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EFATE Geothermal Project, Phase I: SUMMARY REPORT

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(with an Appendix on Hydrochemical Studies
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1. SUMMARY

Phase I of the Pre-Feasbility Study of the geothermal energy prospects of the island of Efate, Republic of Vanuatu, has involved geological mapping of the Project Area (250 km^2) at 1:25,000, and assessment of the thermal springs and their regional context, principally by a thorough geochemical investigation.

The islands of Vanuatu are part of the extensive island arc system of the SW Pacific. Efate island is composed of Early Pleistocene rhyolitic pumice breccias and bedded pumice tuffs overlain by extensive Recent and raised Late Pleistocene reef limestones, with two major centres of Pleistocene basaltic extrusion in the north and on the northerly offshore islands.

The thermal springs are related to the major structural features of the island. Four groups discharge on or near the Eastern Boundary Fault of the Teuma Graben at temperatures ranging from 24 to 59°C, resulting in a total excess heat discharge to the Teuma River of approximately 10 MW. Three groups of springs and other minor springs discharge near Takara on the north coast, in an ESE alignment, at temperatures between 36 and 71°C. They have a maximum combined flow of approximately 110 l/s, and a maximum excess heat discharge of 18 MW. In addition, high ground temperatures up to 100°C occur at Takara over an elongated zone of ground parallel to but south of the spring line over at least 2 km^2, accounting for an extra 2.5 MW heat loss.

In the Teuma Graben the chemical and isotopic characteristics of the three southerly groups of springs suggest they have experienced a similar evolution involving complex mixing of three components, although significant differences indicate different depths of circulation and extents of reaction. The northernmost springs are quite unrelated and result from meteoric water involved in silicate alteration reactions during circulation at modest depths and temperatures, probably not in excess of 65°C. Highest discharge temperatures and highest predicted base temperatures are associated with the Mid Teuma springs, for which it is estimated that chemical equilibration occurs at 200-215°C, either with tuffs of the Efate Pumice Formation, or with basalt intruded as dykes along the graben.

The effects of deep thermal water circulation along the Teuma Graben may be masked by dilution with shallow groundwater in the limestones which overlie and may be expected to be in hydraulic communication with the Efate Pumice. If the thermal water is stored in the Efate Pumice and the heat flow is a regional anomaly then an extensive hydrothermal reservoir may exist at depth. If, on the other hand, basalt dykes intruded along the graben are the source of heat, then the reservoir may be more limited. Geophysical surveys are required to test which of these two possibilities is correct.

At Takara the thermal springs indicate a mixing series for which the thermal component is identified as sea water that has reacted with basalt between 165 and 180°C. Results from groundwater of 88°C at a depth of 3 m in a borehole on Takara airfield are in close agreement. Correlation between rainfall, spring discharge rate, and spring temperature and chemistry suggests that the flow of thermal water is governed by piezometric pressure in Quoin Hill or Mt Sussunatarr, inland from Takara. This further implies that the heat source is also to the south, rather than associated with the more recent volcanism on the northerly offshore islands. A heat source associated with the major basaltic extrusive centres in the north of Efate is suggested.

A hydrothermal reservoir in which temperatures of 165 to 180°C are common, and over 200°C may exist in parts, is demonstrated. It is possible that the reservoir is extensive, and associated with the Efate Pumice which is likely to have favourable hydraulic characteristics. Organic Rankine (Binary) Cycle technology offers the possibility of generating electricity from primary fluids at less than the predicted temperatures. Accordingly, a geophysical survey as Phase 2 of the Pre-feasibility study of the geothermal potential of Efate is encouraged. The geophysical survey should define more precisely the shape of the basaltic intrusions, and indicate the depth and extent of thermal and hydrothermal anomalies associated with them, thereby showing the most favourable sites for deep exploration boreholes on Efate. Proposals include a reconnaissance resistivity survey, a gravity survey and a microearthquake survey. It is suggested that the resistivity survey employs a combination of conventional Schlumberger traversing techniques and an audiomagnetotelluric survey. The total cost is estimated at £225K, of which the highest priority, the resistivity reconnaissance, accounts for £145K.

2. INTRODUCTION

This report summarises the results and conclusions from Phase I of a pre-feasibility study of the geothermal energy prospects of the island of Efate, Republic of Vanuatu, initiated as a Technical Cooperation agreement between the Vanuatu and the UK Governments.

The administrative capital of Vanuatu, Vila, is situated on Efate, which is the only island having a sizable demand for electricity. The total installed generator capacity at Vila is 4 MW, and the demand is expected to increase to 10 MW by the year 1990.

Data obtained previously relating to the geothermal prospects of Efate (Lavigne & Marinelli, 1970; Demange, 1972; Greenbaum, 1973; Hochstein, 1977a; Giggenbach, 1977) have been summarised and discussed by Grindley and Nairn (1974), Hochstein (1977b), Ash et al. (1978) and most recently by Williamson (1980), who defined the 250 km^2 Project Area of the present study. The current programme has employed the pre-feasibility exploration methodology proposed by Williamson, 1980, and is similar to that previously suggested by Hochstein (1977b). Phase I of this pre-feasibility study is the preliminary geological and hydrochemical reconnaissance on the basis of which a geophysical survey (Phase 2) and a shallow drilling programme (Phase 3) might define the thermal anomalies more precisely, with the ultimate objective of assessing the probability that an exploitable geothermal reservoir exists in Efate, and to select sites for deep exploration boreholes.

The Project Area includes the hot springs that discharge along the valley of the Teuma River, and those along the coastal strip at Takara. Geological mapping of the Project Area at a scale of 1:25,000, a thorough spring and river reconnaissance, and a preliminary sampling programme were completed in April 1982, (Carney, 1982). A hydrochemical assessment of these samples (Bath, Carney and Cook, 1982) preceded a follow-up hydrochemical survey carried out in September 1982. The hydrochemical studies are described in full in Appendix I of this report. All sample location numbers refer to sites defined in Appendix I.

3. REGIONAL SETTING

3.1 The Island Arc System.

Efate is one of the central southern group of islands of Vanuatu, a NNW trending archipelago in the extensive island arc system of the South West Pacific (Figure 1). The Vanuatu islands and the Solomon Islands have a deep trench along their western and southern margin respectively, and respectively easterly and northerly dipping Benioff zones indicate subduction of the Indo-Australian plate beneath the Pacific plate - the opposite of the 'normal' Pacific polarity of subduction. A reversal in polarity of subduction along the Vanuatu trench in the Middle Miocene is dated at about 11-8 Ma (e.g. Carney and Macfarlane, 1982) and is associated with rotation and westward migration of the arc. Efate Island is part of the currently active Central Chain of islands, the most recent of four volcanic provinces (Figure 2) which have resulted from the complex plate tectonic evolution of the region - the Western Belt, the Eastern Belt, the Marginal Province and the Central Chain.

3.2 The Volcanic Provinces.

The Western Belt represents an extinct volcanic arc formed during the earlier phase of westerly subduction, (Carney and Macfarlane, 1978 and 1982). Early to Middle Miocene basaltic and andesitic lavas and pyroclastics are common, with some dioritic and gabbroic intrusions. Volcanic activity of the Western Belt was terminated by a Middle Miocene tectonic episode associated with the onset of polarity reversal. The basalts and andesites of the Eastern Belt, Upper Miocene to Lower Pliocene in age, represent the initial arc deposits of early easterly subduction. The Marginal Province, aligned with the Eastern Belt to the south of Efate and north of Mere Lava consists of island arc volcanics dating from 3.5 Ma (Middle Pliocene) to Recent, but is not currently active and is largely submerged.

The Central Chain of islands forms the presently active volcanic arc and dates from the Upper Pliocene. Available exposures suggest that only from Efate southwards do the Central Chain islands contain the older, pre-Mid Pleistocene volcanics.

3.3 The Central Chain Islands.

The earliest volcanism of the Central Chain Islands is dated at 2.4 Ma (Carney and Macfarlane, 1979) on Tanna and Erromango. Following this, volcanic activity spread northwards to Efate in the Pleistocene between 1.5 and 1.1 Ma. Between 0.7 and 0.4 Ma there was a northward migration of volcanism to the islands of Epi, Ambrym, Gaua and Vanua Lava. Since 250,000 a there has been active volcanism on virtually all the Central Chain Islands, represented off the north coast of Efate by the Recent volcanic cones of Nguna, Pele and Emau, all young well preserved but extinct volcanic cones.

In the main this presently active volcanic belt is 20 to 40 km wide and lies 130 to 150 km behind (east of) the trench axis. Efate is only 100 km from the trench and is the most frontally situated of the Central Chain Islands.

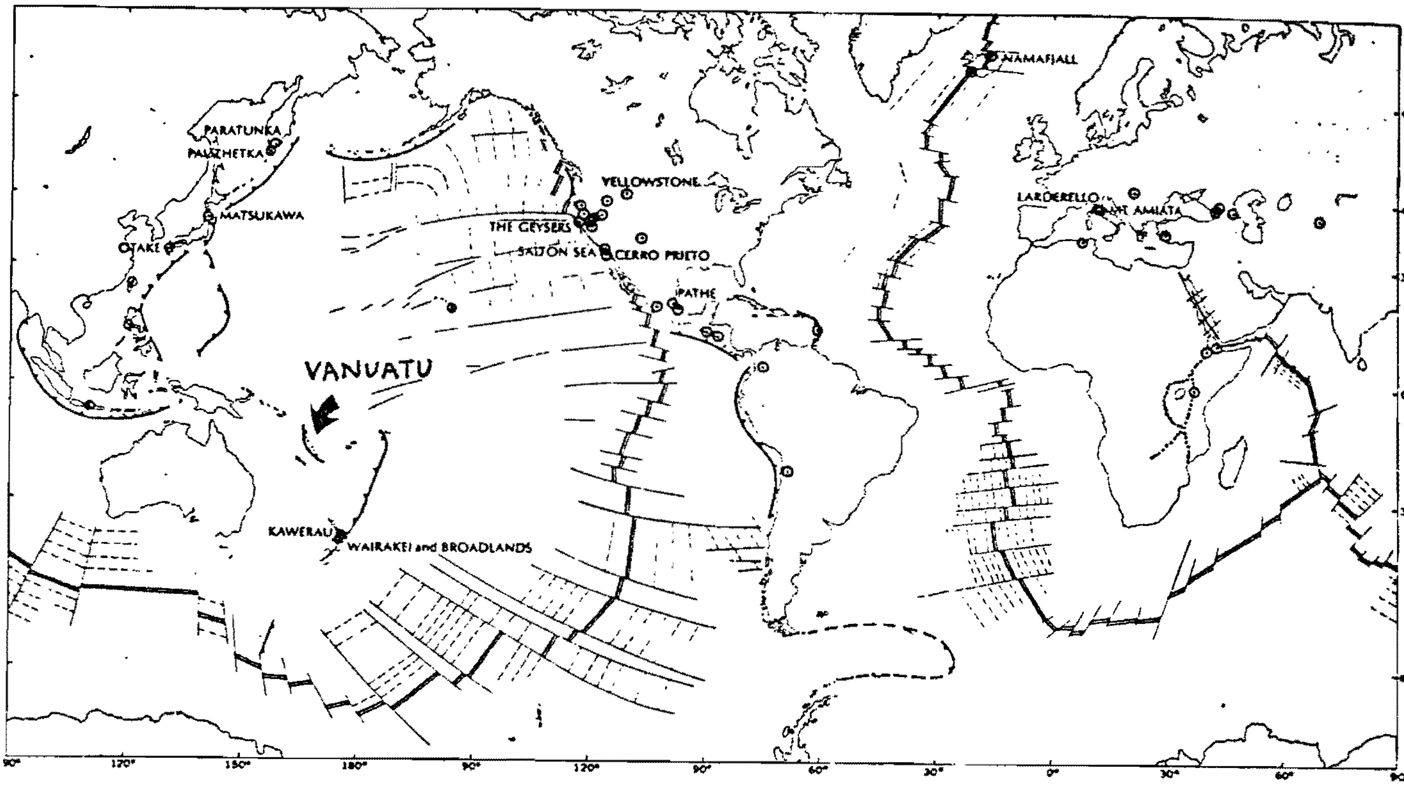

Figure 1. The Island Arc Systems of the SW Pacific as part of the global plate tectonic pattern, showing some major geothermal fields of the world (from White, 1981).

3.4 Geothermal Activity of the Central Chain Islands.

Vanua Lava, Gaua and Aoba (the nothernmost three of the Central Chain Islands) all have fumarolic activity and thermal springs. Strato-volcanoes on Ambrym and Lopevi have recently been intermittently active, submarine volcanoes east of Epi and north of Tongoa have erupted within the last twenty-five years and a strato-volcano on Tanna has been active since 1774.

The area of greatest geothermal potential in Vanuatu is possibly associated with the recently active basaltic volcanoes of the Central Chain of islands such as Mt Suretamati on Vanua Lava (Heming et al., 1982). The rate of heat loss from the Mt Suretamati system is greater than 200 MW and there are numerous hot springs, fumaroles and areas of steaming ground (Hochstein, 1977).

However, Efate is the only island of Vanuatu which has a sizable demand for electricity as well as having thermal springs which exhibit favourable indicators of geothermal potential. The Project Area was defined to include the regions with hot springs of particular interest from the point of view of their chemical indicators, the Takara springs and the Teuma valley springs. The Mele and Rentabau areas were omitted because their thermal spring waters have a substantial seawater component which has not re-equilibrated in a reservoir at high temperature (Williamson, 1980).

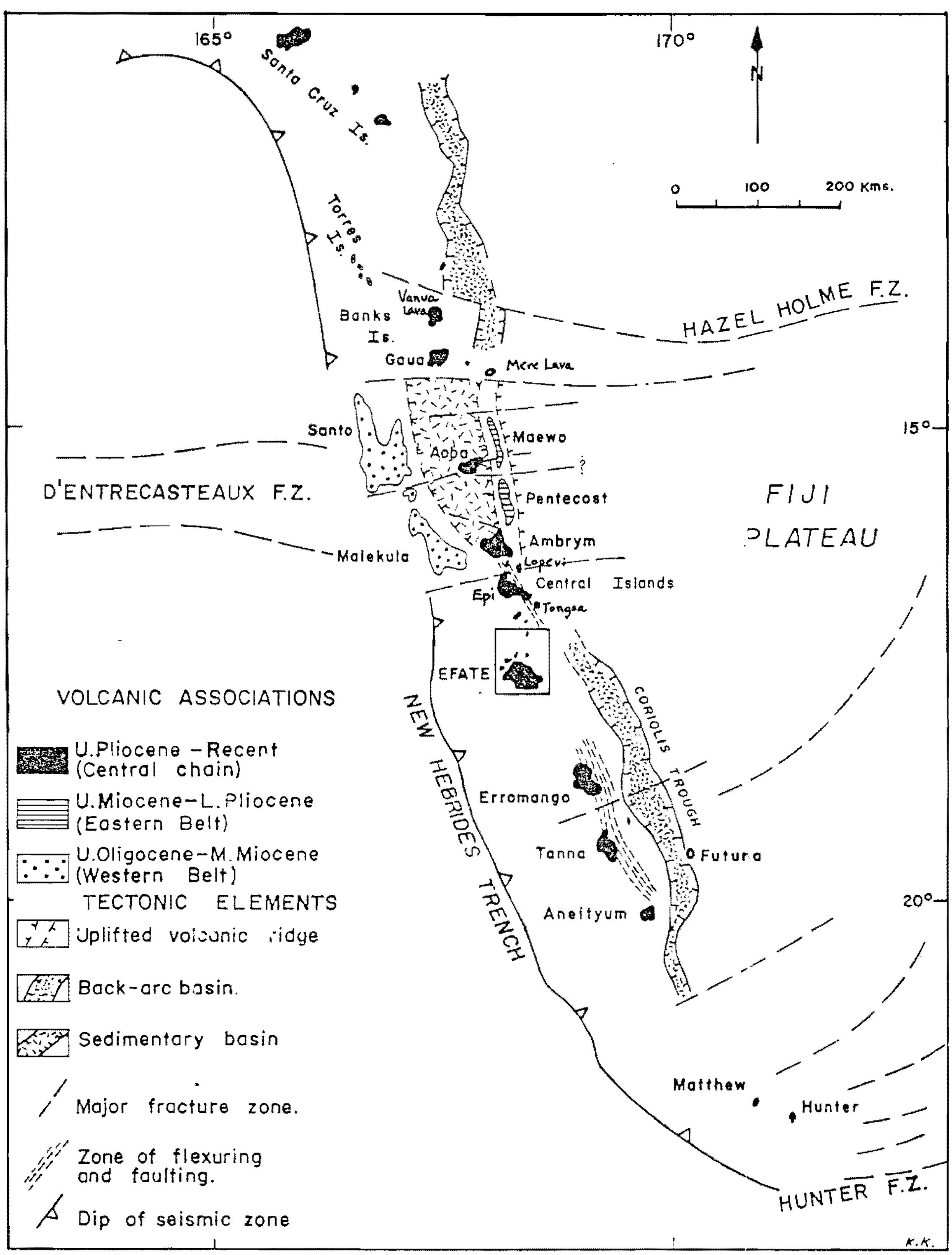

Figure 2. Volcanic Provinces of the Vanuatu Island Arc. (after Ash, Carney and Macfarlane, 1978; Mere Lava and Futuna are now thought to represent the Marginal Province).

