ORIGIN OF MINERAL SPRINGS ON THE EAST COAST, NORTH ISLAND, NZ

T.M. HUNT AND R.B. GLOVER

Wairakei Research Centre, IGNS, Taupo, NZ

SUMMARY - Strongly mineralised waters emerge as warm and cold springs from parts of a Cenozoic accretionary prism which extends along the East Coast of the North Island. The chemistry of these waters is consistent with them having been derived from connate sea water in deeply-buried marine sediments and is distinct from springs in other parts of the prism and elsewhere in New Zealand. Most of these mineral springs are associated with three, long-wavelength, magnetic anomalies which modelling suggests are caused by deeply-buried ophiolite bodies within the prism or by seamounts on the top of the subducted Pacific Plate underlying the prism. It is postulated that these deep-seated bodies have facilitated the dewatering of marine sediments from deep within the prism or from the subducted plate. This "devolved sea water" has then risen, been modified by contact with overlying sediments and mixed with near-surface meteoric waters, before emerging at the mineral springs.

1. INTRODUCTION

In the East Coast region of the North Island lies a thick and growing accretionary prism of marine sediments (Davey et al, 1986) associated with westwards subduction of the Pacific Plate beneath the Indian Plate along the Hikurangi Margin (Fig. 1). A significant portion of the sediments in the prism are exposed onshore, and range in age from Middle Tertiary to Recent; here, fluids from deep within the marine sediments are thus able to make their way to the surface with little mixing other than with meteoric groundwater. Offshore, immediately east of the Hikurangi Margin, the seafloor is presumed to be Cretaceous in age (based on the age of seafloor magnetic anomalies further to the east). There is no evidence for active volcanism within the region.

In the northern part of the East Coast region most of the warm and cold springs discharge strongly mineralised waters, and their composition is different from high-temperature geothermal waters from the Central Volcanic Region (CVR) and from warm springs of tectonic origin in other parts of New Zealand (Hunt and Bibby, 1992). The few chemical analyses of these mineralised waters previously reported are contained mainly in old or relatively obscure publications (Maclaurin 1903, 1906; Herbert, 1921; Macpherson, 1945; Mahon, 1967), and the origin of these springs has not been explained in terms of plate tectonics or recent concepts of accretionary prisms.

2. FLUID CHEMISTRY

Seventeen springs are known in the East Coast Region (Fig. 1); two (Te Puia and Morere) discharge warm water (60 - 70°C). Both the warm springs and eleven of the cold springs discharge strongly mineralised waters; the remaining four cold springs discharge water similar in composition to cold and warm springs elsewhere in the North Island (Table 1).

The waters from all the mineral springs on the East Coast are near neutral (pH = 6.2 to 8.5) and have relatively high concentrations of sodium, calcium, and chloride. The waters from the warm springs are quite distinct from the high- temperature waters in Wairakei and Ohaaki geothermal fields, and from the cold, weakly mineralised

