

CONTRASTING ALTERATION STYLES OF ANDESITIC AND RHYOLITIC ROCKS IN GEOTHERMAL FIELDS OF THE TAUPO VOLCANIC ZONE, NEW ZEALAND

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ABSTRACT

Deep (1–2.25 km) drillholes at several geothermal fields in the Taupo Volcanic Zone, New Zealand, encountered thick sequences of Quaternary rhyolitic and andesitic rocks resting upon Mesozoic greywackes and argillites. The occurrence of andesites is uncommon in New Zealand geothermal fields but here allows comparison of their alteration with that of more silicic tuffs and lavas in a hot (250°–320°C) environment in which circulate dilute alkaline chloride fluids of near-neutral pH. Fluid inclusion geothermometry measurements show that the observed hydrothermal minerals formed under the present field conditions.

The andesites are of medium K, calc-alkaline, orogenic type which, where fresh, contain calcic-plagioclase, augite, hypersthene, titanomagnetite and occasional hornblende. These phases typically alter to chlorite, calcite, epidote, clinozoisite, titanite, adularia, illite, pyrite and quartz, but veins mainly consist of different proportions of calcite, epidote, wairakite, adularia, chlorite and pyrite. The silicic volcanic rocks commonly alter to the same assemblages but the intensity of alteration of the two rock types differs considerably depending mainly upon how fluids move through them. Alteration intensity of the andesites changes sharply even over very short distances (order of cms) because thermal fluids move in them via joints; by contrast, the silicic volcanic rocks commonly have a much more pervasive and homogenous alteration style consistent with thermal fluids penetrating them along grain boundaries and through interconnected pores.

Introduction

Many high temperature (>200°C) geothermal systems are hosted by volcanic rocks so that fluid/rock interactions there are both fast and obvious from examination of the resultant hydrothermal minerals. Factors which affect the identity and intensity of hydrothermal alteration include temperature and fluid composition, especially pH, and the concentration of dissolved gases. Rock permeability is also a factor long known to be reflected both in the mineralogy and the intensity of alteration (Browne, 1970; Reyes and Tolentino, 1982). In fact, these features are a product of reaction time and permeability. Rock composition has also been stressed by several workers as having an important control on hydrothermal alteration especially as it relates to creating environments favourable for ore deposition. We also know that there are marked differences in the distribution of hydrothermal minerals in geothermal systems hosted by rhyolitic and andesitic rocks, but the question arises as to whether these differences are a function of the host rocks themselves or are due to other factors. Although active geothermal fields are, indeed, good places to examine the effect that rock type has on hydrothermal alteration, parameters such as local permeability, temperature and fluid type also vary, even within a single field, so that it is usually difficult to identify separately the effect that rock type alone has on alteration. For this reason it is worth while examining the hydrothermal alteration of two different types of volcanic rock present in reservoirs where these other parameters are nearly constant. This is the situation in several New Zealand geothermal systems of the Taupo Volcanic Zone.

