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VARIATIONS OF $^3He/^4He$ ISOTOPE RATIOS WITHIN THE BROADLANDS GEOTHERMAL FIELD, NEW ZEALAND

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ABSTRACT

The Broadlands-Ohaaki geothermal field is located 20 km NE of Wairakei on the Central Volcanic Zone of New Zealand. It falls within a resistivity low extending 4 km by 3 km.

A study of $^3He/^4He$ ratios within this field has shown R/R_A ratios close to 6.0 in the Ohaaki production area (NW). In contrast the production area to the SE on the east bank of the Waikato River has R/R_A values close to 3.5.

Studies of carbon and hydrogen isotopes in the methane and carbon dioxide gases, however, show no significant variation across the field. The geothermal temperatures and production of the wells is also similar in both groups of production wells but differences in chemical ratios reported previously are found to correlate with the $^3He/^4He$ measurements.

A tentative interpretation of the results indicate that there is a contribution of 'He from the mantle and that the variations in the $^3He/^4He$ ratios are probably related to differences in the geochemistry of the rocks through which the geothermal fluids flow to the surface. Preliminary measurements of the argon isotopes also show a contribution from radiogenic rocks at depth.

INTRODUCTION

Helium isotope measurements of geothermal regions associated with plate boundaries have shown indications of a primordial helium from the mantle with $^3He/^4He$ ratio considerably greater than that of the atmosphere (Lupton, 1983). Measurements of $^3He/^4He$ in the thermal areas of New Zealand made by Torgersen *et al.*, (1982) covered a wide area of New Zealand and confirmed the existence of many areas where the R/R_A value ($R = {}^3He/{}^4He$; $R_A = R_{Air}$) was in the range 5-7. They concluded from the results of their measurements that the R/R_A values obtained did not correlate with gas chemistry, water chemistry etc. but were anticorrelated with absolute He concentration and with $^{40}Ar/^{36}Ar$ ratios, suggesting that the observed $^3He/^4He$ variations are due to mixing between a 'He-rich mantle end-member and a radiogenic component added within the crust either at depth or near the surface.

Since the Torgersen *et al.* survey was only able to collect two or three sites in most areas sampled, a project has been commenced to study each of the main geothermal areas in more detail. This paper presents the results of studies in the Broadlands geothermal area where the Ohaaki geothermal power station of 70 MW, capacity is currently under construction.

THE BROADLANDS FIELD

The Broadlands-Ohaaki geothermal system is situated in the central volcanic zone (CVZ) of the North Island of New Zealand with the subducting Pacific plate some 100 km below (Adams and Ware, 1977). It is located 20 km northeast of Wairakei along the Waikato river. The geology and stratigraphy of the Broadlands area has been described by Grindley and Browne (1968), Browne (1971) and Wood (1983). The chemistry of discharges from the first 19 wells was reported by Mahon and Finlayson (1972); the isotopic composition of water from eight of these wells was interpreted by Giggenbach (1971), and the carbon and hydrogen isotopic composition of the gases was discussed by Lyon and Hulston (1984). Browne and Ellis (1970) determined the mineral-fluid equilibria existing in the Broadlands system; this was elaborated on by Giggenbach (1980, 1981). Weissberg *et al.* (1979) summarise the precious and base metal mineralisation in the system. Recently Hedenquist and Stewart (1985) have described the existence of a CO_2-rich steam heated water which has been responsible for external corrosion of well casings at 300 to 600 m depth.

Of the 44 wells drilled at Broadlands, 25 will be used for production, eight were initially drilled as potential reinjection sites and 11 for monitoring purposes (Figure 1); they range in depth from 358 to 2587 m, and average 1256 m. All of the wells were drilled within or on the approximate resistivity boundary (which encloses the area of low apparent resistivity). All of the production wells are within the 270°C isotherm for 900 m depth (-600 m.a.s.l.), the typical production level. The Waikato River separates the wells into east and west Bank, which fortuitously almost matches a distinction based on some of the chemical characteristics of the discharges (see below). In the Broadlands area the river trend is parallel to the major geological faults.