4. GEOLOGY AND STRUCTURE OF EFATE AND THE PROJECT AREA

4.1 Geology.

The most recent geological map of Efate, at a scale of 1:100,000 (Ash, Carney and Macfarlane, 1978) is reproduced as Figure 3. The Project Area was mapped at a scale of 1:25,000 by Carney (1982), who presented a more detailed subdivision of the stratigraphic nomenclature for Efate (Table I) originally proposed by Ash et al. (1978). The 1:25,000 geological map is attached as Plate I.

The oldest in-situ rocks belong to an Early Pleistocene series of pumice tuffs and breccias known as the Efate Pumice Formation. In North Efate these are overlain by the predominantly extrusive Basalt Volcanoes Formation. Both these volcanic units are unconformably mantled by the highly diachronous Reef Limestone Formation, mainly dating from 450,000 a B.P. The very young extinct cones of the offshore islands Nguna, Pele and Emau represent a recent resurgence of volcanic activity.

Middle Miocene limestone clasts in Pleistocene conglomeratic limestones of the Teuma Graben provide the only evidence for a pre-Pleistocene basement on Efate, which is likely to consist predominantly of older volcanic rocks with minor associated limestones.

4.1.1 Efate Pumice Formation

The Efate Pumice Formation underlies the whole of Efate. Its base is not exposed. An estimate of its thickness of 400 m on Mt Macdonald is therefore regarded as a minimum value. Two units are recognised, massive pumice breccias and bedded pumice tuffs. The former, generally unsorted in beds of up to several metres thickness, constitute 90% of the Efate Pumice Formation in the Project Area, including the whole of the Mt Macdonald massif. The well-bedded pumice tuffs are mainly exposed to the north of the Macdonald Fault and have a minimum thickness of 200 m.

The breccias and tuffs of the Efate Pumice Formation are for the most part friable and porous.

4.1.2 Basalt Volcanoes Formation

The Basalt Volcanoes Formation comprises basalts and olivine basalts outcropping on the northern Efate mainland, and on the offshore islands of Nguna, Pele and Emau, activity on the two provinces being separated by about 800,000 a. On northern Efate the basalts outcrop only north of the Macdonald-Putuet Fault, centred on the two extrusive centres of Mt Fatmalapa and Quoin Hill. On Mt Fatmalapa highly indurated massive volcanic breccias with evidence of submarine extrusion in a westerly/south-westerly direction are cut by NE trending basalt dykes. Northerly dips in pillow lavas to the SW of Mt Fatmalapa are evidence for post volcanic tilting in the area. The massive structureless breccias of Quoin Hill are interbedded further east along the Lukunto River with compound lava flows. NE trending dykes are suggested by faint photolineaments. K-Ar dating of the Quoin Hill basalts indicates an age of approximately 1.14 Ma.

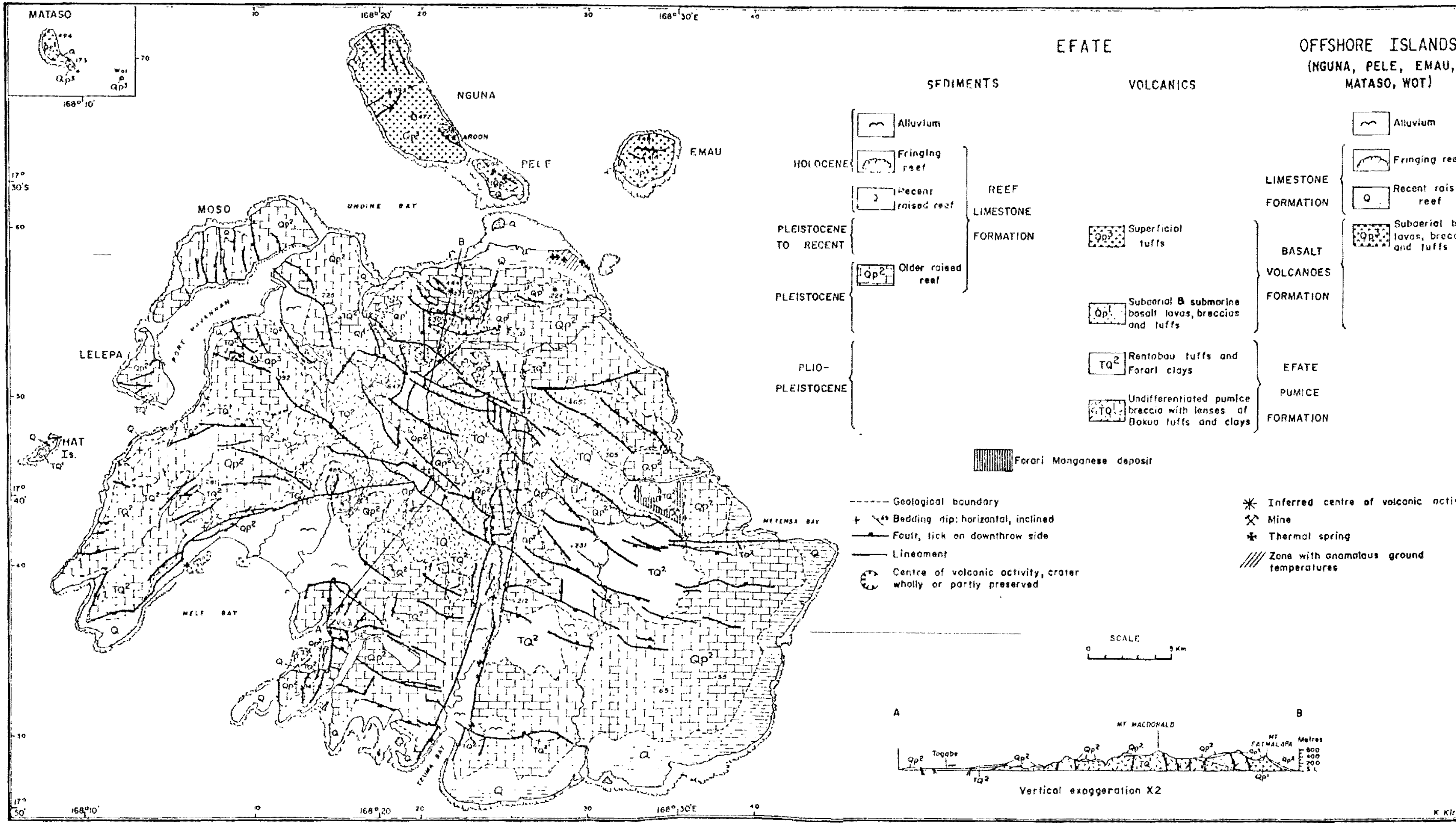

Figure 3. Geological Map of Efate, Vanuatu (from Ash, Carney and Macfarlane, 1978).

TABLE I. Stratigraphic Nomenclature for Efate, Vanuatu.

	Fringing Reefs	
	Present Alluvium	
	Raised Alluvial Plain	
	Older Alluvium	
∿6000 a B.P.	Recent Raised Reef	Reef Limestone Formation
0.2 - 0.08 Ma	Teuma Calcarenites	
0.45 - 0.08 Ma	Plateau Limestones	
> 1.1 Ma	Older Raised Limestones	
	Volcanic Breccias	Basalt Volcanoes Formation
	Paraconglomerates	
1.5 - 1.1 Ma	Pillow Lavas	
	Lithic Tuffs	
	Intrusions	
1.5 Ma	Bedded Tuffs	Efate Pumice Formation
	Pumice Breccias	

The three volcanic centres on Nguna are aligned NW-SE, on a southern continuation of which lies the island of Pele. Emau, to the east of Pele, is the only one of the three volcanic islands to the north of Efate which has signs of present day geothermal activity. The most likely age of the volcanism is thought to be about 200,000 a B.P., deduced from field relationships (Carney, 1982).

4.1.3 Reef Limestone Formation

The Reef Limestone Formation outcrops over 70% of the Project Area. It rests with considerable angular and erosional unconformity on the older formations. Its two modes of occurrence are as reef complexes mantling positive topographic elements and as bedded reef-derived calcarenites infilling structural depressions. The mantling reef complexes are seldom thicker than 130 m, but the infilling calcarenites of the Teuma and Epule basins may be up to 250 m thick. The four subdivisions of the Formation, representing successively-retreating fringing complexes, are diachronous.

The Older Raised Limestones outcrop around the summit of Mt Fatmalapa, fringing the Basalt Volcanoes Formation north of the Macdonald Fault. East of the Teuma Graben they mantle Mt Putuet north of the Sarranamoana Fault. Jasperoid veins and cavity-infilling quartz in the highest limestones around Mt Fatmalapa may indicate the former presence of hydrothermal activity in this area (Section 5.4).

The Teuma Calcarenites, predominantly hard well bedded gritty calcarenites and calcisiltites, infill the Teuma Graben except where the Sarranamoana Fault has uparched the graben axis. The Teuma Calcarenite/Plateau Limestone contact becomes increasingly unconformable southwards, graben faulting and transverse faulting having preceded deposition of the Calcarenites.

Reefal and lagoonal limestones of the Recent Raised Reef are extensively developed as a 500 to 1000 m wide plain extending into the Takara coastal area.

4.1.4 Alluvium

Lacustrine deposits of the Older Alluvium comprise pure steel-grey clays in isolated depressions west of Mt Fatmalapa. Sands and conglomerates, with minor argillaceous intercalations, of the Raised Alluvial Plain are continuous over the southernmost 7 km of the Teuma Graben and as isolated pockets overlying the Teuma Calcarenites further north. An actively forming alluvium comprises flood plain sands and gravels in the channel of the Teuma River.

4.2 Structure.

The main structural features of Efate are the Teuma Graben, the Macdonald-Putuet Fault complex and the NW-SE Crossfault Complex (Figure 4). There are two major zones of anticlinal flexuring, one related to the early northward-throwing movements of the Macdonald-Putuet Complex faults and another further south responsible for the antithetic southward-throwing Crossfault Complex, including the Duck Lake, Bouffa, Namarai, Forari and Sarranamoana Faults. The Teuma Graben first developed across the northern line of flexuring and subsequently propagated southwards coincidentally with the development of the Crossfault Complex. The graben is defined by

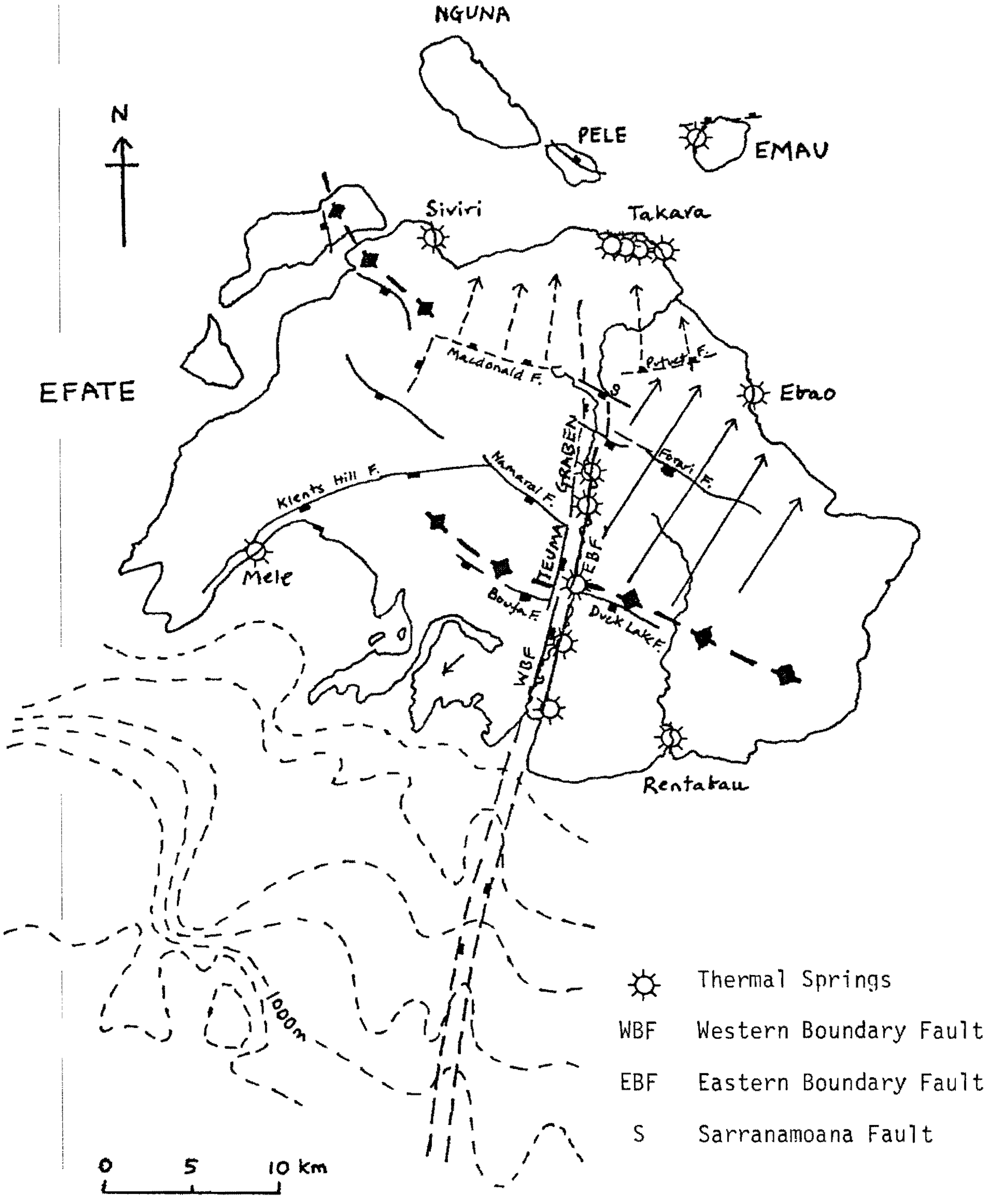

Figure 4. Structural Map of Efate, showing locations of Thermal Springs (Carney, 1982)

Arrows indicate direction of inferred flexuring and tilting. Dashed arrows represent former flexuring north of the Macdonald-Putuet Faults. Bold lines and diamond symbols show axes of inferred major change in direction of flexuring.

two oppositely throwing faults (200 m displacement) separated by less than 1000 m, and probably marks the induced reactivation of a pre-existing structure. The Eastern Boundary Fault appears to be antithetic to the 'main' Western Boundary Fault. A hinge line associated with the Forari Fault divides the graben into a northern and a southern sector. In the northern sector graben faulting preceded deposition of the Plateau Limestones, and in the southern sector faulting continued during and after deposition.

The physiography of Efate reflects the interplay of differential uplift of fault blocks during the Pleistocene and the extensive development of fringing reef complexes. The Teuma Graben forms a major morphological feature over 26 km and acts as a topographic divide between the elevated western massif of Mt Macdonald (max. elevation 650 m) and a lower plateau-like surface to the east (max. elevation 450 m).

5. GEOTHERMAL ACTIVITY

5.1 Thermal Springs and Hot Ground.

There are several thermal springs and seepages in the Project Area (Figure 4).

- along the course of the Teuma River, south of the Sarranamoana Fault

- on the coastal strip at Takara

- minor occurrences at Siviri and on Emau Island

Sketch maps of the individual spring localities, showing sampling locations, are given in Appendix I. An outline summary of their physical and chemical characteristics, as sampled in 1982, is given in Table 2 (page 26).

The Teuma springs, their temperatures ranging from 24 to 59°C, are associated with the Eastern Boundary Fault of the Teuma Graben. Previous accounts have noted the Lower, Mid and Upper Teuma springs; in addition, Carney (1982) has described two more northerly springs called here the Northern springs. The total heat discharge from the known springs of the Teuma Graben is less than 1 MW, of which the Mid Teuma springs contribute nearly 0.25 MW. A conductivity survey of the river has given evidence for substantial thermal discharges to the river in the vicinity of the Upper and Mid Teuma springs. Total excess heat discharge to the river is approximately 10 MW.

Three groups of springs near the coast at Takara, (the West, Central and East Takara springs), aligned ESE, discharge at temperatures between 36 and 71°C with a maximum combined flow of approximately 110 l/s. Total convective heat discharge from the springs at Takara is approximately 18 MW during periods of high flow, above an ambient temperature of 25°C. In addition to this the heat discharge from a zone of anomalous ground temperatures is approximately 2.5 MW (Hochstein, 1977, based on data from Greenbaum, 1973, and an empirical relationship between heat flux and ground temperature given in Robertson & Dawson, 1964). The maximum excess heat flow from the Takara area is therefore approximately 20 MW.