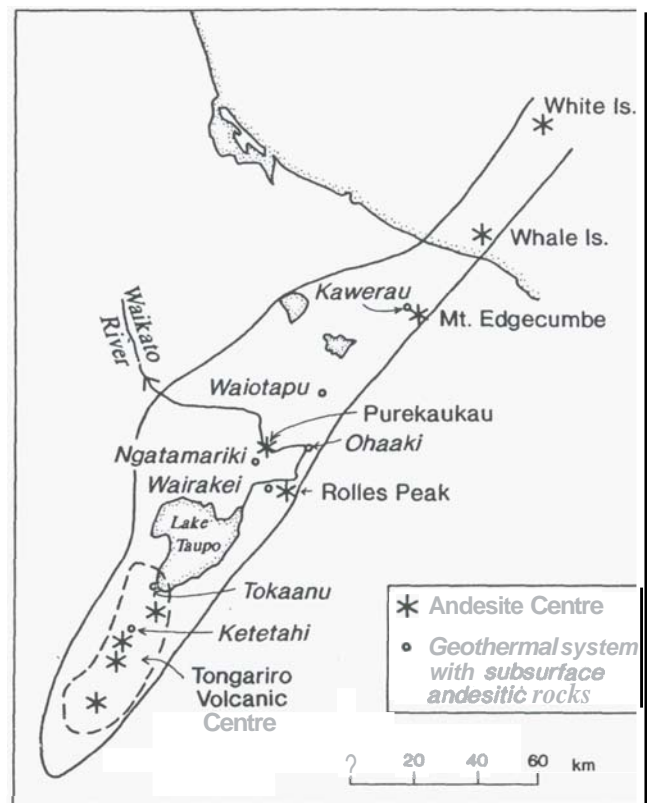


Figure 1: Locations of geothermal systems in the Taupo Volcanic Zone where andesites were encountered during drilling. Also shown are surface occurrences of andesites.

Reservoir rocks of geothermal systems in the Taupo Volcanic Zone

The Taupo Volcanic Zone occupies a north-east-striking rift zone comprising thick sequences of Quaternary calc-alkaline volcanic rocks with interbedded lacustrine sediments. These overlie Mesozoic greywacke and argillite sediments reached by some drillholes at only the Kawerau, Ohaaki and Rotokawa geothermal fields (Fig. 1). Surface volcanic rocks here are dominantly silicic in composition, mostly comprising rhyolite lavas and ignimbrites with subordinate amounts of andesite plus rare basalt lavas and tuffs. The andesites are located in the southern (Tongariro Volcanic Centre) and northern margins of the zone (Mt Edgecumbe, Whale and White Islands), with minor occurrences between (at Rolles Peak, Purekawkau). Geothermal drilling at fourteen active geothermal fields in this zone reveal that the subsurface rocks are also dominantly silicic in composition with only rare dacite and even rarer basalt encountered. However, andesite lavas and tuffs occur at six fields (Table 1), most notably at Rotokawa where they exceed 1100 km in thickness, and locally, at least, rest directly upon the basement sediments. Elsewhere, the andesites are thinner and interbedded with much thicker silicic rhyolites and pyroclastics.

TABLE 1: Occurrence of subsurface andesites in *some* geothermal fields of the Taupo Volcanic Zone

Field	No of wells andesite occurs	Maximum known thickness (m)	Types	Local names	References
Kawerau	14 (min)	259	min, 2 flows, tuff	Upper Kawerau Andesite Lower Kawerau Andesite	Browne, 1978; Bogie, 1981; Christenson, 1987
Ohaaki	3	25	lava	unnamed	Browne, 1971; Wood, 1983
Wairakei	26	200	3 lava flows and flow breccias	Waiora Valley Andesite	Grindley, 1965, 1982; Steiner, 1977
Waiotapu	2	110	? intrusives	Ngakoro Andesite	Hedenquist, 1983; Steiner, 1963
Rotokawa	4	1110	multiple? lava	Rotokawa Andesites	Browne & Lloyd, 1986
Ngatamariki	2	120	multiple lava flows, pyroclastics	Not used	Browne et al., in prep.

Andesites have ~~not~~ been reported ~~from~~ the Orakei Korako, Te Kopia, Mokai or Tauhara fields.

TABLE 2a: Distribution of replacement hydrothermal minerals in andesitic units and overlying and underlying rhyolitic rocks of well Br 15 at the Ohaaki geothermal field

Depths (m)	Overlying Volcanic Unit 1842-1897 Rhyolite tuff	Andesite 2007-2032 Lava	Underlying Volcanic Unit 2136-2284 Rhyolite tuff
primary andesine	—	X	X
chlorite	X	X	X
illite	X	X	X
adularia	X	X	X
albite	X	—	X
titanite	X	X	X
epidote	X	X	X
quartz	X	X	X
calcite	X	X	X
pyrite	X	X	X
pyrrhotite	—	X	—
base metal sulphides	—	—	X

TABLE 2b: Distribution of hydrothermal minerals in Ngakoro Andesite and underlying and overlying rhyolite tuff, Waiotapu geothermal field (from Hedenquist, 1983; Steiner, 1963).