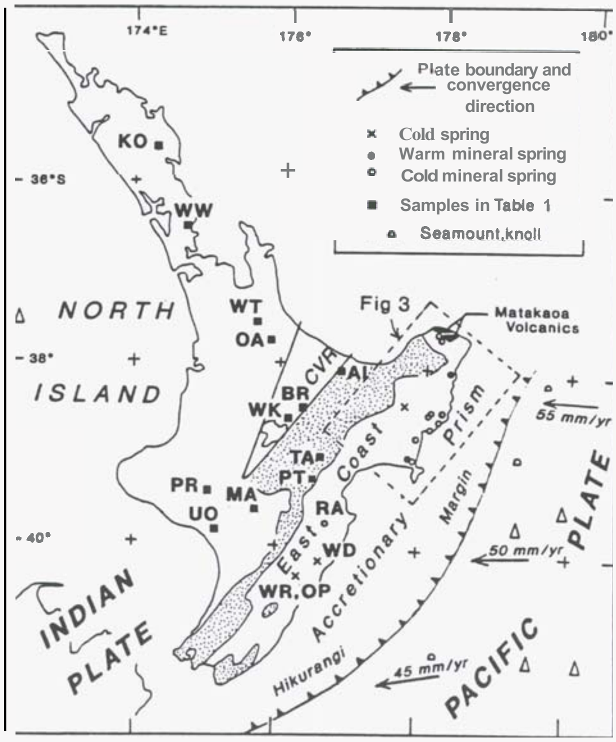

Fig. 1 Structural features of East Coast region, and sample locations referred to in the text. Shaded area indicates extent of pre-Cretaceous basement rocks on the western margin of the region; CVR = Central Volcanic Region.

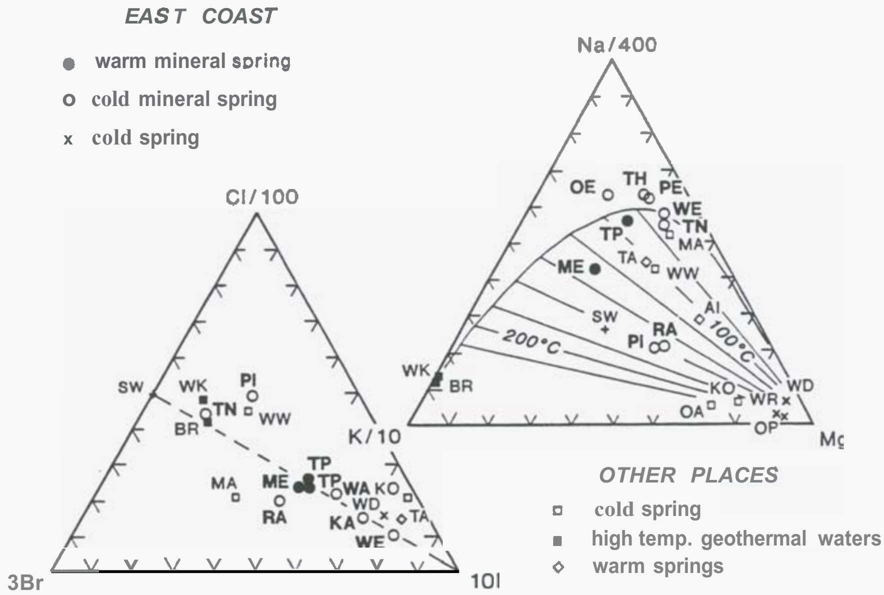

Fig. 2 Chemical plots of spring waters. Data taken from Table 1. The names of the springs and their locations are given in Table 1 and Fig. 1.

"immature" waters with relatively high magnesium found in other parts of the prism (Table 1; Fig. 2). The chloride/boron ratio is low relative to sea water, but not as low as geothermal fluids in the CVR, or the very low values (2 to 5) associated with fluids discharging through greywacke-type basement rocks adjacent to the prism (Table 1). Na/Ca ratios are low (generally <20) compared with geothermal fluids (>100). Calcareous sinter (up to 70% calcium carbonate) is found adjacent to the Te Puia Springs (Ongley and Macpherson, 1928), and aragonite is found near the springs in the Waimata Valley (TN and SE; Table 1). Waters from eight of the ten mineralised springs from the East Coast, for which chloride, bromide and iodide data is available, lie close to or at the Cl/Br ratio of sea water (Fig. 2). The composition of the spring waters suggests they have been derived from sea water; a conclusion also reached by Giggenbach *et* al., (1993b). Very large oxygen -18 enrichment (+3 to +7%: Giggenbach *et* al. 1993b) suggest the mined waters have a relatively minor component of meteoric water (*Allis et* al., in prep.).

The only other strongly mineralised spring in the North Island occurs at Mataroa, near Taihape (MA: Fig. 1): here the water issues from Tertiary marine sediments and is similar in composition to Morere water (Table 1). Elsewhere, springs emanating from Tertiary marine sediments (KO, WW, PR, UO; Fig. 1) are not strongly mineralised and their chemistry is consistent with them having been principally derived from meteoric water (Table 1).