Minor coastal springs and seepages of thermal water occur at Undine Bay south of Siviri (29 to 32°C, combined discharge approximately 20 l/s), and on the beach on the northwest of Emau Island (39°C, discharge > 10 l/s). Other thermal springs and seepages outside the Project Area were omitted because they have been shown (Williamson, 1980) to have a substantial seawater component which has not re-equilibrated in a reservoir at temperatures higher than their moderate discharge temperatures.

5.1.1 Teuma Graben Springs

The Lower Teuma springs, 1.2 km NNE of Teuma Bay, discharge at temperatures between 24 and 29°C and with chloride concentrations between 30 and 1180 mg/l. There is no direct correlation between temperature and salinity. Numerous springs with a combined flow of 100 to 200 l/s discharge into a depression near the termination of the Erkau Fault against the Eastern Boundary Fault of the Teuma Graben, where relatively impermeable alluvial sediments of the graben have been downfaulted against the karstic raised reef limestone. The springs are a major point of discharge from the limestone.

The Mid Teuma spring is a single outflow of up to 61°C (Lavigne and Marinelli, 1970) and about 1 l/s discharging through alluvium on the eastern bank of the river near the Eastern Boundary Fault, opposite the crest of an arched structure on the Western Boundary Fault. A discharge temperature of 55°C was measured in March 1982 and 49°C in September 1982 when the flow was diminishing - four days later it had reduced to a trickle. Earlier accounts (Greenbaum, 1973; Williamson, 1980) have described several hot springs along a few metres of the eastern river bank, but these may be masked at times of high river flow. Total discharge of thermal (saline) water from the Mid Teuma spring to the river has been estimated at 44 l/s by consideration of salinity changes in the river (see 5.2 below). Cooler subsidiary springs in the vicinity persist when the hottest spring has all but disappeared, and these may be dominated by cooler shallow groundwater from the limestone.

The Upper Teuma springs comprise a zone of seepage discharge on the eastern bank of the river from alluvium both just above and below the river level. Although individual springs are little more than seepages the total discharge from this zone has been estimated as approximately 70 l/s by considering river salinity (see 5.2 below). Seepage temperatures have been measured variously between 26 and 40°C, and are clearly influenced by the amount of mixing with river bank storage water.

Two groups of springs and seepages separated by about 1 km, about 5 km north of the Upper Teuma springs, first reported by Carney (1982), have similar characteristics and are together named the Northern Springs. The most northerly constitute a series of warm seepages over a 50 m stretch of the river bank, emerging from pumice breccia at temperatures between 32 and 42°C. A southerly pair discharge at about 1 l/s at temperatures of 27 and 31°C. All are alkaline and of low salinity with dissolved chloride less than 30 mg/l.

5.1.2 Takara Springs

Groups of thermal springs, separated by several hundred metres, discharge from limestones of the Recent Raised Reef in an ESE alignment parallel to the coast, marking the line of intersection of the water table and ground surface at Takara. These perennial discharge sites where the discharge rates vary considerably in response to seasonal rainfall, are an expression of the hot groundwater which occurs at shallow depth in the limestone over an area of at least 4 km^2.

Discharge temperatures increase in direct response to higher flow rates. Temperature and flow variations at one discharge area were monitored for a year by Greenbaum (1973) during which increase in discharge temperature was associated with greater discharge rates, the temperature varying from 57 to 63.5°C and the associated discharge from 36 to 65 l/s. The thermal groundwater is associated with a region of hot ground, where temperatures reaching a maximum of 100°C at a depth of less than 0.5 m occur over a large area (see Section 5.3). In a 19 m deep borehole on the airfield at Takara the water table is 3 m below ground level at a temperature of > 88°C. The ESE orientation of the thermal anomalies and its parallelism with photolineaments crossing Mt Fatmalapa and major E-W fault structures, suggests an underlying structural control, possibly a permeable faulted zone in the basalts which underlie the reef limestone at no great depth.

Previous authors (Greenbaum, 1973; Hochstein, 1977) have named the discharge areas at Takara 'West', 'Central' and 'East', their West and East springs being the largest features (e.g. West 65 l/s total, 63.5°C maximum; East 10 l/s, 75°C maximum in Greenbaum, 1973) and the Central spring being relatively minor (3 l/s, 69°C in Greenbaum, 1973). In the present study the previously named 'Central' springs were not located but a minor more westerly spring (W17) was sampled. The West Takara springs of previous authors therefore become the Central Takara springs of this report. Detailed location sketches and sampling points are given in Appendix I.

As defined here the major springs are at Central and East Takara where temperatures up to 60 and 71°C respectively were measured in 1982 (Table 2) though previously temperatures up to 63°C, (Lavigne and Marinelli, 1970), and 78°C, (Giggenbach, 1977), have been reported. At each location there are numerous dispersed points of discharge from alluvium overlying the limestone having different temperatures and conductivities; this may account for some variation in measurements reported by previous investigators (Table 3). The discharge area of the East Takara springs is smaller in area than the Central Takara springs, and the springs had almost stopped flowing on the second visit in September 1982.

Minor seepages occur along the shore, for example at Takara Landing where the seepages occur in the inter-tidal zone and are likely to be contaminated by seawater.

5.1.3 Minor Coastal Occurrences and Emau Beach Springs

Seepages from beach sands occur along a 100 m section of the shoreline of Undine Bay south of Siviri at slightly elevated temperatures of between 29 and 32°C, and a combined discharge of about 20 l/s. Their relatively high Mg^{2+} and marine Na/Cl (see Appendix I) indicates them to be a mixture of unreacted sea water and fresh water which has been warmed slightly by circulation to only moderate depth. They are not considered further as part of the hydrothermal system.

Hot springs at 39°C on the beach of NW Emau Island, and vents of warm air on the lower western slopes, are the only surface thermal activity on the three offshore volcanic islands. The combined discharge of the seepages is approximately 10 l/s, but the diluted salinity of a seawater sample taken from the incoming tide suggests there may be significant sub-marine seepage of thermal water from the area. Hydrochemical analysis (Appendix I) indicates a thermal fresh-water component that may have equilibrated at about 150°C.

5.2 Discharge of Thermal Water to the River Teuma.

Increases in the electrical conductivity values for Teuma River water downstream of the Upper and Mid Teuma springs were reported in Carney (1982). These changes have been investigated in more detail and confirmed by chemical analyses (Table I, Appendix I). No significant temperature changes can be distinguished, but small changes would be masked by diurnal temperature fluctuations in the open reaches of the river. It is also impossible to discern any change in total flow rate of the river, which was gauged as $\sim$3.9 m^3/s at Bordes' House in September 1982 (J-M Bouchez, ORSTOM data). The downstream changes in EC_{25} in September 1982 are illustrated in Figure 5 which is comparable with data for March 1982 in Figure 2 of Bath et al. (1982). The changes can be summarised as:

		River before		River after	
		EC_{25}	Cl^-, mg/l	EC_{25}	Cl^-, mg/l
U Teuma	March 82	250	9	342	33
U Teuma	Sept 82	300	13	370	27
M Teuma	March 82	358	37	400	41
M Teuma	Sept 82	395	34	425	46

These changes, accompanied by small increases in Na^+, K^+, Ca^{2+}, HCO_3^- and B, are indicative of inflow of thermal spring water through the river bed in quantities greater than via the springs observed above river level; at the Upper Teuma springs some discharge into the alluvium and river bed was observed.

Heat losses to the river (Appendix 2) have been estimated from determination of electrical conductivity and from chloride ion concentration. Heat loss in the vicinity of the Mid Teuma springs is approximately 6 MW, and in the vicinity of the Upper Teuma springs is approximately 3 MW. There are no temperature anomalies in the river because an overall rise in river temperature by 1°C would require a heat gain of approximately 16 MW.

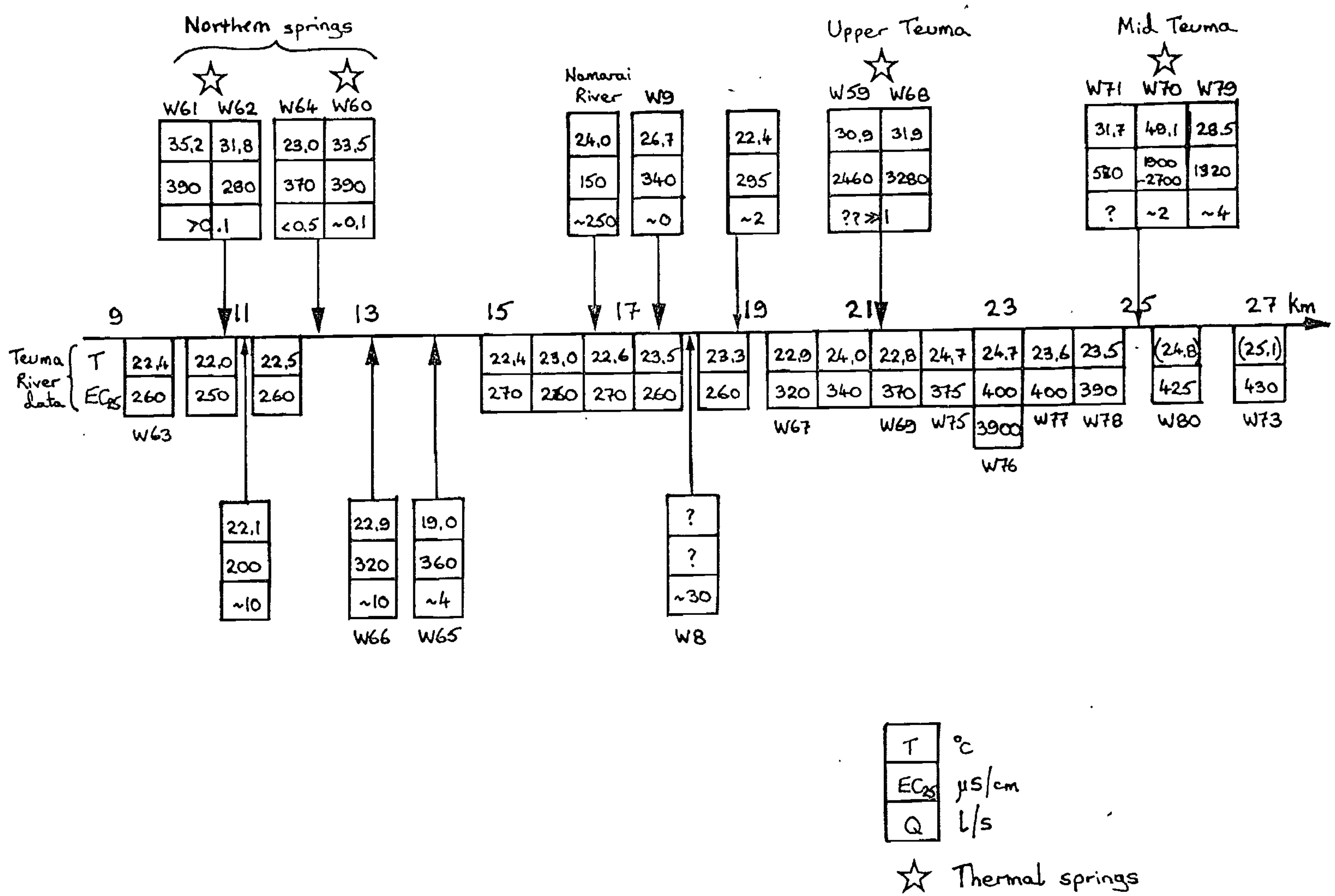

Figure 5. Temperature, Electrical Conductivity and Flow Rates of Springs and Streams flowing into the Teuma River.

5.3 Ground Temperature Surveys at Takara Airfield.

A survey of ground temperatures carried out by Greenbaum (1973) delineated the areal extent of the temperature anomalies of which the most obvious evidence is shallow temperatures up to 100°C. The areal anomaly so defined has been refined by a second survey (September 1982), the contoured results of which are shown in Figure 6. The anomalous zone is elongated parallel to but south of the spring line over an area of approximately 2 km^2

The anomaly appears limited to the west at the end of the airfield and to the south by the rising ground which represents the contact between the raised reef limestone and the Quoin Hill basalt. The greatest concentration of 'hot-spots' occurs roughly E-W parallel to and south of the airstrip. This may be the result of upwelling of hot water which is effectively confined in or by the basalts to the south. The hot ground must represent the surface manifestation of a hot water-table at shallow depth in the reef limestone. This is confirmed by the presence of hot water at ∿ 3 m in the airfield borehole. The hot spots themselves are very localised, suggesting that the bulk of the limestone acts as an 'impermeable' cap which is broken only by fissures or solution features up which steam can travel rapidly, condensing in the shallow sub-soil to give ground temperatures around 100°C.

5.4 Hydrothermal Alteration.

There are no significant signs of active hydrothermal alteration or deposition of hydrothermal minerals on Efate. None of the thermal discharges are acidic and there are no corrosive gases emitted. There is therefore no evidence for a condensate phase; the near neutral or slightly alkaline discharge indicate a hydrothermal rather than a vapour dominated geothermal system. Dissolved silica levels at the discharge points have generally been reduced by mixing to concentrations below which deposition of siliceous sinters is expected (i.e. dissolved silica levels not exceeding amorphous silica saturation) although in the immediate vicinity of the East Takara springs a thin deposit of amorphous silica crusts the sandy calcareous surface debris. Minor travertine deposition is associated with the Lower Teuma springs, but not more than is usual for springs from a karstic limestone system.

There is evidence of a former hydrothermal system in the area of Mt Fatmalapa from the presence of jasperoid veins, usually barren of metalliferous mineralisation, cutting basaltic breccias, and of associated silicification of limestones of the raised reef complex fringing Mt Fatmalapa, Maona and Bald Hill at an elevation of approximately 400 m. A white clay mineral and abundant interspersed barite laths are sometimes present in the microcrystalline quartz of the jasperoid veinlets and quartz encrustations in the limestone. The jasperoid veins have a preferred orientation NE, EW and NNE, probably controlled by structural lineaments, and the hydrothermal system may have been active prior to the uplift which followed cessation of the Basalt Volcanoes Formation at about 1.1 Ma, in a setting analagous to the presently active system at Takara.

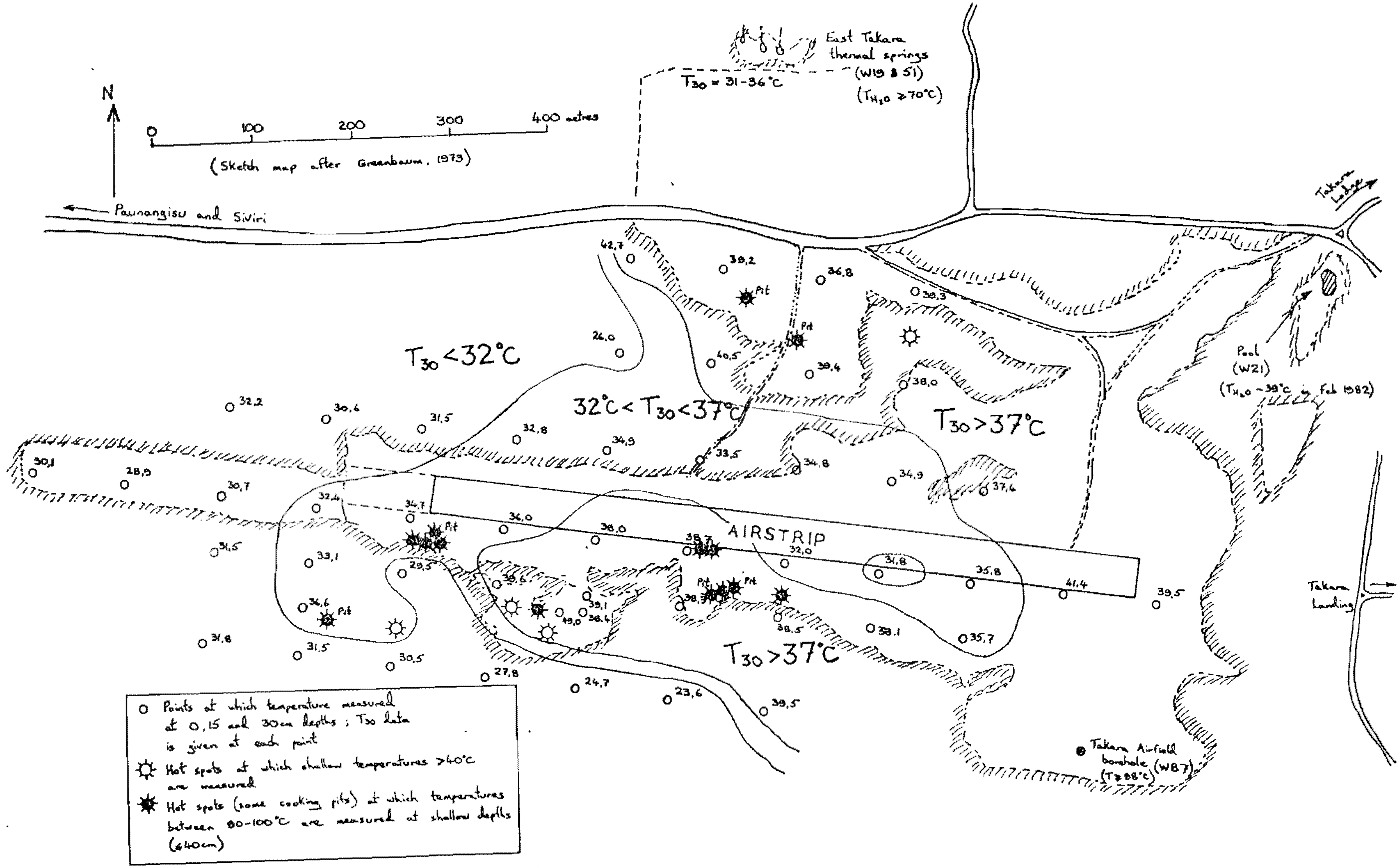

Figure 6. Sketch Map of Takara Airfield showing Results of the Ground Temperature Survey carried out in September 1982. Contours are drawn dividing zones in which T_{30} (temperature at 30 cm depth) is < 32°C, 32-37°C, and > 37°C. Hot spots with temperatures up to 100°C are also shown.