Mineral	WELL WT 6			WELL WT 7		
	Overlying rhyolite tuff, 748 m	Andesite 800-853 m	Underlying rhyolite tuff, 860m	Overlying rhyolite tuff, 787-802 m	Andesite 817-930m	Underlying rhyolite tuff 937m
primary andesine	—	X	X	X	X	X
chlorite	X	x ; v	X	x ; v	x ; v	X
illite	X	—	X	X	X	X
adularia	—	—	—	X	—	—
albite	X	X	X	X	X	X
titanite	X	X	X	X	X	X
epidote	—	—	—	—	—	—
quartz	X	X	X	X	x ; v	X
calcite	X	x ; v	X	x ; v	X ; V	X
pyrite	X	—	X	X	—	—
wairakite	—	v	—	—	—	—

v = vein α vug filling

TABLE 2c: Distribution of hydrothermal minerals in Kawerau basaltic andesites and closest underlying and overlying rhyolites lavas and tuffs (from Browne, 1978)

Drillhole No.	KA 19			KA 22			KA 24		
Mineral	Overlying rhyolite (802m)	Andesite (876-960m)	Underlying rhyolite (1106m)	Overlying rhyolite (792m)	Andesite (853-913m)	Underlying rhyolite tuff (976m)	Overlying rhyolite lava (635m)	Andesite breccia (700m)	Underlying rhyolite lava (742m)
primary minerals		And;cpx	-	-	And;cpx	-	-	And.	-
chlorite	-	X	X	X	X	X	-	X;V	X
illite	X	X	X	X	X	X	X	X	-
adularia	-	-	-	X	X	-	-		
albite	X	-	X	-	X	-	-		
titanite	X	X	X	X	X	X	X	X	
epidote	X	X	X	X	-	X	-		-
quartz	X	X;V	-	X	X	-	X	X	X
calcite	X	X;V	X	X	X	X	X	X;V	X
pyrite	X	X	X	X	X	X	X		X
others	-	-	-	-	hematite	-	-	-	-

And = andesine; cpx = clinopyroxene; v = vein or vug filling.

TABLE 2d: Distribution of hydrothermal minerals in deep andesites and interbedded silicic volcanics, B 121, Wairakei geothermal field

	Andesite (1810 and 2202 m)	Interbedded rhyolitic tuffs (1757, 2109, 2111 m)
primary plagioclase	X	-
chlorite	X	X
illite	X	X
adularia	-	X
albite	X	X
wairakite	-	X
epidote	X	X
quartz	X	X
calcite	X	X
pyrite	X	X
pyrrhotite	-	X

TABLE 3: Common alteration products of primary minerals in Rotokawa Andesite and closest silicic volcanic rocks

ANDESITE	RHYOLITIC IGNIMBRITE
Andesine → chlorite, quartz, epidote, titanite, calcite	Andesine → quartz, epidote, calcite, adularia, albite
Hypersthene → chlorite, quartz, titanite	
Augite → chlorite, calcite, quartz (epidote)	
Hornblende → oxidised, chlorite, titanite	
Groundmass → chlorite, calcite, quartz, titanite, hematite	Groundmass → chlorite, illite, quartz, titanite, calcite, pyrite
Veins: chlorite, calcite,	

Mineralogy of andesites and surrounding silicic volcanic rocks

Temperature gradients are slightest and the reservoir fluids are mostly nearly uniform in composition (dilute alkaline chloride) at greatest depth in a field, so any observed difference in alteration mineralogy can be attributed solely to rock type. Table 2 identifies the hydrothermal minerals that occur in altered andesite and the silicic volcanic rocks above and below them at four of these fields.

Ohaaki

At Ohaaki, andesites occur only as two thin (<25 m) flows (Browne, 1971), one deep in well No. Br 15 where the temperature is 293°C, and the other at the bottom (1082 m) of well Br 17 and at about 990 m depth in well Br 11. The hydrothermal minerals which occur in the overlying and underlying rhyolitic tuffs of well Br 15 are the same as those present in the andesite lava (Table 2a) except for the absence of albite and base-metal sulphides in the latter but the presence here of pyrrhotite. Note, however, that some primary andesine survives in both the andesite and the rhyolite tuff below it. The bottom andesite core (1083 m) from well Br 17 contains hydrothermal chlorite, albite, pyrite, calcite, titanite and minor adularia, and all of these minerals except titanite also occur in cores of the overlying (728-1082 m) rhyolitic tuff. Similarly, andesite core from 991 m depth, BR8, contains ferromagnesian minerals replaced by chlorite, calcite, and epidote; andesine here has been mostly replaced by adularia, calcite, albite and minor chlorite, quartz and epidote. Overlying rhyolitic tuff (728-1082 m) also contains all these phases except epidote.

