the mountain in a canyon where steam vents deposit small amounts of sulphur. Warm springs occur at two separate localities on its flanks.

Mt Iriga is considered to be older than Mt Isarog, possibly middle-to-early Pleistocene in age. Augite andesites are reported to be the predominant rock type (Divis 1980) with some small basaltic cinder cones (Newhall 1977). There is a large collapse feature on the southern side of Iriga which appears to be a sector collapse, rather than a summit caldera.

Mt Malinao is considered to be late Pleistocene in age, and was erupted onto a volcanic pile as old as late Miocene. The volcano has a large breached summit caldera in which a few resurgent domes are found. An extensive laharic fan extends from the breach down to the sea. Impressive thermal features including boiling springs, fumaroles and large sinter mounds, which are otherwise rare in the Philippines, occurred in the coastal lowlands. The area has been developed for power (Horton et al. 1981) and currently produces 330 MW(e). The thermal features have subsequently been affected by drawdown in the field which has also resulted in a number of hydrothermal eruptions (Grindley 1982).

Mt Masaraga is considered to be of late Pleistocene age; it forms a simple tapering cone with no summit caldera or domes.

Mt Mayon is an active volcano, last erupting in September 1984 (Punongbayan et al. 1986). Prior to this eruption Mt Mayon laid claim to being one of the world's most perfect volcanic cones. However repeated nuee ardentes during the 1984 eruption excavated a large gully on its south eastern side. Between major eruptions, steam rises from the crater. A hot spring was also reported from the eastern base of the mountain in 1901 (Becker 1901), but has not been found since.

The Pocdol Mts are an area of coalescing volcanic centres, none of any great size. At least 20 individual centres are present, some with multiple vents and evidence of repeated episodes of volcanism. This has lead to a jumble of small volcanic peaks in varying stages of erosion. There are no records of historic eruptions from the area, but the youngest volcanoes have well-preserved vent features and are unlikely to be older than a few tens of thousand years. Most of the volcanism has been andesitic and the landforms developed are typical of this type, though dacite domes are also found.

Numerous thermal features occur in the Pocdol Mts. Those in the central highlands are mainly steam-or gas-heated, but large chloride springs occur along the coast (Lawless et al. 1983). Springs with mixed chemistries are common. The Bacon-Manito geothermal field is currently being developed for an initial 110 MW(e) electrical generating capacity by the Philippine National Oil Company (Tolentino et al. 1985).

Mt Juban is a strongly dissected composite volcano. possibly of early Pleistocene age. Erosion has largely obscured original volcanic landforms but no obvious caldera feature is present. No thermal features directly associated with Mt Juban have been reported.

Mt Bulusan is an active volcano with a well shaped cone and large crater. Its last eruption was in 1984. It occupies a large caldera approximately 15 km wide which shows as a distinct semi-circular feature on LANDSAT images. A plug dome, Mt Jormajan. also lies within the caldera, along with smaller dacite domes. A number of strongly active solfataras surround the summit (Pelaez 1953) and hot springs occur in the lowlands surrounding the volcano. Except for coastal springs, these are apparently restricted to within the caldera.

A number of volcanic centres older than Bulusan but younger than Juban occur outside of the caldera; little information about. them is available.

The Gate Mts lie to the south of the Bulusan caldera and consist of a number of small, coalescing volcanic centres. Few other details have been reported.

GENERALISED MODEL OF PHILIPPINE HYDROTHERMAL SYSTEMS APPLICABLE TO THE BICOL VOLCANIC CHAIN

Philippine hydrothermal systems have been interpreted to be the near-surface expression of Porphyry-Cu type systems (Henley and Ellis 1983. Sillitoe and Bonham 1984). By analogy, the heat sources for such systems are considered to be subvolcanic intrusives (Sillitoe 1973; Branch 1976). Generally there is a history of multiple intrusion and a tendency for the intrusive which develops a hydrothermal system, to be a late stage porphyritic body on the margins of a larger body (Sillitoe and Gappe 1984). Hydrothermal alteration in the shallow parts of such deposits (Sillitoe and Gappe, 1984) is directly comparable to that observed in active Philippine hydrothermal systems (Leach and Bogie 1982; Reyes, 1985). This includes not only the occurrence of the same mineral assemblages with the same zoning pattern, but the overprinting and telescoping of alteration zones so typical of porphyry systems.