The general lack of abundant siliceous deposits at Takara and along the Teuma is not in itself evidence for reservoir equilibration temperatures being less than about 180°C (Ellis and Mahon, 1977), because the silica levels are likely to have been reduced by mixing. At the Teuma Graben springs the low rates of flow may have allowed precipitation of amorphous silica prior to discharge. But the lack of abundant siliceous deposits does imply that the discharge rates and temperatures of the flow systems have not been significantly higher in the recent past, However, on the north coast, if the 'fossil' geothermal system on Mt Fatmalapa is indeed an analogue to the present day activity at Takara, the implication is that location of the surface activity has changed in the last one million years.

6. HYDROLOGY

6.1 Regional Aspects.

A summary of the hydrology of the Project Area is given by Carney (1982). The 30-year (1948-77) average annual rainfall at Vila (altitude 20 m) is 2367 mm, and the average annual termperature is 24.7°C. Lower temperatures are to be expected at the higher altitudes within the Project Area.

The oxygen and hydrogen isotope compositions of the non-thermal springs and seepages are grouped according to their locations on either side of the groundwater divide, (Figure 7). Thus stable isotope composition distinguishes between precipitation falling in the north (-6.6 to -6.0‰ $\delta^{18}O$ and -37 to -34‰ $\delta^{2}H$) and central/south (-6.0 to -4.8‰ $\delta^{18}O$ and -35 to -28‰ $\delta^{2}H$) parts of the Project Area. The north of Efate, to the leeward side of the prevailing south-easterly winds, has a significantly lower rainfall than the south.

The southern and central part of the area is dominated by the Teuma River whose flow, measured as 3.9 m^3/s at Bordes House (J-M Bouchez, ORSTOM data), is predominantly the discharge from groundwater contained in the karstified limestone formations. Relatively minor contributions to its total flow derive from small streams flowing off outcrop of the Efate Pumice formation and from springs and seepages from fracture zones in the Efate Pumice or from contact zones between limestone and pumice. Karstic limestone springs (some with discharge > 100 l/s) have temperatures in the range 22.5-24.4°C throughout the upper Teuma River region, and in the source regions of the Nailep, Epong, Epule and Lukunto Rivers which occur at altitudes over 50 m asl. A similar spring with high discharge into the Teuma River at lower altitude (W8) flows at 500 l/s and 25.7°C which suggests a deeper circulation. Springs in other lithologies have a similar temperature range between 21.5-25.7°C. Streams flowing into the Teuma River have temperatures (measured at confluence) between 19.0°C (W65) and 24.0°C (Namarai R). Springs associated with the Basalt Volcanoes Formation in the northern part of the area are probably all derived from overlying limestone; their temperatures are between 21.8-23.0°C. River temperatures, where there is no known contribution from thermal inflow, are between 22.0-23.5°C which must represent the groundwater inflow temperatures modified to varying extents by diurnal fluctuations in ambient temperature and by solar heating.

6.2 Hydrogeological Aspects.

In the absence of quantitative data describing the hydrogeology of the Project Area only limited generalisations may be made about the hydraulic characteristics and relationships of the formations encountered. The pumice tuffs of the Efate Pumice Formation are noticeably porous and friable at outcrop and are likely to have

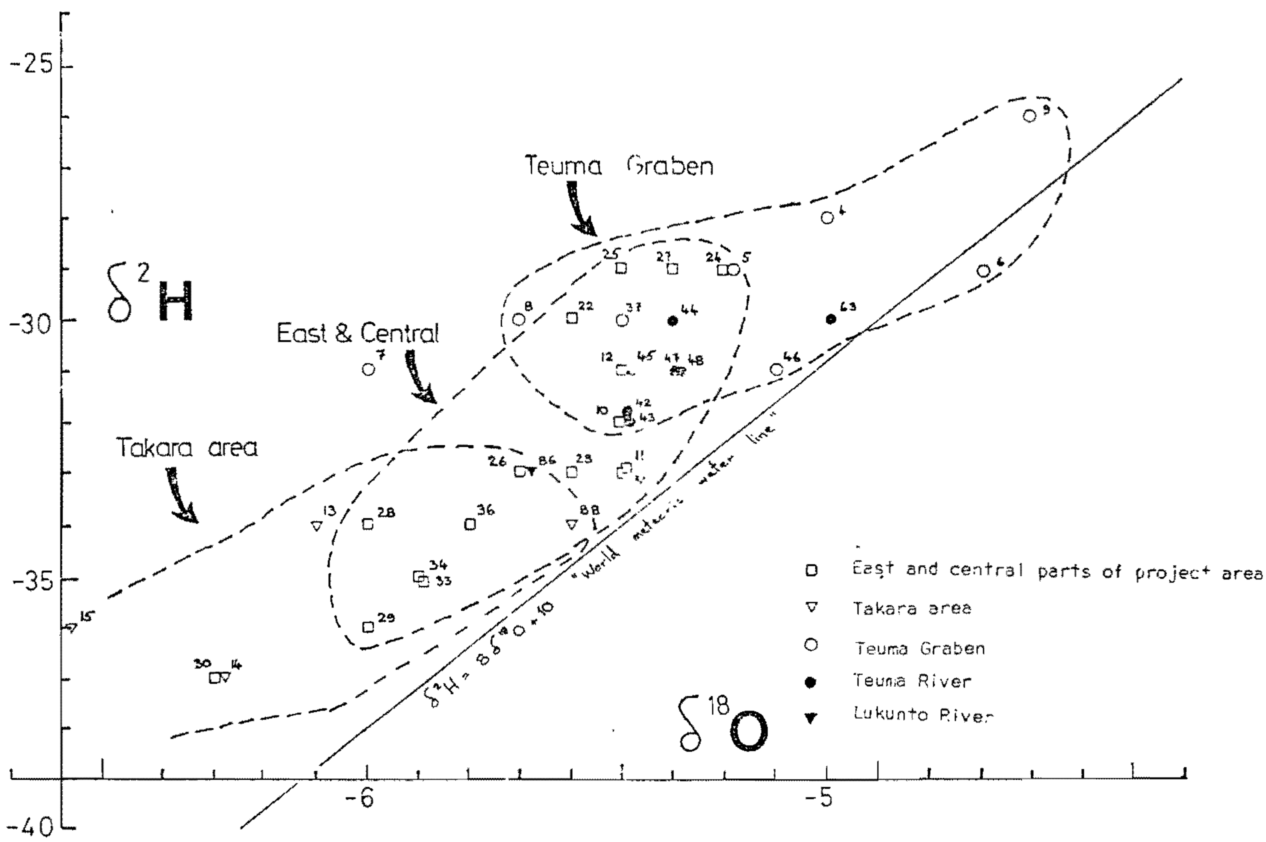

Figure 7. Stable Isotope Compositions of Cold Springs, Seepages and Rivers (solid symbols) in Project Area.

favourable storage and permeability. The lithic tuffs and basalt flows of the Basalt Volcanoes Formation are likely to have a low storage and low primary permeability but where they are fractured or at interfaces between individual flows a secondary permeability may be developed. The large source springs of the Teuma River and other rivers are evidence for the dramatic fissure permeability of the karstified limestones of the Reef Limestone Formation in which shallow groundwater circulates rapidly.

Groundwater in the Efate Pumice Formation may be in hydraulic continuity with the karstic limestone system where the limestones directly overlie the pumice, but where the Basalt Volcanoes Formation separates the two (in the vicinity of Mt Fatmalapa, Mt Sussunatarr and Quoin Hill) it may act as a confining barrier to the pumice.

Piezometric pressures in the basalts must be controlled by the water tables on Mt Sussunatarr, Mt Fatmalapa and Quoin Hill. The large seasonal variation in flowrate of the Takara springs and the direct relationship between springflow and temperature (Section 5.1.2) suggests that the thermal component of the discharge is controlled by the piezometric head in Quoin Hill. This in turn suggests the heat source is located south of the Takara discharge area, towards Quoin Hill rather than to the north towards the more recently active volcanoes of the offshore islands.

There also appears to be a seasonal variation in flowrate and temperature of the springs associated with the Eastern Boundary Fault of the Teuma Graben, suggesting that in this case also the piezometric control of the thermal component is an unconfined water table - possibly on Mt Macdonald or Mt Putuet for the Northern Springs, and the lower ground adjacent to the graben for the more southerly springs. Further monitoring of springflow, chemistry and temperature of the thermal springs may give a better indication of these controlling factors.

7. HYDROCHEMISTRY

A detailed account of the hydrochemical studies of the thermal springs of the Project Area is given in Appendix I. An outline of the springs' physical and chemical characteristics as of April 1982 is given in Table 2, and their chemical features, including the results of geothermometry, in Table 3.

7.1 Teuma.

The three groups of springs and seepages in the lower part of the Teuma Graben have similar maximum observed salinities and their chemical and isotopic characteristics imply that they have a common source. Apparent differences reflect different circulation depths and extents of reaction for each.

At Lower Teuma the discharge temperatures are low (up to 28.4°C) and the total discharge is relatively high. The spring chemistries are colinear with respect to chloride, suggesting that they have a common saline component which might be seawater after reaction with silicates. The dilution mixtures with this component have formed before circulation, rather than close to the spring outflows, and have achieved temperatures of up to 110°C according to quartz geothermometry.

Highest discharge temperatures and predicted base temperatures occur at Mid Teuma where up to 61°C has been measured. These springs are characterised by marked K^+ enrichment and extreme Mg^{2+} depletion in the thermal water which is mixed with shallow groundwater or river water prior to sampling. There is a possibility of two separate thermal groundwaters at Mid Teuma, one with low salinity and one with higher salinity, based on the evidence of different mixing relationships of K^+ and SiO_2 with Cl^-. A maximum base temperature of 205°C is predicted by quartz geothermometry, for the spring water with highest determined dissolved SiO_2 (Goguel, 1977), by correcting for the assumed dilution of the reservoir SiO_2 concentrations due to addition of cold groundwater. The highest dissolved SiO_2 determined during the present study indicates a base temperature of 185°C by the same method. Na-K-Ca geothermometry supports this base temperature prediction with values of 200-215°C for the inferred high-temperature components.

The Upper Teuma seepages may have a thermal component similar to that at Mid Teuma, with depleted Mg^{2+}, but in which the chemistry has been disturbed due to shallow groundwater mixing and possibly also by exchange reactions with fine-grained sediments through which seepage occurs. Therefore chemical geothermometry provides minimum estimates of base temperature which range up to 145°C from quartz solubility, although the dilution corrections cannot be applied due to the probability of conductive cooling.

The Northern Springs are not related to the three groups of saline springs and are characterised by low-chloride chemistries resulting from silicate alteration reactions only during deep circulation; Na-K-Ca geothermometry predicts maximum temperatures up to only 65°C whilst predictions up to 145°C due to quartz solubility may be erroneously high.

	Sample No.	Temperature °C	Flow Rate l/s	pH	Elevation (m.a.s.l)	Cl	Na	K	Ca	Mg	SO_4	HCO_3	SiO_2
						mg/l							
TEUMA GRABEN (from south to north)													
Lower Teuma Springs		24-29	100-200										
	JC/W31	27.2	4	6.95	18	1180	638	52	150	38.0	124	244	42.6
	JC/W32	27.2	5	6.9	18	43	32	4.7	74	3.7	6	212	48.3
	AB/W55	26.3	2	6.90	18	30	24	4.7	73	42	6	276	40.2
	AB/W57	27.1	>10	7.00	18	860	469	37	115	28	91	229	52.0
Mid Teuma Springs		49-59	1-2										
	JC/W41	54.8	1	7.25	5	760	400	60	84	1.1	14	75	141
	AB/W70	49.1	2	7.85	5	588	315	50	54	1.0	12	79	135
Upper Teuma Springs		31-40	seepages										
	JC/W3	30.6	-	6.05	16	465	190	23	133	3.6	7	256	114
	AB/W68	31.9	-	6.75	16	850	305	33	214	3.4	10	154	88
Northern Springs		27-41	2										
(S)	JC/W39	31.5	1	6.95	50	15	43	3.7	34	2.0	5	178	115
(N)	JC/W38	35.5	-	7.95	70	25	47	3.2	14	0.4	6	149	118
(N)	AB/W61	35.2	0.1	8.50	70	28	54	2.9	10	0.4	6	117	99
TAKARA (from west to east)													
West Takara		40-63	<0.5										
	JC/W17	40.8	<0.5	7.05	c.5	3400	1330	74	669	36.0	89	158	50.1
Central Takara		36-64	c.20-70										
	JC/W18	60	2	6.7	c.5	7000	2650	144	1570	34.0	137	73	75.7
	AB/W50	60.5	<0.5	6.25	c.5	9960	3810	200	2140	53.0	195	63	87.5
East Takara		66-78	low-c.50										
	JC/W19	70	2	6.85	c.5	11900	4790	247	2670	43.0	199	58	117
	AB/W51	71.4	<0.1	6.40	c.5	11700	4420	243	2560	39.0	228	42	112
Takara Borehole	AB/W87	88.1	-	-		14000	4910	272	3080	14.6	194	29	129
Takara Landing		30-42	<1										
	JC/W20	41.2	-	7.15	0	8900	3810	183	1710	180	382	88	78
	AB/W83	41.2	-	6.85	0	12280	5990	250	1440	493	1050	78	59

Table 2. Outline physical and chemical characteristics of the thermal springs in the Teuma Graben and Takara area.

JC/W : sampled between January and April, 1982 (Carney, 1982)
AB/W : sampled in September, 1982 (Appendix 2)

Location	Ref	T (^oC)	Cl (mg/l)	Na/Cl	Ca/Mg	Cl/Br	Cl/SO_4	SiO_2 (mg/l)	Geothermometers* (^oC) T_{quartz}	$T_{Na-K-Ca}$	$T_{Na-K-Ca-Mg}$
Takara West	B,C,C (W17)	40.8	3400	0.39	18.6	-	38	50	102	156	138
Takara Central†	L,M	63	10224	0.42	28	-	40	78	124	157	151
	H	56	8670	0.41	37	-	62	83	127	156	156
	WG	57	8230	0.25	70	-	58	99	137	178	178
	WG	50	5780	0.39	33	-	38	81	126	162	157
	RG	59	7658	0.41	43	-	43	93	133	154	154
	W	61	9750	0.37	27	361	23	79	124	161	150
	B,C,C (W18)	60	7000	0.38	46	311	51	75.7	122	159	157
	B,M (W50)	60.5	9960	0.38	40	398	51	87.5	130	161	158
Takara East	L,M	44	9940	0.39	32	-	44	95	134	162	156
	H	66	10700	0.44	67	-	63	94	134	152	152
	WG	78	10700	0.39	62	-	51	132	153	168	168
	WG	71	11530	0.39	63	-	162	115	145	165	165
	B,C,C (W19)	70	11900	0.40	62	-	60	117	146	162	162
	B,M (W51)	71	11170	0.40	65.6	349	49	112	144	164	164
Takara Borehole	B,M (W87)	88.1	14000	0.35	211	368	72	129	152	165	165
Lower Teuma	L,M	28	44	0.75	19	-	6.3	39	91	40	-
	L,M	25	115	0.61	16	-	9.6	22	67	47	-
	H	25	177	0.46	9.6	-	>88	47	99	66	-
	W	27	750	0.41	-	-	9.3	34	85	178	-
	W	26	37	0.76	-	-	2.0	19	62	27	-
	B,C,C (W31)	27.2	1180	0.54	3.9	257	9.5	43	95	175	66
	B,C,C (W32)	27.2	43	0.74	20	270	7.2	48	100	38	-
	B,M (W57)	27.1	860	0.54	4.1	307	9.5	52	104	170	67
	B,M (W55)	26.3	30	0.80	17	214	5.0	40	92	36	-
Mid Teuma	L,M	61	156	0.59	44	-	49	156	163	214	210
	L,M	54	409	0.59	10	-	41	100	137	197	140
	H	42	156	0.84	1	-	20	113	144	199	40
	WG	54	250	0.70	50	-	11	163	166	209	203
	WG	30	654	0.37	8.5	-	33	86	129	199	139
	RG	50	41	1.73	-	-	2	165	167	218	218
	W	56	146	0.78	-	-	7	149	161	206	-
	W	50	700	0.53	136	280	30	131	153	214	-
	B,C,C (W41)	54.8	760	0.53	76	-	54	141	157	206	206
	B,M (W70)	49.1	588	0.54	54	372	49	135	155	210	208
Upper Teuma	H	31.5	640	0.49	5.4	-	10	82	126	181	86
	B,C,C (W3)	30.6	465	0.41	37	-	66	114	145	175	175
	B,M (W68)	31.9	850	0.36	63	386	85	88	130	174	174
Northern Springs(S)	B,C,C (W39)	31.5	15	2.89	17	-	3	115	145	48	-
	B,M (W60)	33.5	13	3.46	18.7	-	3.3	80	125	54	-
Northern Springs(N)	B,C,C (W38)	35.5	25	1.88	35	-	4.2	118	147	62	-
	B,M (W61)	35.2	28	1.93	25	-	4.7	99	137	66	-

TABLE 3. Summary of the Chemical Features and Geothermometry Results of the Efate Thermal Springs.