Application of Na-K-Mg geothermometry to data from Te Puia and Morere warm springs gives equilibration temperature estimates of 100 and 110°C respectively (Giggenbach et *al.*, 1993b). However, the concentration of lithium in the mineral waters is generally much greater than that of sea water or other warm and cold springs; in some instances it approaches that of the high-temperature geothermal waters in the CVR. This suggests that some of the waters may have attained the temperatures of 200 - 300°C (Ellis and Mahon, 1977). There are no high temperature igneous bodies in the region, therefore the most likely explanation is that the mined waters acquired the lithium while at great depth. This is supported by the low sulphate values relative to sea water; sulphate has retrograde solubility and the low sulphate values in most of the cold mineral waters indicate they have been heated. However, most of the strongly mineralised waters are near equilibrium w.r.t sodium, potassium, and magnesium at temperatures below 100°C (Fig. 2; Giggenbach et al. 1993b). The attainment of full equilibrium indicates that they have been at these low temperatures for a relatively long period; this is consistent with the low flow rates from the cold springs.

To summarise, the chemistry of the East Coast mineral waters suggests that they have been derived from sea water. may at some stage attained temperatures of several hundred degrees, but have travelled slowly enough towards (or remained near) the surface for Na, K, and Mg to equilibrate at lower temperatures.

Some of the mineral springs also discharge gas; data from Te Puia shows high methane and other hydrocarbons (Ongley and Macpherson, 1928) and similar results are reported from Morere, Waimata Valley, and Kopuawhara (Giggenbach *et al.*, 1993a,b). The gases are probably generated biogenically from within the prism sediments Isotope data show that helium in the Te Puia and Morere waters has 24 and 41% mantle components respectively (Giggenbach *et* al., 1993a,b); these high values of mantle components suggest that high permeability paths exist down to the subducted plate and along the fracture zone between the plates.

TABLE 1: Chemistry of spring waters from North Island, New Zealand.