A model for the parts of these systems accessible to geothermal drilling was put forward by Mahon et al. (1980) using data from Indonesian geothermal fields, which have a similar geotectonic setting to most Philippine fields. The model was adopted by Henley and Ellis (1983) with adaptation to the Philippine setting by Barnett and Espanola (1984). This model has been further refined by Bogie et al. (1986) (Figure 3). Such a model treats these geothermal systems as convective hydrothermal systems in which deeply circulating meteoric waters (Hulston et al. 1982) are heated and upflow towards the surface beaneath an area of high relief.

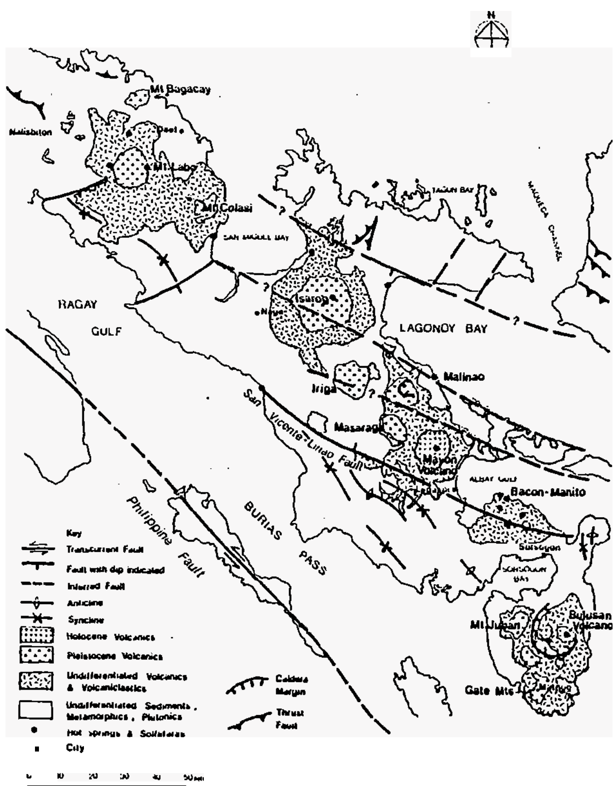
However, if interpretations of Porphyry-Cu systems are correct early stage activity will he marked by the exsolution of magmatic volatiles from the intrusive which acts as the heat source of the system. Hydraulic fracturing occurs around the margins of the intrusive due to the increase in volume of exsolved water upon its release from the melt (Burnham 1979). If this fracture network connects with the surface without triggering an eruption (Morey 1922), a magmatic solfatara marked by the presence of superheated fumaroles, abundant sulphur deposition and advanced argillic alteration will form. A good example of this is found on Biliran Island (Lawless and Gonzales 1982) which lies south of the Bicol region but is related to the same subduction zone. Solfataric activity at Bulusan may be similar. With time an annular, hydrothermal system will develop (Henley and McNabb 1978) as surrounding meteoric waters are heated.

Eventually pressures in the vicinity of the intrusive decline, resulting in the encroachment of the meteoric system (Gustafson and Hunt 1975). The meteoric waters become less dense as they are heated and rise in response to the pressure of surrounding colder, denser waters which provide the deep recharge of the system. Provided that the necessary permeability exists, the fluids will rise directly above the heat source. Since the heat source is a subvolcanic intrusive below an andesite volcano, the water will tend to rise to high elevations. The height reached by the column will depend upon the temperature and gas content of the water, the depth of the recharge and the ratio of horizontal to vertical permeability. As this ratio may be as high as 10 to 1 in the upper parts of hydrothermal systems (Grant, et al. 1983) and elevations can be over 1000m in such a setting, the upflowing waters are unlikely to reach the surface directly above the upflow. As a consequence, in areas of high rainfall groundwater aquifers are likely to intervene between the groundsurface and the piezometric surface of the single phase hydrothermal reservoir.