Waiotapu

At Waiotapu, the Ngakoro Andesite, penetrated by two wells, is up to 110 m thick; it is underlain directly by the quartzose ignimbrite and overlain by tuffaceous silicic breccia, crystal tuff and hornblende and pyroxene-bearing quartzose ignimbrite (Steiner, 1963; Hedenquist, 1983). Measured temperatures are 262-265°C in well 6 and 282-292°C in well WT 7 (Banwell, 1963). Table 2b shows the identity of the hydrothermal minerals present in both the andesite and the rhyolitic units above and below it. Fresh andesine persists in all except the rhyolite tuff overlying the andesite in well no. 6, and the hydrothermal minerals common to all sets of samples are chlorite, albite, titanite, quartz and calcite. Further, there is no hydrothermal mineral present in the andesite that does not also occur as a replacement phase in the surrounding silicic tuffs. Note also that epidote is absent in all samples but wairakite occurs as a vug mineral in only the andesite of well 6.

Kawerau

Andesite lavas are much more extensive at Kawerau than they are at both Waiotapu and Ohaaki (Browne, 1978; Bogie, 1981; Christenson, 1987). They constitute an important aquifer in the northern part of the field, being more than 250 m thick in places at measured temperatures between 255° and 285°C. However, we here consider only thinner flows whose alteration can be compared directly with that of the overlying and underlying silicic volcanic rocks. Where fresh, the Kawerau andesites contain phenocrysts of bytownite, augite, hypersthene and magnetite, but these are replaced by an assemblage (Table 2c) that includes the phases also found in the other fields. Primary plagioclase and some pyroxene survives in the andesites but not in the more silicic units, and the hydrothermal minerals present in both rock types are very similar.

Wairakei

Andesite lavas are also present in the Wairakei geothermal field (Steiner, 1977; Grindley, 1982) but are not widespread. Three thin flows occur deep in the system, below 1750 m, interbedded with silicic pyroclastic rocks. The hydrothermal minerals which occur in these flows (Table 2d) are the same as those found also in the interbedded silicic volcanic rocks. The alteration of a shallower andesite unit, the Waiora Valley Andesite (about 500 to 600 m deep), has been studied in more detail by Steiner (1977) who concluded (p.47) that "there is no difference between the alteration products of andesine phenocrysts in andesite and the alteration products of plagioclase in silicic rocks". The only difference here is the incomplete alteration of the plagioclase present in the andesite.

Alteration of silicic and andesitic rocks at the Rotokawa geothermal field

The Rotokawa geothermal field, 13 km north-east of Wairakei, has more voluminous andesites than any other field drilled to date in the Taupo Volcanic Zone. The andesites occur below 1300 m depth and locally, at least, rest upon Mesozoic greywacke and argillite. They are overlain by silicic volcanic rocks including ignimbrites and rhyolite lavas.

Mineralogy of andesite alteration

The primary phenocryst minerals present in the fresh andesite are calcic plagioclase (An₆₀ - An₆₈), augite and hypersthene; some titanomagnetite and magnetite survives in places, and hornblende was formerly present locally. The most stable primary mineral is plagioclase, followed by augite, hornblende, hypersthene and magnetite/titanomagnetite. Common replacement minerals are chlorite, calcite, epidote, wairakite, adularia, and pyrite (Table 3). Veins consist of various proportions of quartz, calcite, epidote, wairakite, adularia, chlorite and pyrite. However, a striking feature of the alteration is the sharp variations in its intensity; even cores from the same depth show a range of colour from near black to pale green. For example, in the least-altered pieces of dark grey andesite core from 2280 m depth, RK6, augite and plagioclase survive, but in pale-coloured core from the same depth all primary constituents have been entirely replaced. Similarly, sections of core recovered from 2219 m, RK8, contain fresh andesine and augite, but elsewhere in the same core augite has been mostly altered and there is also extensive, very local, microveining, with pervasive epidote present in the groundmass.