Location	Code	Temp. °C	pH	Concentrations in ppm Na	K	Ca	Mg	F	Cl	Br	I	Li	SO_4	TotB	SiO_2	T NI
EAST COAST WATERS																
WARM MINERAL SPRINGS																
Te Puia	TP	67	7.1	4320	35		25	2.4	8090	28.9	17.8	12.5	70	70	42	2.
Te Puia	TP	69.5	7.3	4800	37	800	-	2.5	8760	28.4	17.4	13.5	65	76	48	
Morere	ME	62.4	7.1	7800	150	3750	130	1.1	15940	63	33	9.5	1	45.5	22	2
COLD MINERAL SPRINGS																
Otopotehctehe	OE		7.7	5200	41	370	12.3		8350			14.2	<1	133	7	
Tohora	TH		7.2	5150	22	360	31.2		8075			6.2	<1	107	10	
Potoe	PE		7.9	4400	18	43	25		5684			1.4	6	26.8	35	
Twistleton's	TN		7.0	3950	19	240	40	1.1	6560	19.8	2.4	5.6	52	64.7	11	0
Savage's	SE		7.8	3460	10	97		1.2	5385			2.8	7	24.4	11	n
Glenroy Rd	GY		7.3	6020	35	430		4.2	9860	36.1	23.6	7.6	94	28.6	19	
Waiherere	WE		8.5	2950	11	36	18	0.8	4600	17.3	36	2.3	9	26.9	11	n
Papawhariki	PI		6.9	3950	140	219	543	3.4	7310	13.1	3.7	4.4	1650	2.9	17	n
Wairakaia	WA		7.0	1305	4	45		1.8	1930	5.7	15.2	0.9	14	5.6	14	n
Kopuawhara	KA	16	7.7	4940	22	538		1.1	9210	33	42	9.7	1	18.8	5	6
Raukawa	RA	15	7.8	1860	55	60	125	0.3	2950	16.6	6.89	1.9	5	2.45	45	8
COLD SPRINGS																
Waikohuiti	WI		5.1	47	5	113			14		0.4		395	0.49	6	n
Wallingford	WD		7.8	110	2	84	17	0.6	85	0.2	0.4	0.3	33	0.10	35	0
Weber	WR		7.8	20	2	27	5	0.3	-		0.4	0.3	30	0.15	25	0
Oporae Rd	OP		8.2	52	4	29	21	1.5	95		0.3	0.3	115	0.21	14	1
OTHER WATERS																
WARM SPRINGS IN BASEMENT ROCKS ADJACENT TO THE PRISM																
Puketitiri	PT	52	8.5	97	1.5	3.3	-	21	54		0.32	nil	19	8.1	66	0
Tarawera	TA	49	8.4	475	5.2	12.5	1.0	13.3	637	1	3.4	1.4	19	79	40	2
Awakeri	AI	70	8.4	110	1.5	1.9	0.3	3.9	40	<0.2	0.2	-	13	2.7	65	0
WARM SPRINGS IN SEDIMENTARY ROCKS																
Kamo	KO	25	7.0	239	16	156	55	0.4	240	0.1	0.9	2.0	17	20.3	111	2
Waiwera	WW	48	8.0	635	7	34	2.2	1.8	1032	2.2	0.6	0.8	4	11.1	38	0
Waitoa	WT	77	8.8	206	48	17	17		51	-	-	0.3	10	4.5	150	
Okauia	OA	40	7.5	102	11	21	11	-	15	-	-	0.2	7	0.9	84	
COLD SPRINGS IN SEDIMENTARY ROCKS																
Mataroa	MA	5	6.8	8700	42	500	257	0.95	15330	104	26	8	9.5	6.7	5	4
Upokongaro	UO	18	8.0	62	5.0	43		0.5	30		0.3	0.1	75	0.5	24	1
Pipiriki	PR	23	7.6	840	4.4	14.5		1.75	1166			0.8	9.5	82	12	1
HIGH TEMPERATURE GEOTHERMAL WATERS IN CVR																
Wairakei	WK	240	8.5	1200	200	17.5	0.05	8.1	2156	5.9	0.6	13.2	25	28.4	660	
Ohaaki	BR	262	8.3	1050	210	2.2	0.1	7.3	1743	5.7	0.8	11.7	8	48.2	805	2
AVERAGE SEA WATER																
	SW		7.8-8.3	10760	387	413	1290	1.9	19355	65	0.05	0.17	2710	4.6	5	0

3. GEOTHERMAL GRADIENT AND HEAT FLOW

Values for geothermal gradient, obtained from 9 deep drillholes (620 - 2740 m depth), range from 16 - 56°C/km (Pandey, 1981) (Fig. 3); the greatest value, however, was determined from the shallowest hole and if this is neglected the values range fiom 16 - 35°C/km. Similarly, values for heat flow range from 29 - 138 and 29 - 105 mW/m^2. The geothermal gradient near Te Puia Springs is 32°C/km, and that near Morere Springs is 35°C/km; both these values are close to the "normal" gradient of 30°C/km. Such temperature gradients imply that depths of 6 - 12 km would be required to attain the 200 - 300°C suggested by the lithium chemistry of the mineral waters.

4. MAGNETIC *ANOMALIES*

Aeromagnetic surveys (Fig. 3) show that large and variable, magnetic anomalies (+260 to -340 nT) occur at the northern end of the region. These anomalies are associated with outcrops of mafic and ultramafic igneous rocks of the Matakaoa Volcanic Formation, which are considered to be a disrupted ophiolite sequence that was tectonically emplaced (obducted) during late Oligocene - early Miocene times (Brothers and Delaloye, 1982). The Matakaoa Volcanics are the only extensive outcrops of igneous rocks in the East Coast region. Three other large Scale magnetic anomalies occur: near Tokomaru Bay (about +140 nT), at Poverty Bay (+70 nT), and near Morere (+70 nT). Elsewhere in, and over most of, the region the magnetic anomalies are smooth and subdued.