With upward movement there is a steady decrease in hydrostatic pressure. When this equals the vapour pressure of the water, boiling takes place. The vapour pressure is dependent upon the temperature of the waters and their chemistry, in particular gas content. As Philippine systems are typically hot and gas rich, high vapour pressures are found at depth and boiling can take place at depths greater than 2km. Such extensive boiling may also produce a vapour dominated zone at the top of the upflow. The ascent of the waters to high elevations also provides a gravitational gradient along which the fluid may outflow.

The gas and steam separation which take place upon boiling means that these fluids can move to the surface above the area of boiling if permeability permits. What actually appears at the surface however is dependent upon the degree of condensation that takes place in the intervening groundwater aquifer. In some instances the flow of gas and steam is sufficient to form a fumarolic area on the surface. However, the steam and a proportion of the gas may be condensed into the groundwater resulting in the discharge of cold gas at the surface, a kaipohan (Bogie et al. 1986), or possibly. 'nothing at all, if the groundwater aquifer is thick or has a high rate of recharge.

Condensation of steam and gas into shallow groundwaters produces secondary geothermal fluids which are acid SO_4 or HCO_3 waters, such fluids being produced by oxidation of H_2S above the watertable in the vadose zone or by neuetralisation of H_2CO_3 by the country rock, respectively. The result is a chemically zoned system with fluids at the highest elevation being acid -SO_4, while the upwelling fluids will be neutral -Cl waters. At intermediate levels, waters are mixtures of the two. When neutralisation of the acid SO_4-water occurs or if no oxidation takes place, HCO_3-rich waters are found, usually at lower elevations than the acid-SO_4 waters.



THE BICOL VOLCANIC CHAIN-GENERAL GEOLOGY
Fig 2

With time mineral deposition at the interface of deep hot Cl waters and overlying ground water may take place, due to mixing. Such mineral deposition, especially of anhydrite, may produce' an aquiclude between primary and secondary geothermal waters resulting in perched groundwater aquifers. These may be best developed on the flanks of the upflow. as in the centre a vapour-dominated zone may inhibit fluid mixing. These perched aquifers will however still have an acid-SO_4 chemistry due to the drainage of condensate from the vapour dominated zone into them. They will also outflow and tend to become more HCO_3^- rich and -SO_4 poor with neutralisation. As a consequence, the zonation of spring chemistries with elevation will become more pronounced with acid -SO springs at high elevation, HCO_3 - SO_4 spring% at lower elevation, mixed Cl-HCO_3 -SO_4 further down outflows where the aquiclude has not formed, and Cl hot springs at the lowest elevations. The latter may only occur close to sea level, and may possibly be channelled to the surface along the seawater-groundwater interface. The point where the neutral Cl outflow intersects the surface can be a substantial distance away from the upflow. up to 20km in some instances.

This model fits what is known of the two drilled systems of Bacon Manito and Tiwi. If the distribution of thermal features around other centres is considered in relation to the same model, substantial hydrothermal systems can also be expected to exist at Mt Labo. Mt Isarog and at Bulusan. That at Bulusan may however be at an early stage of its development, being most closely associated with active volcanism. A single spring is found near Mt Colasi and one other spring is found on the San Vicente-Linao fault. Which centres these are associated with or whether they are directly related to large individual hydrothermal systems is unclear.