METHODS

Samples were collected in 50 cm^3 glass flasks (Coming glass type 1720) fitted with high vacuum stopcocks. The sample gases were initially extracted and stored in breakseal tubes made of 1720 glass before analysis on a specially constructed static mass spectrometer in the second author's laboratory. The analysis techniques generally follow those described for SIO (Scripps Institute for Oceanography, San Diego, California) in Torgersen *et* al. (1982). Argon isotope measurements were also made on this instrument with frequent calibration with atmospheric argon. $^{40}Ar/^4He$ ratio measurements were also commenced on this instrument but at the time of writing the calibration techniques have not been perfected and consequently the data have not been included in the table of results, although they have been shown in some of the figures.

Sampling for this survey of Broadlands has extended beyond the production area of the field into peripheral monitor and reinjection holes. Wherever possible wells were sampled while in full discharge but to obtain adequate coverage of the field it was necessary to sample some wells which were "bleeding" (viz. discharging through a pipe of less than 30mm diameter to restrict the flow while still maintaining fluid discharge), or in a near closed state with only a gas head on the well. These are distinguished by D, B or G in the "discharge" column of Table 1. Note that well Br25 has been sampled in both the bleeding and discharge states and very similar results obtained. Unfortunately it was not possible to sample Ohaaki pool but the results from a small pool close to Br3 have been included in Table 1.

RESULTS

The results of these measurements are listed in Table 1. The R/R_A values listed indicate the ratio of $^3He/^4He$ in the sample to that in atmospheric helium. The He/Ne ratio relative to air is

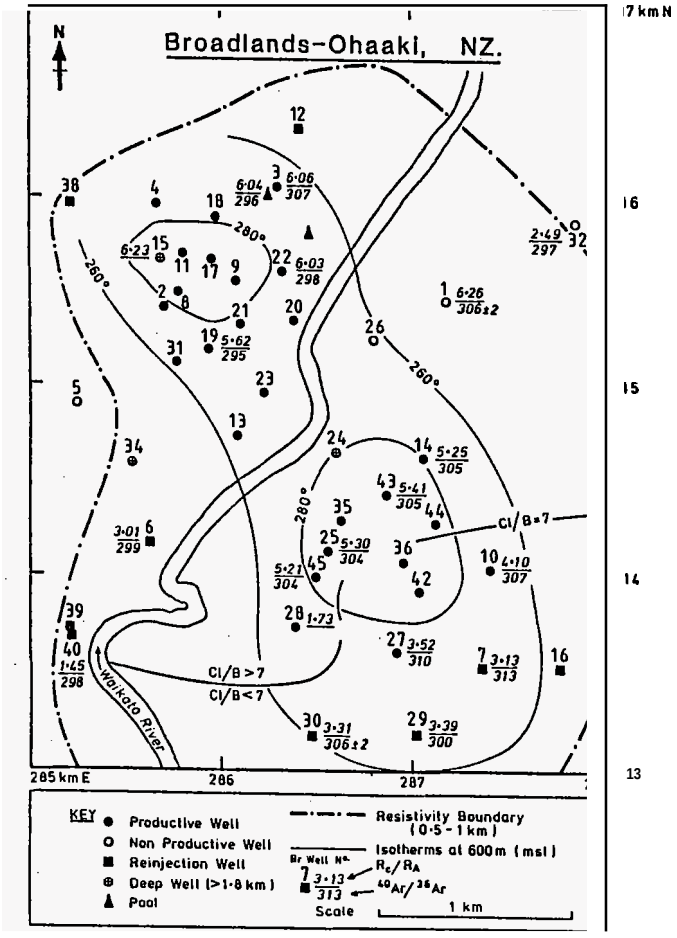

Figure 1: Location of wells

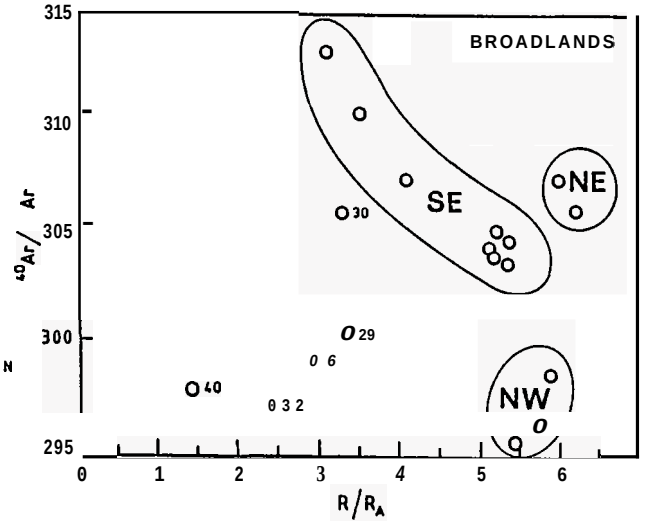

Figure 2: Plot of Argon isotopic ratios against Helium isotopic ratios

also shown and this has been used to calculate the R_c/R_A value which indicates the corrected R/R_A value of the sample for the situation where the Ne content is derived from air leakage into the sample bottle or as part of the hydrothemial cycle using the formula