The warm mineral spring at Morere lies near the centre of the Morere magnetic anomaly, and that at Te Puia lies on the flank of the Tokomaru Bay anomaly (Fig. 3). Most of the cold mineral springs lie on the flanks of the Poverty Bay and Morere anomalies; OE and TH are associated with the magnetic anomalies over the Matakaoa Volcanics. None of the cold unmineralised springs, either in the East Coast region or elsewhere in the North Island, are known to be associated with long-wavelength magnetic anomalies.

5. ORIGIN OF THE MAGNETIC ANOMALIES

The smoothness of the anomalies at Tokomaru Bay, Poverty Bay, and Morere, their long wavelength, and absence of significant negative dipoles suggest that the source rocks are deep. The intensity of (total) magnetisation of the sedimentary rocks in the region rarely exceeds 1 x 10^{-3} A/m (Walcott and Mumme, 1982) and so they *can* be considered to be non-magnetic.

One explanation for the magnetic anomalies is that they are caused by buried ophiolite bodies, similar to the Matakaoa Volcanics, which have been detached from the upper part of the Pacific plate and tectonically emplaced in the accretionary prism. To determine the approximate size and depth of such bodies we undertook simple 2½ D magnetic modelling of the largest anomaly (Tokomaru Bay) using magnetisation values

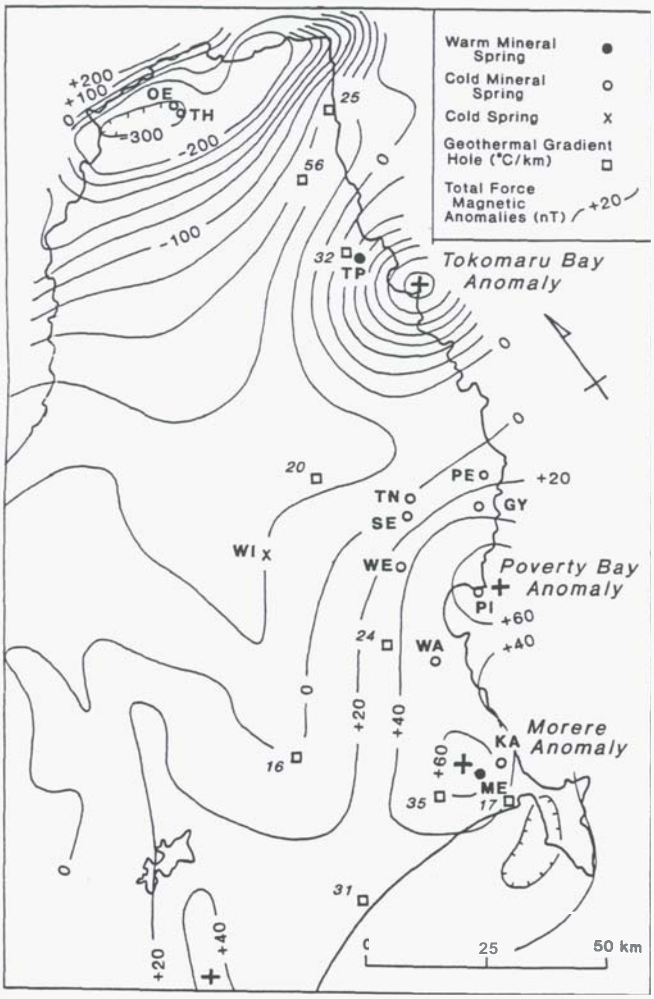

Fig. 3 Magnetic anomaly map of East Coast region. Total force anomalies (nT) at 3 km (asl) with line spacing of 9 km (E-W) taken from Hunt and Whiteford (1979a, b). Geothermal gradient data from Pandey 91981).