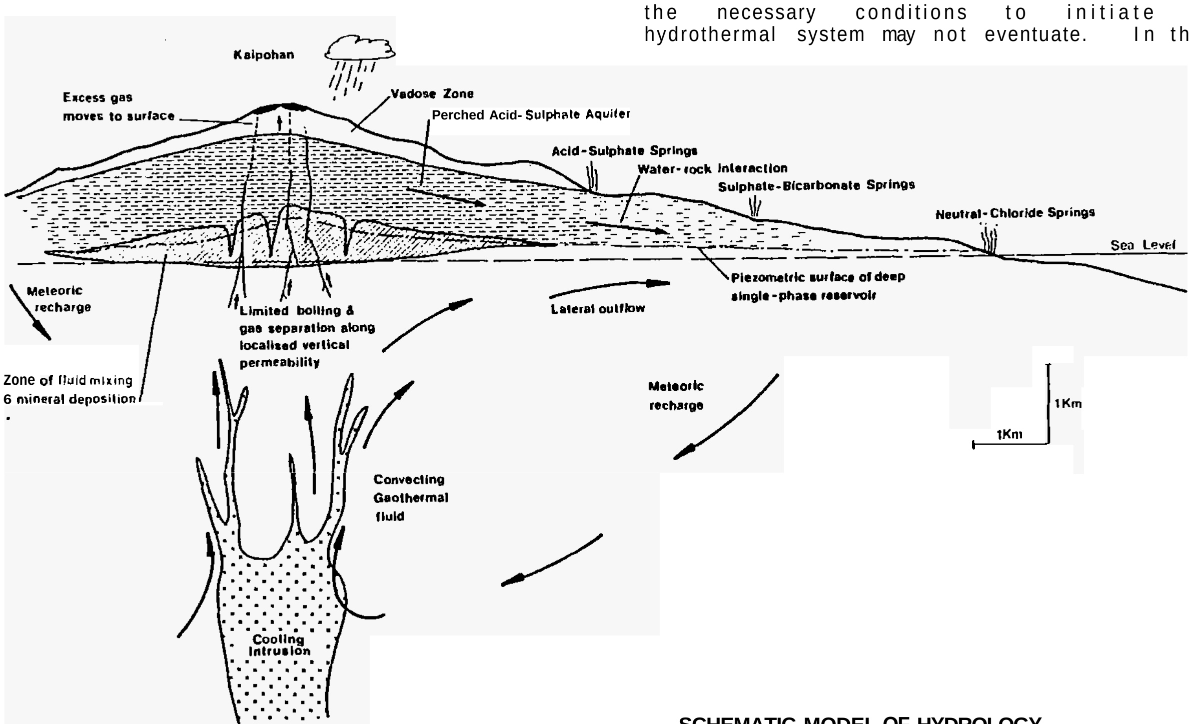
RELATIONSHIP OF VOLCANIC CENTRES TO HYDROTHERMAL SYSTEMS.

The volcanic centres of the Bicol Peninsula show a full range of volcanic and hydrothermal activity, with regular volcanic eruption of Mayon and Bulusan, strong solfataric activity at Bulasan, the development of meteoric hydrothermal systems at Bulusan, Bacon-Manito, Tiwi, Isarog and Labo. and possibly a complete lack of volcanic or hydrothermal activity at Iriga, Masaraga and Bagacay.

It is possible that this range in activity reflects different stages of the evolution of geothermal activity of an andesitic stratovolcano along a single pathway, in that some centres may be too youthful for hydrothermal systems to have formed while others are moribund. However there may also be fundamental differences between two different types of volcanic centre. One type of andesitic stratovolcano, of which Mayon is an example, erupts only basaltic andesites, and except for the escape of magmatic gases from a central crater between eruptions has little associated hydrothermal activity. Such volcanoes tend towards a perfect cone in shape and do not have a summit caldera or endogeneous domes. Masaraga and Iriga may also fall into this category.

The other type of volcanic centre erupts a progressively differentiated rock type, one or more times over its lifetime, (Gill 1981). Solfataric activity associated with this type of centre exhibits marked periodicity being strongest at either soon after the end of the volcano's eruptive history or between eruptive cycles (Pelaez 1953). Topographically such volcanoes are more complex than the first type, forming composite volcanoes with summit calderas and domes. Labo, Isarog, Malinao, the Pocdol mountains and Bulusan exhibit the topographic features typical of this second group.

A possible reason for these two separate trends is that in the first case the development of shallow magma chambers may not occur, or where it does, the residence time of the magma is small. Therefore little differentiation will occur and the necessary conditions to initiate a hydrothermal system may not eventuate. In the



SCHEMATIC MODEL OF HYDROLOGY OF BICOL VOLCANICS GEOTHERMAL FIELDS **Fig 3** second type shallow magma chambers may form and produce differentiated lavas which, when erupted may result in the formation of a caldera. Such shallow bodies can then degas to produce magmatic solfataras. and serve as heat sources for later meteoric hydrothermal systems. Whether or not a magma at depth exhibits this behaviour and undergoes later fracturing of its margins may depend on how hydrous the melt is (Burnham 1979).