Mineralogy of overlying volcanic rocks

The silicic pyroclastic rocks overlying the andesites at Rotokawa contained primary phenocrysts of quartz, andesine, iron oxides and, locally, biotite and probably rare pyroxenes. Quartz has remained unaltered, but, typically, andesine is partly replaced by albite, adularia, quartz and calcite. Where present, biotite has altered to illite. Although alteration of the rhyolitic ignimbrite is slight it is of a more uniform intensity than the alteration of the andesite below.

Chemical composition of altered andesites

In three places, cores from the same depth and having the same density show different alteration intensity. Different parts of the same core were kindly analysed by Dr Robin Parker, Geology Dept., University of Auckland, and compared (Browne et al., in press). In two cores, from RK4 and RK6, hydrothermal alteration has caused a local reduction in silica content of 1 to 3%; the same two cores increased in their Na₂O contents (0.3 to 1.3%), however, during alteration but there is very little difference in the K₂O contents of any of the three samples. MgO was depleted by as much as 1% in the altered part of all three cores, and Fe₂O₃ by 0.3 to 0.5%. Titania, MnO and P₂O₅ did not move overall, and H₂O differences are surprisingly slight. Rubidium is concentrated in the more altered sections of all three cores, and both strontium and barium are also slightly higher here.

Overall, however, the chemical composition of the lavas does not noticeably reflect their intensity of alteration nor the identity of the hydrothermal phases present. Obviously, the more altered sections of the cores must have been affected by the addition of at least some water, carbon dioxide, and sulphur since these constituents are needed to form chlorite, illite, calcite and pyrite. This has largely occurred, however, without significant major element addition, as the analyses suggests that the observed alteration, even in the most intensely altered cores, was largely isochemical. This contrasts with the usual chemical style of alteration in silicic pyroclastic rocks whose extensive mass transfer between rock and fluid phases has taken place (e.g. Bogie and Browne, 1979; Kakimoto and Browne, 1986; Henneberger and Browne, 1988).

Discussion

Comparison of the hydrothermal mineral assemblages formed in adjacent andesite and rhyolitic volcanic rocks show only slight differences. Albite and illite are, slightly more common in the rhyolites, whose initial compositions were richer in both potassium and sodium. Chlorite is more abundant in the andesites but it is also widespread in the rhyolitic rocks. However, clearly there is no alteration assemblage that is typical of andesites only.

The independence of alteration mineralogy and starting rock composition is also illustrated by the observation that the same hydrothermal minerals occur in andesite clasts present within some silicic pyroclastic rocks and in these hosts themselves.

There are, however, differences in the intensity of alteration between the andesites and the silicic volcanics. The latter have a much more uniform intensity of alteration, even where replacement reactions are incomplete. There is also a uniform intensity of alteration for the few andesite tuffs encountered during drilling, but this contrasts markedly with the uneven intensity of alteration seen in many individual cores of andesite lava and throughout the lava flows themselves.

The reason for this contrast in alteration intensity reflects the different ways that fluids move in these rocks. Fluids can move through silicic volcanics via interconnected pores, but in andesite lavas they move exclusively along joint channels and penetrate these host rocks only very slowly. Hydrothermal minerals deposited onto joint surfaces effectively seal the rock from further fluid access and reactions. When thermal fluids do react with andesite lavas, however, they merely serve as catalysts to "reshuffle" the original constituents on a very local scale. Thus elements, such as calcium, iron, magnesium, silicon, titanium and aluminium are thereby fixed into hydrothermal minerals which are more stable than their precursors in the geothermal environment.