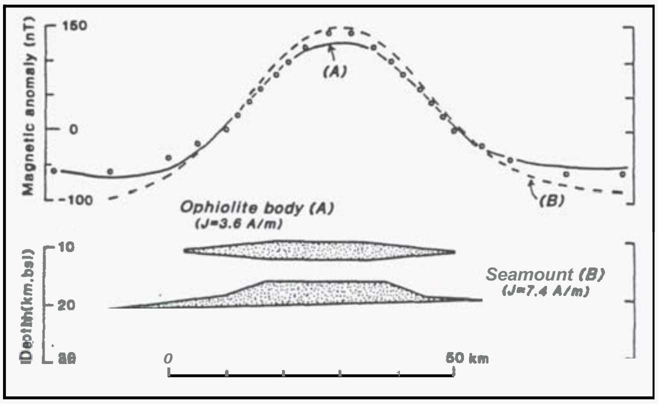

Fig. 4 Observed (open circles) and calculated (solid, broken lines) magnetic anomalies along an east-west profile through the Tokomaru Bay anomaly (near Te Puia). Calculated anomalies (2.5D) computed (Webring, 1985) assuming strike length of 15 km. Magnetic normal field in the vicinity is 55000 nT, D = 20°E, I = -60°.

for the Matakaoa Volcanics (J_{NRM} = 3.6 (± 7.4) A/m, D = 23 (± 8) "E, I = -58 (± 15)°, vol. susceptibility = 5.1 (± 2.3) x 10^{-2}; mean of 20 samples (Woodward, 1985). The results of this modelling (Fig. 4) suggest a lensoidal source body, about 3 km thick (maximum), about 30 to 50 km in lateral extent, located at a depth of about 10 km. It was difficult to derive simple, credible, and coherent source bodies lying at depths (to top) of less than 10 km (these resulted in very localised anomalies) or greater than 25 km (the thicknesses required became too great).

An alternative explanation is that the magnetic anomalies are caused by Cretaceous seamounts on the upper part of the Pacific plate which have been subducted beneath the prism. Four seamounts and three knolls occur on the seafloor of the Pacific Plate, within 200 km of the East Coast (Fig. 1). At the present rate of relative plate movement of about *50* (± 5) mm/yr (Walcott, 1978) these features will be subducted within about 4 Ma. Similarly, if the magnetic anomalies are associated with subducted seamounts, then this event will have occurred within the last 2 Ma (neglecting underplating).

Seismic data show that in the southern part of the East Coast region the top of the subducted plate lies at about 15 -20 km depth beneath the coastline, and dips about 5 - 10" to the west (Reyners, 1980; Davey et al., 1986). Assuming similar geometry in the northern part, the upper surface of a seamount now lying beneath Tokomaru Bay would be at a depth of 15 to 20 km. Seamounts on the Pacific plate east of North Island (Fig. 1) have topographic expressions extending for about 50 km laterally, and rise to more than 1 km above the seafloor (Baldwin and Lewis, 1991), but their lower flanks are covered in sediment and so they could extend over a much wider area and their total thickness could be several kilometres. Data given by Harrison et *al.* (1975) for 50 Cretaceous seamounts in the Pacific provide a mean intensity of magnetisation of 7.8 (± 5.6) A/m. Modelling shows (Fig. 4) that the observed magnetic anomaly at Tokomaru Bay *can* be matched by the magnetic effects of a body resembling a seamount at a depth (to top) of about 15 km, extending for about 65 km laterally, about 5 km thick, and an intensity of magnetisation of 7.4 A/m.

6. GRAVITY ANOMALIES

The Bouguer gravity anomaly pattern in the region (Reilly 1972; Woodward and Boyle, 1972) is relatively smooth and is dominated by lateral density changes associated with subduction of the Pacific plate (Smith et al., 1989). There are no significant (> 10 mgal) local anomalies associated with the warm mineral springs at Te Puia or Morere, or with any of the cold mineral springs; this is consistent with deep burial of the magnetic source bodies.