This interpretation is consistent with the models developed for the occurrence of precious metal deposits closely associated with volcanic centres; in particular the high sulphur deposits of Bonham 1986. Such deposits are interpreted to result from the interaction of magmatic volatiles with shallow groundwater (Hayba et al. 1985) in volcanic centres (Sillitoe 1975) and are considered to be high level parts of porphyry systems (Sillitoe 1983). Hence they are the fossil equivalents of youthful hydrothermal systems in the island arc setting. Bonham in his compilation of diagnostic features of high sulphur deposits observes that they usually occur within calderas with associated dacite domes and are penecontemperaneous with volcanism. These are exactly the same features as are noted for the volcanic centres which host active hydrothermal systems in the Bicol Chain.

IMPLICATIONS FOR GEOTHERMAL EXPLORATION

If the relationship between volcanic landforms produced by a complex eruptive history involving shallow magma chambers and the occurrence of large hydrothermal systems holds true, such volcanic centres may be more prospective than those with relatively simple volcanic landforms. However the stage of development of any such system must also be considered. Magmatic volatiles present during the early history of such systems may produce acidic fluids as they condense into groundwaters. Acid fluids may render the system less suitable for utilisation. Such fluids may be neutralised sufficiently to exploit as they outflow, but they are also likely to lose heat as they do so. In these systems there may be a trade off between temperature and acidity. It may not be until the supply of magmatic volatiles is sufficiently exhausted that an exploitable hydrothermal system is available.

The most prospective geologic setting for finding large hydrothermal systems in this environment will therefore be volcanic centres with complex morphology and eruptive history, but lacking active magmatic solfataras.

CONCLUSIONS

The Bicol Volcanic Chain has been the site of volcanism since the Miocene, as a result of subduction along the Philippines Trench. A number of individual volcanic centres can be identified, of varying ages, along the chain.

Two of the volcanic centres in the Bicol Chain have been proven by drilling to be associated with large, exploitable hydrothermal systems. These are Malinao (Tiwi) and the Pocdol Mountains (Bacon Manito). The characteristics of these hydrothermal systems can be related to the models of hydrothermal systems in regions of high relief developed by Mahon et al. (1980) and Henley and Ellis (1983). On this basis, it can be anticipated that large hydrothermal systems are probably associated with Labo. Isarog and Bulusan.

There appears to be a correlation between volcanic centres with complex eruptive history and morphology. summit calderas, eruptive products indicating magma differentiation. especially dacite domes, and the occurrence of large hydrothermal systems. This is in contrast to more simple stratovolanoes such as Mayon. which do not appear to be associated with extensive hydrothermal systems. It is suggested that the difference may reflect the relatively long residence time of magma in shallow chambers in volcanoes of the first type but not in the second.

These concepts should provide a useful exploration tool for exploitable geothermal systems.

The interpretations are consistent with the occurrence models of the hydrothermal ore deposits found within the same setting, in terms of hydrothermal alteration patterns and volcanic landforms. Hence the large active hydrothermal systems hosted by the Bicol volcanics can be considered to be the contemporary equivalents of the hydrothermal systems which may produce such deposits.

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REFERENCES

ACHARYA, H.K. and AGGARWAL, Y.P. (1980) Seismicity and Tectonics of the Philippine Islands. Geophys. Res. V85, 3239 - 325.

ALCARAZ, A. (1976) Geothermal Exploration and Development in the Philippines - Summary. In Circum-Pacific Energy and Mineral Resources. M.T. Hakbouty. J.C. Maher, H.M. Lianl Eds. A.A.P.G. Mem 25, 140-145.

ALLEN, C.R. (1962) Circum-Pacific Faulting in the Philippines-Taiwan Region, J. Geophys. Res., V67, 4795-4811.

BECKER, G.F. (1901) Report on the Geology of the Philippine Islands. U.S.G.S. 21st Ann. Report Pt 3. 487-614.