The main conclusion of the comparison between andesitic and rhyolitic rock alteration in geothermal systems of the Taupo Volcanic Zone, therefore, is that inherited compositional differences have no bearing on the identity of the hydrothermal minerals that form. The homogenising effect of hydrothermal alteration is also apparent in geothermal reservoirs hosted by rocks of different composition. For example, a deep hydrothermal mineral assemblage comprising quartz, chlorite, calcite, epidote, illite, pyrite ± albite, ± adularia, ± amphibole, ± other calc-silicates occurs in the highly alkaline volcanic reservoir rocks of the Olkaria, Kenya, geothermal field (Browne, 1984), the fluvial sediments of the Salton Sea, California, and the nearby Cerro Prieto field in Mexico (Elders and Sass, 1988; Elders et al., 1984). The basalts of Iceland also typically alter to a similar mineral assemblage but without hydrothermal feldspars (Kristmannsdottir, 1975), as do a wide variety of igneous rock types at the Los Hornos field, Mexico (Viggiano, 1988).

If the effect of rock type on alteration is due to the way in which fluids move through them then an explanation must be sought for the reason why many hydrothermal mineral assemblages in hydrothermal ore deposits do indeed show an apparent association with a particular rock type.

This seems largely due to the different hydrological settings of the host rocks. The hydrology, in turn, is controlled by the terrain. Briefly, there are two settings of high temperature geothermal systems in volcanic environments:

1. In gentle terrains where any surface expression of a field is most obvious at lowest elevations;
2. In steep terrains. These discharge steam and gas at highest elevations with thermal water reaching the surface in diluted form, if at all, several kilometres distant from the region of fluid upflow. Above the steam/water interface there are commonly one or more perched bodies of meteoric water into which ascending steam and gases condense, producing CO₂-rich, bicarbonate and acid sulphate waters. Local mixing of these different waters leads to a thermal field with a range of compositions and matching alteration. This has been very well demonstrated by Leach et al. (1985) in their description of alteration at the Bacon-Manito geothermal system, Philippines.

It happens that the first type of geothermal system commonly occurs in rift-type settings where silicic volcanic rocks predominate, such as in the Taupo Volcanic Zone and the Rift Valley of Kenya. Many geothermal systems, however, are located in steep terrain within individual volcanoes of andesite and basaltic andesite composition such as occur in island arc environments bordering the Pacific Ocean (Figure 2a).

Deep fluids ascending in geothermal systems of gentler terrain approach closer to ground surface and many even discharge there so they have less opportunity to develop perched waters of different composition. Nor would one expect major fluctuations in the position of the steam/deep water interface so that the hydrothermal alteration produced in these systems mainly reflects the composition of the deep alkaline chloride fluid without any widespread overprinting. Geothermal systems in steep terrain, by contrast, typically have a much more extensive development of alteration minerals produced by acid sulphate, CO₂-rich and mixed waters (Figure 2b). The location of the steam/deep water interface here fluctuates readily in response to even slight perturbations in hydrology; this produces the alteration overprints commonly seen in hydrothermal systems with andesite-hosted settings. Sulphate and CO₂-rich waters produced above the steam water interface encounter hotter rock as they descend, causing anhydrite and calcite to precipitate because of their inverse solubility with respect to temperature. Normal and strike-slip faults in these systems provide channels that allow perched acid condensate waters to penetrate to great depth (~2 km) within a geothermal field, producing deep hot acid fluids and their associated hydrothermal minerals such as diasporite, pyrophyllite and alunite (Reyes, 1985).

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The hydrological setting of a geothermal field, therefore, has a much greater effect on its associated hydrothermal alteration than does the compositions of its host rocks. The hydrology affects the alteration by determining the extent and distribution of derivative fluids. However, the observed contrasts in alteration intensity between silicic volcanic rocks and andesite lavas is caused by their two different types of permeability - general pervasive, intergranular porosity in the case of the former, and mainly channel type in the latter.