7. DISCUSSION

With one exception (RA; Fig. 1) all the East Coast mineral springs (both cold and warm) appear to be confined to the northern part of the region, and occur at the centre or on the flanks of magnetic anomalies (Fig. 3). We postulate that the association (in space) between the mineral springs and the source bodies of the magnetic anomalies is not fortuitous. It is unlikely that the mineral waters are originating from sea water contained within the source bodies themselves, be they ophiolites or seamounts, because such igneous bodies have very low porosity. Therefore, we suggest that the presence of these bodies is facilitating the upflow of interstitial waters from marine sediments deep in the accretionary prism or the top of the subducted plate in the vicinity of the bodies.

The concept that sea water in the pores of marine sediments can be transported considerable distances, both laterally and vertically downwards, at convergent plate margins and later released, is not new. Such a mechanism has already been proposed by Giggenbach (1992) to explain the chemical and isotopic compositions of andesite lavas and high-temperature geothermal waters in the CVR. Indeed, Giggenbach (1992) names such water "devolved sea water". What we find new is the connection between deep-seated bodies associated with the subduction process and the emergence of strongly mineralised waters derived from this devolved sea water from springs at the surface.

We speculate that the process of imbricate thrusting in the prism, or subduction, has resulted in increased fracturing in zones around the bodies allowing dewatering of the pores in the marine sediments. This sea water is then rising (under buoyancy forces or over-pressuring), being modified by contact with sediments, and mixing with near-surface meteoric waters, before emerging at the mineral springs.

We acknowledge that some of the data used to derive our hypothesis are open to alternative explanations, but contend that the hypothesis probably represents the simplest explanation which is consistent with the data and with the concepts of plate tectonics and accretionary prisms. We suggest further geochemical studies of these mineral springs be made to try and resolve the origin and the history of their waters, and that magnetic measurements be made over the southern part of the region to establish the presence or absence of magnetic anomalies over the cold, unmineralised springs there. Geochemical and geophysical studies should also be made at mineral springs emerging from accretionary prisms at other active convergent plate margins to see if our hypothesis *can* be validated.

8. ACKNOWLEDGEMENTS

We thank R G Allis, H M Bibby, F J Davey, W F Giggenbach, and S Simmons for helpful discussions and criticism of the manuscript.

9. REFERENCES

Allis, R.G., Stewart, M.K., Giggenbach, W.F. Review of New Zealand springs and their implications for fluid movement in the crust (in prep.)

Baldwin, R.P., Lewis, K.B. 1991. *Cook Bathymetry*, (2nd ed.), Oceanic Series Chart 1 : 1 000 000, DSIR, Wellington, New Zealand.

Brothers, R.N., Delaloye, M. 1982. Obducted ophiolites of North Island, New Zealand. NZ Journal *of Geology and Geophysics*, 25: 257-274.

Davey, F.J., Hampton, M., Childs, J., Fisher, M.A., Lewis, K., Pettinga, J.R. 1986. Structure of a growing accretionary prism, Hikurangi margin, New Zealand. *Geology*, 14: 663-666.

Ellis, A.J., Mahon, W.A.J. 1977. *Chemistry* and *Geothermal System*. Academic Press, New York, 392 p.

Giggenbach, W.F. 1992. Isotopic shifts in waters from geothermal and volcanic systems along convergent plate boundaries and their origin. *Earth and Planetary Science Letters*, 113: 495-510.

Giggenbach, W.F., Sano, Y., Wakita, H. 1993a. Isotopic composition of He and CO_2, and CH_4 contents in gases produced along the New Zealand part of a convergent plate boundary. *Geochemica and Cosmochimica Acta*, 57: 3427-3455.