$$R_c/R_A = [(R/R_A)X - 1]/(X - 1)$$

where $X = (He/Ne)_{air}$ for gas samples

or $X = (He/Ne)/0.82(He/Ne)_{air}$ for fluid samples – where the factor 0.82 accounts for the differing solubilities of He and Ne in water.

In Figure 1 the R_c/R_A and $^{40}Ar/^{36}Ar$ values have been plotted beside the well locations on the map of the area. The R_c/R_A values in the production area generally decrease from ~ 6.0 in the north west (wells 15, 3 and 22) to ~ 3.3 in the south east, while the peripherial wells and well 28 have R_c/R_A values of 1.45 to 3.0.

The $^{40}Ar/^{36}Ar$ values generally follow the opposite trend with higher values in the SE and generally lower values closer to atmospheric in the NW and in the peripheral wells. The $^{40}Ar/^{36}Ar$ results from tlie most north easterly wells within the resistivity boundary (wells 1 and 3) are however almost as high as those in the SE.

The plot of $^{40}Ar/^{36}Ar$ against R/R_A in Figure 2 is somewhat more complex and appears to comprise at least four groups of samples. The first of these is the SE east bank wells with R/R_A —3.5 and higher $^{40}Ar/^{36}Ar$ which appear to show the anticorrelation trend found by Torgersen *et al.* and ascribed by them as a mixture of mantle and radiogenic helium and argon. The second group is the NW west bank wells which have R/R_A of ,5-6 and near atmospheric $^{40}Ar/^{36}Ar$ value. The third group is a high $^{40}Ar/^{36}Ar$ group consisting of wells 3 and 1 in the NE and R_c/R_A values close to that of the SE group. The fourth group is the peripherial wells which have low $^{40}Ar/^{36}Ar$ and low R/R_A and appear to be dominated by atmospheric argon.

DISCUSSION

The three principal sources of helium, argon and neon in geothermal systems are atmospheric, radiogenic and mantle (Lupton 1983, Mazor 1977). The atmospheric component arises from dissolved atmospheric gases being carried into the geothermal system with the meteoric water component and contains neon, argon with a $^{40}Ar/^{36}Ar$ ratio of 295.5 and helium with a R/R_A value of 1. The radiogenic helium component arises from uranium and thorium series elements in crustal rocks producing 'He as alpha particles and ^3He from neutron reaction with lithium. The R/R_A value of this helium varies with the lithium content but is typically about 0.02 (Andrews, 1983). Radiogenic ^{40}Ar is produced from the decay of ^{40}K with virtually no production of

Table 1: Results

Well	Date	Dis	$\frac{R}{R_A}$	$\left(\frac{He}{Ne}\right)_A$	$\frac{R_c}{R_A}$	$\frac{^{40}Ar}{^{36}Ar}$
West Bank						
Br1	860319	B	6.24	322	6.26	306.1
Br3	840221	B	6.0	> 80	6.06	307.4
Br22	840221	B	5.91	41.2	6.03	298.4
Pool	840221	G	5.77	18.9	6.04	296.4
Br19	860319	B	5.45	27.6	5.62	295.5
Br6	840221	G	2.99	81.2	3.01	299.2
Br40	860319	B	1.44	59.85	1.45	297.8
East Bank						
Br43	860319	B	5.4	389	5.41	304.5
Br25	840123	B	5.37	157	5.4	**303.5**
Br25	840618	D	5.15	> **212**	5.17	304.2
Br14	860319	B	5.24	399	5.25	305.1
Br45	840601	D	5.18	> **149**	5.21	303.9
Br10	860319	B	4.09	239	4.1	307.4
Br27	840221	D	3.51	> **390**	3.52	310.5
Br29	840221	B	3.36	90.45	3.39	300.3
Br30	860319	B	3.3	309	3.31	305.9
Br7	840223	B	3.12	> **171**	3.13	313.3
Br32	860319	B	2.47	60.2	2.49	297.1

^{36}Ar or of neon isotopes. The mantle component consists largely of helium with a R/R_A value above 7 in subduction zones and rising to over 20 in "hot spot" plume areas. The $^{40}Ar/^{36}Ar$ ratio of mantle argon is not well known but is probably —400 (Lupton, 1983) while the mantle He/Ar ratio is probably ~100 (Dymond and Hogan 1973).