BOGIE. I., LAWLESS, J.V. and PORNUEVO. J.B. (1986) Kaipohan : a "Non-thermal" Manifestation of Hydrothermal Systems. Submitted to Journal of Volcanological and Geothermal Research.

BONHAM. H.F. Jr (1986) Models for Volcanic Hosted Epithermal Precious Metal Deposits, a review. Proceedings Symposium 5. Volcanism, Hydrothermal Systems and Related Mineralisation. International Volcanological Congress New Zealand, 13-18.

BRANCH, C.D. (1976) Development of Porphyry Copper and Stratiform Volcanogenic Orebodies during the Life Cycle of Andesitic Strato-Volcanoes in Johnson, R.W. ed. Volcanism in Australia : Amsterdam, Elsevier, 337-342.

BURNHAM, C.W. (1979) Magmas and Hydrothermal Fluids in Barnes, H.L. ed. Geochemistry of Hydrothermal Ore Deposits, 2nd Ed, 71-136.

CARDWELL, R.K., ISACKS, B.L. and KARIG, D.E. (1980) The Spatial Distribution of Earthquakes, Focal Mechanism solutions and Subducted Lithosphere in the Philippine and Northeastern Indonesian Islands. In The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands - Hayes, D.E., Ed. Geophysical Monograph 23 pp 1-36.

DIVIS. A.F. (1980) The Petrology and Tectonics of Recent Volcanism in the Central Philippine Islands. In the Tectonic and Geologic Evolution of Southeast Asia Seas and Islands. Geophysical Monograph 23, 127-144.

GILL, J.B. (1981) Orogenic Andesites and Plate Tectonics; Springer-Verlag, Berlin, 390p.

GRANT, M.A., DONALDSON, I.G. and BIXLEY, P.F. (1982) Geothermal Reservoir Engineering. Academic Press, New York.

GRINDLEY, G.W. (1964) Geothermal Resources of the Island of Luzon, Philippines. Report of the U.N.S.F.

GRINDLEY, G.W. (1982) Report on a Visit to Geothermal Fields under Exploration in Leyte, S. Negros and S. Luzon, Republic of the Philippines. N.Z. Geol. Surv. Report G.59

GUSTAFSON, L.B. and HUNT, J.P. (1975) The Porphyry Copper Deposit at El Salvador, Chile. Econ. Geo. V70, 857-912

HAMBURGER, M.W., CARDWELL, R.K. and ISACKS, B. (1983) Seismotectonics of the Northern Philippines Island Arc. In The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2. hayes D.E. Ed Geophysical Monograph 27 1-22.

HAMILTON, W. (1979) Tectonics of the Indonesia Region. U.S.G.S. Prof. Pap. 1078.

HAYBA, D.O., BETHKE. P.M., HEALD. P. and FOLEY, N.K. (1985) Geologic, Mineralogic, and Geochemical Characteristics of Volcanic-Hosted Epithermal Precious-Metal Deposits. In Berger, B.R. and Bethke, P.M. Eds. Geology and Geochemistry of Epithermal Systems. Society of Economic Geologists, Reviews in Economic Geology V2, 129-168.

HENLEY. R.W. and ELLIS, A.J. (1983) Geothermal Systems, Ancient and Modern. Earth Science Reviews 19, 1-50.

HENLEY, R.W. and McNABB, A. (1978) Magmatic Vapor Plumes and Ground Water Interaction in Porphyry Copper Emplacement. Econ. Geo. V73, 1-20.

HORTON, R.M., MINETTE, T.N., BUDD, C.F. JR and ALCARAZ, A. (1981) Commercial Development of the Tiwi and Mak-Ban Geothermal fields of the Philippines. In Proc. Ascope 2nd Conf. 533-540.

HULSTON, J.R., STEWART, M.K., GLOVER, R.B., CAMALES, R.A.. BOGIE, I., and BARNETT, P.R. (1982) Stable Isotope Geochemistry of the Tongonan Geothermal Sysem, Leyte, Philippines. Proc. 1982 Pacific Geothermal Conference.