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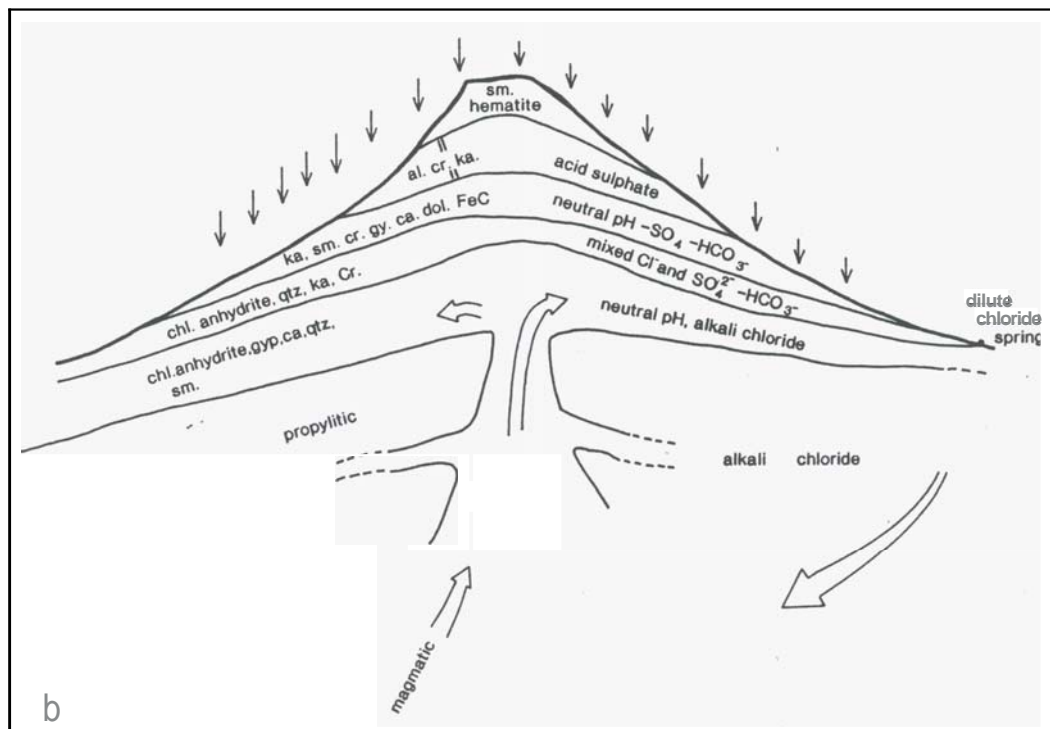
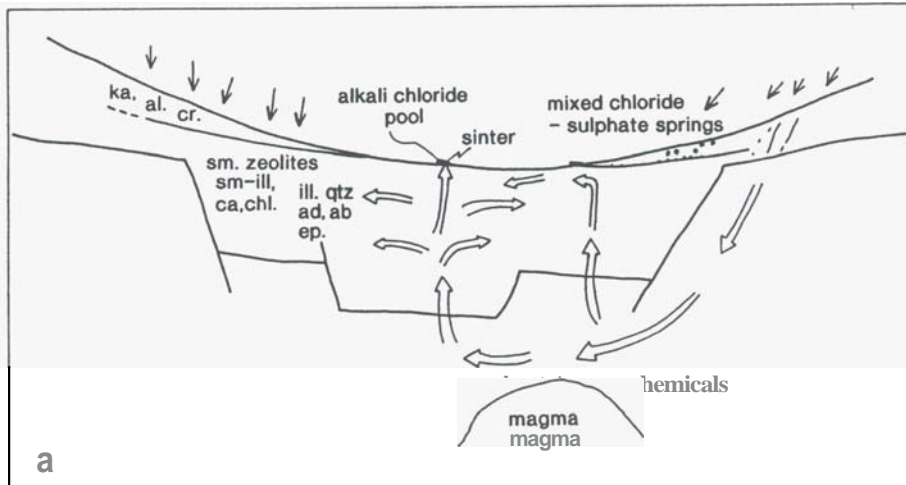


Figure 2: Diagram showing simplified relationships between hydrology and hydrothermal alteration for a geothermal system in (a) gentle terrain such as the Taupo Volcanic Zone, and (b) steep terrain such as Bacon-Manit0 (from Leach et al., 1985). Symbols used: Ka = kaolin; al = alunite; cr = cristobalite; sm = smectite; sm-illite = interlayered smectite-illite; ca = calcite; ill = illite; qtz = quartz; ad = adularia; ab = albite; ep = epidote; gy = gypsum; dol = dolomite; FeC = siderite; chl = chlorite.