Giggenbach, W.F., Stewart, M.K., Sano, Y., Goguel, R.L., Lyon, G.L. 1993b: Isotopic and chemical composition of waters and gases from the East Coast accretionary prism, New Zealand. *Proceedings of the Research Co-ordination Meeting on the Application of Isotope and Geochemical Techniques to Geothermal Exploration*: 209-231.

Harrison, C.G.A., Jarrard, R.D., Vacquier, V., Larson, R.L. 1975. Palaeomagnetism of Cretaceous Pacific seamounts. *Geophysical Journal of the Royal Astronomical Society*, 42; 859-882.

Herbert, A.S. 1921. *The hot springs of New Zealand*. H.K. Lewis, London.

Hunt, T.M., Bibby, H.M. 1992. Geothermal Hydrology in *Waters of New Zealand*. (Mosley, M.P. ed.) NZ Hydrological Society: 147-166.

Hunt. T.M., Whiteford, C.M. 1979a. Sheet 6, *East Cape* (1st ed.) Magnetic Map of New Zealand 1 : 250 000: DSIR, Wellington, New Zealand.

__________ 1979b. Sheet 9, *Gisborne* (1st Ed.) Magnetic Map of New Zealand, 1 : 250 000: DSIR, Wellington, New Zealand.

Maclaurin, J.S. 1903. Thirty-sixth annual report of the Colonial Laboratory, Mines Department, NZ Government Printer, Wellington, New Zealand.

__________ 1906. Fortieth annual report of the Colonial Laboratory, Mines Department, NZ Government Printer, Wellington, New Zealand.

Macpherson, E.O. 1945. Te Puia Hot Springs. *NZ Journal of Science and Technology*, 26B: 244-254.

Mahon, W.A.J. 1967. Natural hydrothermal systems and the reaction of hot water with sedimentary rocks. *New Zealand Journal of Science*, 10, 206-221.

Ongley, M., Macpherson, E.O. 1928. The Geology of the Waiapu Subdivision, Raukumara Division. *NZ Geological Survey Bulletin 30*.

Pandey, O.P. 1981: Terrestrial heat flow in the North Island of New Zealand: Journal *of Volcanology and Geothermal Research*, 10: 309-316.

Petty, D.R. 1972. Springs of the Auckland region: *Report 57*, NZ Geological Survey, DSIR, Lower Hutt, New Zealand.

Reilly, W.I. 1972. Sheet 9, *Gisborne* (1st Ed.) Gravity Map of New Zealand, 1 : 250 000, Bouguer Anomalies. DSIR, Wellington, New Zealand.

Reyners, M. 1980. A microearthquake study of the plate boundary, North Island, New Zealand. *Geophysical Journal of the Royal Astronomical Society*, 63: 1-22.

Smith, E.G.C., Stern, T., Reyners, M. 1989. Subduction and back-arc activity at the Hikurangi convergent margin, New Zealand. *Pure* and *Applied Geophysics*, 129: 203-231.

Walcott, R.I. 1978. Present tectonics and late Cenozoic evolution of New Zealand. *Geophysical Journal of the Royal Astronomical Society*, 52: 137-164.

Walcott, R.I.; Mumme, T.C. 1982. Palaeomagnetic study of the Tertiary sedimentary rocks from the East Coast of the North Island, New Zealand. *Report 189*, Geophysics Division, DSIR, Wellington, New Zealand.

Webring, M. 1985. *SAKI*, a Fortran programme for generalised linear inversion of gravity and magnetic profiles. *Open file report 85-0122*. US Geological Survey, 108 p.

Woodward, D.J. 1985. Geophysics Division DSIR Rock Catalogue. *Technical Note* 86, Geophysics Division, DSIR, Wellington, New Zealand.

Woodward, D.J., Boyle, L.M. 1972. Sheet 6, *East Cape* (1st Ed.) Gravity Map of New Zealand, 1 : 250 000, Bouguer Anomalies: NZ DSIR, Wellington, New Zealand.