L,M : Lavigne & Marinelli (1970), sampled August 1970
H : Hochstein (1977), sampled November 1975
WG : Giggenbach (1977), sampled March-April 1977
RG : Goguel (1977), sampled August 1977
W : Williamson (1980), sampled October-November 1980
B,C,C : Bath, Carney and Cook (1982), sampled January-April 1982
B,M : Bath and Marks (Appendix I, this report), sampled September 1982

† 'Takara West' of previous authors - see text

* Geothermometry formulae of Truesdell (1975), Mg correction of Fournier & Potter (1979).
N.B. No allowance for mixing in these figures. For discussion of the applicability of the geothermometry results see text.

7.2 Takara.

The springs at Takara are the discharge from a shallow thermal groundwater which is also present at the water-table intersected by the airfield borehole and accounts for the occurrence of hot-ground over an extensive area where the water-table in the reef limestone approaches the surface. Chemical and thermal characteristics respond to flow variations which suggest a seasonal effect of recharge with limestone groundwater as well as probable mixing with normal sea water. The thermal water which feeds this shallow re-reservoir is seawater which has reacted with basaltic rock at high temperature thereby depleting Mg^{2+}, SO_4^{2-} and Na^+, and enriching Ca^{2+}. Anomalous Cl^-/Br^- ratios suggest that Cl^- enrichment or Br^- depletion relative to seawater is occurring. Na-K-Ca geothermometry predicts a base temperature of 165°C from the water sampled at the airfield borehole, and a similar temperature is predicted from the composition deduced from extrapolation of spring chemistries to marine Cl^- concentration. SiO_2 concentrations, which also correlate roughly with Cl^-, suggest a base temperature of around 180°C by extrapolation and dilution correction procedures on quartz geothermometry.

There is insufficient evidence available to support one geothermometer against the other so it is concluded that the base temperature of the circulation feeding the Takara system is probably in the range 165°-180°C.

8. GEOPHYSICS

As a result of regional surveys a limited amount of gravity, magnetic and seismic data exist for Efate. Two preliminary resistivity traverses have also been carried out. The geothermal implications of these data have been considered by Hochstein (1977a) and Williamson (1980). They provide the basis for a preliminary geophysical interpretation of Efate, but are inadequate for a geothermal assessment of the Project Area. There have been no measurements of conductive heat flow on Efate.

8.1 Gravity and Aeromagnetic Data.

Gravity data relating to Efate are described by Malahoff (1970) from approximately 60, predominantly coastal, stations and ORSTOM (1977) from offshore data. Aeromagnetic data are also described by Malahoff (1970). The prominant gravity and aeromagnetic anomalies on the north-east of Efate in the Project Area (+ 170 mgal Bouger anomaly peak, 300 gamma peak to peak magnetic anomaly) have the same source body, interpreted as an eroded volcanic plug (Figure 8, after Malahoff, 1970), which the most recent, offshore, data (ORSTOM, 1977) suggest is centred further north in the Takara geothermal area. Other magnetic anomlies, and the southward positive gravity salients along the Teuma Graben and the Forari Fault, are interpreted as due to dyke intrusions.

8.2 Seismicity.

The regional seismicity of the central New Hebrides Island Arc has been described by Isacks et al. (1981) from data of large earthquakes (Ms > 6.9) of the past 75 years, moderate sized earthquakes (Ms < 7.0, mb > 4.4) over the past 20 years, and smaller earthquakes (mb 2.5 to 4.5) located by local networks.

Marked variations in the pattern of seismicity along the strike of the New Hebrides Island Arc define four segments, each about 100 km long. The Efate segment is characterised by a persistently high rate of earthquakes of magnitude Ms < 6.5, contrasting with large fluctuations in activity elsewhere. Since 1978 the networks have monitored activity at a threshold level of mb 3.0. Microearthquakes (mb -2 to 3) which might be associated with faults at a depth of less than 5 km, of interest to the shallow geothermal system, would not be recorded on these networks. The lack of recorded data for earthquakes on Efate with hypocentres shallower than 35 km does not therefore imply the absence of microseismicity.

8.3 Resistivity.

Two preliminary DC resistivity traverses across the boundary of the Takara geothermal area (inferred from the occurrence of hot ground) have been carried out using the Schlumberger array (Hochstein, 1975; Saos, pers. comm. in Williamson, 1980). Saos used an extremely short electrode separation (AB/2 = 10 m) and found apparent resistivity values typically between 5 and 20 Ωm and locally less than 5 Ωm within the thermal area, and between 30 and 100 Ωm outside. Hochstein used a separation of AB/2 = 500 m and found apparent

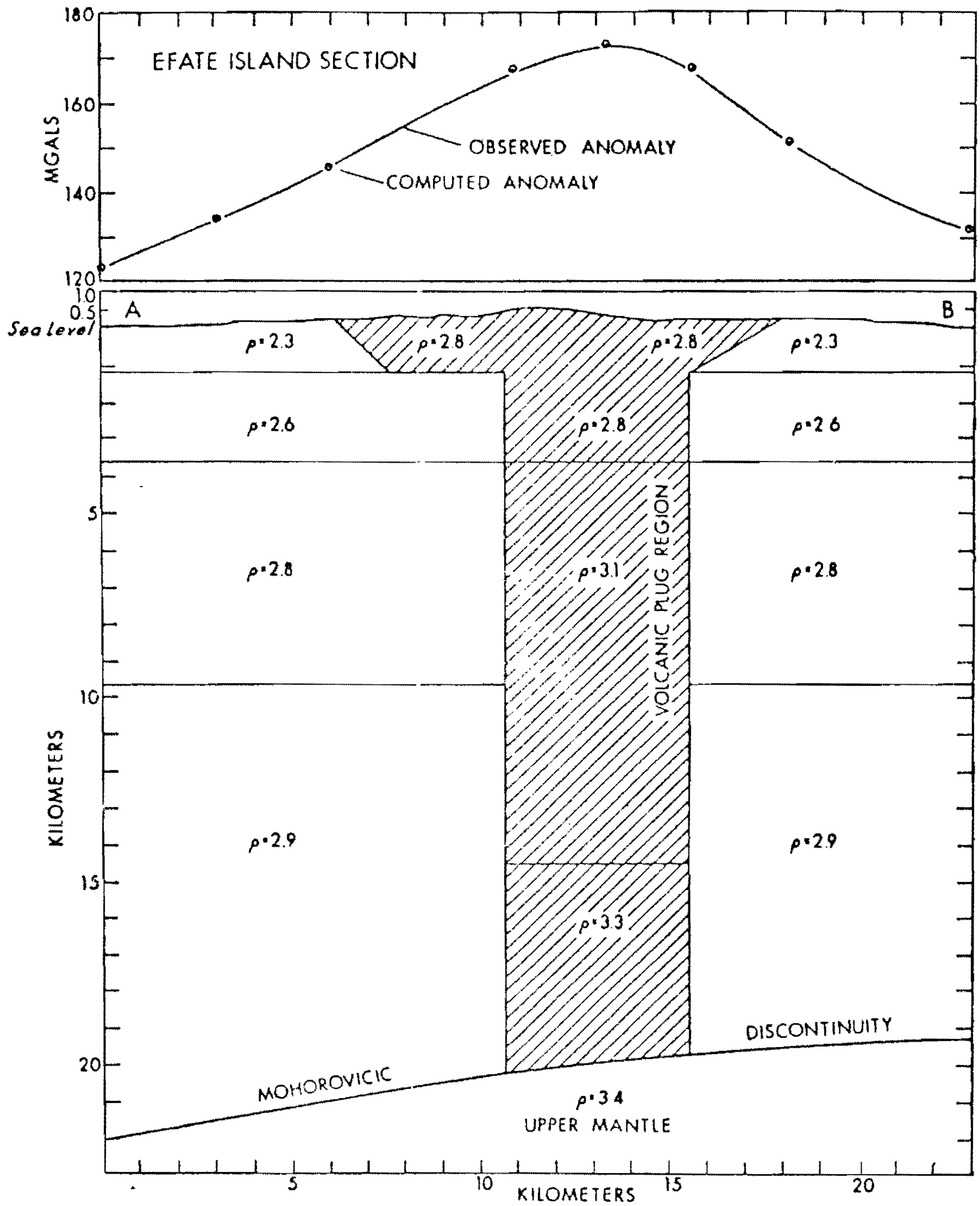

Figure 8. Fast-West Crustal Cross-Section across Northern Efate, interpreted from the Bouger gravity anomalies (Malahoff, 1970).

resistivities of between 1.5 and 2.6 Ωm, and uniformly low resistivities to depths of at least 300 m. Both traverses were close and parallel to the coast. It is likely that ubiquitous sea water intrusion dominates the resistivity structure of the coastal region, masking the effect of the geothermal anomaly. The consequences of this are discussed below.

8.4 Heat Flow.

The background conductive terrestrial heat flow of Efate has not been measured, but a model has been proposed by Hochstein (1977) to estimate the conductive heat flow anomaly due to a 3 km thick layer of cooling lavas 0.7 Ma old. The present day temperature gradient would be increased by 20°C/km and the conductive heat flow would be 40 mWm^{-2} above the regional heat flow. A cooling lava pile 1.5 km thick would result in a present day heat flow anomaly of 10 mWm^{-2}.

8.5 Summary.

The interpretation of the gravity anomaly data in terms of a basaltic magma centre in the north of the Project Area is in accord with the field observations. While it is likely that these intrusions are the source of heat for the hydrothermal systems at Takara and along the Teuma Graben, existing geophysical data are inadequate to define the heat sources precisely or to indicate anomalies due to the presence of thermal fluids in a reservoir at depth. There is no direct evidence for dyke intrusion along the Teuma Graben and Forari Faults such as may be responsible, at least in part, for the gravity anomaly salients. To refine the gravity interpretation of Efate in terms of more precise location of centres of intrusion a greater inland spread of gravity measurements is needed.

An electrical resistivity reconnaissance of the Project Area and its environs is required to search for resistivity mining that may relate to a geothermal reservoir associated with the source(s) of heat. Resistivity surveying is the most widely used geophysical technique in geothermal exploration. Reconnaissance mapping by resistivity traversing is the first step in determining the resistivity structure and has been extensively and successfully applied, notably in New Zealand (e.g. Risk, 1981).

There is no doubt that the location of the surface features of the hydrothermal system are fault-controlled. Records of the microseismicity may allow determination of the depths over which these faults are seismically active due to fluid movement, and give clues to the relationship of the spring discharges to the heat source, and of the Takara geothermal area to the Teuma Graben geothermal area.

A recommended strategy for the collection of further geophysical data relating specifically to the geothermal potential of Efate is discussed in Section 9,, and outlined in Appendix 3.

9. CONCLUSIONS

9.1 The Thermal Anomalies.

The thermal anomalies on Efate are restricted to two areas within the Project Area. One, associated with the Teuma Graben, manifests itself as a series of thermal springs and seepages at or close to river level. Another is manifested as a series of springs and an elongated area of hot ground in an ESE alignment along the Takara coastal area. The locations of the surface features of both hydrothermal systems are fault controlled.

Heat loss from the Teuma springs is approximately 10 MW (thermal), estimated from spring discharge measurements and a river conductivity survey. At Takara the maximum heat loss is approximately 20 MW, (18 MW during periods of high flow from the springs and 2.5 MW from the hot ground area).

Both hydrothermal flow systems discharge close to sea level or at river level in the Teuma Graben. There is no evidence for pressures other than hydrostatic pressures acting on Efate; the anomalies are evidence for a hydrothermal rather than a vapour dominated geothermal system.

At Takara the direct relationship between rainfall, and temperature and flow rate of the thermal springs, suggests that the hydrothermal flow system may be driven by the piezometric pressure of groundwater in the Basalt Volcanoes Formation of Quoin Hill or even Mt. Sussunatarr to the south-west. This suggests that the source of heat also lies to the south of Takara, rather than towards the sites of more recent volcanic activity on the offshore islands of Nguna, Pele and Emau to the north.

The Teuma Graben springs exhibit no such straightforward relationship, and their chemistry implies a more complex mixing pattern.

9.2 Reservoir Temperature and Sources of Water.

Maximum reservoir temperatures are estimated to be 200-215^{o}C in the Teuma Graben and 165-180^{o}C at Takara. At Takara seawater reacts in a basalt 'reservoir', the conditions of which may be quite uniform. Along the Teuma Graben there appear to be other discrete flow systems which equilibrate at lower temperature, and a more complex mixing pattern involves a saline component and a meteoric component (probably groundwater from the Teuma Calcarenites) which mix prior to deep circulation.

9.2.1 Reservoir Temperature in the Teuma Graben

Chemical studies indicate that the Lower, Mid and Upper Teuma springs are not the result of simple two component mixing, but have a complex origin. Although the thermal components of each have a common source, independent flow histories have led to different temperatures of chemical equilibration. The temperature of chemical equilibration is commonly taken as the reservoir temperature. In this case the highest reservoir temperature is indicated by the Mid Teuma spring; 205^{o}C by quartz geothermometry after correction for dilution and 200-215°C by cation geothermometry. Equilibration probably occurs in a silicate lithology underlying the Teuma Calcarenites, either tuffs of the Efate Pumice Formation or basalt dykes of the Basalt Volcanoes Formation which may have been injected along the Teuma Graben. The thermal component at Upper Teuma may be similar, but the situation is less clear due to shallow groundwater mixing and exchange reactions close to the seepage points. The thermal component of the Lower Teuma springs has a lower temperature of chemical equilibration, up to approximately 110°C, according to silica geothermometry (quartz).

The Northern Springs, previously undescribed, are unrelated to the more southerly three groups, and their less saline character may be explained by silicate alteration reactions during circulation of meteoric groundwater at only 65°C.

The range of apparent temperatures of chemical equilibration in the Teuma Graben are associated with a number of discrete groundwater circulation systems, and a complex mixing pattern.

9.2.2 Reservoir Temperature at Takara

The thermal springs at Takara are also mixtures, but in this case the thermal component can be more precisely defined as sea water which has reacted with basaltic rock at a more uniform elevated temperature, between 165°C (cation geothermometry) and 180°C (silica geothermometry with dilution correction).

9.3 The Heat Source.

The most realistic assumption is that a cooling igneous body at some depth is the ultimate source of heat responsible for the observed surficial thermal anomalies on Efate. Major fault structures allow the flow of groundwater which results inconvective loss of heat. The conductive heat flow on Efate has not been measured, but model studies suggest a cooling layer of lavas 0.7 Ma old and 3 km thick would increase the heat flow locally by 40 mWm^{-2}, and the present day temperature gradient by 20°C/km.

Gravity and magnetic anomalies may be guides to the location of the heat source at depth. A positive 50 m Gal gravity anomaly, previously thought to be centred at the north end of the Teuma graben (Malahoff, 1970) is shown by more recent ORSTOM data to be centred further north at Takara. There is an approximately coincident magnetic anomaly near Takara. A shallow basaltic body in northern Efate is the most convincing explanation of the gravity and magnetic anomalies.

Although the flow of groundwater and the resulting convective heat loss is controlled by major fault structures which apparently define two separate hydrothermal systems, the actual source of heat may be common to both.

9.4 The Nature of the Reservoir.

The indications from all the thermal springs are that the chemical character of their thermal component is determined by reaction of circulating groundwater with silicate rocks. At Takara, the water is seawater and the reservoir is probably basalts of the Basalt Volcanoes Formation. In the Teuma Graben the water is meteoric and the reservoir may be tuffs of the Efate Pumice Formation, or basalt dykes intruded along the Graben from the north.

The chemistry of the thermal component of the springs at Takara is similar to that expected for sea water which has reacted with the basaltic Layer 2 of the oceanic crust (e.g. Humphris and Thompson, 1978). Such reaction is commonly observed at spreading centres of mid-oceanic ridges (Spooner and Fyfe, 1973). Reykjanes, in Iceland, is a geothermal field in which sea water reacts with basalt at temperatures up to 300°C (Tomasson and Kristmansdottir, 1972). In the vicinity of Takara the temperature of reaction is more moderate, between 165 and 180°C, but there may be extensive association between sea water and basalt at depth where fracturing allows the sea water access.