From table 1 it will be seen that (with a few exceptions) the He/Ne ratios of the samples is greater than 50 times the atmospheric ratio and thus the atmospheric helium is less than 2% of the total. Conversly the $^{40}Ar/^{36}Ar$ results do not exceed 315 compared to 295.5 for atmospheric argon which indicates that the argon is largely atmospheric in origin. (The < 7% excess ^{40}Ar in these samples is then a measure of the crustal argon from ^{40}K decay). We therefore discuss the helium and argon results individually in the following sections.

Helium

As indicated earlier there is a decreasing trend of helium-3 from NW to SE across the field. Most geochemical parameters particularly temperature, chloride content and isotopic geothermometry have not shown significant differences between the east and west sections of the Broadlands field but Hedenquist (1983) has shown a consistent variation in the Cl/B ratio from 15 in the NW to 4 in the SE. Figure 3 shows a plot of R/R_A against Cl/B which suggests Cl/B = 7 as the dividing line between the R/R_a values of —3.5 and those of 5 to 6. This contour line has also been drawn on Figure 1 to illustrate this difference spatially. It should be noted that our samples were collected somewhat later than the measurements reported by Hedenquist (1983), which normally is satisfactory for this type of correlation but it now appears that between these sampling dates well Br28 suffered a casing failure at 257 metres depth probably due to corrosion by the COS-rich steam heated waters as described by Hedenquist and Stewart (1985). This could explain both the relatively low R/R_A ratio and the low He/Ne ratio found in our sample (collected February 1984).

In order to give some explanation of these results it would appear useful to look at the geology. Figure 4 shows a cross-section of the field (Grindley. 1977) which shows an uplifted block of greywacke beneath Br27 and other wells on the eastern part of the field where R/R_A values of —3.5 are found. It would thus appear likely that interaction of ascending geothermal fluid

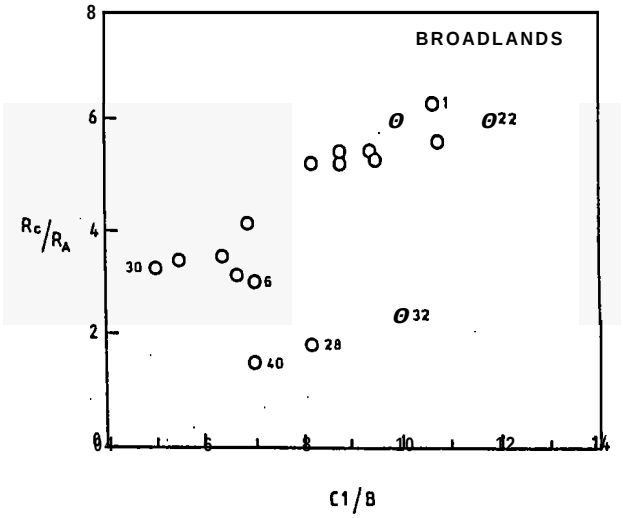

Figure 3: Plot of Helium isotope ratios (R_c/R_A) against Chloride/Boron ratios for Broadlands wells

with this greywacke is releasing radiogenic ^4He and ^{40}Ar. Although this greywacke extends at depth under the western part of the field it appears to have made a less significant effect on the west bank One possibility is that the intrusive body providing the heat source in the west is closer to the top of the greywacke than in the east while another possibility is that the heat source is beneath the western part of the field and that a proportion of the fluid is being diverted by the (presently unexplored) tilted greywacke into the eastern field thus increasing significantly the contact with the radiogenic bearing elements.