LAWLESS, J.V. and GONZALES. R.C. (1982) Geothermal Geology and Review of Exploration, Biliran Island : Pacific Geothermal Conference Proceedings, pt 1, 179-184.

LAWLESS, J.V., BROMLEY, C.J., LEACH, T.M., COPE, D.M., RECIO, C.M. and LICUP, A.C. (1983) Bacon Manito Geothermal Field : A Geoscientific Exploration Model. Proc. 5th Ann. Geothermal Workshop, Auckland University, 97-102.

LEACH, T.M. and BOGIE, I. (1982) Hydrothermal Overprinting of the Okoy Geothermal Field, R.P. Proc. 1982 Pacific Geothermal Conference.

LEWIS, S.D. and HAYES, D.E. (1983) The Tectonics of Northward Propagating subduction along Eastern Luzon. Philippines Islands. In The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands : Part 2. Hayes , D.E. Ed. Geophysical Monograph 27, 57-78.

MAHON. W.J.A., KLYEN, L.E. and RHODE, M. (1980) Hot Waters in Geothermal Systems. Chinetsu (Journal of the Japan Geothermal Energy Association) V 17, 11-24.

MOREY, G.W. (1922) The Development of Pressure in Magmas as a Result of Crystallisation. Washington Academy of Science Journal, V12, P219-230.

NEWHALL C.G. (1977) Geology and Petrology of Mayon Volcano, Southeastern Luzon, Philippines. MSc Thesis, University of California, Davis.

PELAEZ, V.R. (1953) The Behaviour and Characteristics of Volcanoes in the Solfataric and Fumorolic Stage of Activity. Proc. Pacific Science Congress V2 p364-368.

PHILIPPINE BUREAU OF MINES (1963) 1:1,000,000 Geological Map of the Philippines.

PHILIPPINE BUREAU OF MINES AND GEOSCIENCES (1982) Geology and Mineral Resources of the Philippines. Vol 1.

PUNONGBAYAN, R.S., CORPUZ, E.G., RAMOS, E.G., RUELO, H.B., CRUZ. J.B., NEWHALL, C.G., BANKS, N.G., and MELSON, W.G. (1986) Pyroclastic Flows at Mayon Volcano, Philippines, September 1986. Abstract in Int Volc Cong. New Zealand 1986 p 265.

REYES, A.G. (1985) A Comparitive Study of 'Acid' and 'Neutral pH' Hydrothermal Alteration in the Bacon Manito Geothermal Area, Philippines, MSc Thesis, Auckland University.

REYES, A.G. and TOLENTINO, B.S. (1981) The Distribution of Alteration Minerals in Philippine Geothermal Areas. Proc. ASCOPE 2nd Conf. 553 - 580.

SILLITOE, R.H. (1973) The Tops and Bottoms of Porphyry Copper Deposits. Econ. Geol. V68. 799 - 815.

SILLITOE, R.H. (1975) Lead Silver, Manganese and Native Sulphur Mineralisation Within a Strato Volcano, El Queva, Northwest Argentina. Econ. Geol. V70, 1190, 1201

SILLITOE, R.H. (1983) Enargite-bearing Massive Suphide Deposits high in Porphyry Copper Systems. Econ. Geol. V78, 348-352.

SILLITOE, R.H. and BONHAM. H.F. JR (1984) Volcanic Landforms and Ore Deposits. Econ. Geol. V79, 1286 - 1298.

SILLITOE, R.H. and GAPPE, I.M. JR (1984) Philippine Porphyry Copper Deposits : Geologic Setting and Characteristics. CCOP Report RAS 81/120.

TOLENTINO, B.S., ALCAREZ. A.P.. RECIO, C.M., BUNING, B.C. and BERNARDO, R.O. (1985) Strategies Relating to the Exploration and Development of a Geothermal Field : A Case for Bacon-Manit0 Geothermal Project, Albay/Sorsogon Provinces, Luzon. Philippines. GRC Int Symp on Geothermal Energy, 379-386.

WARING, G.A. (1965) Thermal Springs of the United States and Other Countries of the World - A Summary. U.S.G.S. Prof. Pap. 492.