In the north of Efate, in places where the basalt is unfractured it may act as a cap rock to the Efate Pumice, and if association with the heat source allows, the pumice may also act as a reservoir for geothermal fluids. It is likely to have favourable storage capacity and reservoir characteristics.

South of the Basalt Volcanoes Formation the Efate Pumice is unconfined. It contains cold meteoric groundwater that is in hydraulic communication with groundwater of the Reef Limestone Formation and may be suppressing by dilution and cooling, uprising thermal water. The possibility that the Efate Pumice in the south of the island forms the reservoir for the thermal component of the Teuma Graben Springs has yet to be demonstrated. Although the highest temperature of geochemical equilibration is seen in the Teuma Graben there is evidence for more moderate base temperatures and a complex mixing pattern. If heat is supplied by cooling dyke intrusions rather than from a larger regional heat source then the availability of thermal water for exploitation may not be extensive.

9.5 Discussion and Recommendations.

Although not unconditionally favourable, geochemical indications encourage the view that extensive water-rock reaction is taking place at moderate to high temperatures, associated with a heat source in the north of Efate. More precise indication of the size and location of the thermal anomalies is needed, and an estimate of their probable depth, to allow the location of exploration boreholes with the minimum risk of failure. To do this, further geophysical investigations must be undertaken.

The minimum temperature at which a hydrothermal system becomes exploitable for generation of electricity by conventional turbogenerators is 200°C. On this criterion the grounds for further investigation of the geothermal system on Efate as a potential resource for electricity generation are marginal. However, plant is now available for generation of electricity from fluid sources at temperatures well below 200°C, using a system known as the Organic Rankine Cycle. Under this system, heat is transferred from the geothermal fluid via a heat exchanger to an organic working fluid, which can then be flashed at atmospheric pressure to drive a turbine. Key system components are commercially available at a total cost of approximately £1000/KW, in units of the order of 10 KWe. Although initially developed to generate electricity from waste industrial heat, they are suitable for geothermal sources (Wood and Ram, 1983).

Minimum temperatures required by an ORC turbogenerating system are 110°C (for water) and 100°C (for steam at atmospheric pressure).

In view of

(a) the great value to Efate of any electrical energy generated from indigenous geothermal resources,

(b) the likelihood of the existence of a geothermal resource in the range 165 to 180°C, if not greater than 200°C,

and

(c) the possibility of exploitation offered by ORC turbogenerators,

it is recommended that geophysical investigations be undertaken with the aim of locating sites for deep exploration boreholes. As indicated in Section 8, the requirements in order of priority are:

(1) an electrical resistivity survey,

(2) an extension of the available measured gravity stations,

and

(3) a survey of the microseismicity.

The aim of the resistivity survey would be to locate areas of anomalously low apparent resistivity, attributable to hot thermally altered rocks at depth rather than to shallow saline intrusion in the coastal areas. A combination of conventional resistivity profiling using the Schlumberger technique, and an audio-magnetotelluric (AMT) survey is recommended. The AMT survey would allow greater depth of investigation in the coastal areas by use of long period natural electromagnetic fluctuations, and an interpretation of the resistivity structure to be made in terms of formation depths. It would also allow the resistivity reconnaissance more readily to cover the difficult inland terrain on Mt MacDonald, Mt Sussunatar, and the Teuma Graben.

The aim of the gravity survey would be to define more precisely the three-dimensional shape of the basaltic intrusions in northern Efate, that are likely to be associated with the heat source, and to investigate the possibility of dyke intrusion along the Teuma Graben.

A survey of the natural microseismicity would be used to investigate whether seismic activity is associated with the movement of thermal fluids along faults. If so, the depth limits of such movement should be estimated, which may indicate more favourable areas for exploration drilling.

A listing of necessary personnel, time and estimated costs for the proposed geophysical surveys of Phase 2 is given in Appendix 3.

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APPENDIX 1

Hydrochemical Studies of the Thermal Springs of Efate

by

A H Bath and R J Marks

APPENDIX 1

Figures

APPENDIX 1

Tables

1. INTRODUCTION

In September 1982 a follow-up visit to the Project Area was made with the following objectives:

(a) to make temperature and flow measurements of Teuma River to estimate thermal inflows;

(b) to make temperature, flow, conductivity measurements at Takara and to establish regular monitoring;

(c) to re-sample Mid- and Upper-Teuma springs at low flow of Teuma River and to establish regular monitoring of one thermal spring in Teuma Graben;

(d) to attempt to evaluate thermal yield of 'hot ground' area near Takara airstrip;

(e) to obtain gas/condensate sample, if possible, from reported vents on Emau Island;

(f) to obtain any further geochemical information which might help to improve the prediction of reservoir temperature.

Estimates of the thermal inflows to the Teuma River are described in Appendix 2 of the main report. A re-definition of the hot ground anomaly at Takara is summarised in the main report. Regular monitoring of the mid-Teuma spring, the Teuma River at Borde's House, the Central and East Takara Springs, and the Takara airstrip and Takara Lodge boreholes has been established: an assessment of the data will be made in a further report as necessary.

This Appendix outlines a more detailed hydrochemical assessment of the thermal springs of Efate than was possible after the preliminary hydrochemical survey (Carney, 1982; Bath et al., 1982).

All sample numbers refer to sites defined in the spring location sketches.

A summary of the geothermometry results from this and previous studies is given in Table 6.

2. REGIONAL HYDROCHEMISTRY

The oxygen and hydrogen isotope compositions of non-thermal springs and seepages are grouped according to their locations on either side of the water divide (Figure 1); thus stable isotope composition distinguishes between precipitation falling in the north (-6.6 to -6.0‰ $\delta^{18}O$ and -37 to -34‰ $\delta^{2}H$) and central/southern (-6.0 to -4.8‰ $\delta^{18}O$ and -35 to -28‰ $\delta^{2}H$) parts of the project area. The north of Efate, to the leeward side of the prevailing south-easterly winds, has a significantly different pattern of rainfall with lower amounts than the south.

The cold springs, seepages and streams have conductivities (EC_{25}) in the narrow range 100-450 µS cm^{-1}, with the limestone springs tending to be slightly more mineralised. They are all Ca-HCO_3 type water with chloride between 10-20 mg/l Cl^- and low sulphate (<7 mg/l). In contrast to these figures, the Teuma River rises to 430 µS cm^{-1} and 57 mg/l Cl^- downstream of the Upper and Mid Teuma thermal springs (Table 1); the significance of this has been discussed in Section 5.2 of the main report. A possible temperature anomaly in the Lukunto River in northern Efate (Carney, 1932) was investigated and found to have been a result of solar warming. A shallow borehole (4.2 m depth) drilled in 1980 into recent reef limestone close to the shore at Onesua (W88) contains slightly salty water with EC_{25} = 1400 µS cm^{-1} and 280 mg/l Cl^-, Table 2; the fresh-water component of this mixture is probably representative of the non-thermal groundwater in the reef limestone of northern Efate.

Dissolved silica concentrations in springs vary widely between 4 and 154 mg/l SiO_2 and there is no obvious dependence upon lithology or flow rate, though the only two measurements above 85 mg/l are both for very low flow springs (W4 & 6) associated with calc-arenite in the Teuma Graben. Cold springs contributing significantly to the Teuma River have SiO_2 between 60-80 mg/l and this is reflected in values for the river itself which are between 64-73 mg/l; there is no significant SiO_2 anomaly in river water associated with the thermal springs (Table 1). The range in background dissolved SiO_2 values corresponds to that between quartz and amorphous silica solubilities; there is no single mineral buffer corresponding to the values found in the non-thermal Teuma springs.

3. TEUMA GRABEN THERMAL SPRINGS

3.1 Lower Teuma.

The springs have measured temperatures between 24.3 and 28.4°C and chloride concentrations between 30 and 1180 mg/l Cl^- (Table 3, Figure 2). There is no direct correlation between temperature and Cl^-, although the warmest tend to have high Cl^-. The spring chemistries seem to fall along mixing series for Na^+, K^+, Mg^{2+} and SO_4^{2-} (Figure 3) which suggests a single source of salinity. The Na/Cl ratio in the saline springs is around 0.54 (cf.0.56 in seawater), but the Mg/Cl ratio is lower than for seawater and the K/Cl ratio is higher (Table 4).

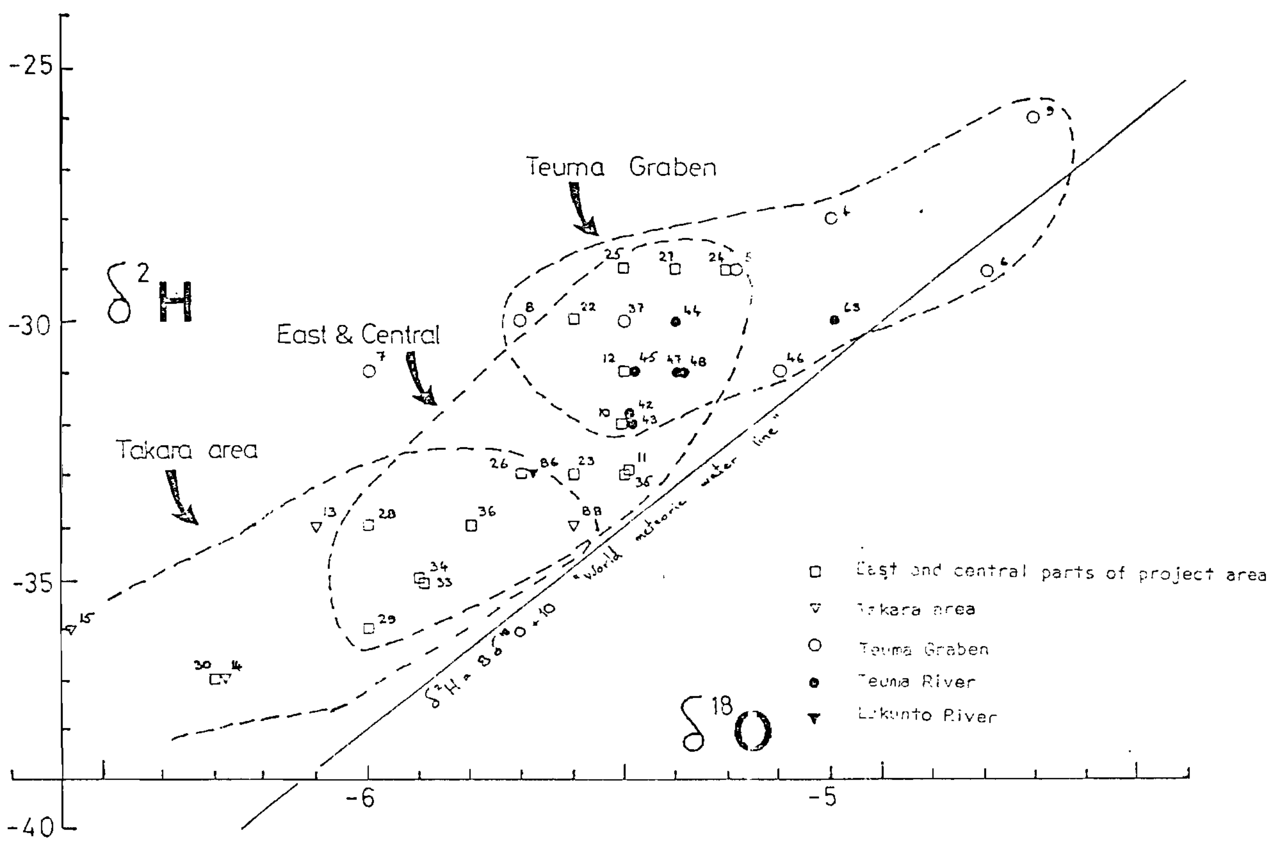
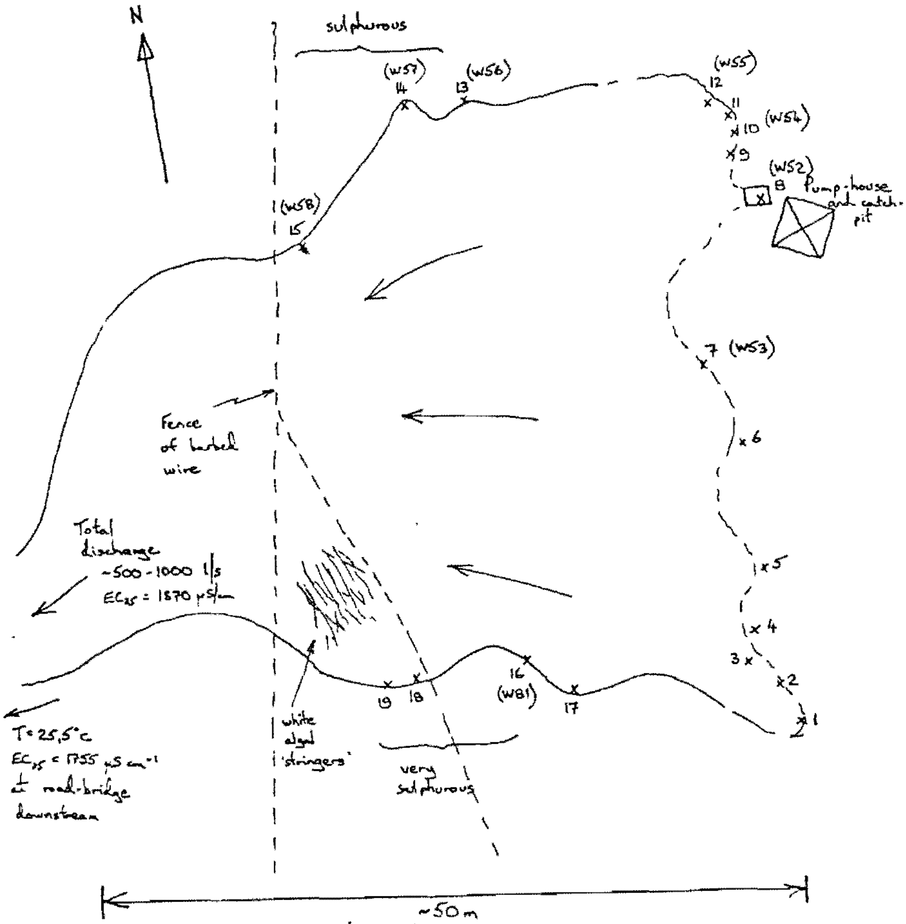


Figure l. Stable Isotope Compositions of Cold Springs, Seepages and Rivers (solid symbols) in Project Area.

Sample	Location	EC25 μScm^{-1}	$T^{o}C$	Na	K	Ca	Mg	HCO_3	SO_4	Cl	Br	B	SiO_2	$\delta^{18}O$	$\delta^{2}H$
				milligrammes per litre										‰ SMOW	
March 1982															
W47	10 km u/s of M.Teuma	271	25.0	12	4.7	39	2.7	144	3	8		<0.02	70.6	-5.4	-31
W48	7 km " " "	264	25.9	13	4.7	40	2.7	156	3	8		<0.02	72.5	-5.4	-31
W45	5 km " " "	250	26.2	13	4.7	37	2.5	122	3	9		<0.02	63.3	-5.5	-31
W44	3 km " " "	342	26.0	22	5.4	44	2.6	144	4	33		0.034	61.8	-5.4	-30
W42	300 m " " "	358	26.0	24	6.1	47	2.8	129	4	37		0.062	67.2	-5.5	-32
W43	4 km d/s of M. Teuma	400	27.1	26	5.9	51	2.8	154	4	41		0.046	61.4	-5.5	-32
September 1982															
W63	u/s of Northern Springs	260	22.4	12	5.1	32	2.4	117	3	8		<0.02	67.8	-5.1	-30
W74	just u/s of U.Teuma	300	24.5	15	5.0	37	2.5	132	3	13		<0.02	63.7		
W67	" " " "	320	22.9	16	5.3	38	2.6		3			0.023	64.6		
W69	just d/s of U. Teuma	370	22.8	21	5.5	42	2.6		3			0.035	64.4		
W75	200 m " " " "	375	24.7	21	5.8	41	2.5	207	3	27		0.039	64.8		
W76	at Bordes	400	24.7	24	5.8	43	2.5	207	3	34		0.042	65.0		
W77	1.5 km d/s of Bordes	400	23.6	24	5.8	44	2.6	146	3	34		0.044	64.2		
W78	300 m u/s of M.Teuma	395	23.5	24	5.7	44	2.6	166	3	34		0.040	64.8		
W72	30 m u/s of M.Teuma	400	24.8	26	6.5	46	2.7	144	3.7	49		0.047			
W80	200 m d/s of M. Teuma	425	24.8	29	6.4	45	2.7	149	3	46		0.054	66.1		
W73	road bridge	430	25.1	28	6.7	48	2.8	130	5	57		0.052			
W73A	" "	430		28	6.5	49	2.9	158	3.6	42		0.056			
Cold seepages/springs into Teuma River.															
W4	Spring	217	23.7	13	8.0	29	2.9	255	3	13		0.040	132	-5.1	-28
W5	Seepage pool	103	25.7	8	6.1	4	2.4	73	5	50		0.038	44.3	-5.3	-29
W6	Spring	205	28.5	12	9.5	20	2.3	129	1	14		0.037	154	-4.8	-29
W7	Spring	446	23.6	11	5.7	83	2.3	295	3	15		0.026	64.0	-6.0	-31
W8	Spring	324	25.7	24	4.6	38	2.7	243	4	28	0.093	0.048	76.8	-5.7	-30
W9	Seepage	494	26.7	17	11.6	64	8.2	288	1	15		0.047	63.7	-4.7	-26
W37	Spring	257	24.8	19	3.4	26	2.7	105	3	8		0.021	85.3	-5.5	-30
W46	Spring	288	23.0	11	4.5	45	1.9	149	3	8		<0.020	60.7	-5.2	-31
W64	Seepage	370	23.0	12	4.9	54	3.7	183	4	8		<0.02	60.5		
W65	Stream	360	19.0	5	0.3	63	1.5	178	3	8		<0.02	4.1		
W66	Seepage	320	22.9	11	4.6	45	1.8	171	3	8		<0.02	58.8		

TABLE 2. Hydrochemistry of Cold Springs, Seepages and Streams in Eastern and Northern Efate.