Argon

Since geothermal gases can easily be separated from their associated water by boiling (Mazor and Truesdell, 1984) as indicated by the variation in Ar/water measurement on New Zealand samples (Hulston and McCabe, 1962) we have not quoted absolute helium and argon concentrations which involves the relatively inaccurate measurement of gas-to-water ratios. Instead the helium/argon ratio has been used in this paper as a measure of the relative contributions of these two sources. Figure 5 shows a plot of $^{40}Ar/^{36}Ar$ against approximate He/Ar ratio values. It will be noted that there is a strong correlation of $^{40}Ar/^{36}Ar$ with He/Ar ratios. Since the majority of the argon is of atmospheric ratio this implies that the ratio of ^4He to ^{40}Ar is constant — particularly for samples of higher $^{40}Ar/^{36}Ar$ ratio. Furthermore since samples with higher $^{40}Ar/^{36}Ar$ ratios have R/R_A values ranging from 3 to 6 this implies that both radiogenic helium and the "subduction mantle" helium beneath Broadlands have the same $^4He/^{40}Ar$ ratio. It is interesting to note that prior to the discovery of helium-3 from the mantle in geothermal gases Mazor and Fournier (1973) found a value of 4 for this ratio. One possible explanation of this is that subduction mantle helium of R/R_A —7 is really a mixture of mantle helium of $R/R_A > 20$ diluted with radiogenic ^4He *en route* to the surface.

CONCLUSIONS

This study has shown that Broadlands geothermal gases have a significant contribution of mantle helium helium but that there is a variable contribution of radiogenic helium which may result from the interaction of hot fluid with greywacke and other uranium series bearing rocks. Studies of helium and argon isotopes show promise of providing information on the deep geothermal system not presently available from other analyses.

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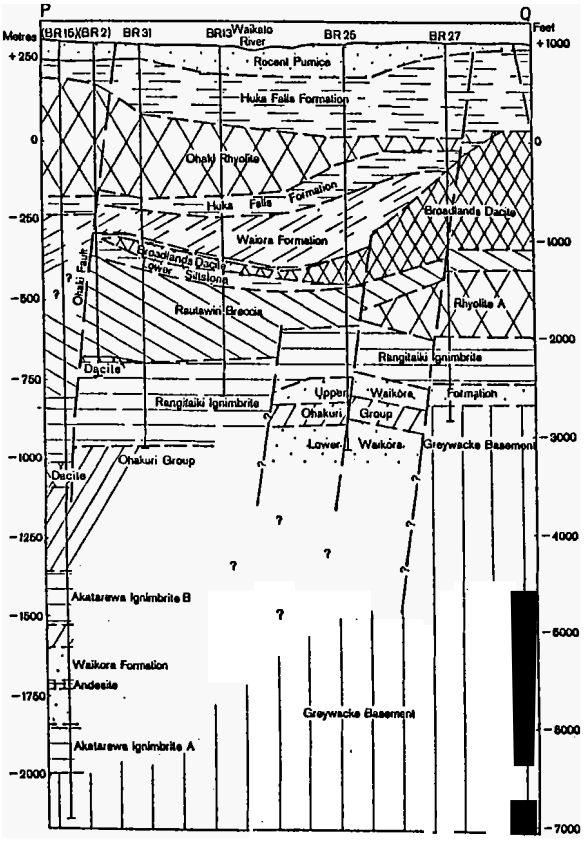

Figure 4: **NW-SE** cross-section **of** Broadlands Field

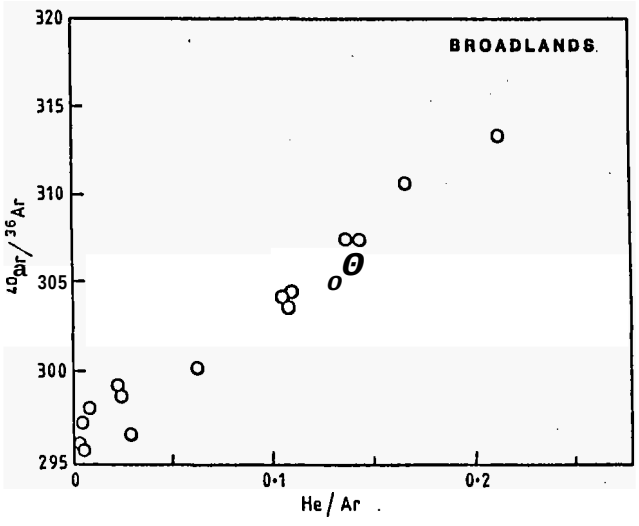

Figure 5: Plot **of** Argon isotopic ratio against Helium/Argon Ratio (arbitrary scale)

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