		EC25 $\mu S cm^{-1}$	$T^{o}C$	Na	K	Ca	Mg	HCO_3	SO_4	Cl	Br^-	B	SiO_2	‰ SMOW $\delta^{18}O$	$\delta^{2}H$
				milligrammes per litre											
Eastern Efate															
W10	Epong R. spring	345	23.6	13	3.7	55	2.9	244	3	14		0.026	48.6	-5.5	-32
W11	" " "	355	23.7	14	3.8	56	3.0	188	3	16	0.068	0.034	62.9	-5.5	-33
W12	Nailep R. spring	350	22.5	7	1.7	65	2.0	188	3	12		<0.02	20.3	-5.5	-31
W22	Epule R. spring	417	24.2	12	3.0	78	3.4	244	5	12	0.076	0.032	42.4	-5.6	-30
W23	Epule R. " (tidal)	1340	24.4	155	7.0	89	22	268	42	256		0.087	60.7	-5.6	-33
W24	Limestone spring	405	22.5	6	<0.6	85	3.1	273	3	10		0.021	9.0	-5.3	-29
Mt. Macdonald-Mt. Putuet area															
W25	Epule R. spring	285	23.0	11	4.0	49	2.2	163	4	10	0.038	0.050	51.1	-5.5	-29
W26	" " "	451	23.0	5	<0.6	99	1.4	280	2	10		<0.02	5.6	-5.7	-33
W27	" " "	187	23.2	12	4.9	23	1.8	90	3	10	0.032	0.020	67.6	-5.4	-29
W28	Malatao R. spring	352	23.0	11	0.9	62	3.1	183	6	20		0.035	20.1	-6.0	-34
W29	" " "	297	21.8	7	0.6	56	1.9	144	4	16	0.058	0.027	8.8	-6.0	-36
W30	" " "	411	22.0	7	<0.6	80	1.9	232	4	12	0.052	<0.02	5.1	-6.3	-37
W33	U. Teuma R. spring	342	23.2	5	<0.6	73	2.0	227	3	8		<0.02	12.4	-5.9	-35
W34	" " " "	300	21.5	7	2.1	61	1.8	197	3	9		<0.02	23.1	-5.9	-35
W35	" " " "	165	22.0	13	9.0	14	2.3	85	3	10		<0.02	81.5	-5.5	-33
W36	" " " "	492	22.8	5	<0.6	102	1.8	280	3	9		<0.02	5.1	-5.8	-34
Northern Efate															
W13	Lukunto R. spring	357	23.1	7	0.9	63	2.8	190	3	10		0.023	22.0	-6.1	-34
W14	Siviri spring	876	~25	66	11.5	69	23	256	22	125		0.101	61.0	-6.3	-37
W15	Lukunlva R. spring	417	22.8	7	0.6	82	2.1	244	3	13	0.049	0.021	6.6	-6.6	-36
W86	Lukunto River	370	19.4	10	1.2	63	3.3	185	4	27		0.025	18.4	-5.7	-33
W88	Onesua borehole	1400		176	5.8	71	19	251	53	280	0.81	0.092	21.1	-5.6	-34



4th Sept/6th Sept 1982

	T°C	EC_{25} µS/cm	Q l/sec	
#1	25.0	735	<0,5	
#2	25.0	745	~1	
#3	24,6	750	~2	
#4	24,4	735	~0.5	
#5	24,0	745	~0.5	
#6	23,8	855	<0.5	
#7	24,1 (24,3)	900 (1010)	?5	WS3
#8	24,8 (25,2)	785 (810)	?3	WS2
#9	24,9	805	?5	
#10	26,3 (25,1)	700 (725)	~1	WS4
#11	25,5	595	~5	
#12	25,7 (26,3)	560 (550)	~2	WS5
#13	26,6 (26,5)	1150 (1150)	~10	WS6
#14	26,5 (27,1)	2810 (3280)	? >10	WS7
#15	28,1	2520	?~4	WS8
#16	(27,2)	(1700)	(~5)	WB1
#17	(26,0)	(1160)	(~10)	
#18	(27,3)	(2400)	(~20)	
#19	(28,0)	(3280)	(~1)	

(measurements on 6/9/82 in brackets)

Figure 2. Sketch Diagram of Lower Teuma Springs showing Locations of Samples and Measurements of Temperature and Conductivity.

TABLE 3. Hydrochemistry of Teuma Graben Thermal Springs.

			EC_{25}							milligrammes per litre						‰ SMOW	
			μScm^{-1}	T^oC	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	Br	B	SiO_2	$\delta^{18}O$	δ^2H
W31	Lower Teuma	3/82	2435	27.2	6.95	638	52	150	38	244	124	1180	4.6	0.55	42.6	-4.8	-26
W32	"	3/82	535	27.2	6.90	32	4.7	74	3.7	244	6	43	0.056	0.16	48.3	-5.4	-33
W55	" #12	9/82	550	26.3	6.90	24	4.7	73	4.2	276	6	30	0.14	0.032	40.2	-5.4	-33
W54	" #10	9/82	725	25.1	6.95	51	4.2	87	4.7	283	9	89		0.052	16.5	-5.5	-33
W52	" # 8	9/82	810	25.2	6.85	60	4.5	90	5.0	239	10	112	0.53	0.054	18.0	-5.5	-33
W53	" # 7	9/82	1010	24.3	6.90	85	7.1	91	7.3	239	15	160	0.49	0.070	18.8	-5.4	-31
W56	" #13	9/82	1150	26.5	6.90	103	11.3	79	9.1	232	20	169	0.50	0.095	47.7	-5.4	-32
W58	" #15	9/82	2570	28.4	6.95	333	28	102	21	207	59	600	1.58	0.32	64.2	-5.0	-28
W81	" #16	9/82	3280	28.0	7.15	416	35	124	24	254	81	781	3.0	0.34	42.4	-4.8	-28
W57	" #14	9/82	3280	27.1	7.00	469	37	115	28	229	91	860	2.8	0.35	52.0	-5.1	-30
W41	Mid Teuma	3/82	3100	54.8	7.25	400	60	84	1.1	75	14	760		0.91	141	-4.9	-29
W70	"	9/82	2000	49.1	7.85	315	50	54	1.0	79	12	588	1.58	0.69	135	-4.7	-26
W71	"	9/82	580	31.7	6.85	90	16.7	31	2.7	112	6	140	0.42	0.20	106	-5.1	-31
W79	"	9/82	1320	28.5	6.95	143	21	95	3.0	193	8	283	0.99	0.38	88	-5.2	-24
W1	d/s of Upper Teuma	2/82	580	31.3	8.85	19	7.9	99	4.4	305	< 0.4	29		0.038	66.1	-4.7	-25
W2	"	2/82	1320	29	6.75	122	8.7	127	3.7	204	6	295		0.33	68.2	-5.3	-29
W3	Upper Teuma	2/82	1820	30.6	6.05	190	23	133	3.6	164	7	465		0.51	114	-5.2	-29
W59	"	9/82	2460	30.9	6.85	273	31	174	3.5	171	9	680	1.70	0.77	80	-5.4	-29
W68	"	9/82	3280	31.9	6.75	305	33	214	3.4	154	10	850	2.2	0.87	88	-5.0	-33
W39	Northern springs (S)	3/82		31.5	6.95	43	3.7	34	2.0	191	5	15		0.133	115	-5.3	-31
W60	"	9/82	390	33.5	7.35	45	3.9	28	1.5	181	4	13		0.083	80	-5.3	-28
W38	Northern springs (N)	3/82	460	35.5	7.95	47	3.2	14	0.4	130	6	25		0.061	118	-5.3	-31
W61	"	9/82	390	35.2	8.50	54	2.9	10	0.4	117	6	28		0.071	99	-5.2	-29
W62	"	9/82	280	31.8	8.10	38	3.0	11	0.5	107	4	14		0.035	91	-5.3	-31

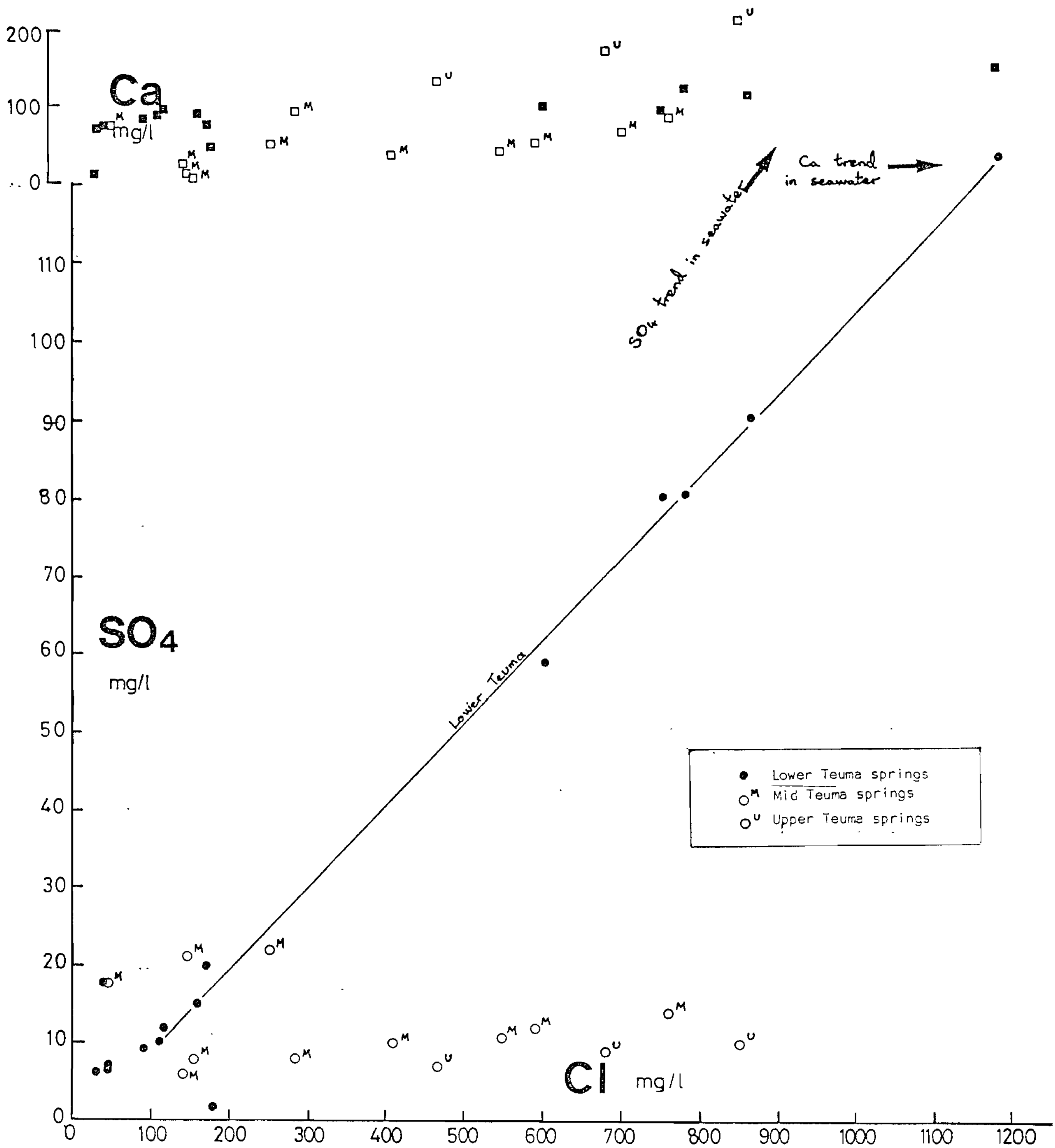


Figure 3a. Ion Concentrations (Ca^{2+}, SO_4^{2-}) versus Chloride in Teuma Graben Springs (including data from previous studies).

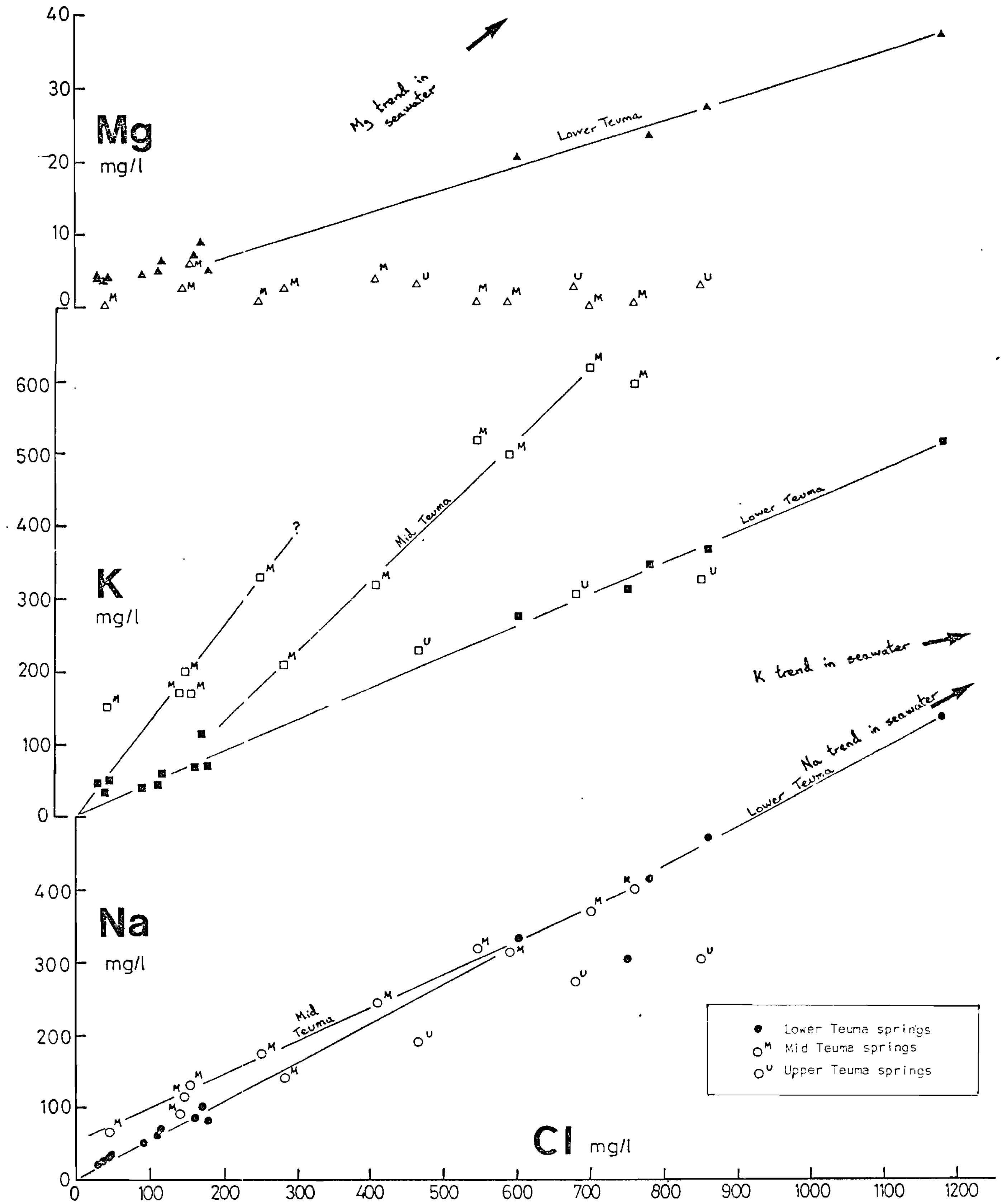


Figure 3b. Ion Concentrations (Mg^{2+}, K^{+}, Na^{+}) versus Chloride in Teuma Graben Springs (including data from previous studies).

TABLE 4. Chemi(of Teuma Graben Thermal Springs.

				T°C 'Cl	Ca/Mg	wt/wt ratios Cl/SO_4	Cl/Br	Cl/B	K/Cl
W31	L. Teuma		3/82	27.2 54	3.95	9.5	257	2145	0.04
W32	"		3/82	27.2 74	20	7.2	270	759	0.11
W55	"	#12	9/82	26.3 80	17.4	5.0	214	938	0.16
W54	"	#10	9/82	25.1.57	18.5	9.9		1712	0.05
W52	"	# 8	9/82	25.2.54	18	11.2	211	2074	0.04
W53	"	# 7	9/82	24.3.53	12.5	10.7	327	2286	0.04
W56	"	#13	9/82	26.5.61	8.7	8.5	338	1779	0.07
W58	"	#15	9/82	28.4.56	4.9	10.2	380	1875	0.05
W81	"	#16	9/82	28.0.53	5.2	9.6	260	2297	0.04
W57	"	#14	9/82	27.1.54	4.1	9.5	307	2457	0.04
W41	Mid Teuma		3/82	54.8.53	76	54		835	0.08
W70	"		9/82	49.1.54	54	49	372	852	0.09
W71	"		9/82	31.7.64	11.5	23	333	700	0.12
W79	"		9/82	28.5.51	31.7	35	286	745	0.08
W1	d/s of Upper Teuma		2/82	31.3.66	22.5	>73		763	0.27
W2	d/s of Upper Teuma		2/82	29 .41	34.3	49		894	0.03
W3	U. Teuma		2/82	30.6.41	37	66		894	0.05
W59	"		9/82	30.9.40	49.7	76	400	883	0.05
W68	"		9/82	31.9.36	63	85	386	977	0.04
W39	Northern Springs (S)		3/82	31.5.89	17	3		115	0.25
W60	Northern Springs (S)		9/82	33.5.46	18.7	3.3		157	0.30
W38	Northern Springs (N)		3/82	35.5.88	35	4.2		410	0.13
W61	Northern Springs (N)		9/82	35.2.93	25	4.7		394	0.10
W62	Northern Springs (N)		9/82	31.8.71	22	3.5		400	0.21

The Cl/Br ratio varies irregularly with salinity and exceeds the value for seawater (Cl/Br = 288) in several cases. Also, the oxygen and hydrogen isotope compositions do not form a regular mixing series against Cl^- (Figure 4). It is concluded that the Lower Teuma springs are not the result of a simple 2-component mixing, but have a complex origin. The chemical and isotopic evidence indicates that seawater alone is not the major source of salinity. It seems that groundwater with many different flow paths and possibly also recharge sources, indicated by $\delta^{18}O$ and $\delta^{2}H$ variations, converges on this location as a point of discharge from the limestone. The presence of some recently-recharged groundwater is indicated by a small but positive amount of thermonuclear (post-1953) tritium in sample W81 (Table 5).

It is not possible to define the sources of salinity although the increased K/Cl and decreased Mg/Cl suggest seawater after reaction with silicates at low temperatures as a possible component. The SiO_2 concentrations are fairly well correlated with temperature (Figure 5) rather than with Cl^- which again indicates that the solutions with different salinities evolved before circulation to depth and are not mixtures of two or more components close to the discharge point. The lowest SiO_2 concentrations at these springs represent equilibrium with chalcedony at discharge temperature but the higher concentrations suggest circulation temperatures up to 80°C if a chalcedony solubility model is applied, and up to 110°C if quartz is assumed to buffer SiO_2 (Table 6). Predicted base temperatures from Na-K-Ca cation geothermometry are of dubious reliability in a predominantly limestone environment with complex mixing.

In summary, it is concluded that the Lower Teuma springs are the convergence of many different flow-paths through the karstic plateau limestone. Some of the deeper and longer flow-paths could have penetrated to underlying pumice and undergone chemical modification particularly of K^+ and Mg^{2+}. The general increase in salinity which is likely to be correlated with depth of circulation may derive from residual marine fluids in the limestone or from similar fluids derived from previous lagoonal conditions and trapped in the alluvium and/or calcarenites of the lower part of the Teuma Graben.

3.2 Mid Teuma.

The Mid Teuma spring (Figure 6) comprises a single outflow at which temperatures up to 61°C have been measured (Lavigne & Marinelli, 1970); 55°C was measured at relatively high flow in March 1982 and 49°C in September 1982 when flow was diminishing - it was only a trickle 4 days after this last measurement. Cooler flows occur in the immediate vicinity and one (W79) was found to persist (∿1 l/s) when the hot spring had virtually ceased to flow. These cooler subsidiary springs must be mixtures dominated by cooler limestone groundwater. There is the added problem that the springs discharge at river level in the loose alluvium, close to apparently 'in-situ' limestone outcrop, and therefore suffer varying degreees of dilution by river water. The low but detectable thermonuclear tritium in W70 (Table 5) probably originates from dilution by river or shallow groundwater.

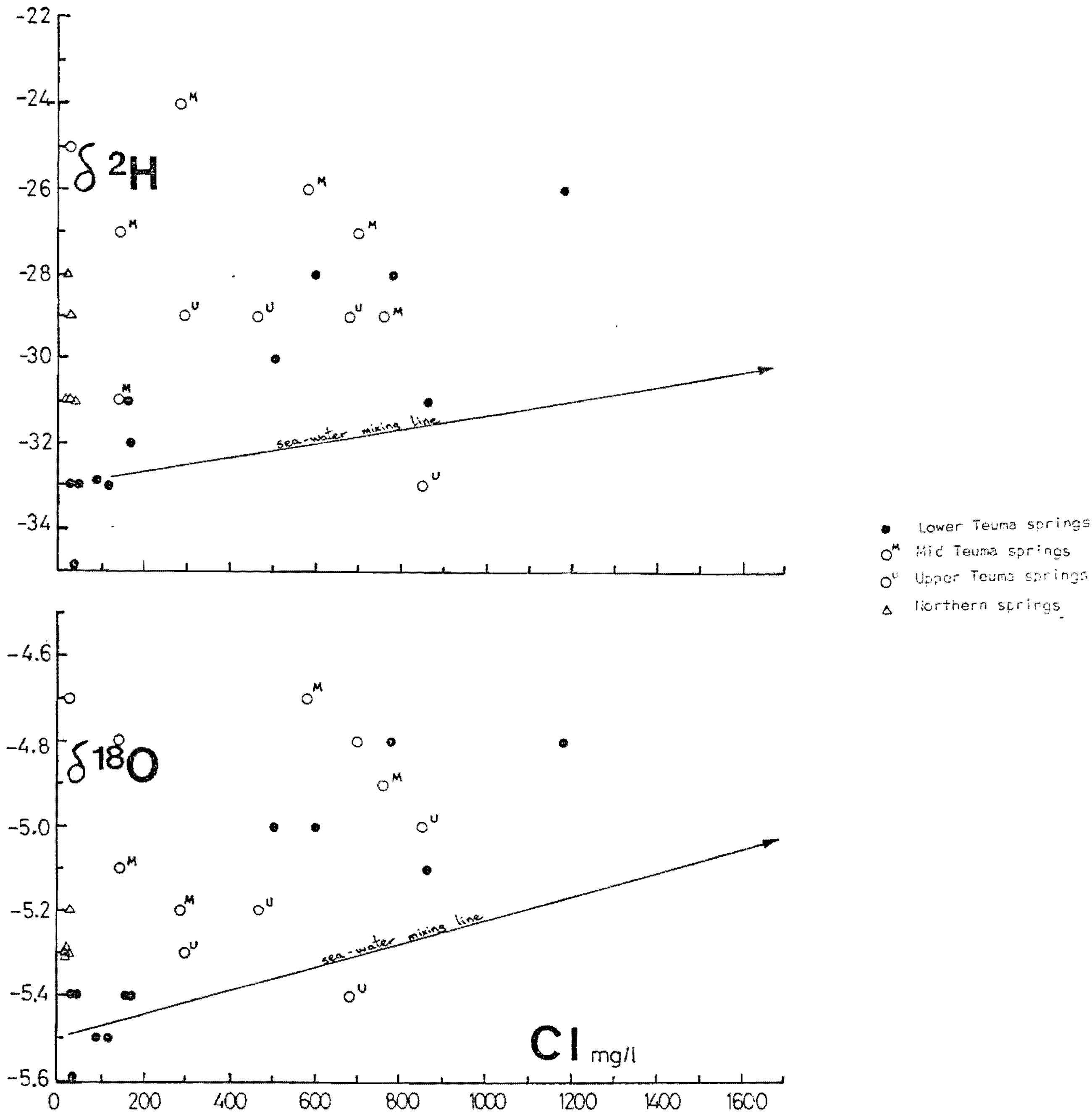


Figure 4. Relationship between Stable Isotope Compositions and Chloride in Teuma Graben Springs.

TABLE 5. Thermonuclear Tritium Analyses of some Teuma Graben Thermal Springs.

No.	Description	TU*
W61	Northern Springs (35.2°C)	5 ± 2
W70	Mid Teuma Spring (49.1°C)	3 ± 2
W81	Lower Teuma Spring #16 (28.0°C)	4 ± 2

* TU is Tritium Unit which is 1 tritium atom in 10^{18} H atoms. (Measurements by AERE Harwell)

(Average TU values in rainfall at the nearest WMO/IAEA monitoring station which is Brisbane, Australia were down to ∿ 10 TU in 1975: the most recent data available).

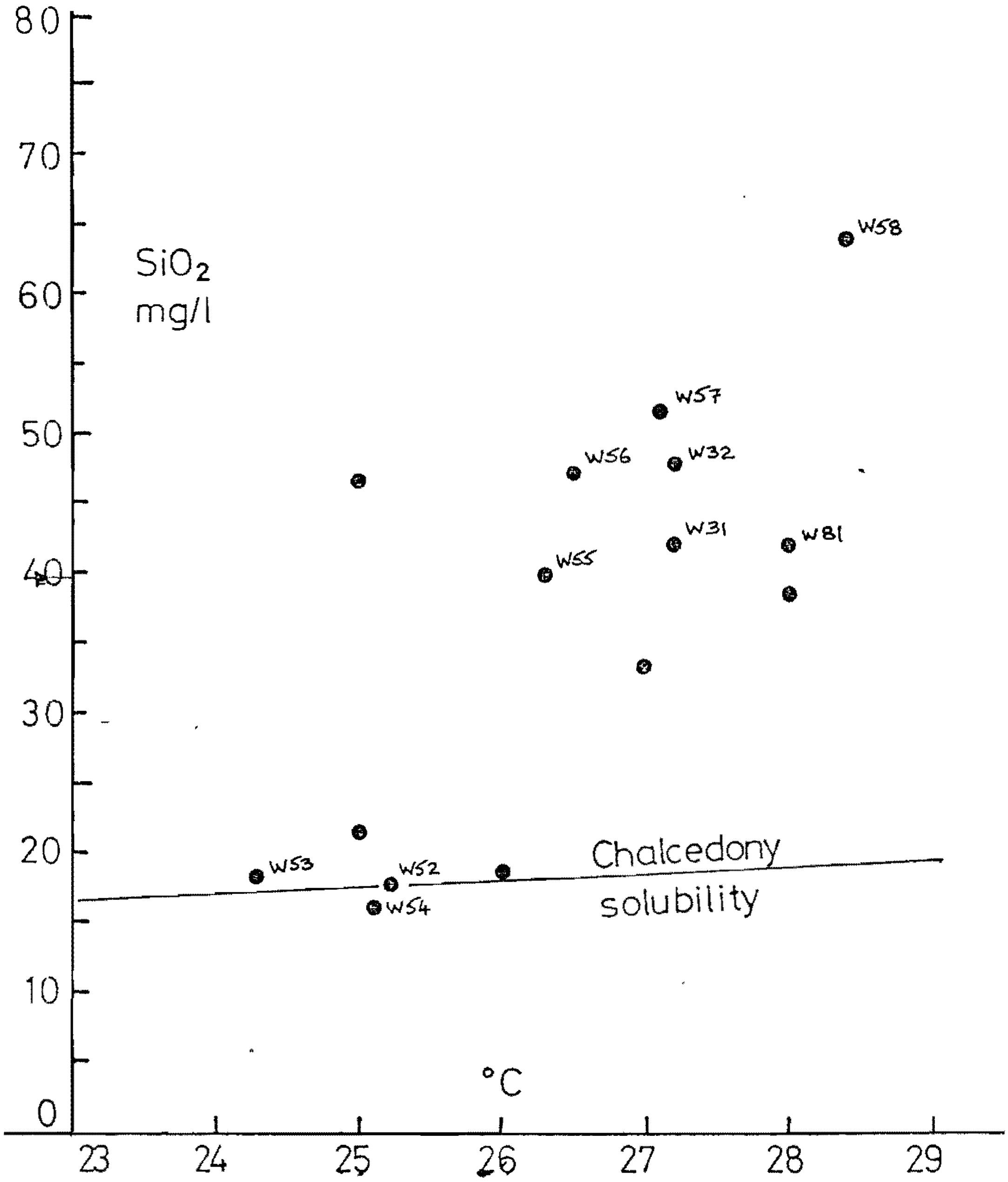


Figure 5. Dissolved Silica versus Temperature for Lower Teuma Springs (data from previous studies included).

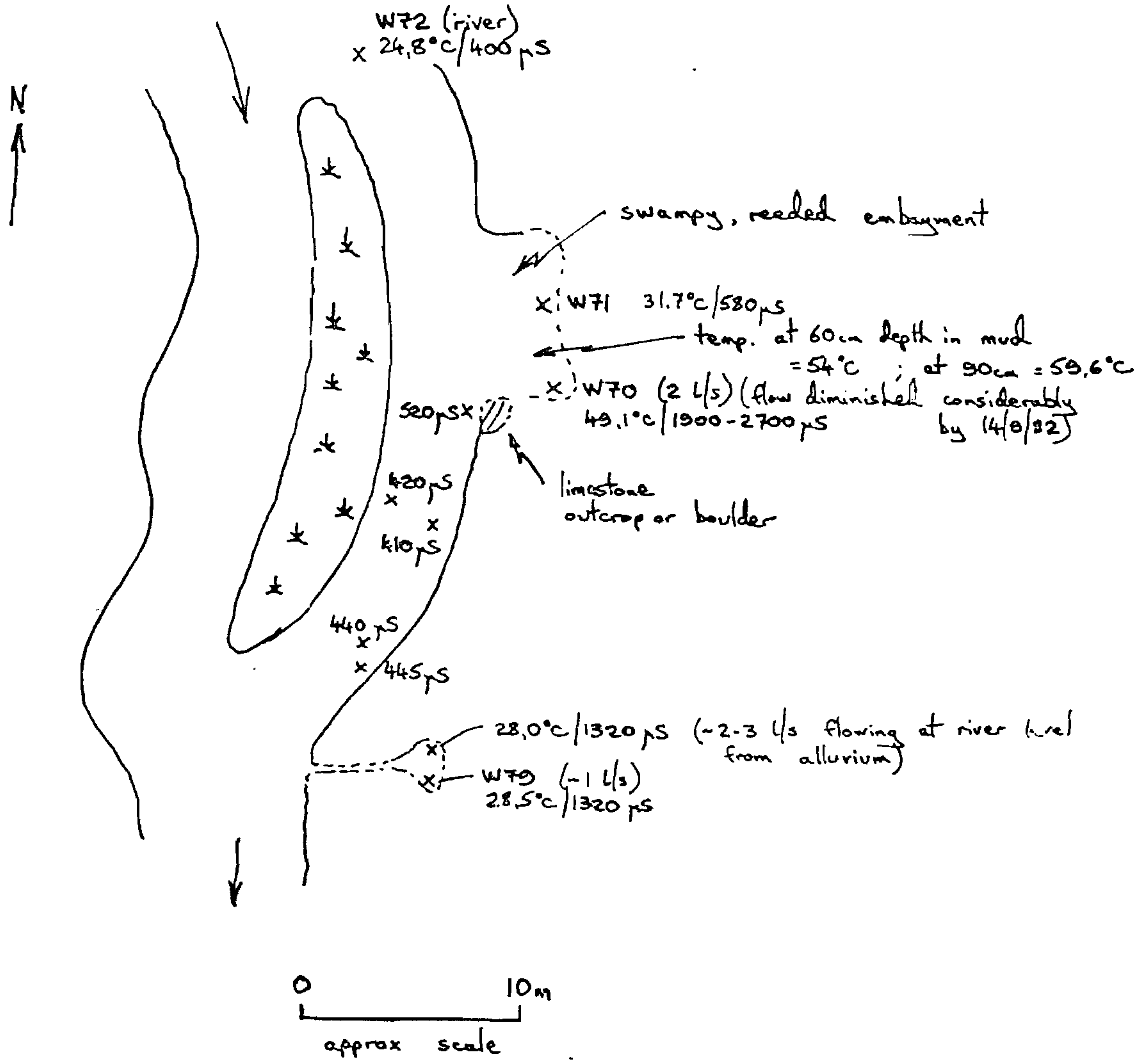


Figure 6. Sketch Diagram of Mid Teuma Springs and Associated River Measurement

The record of temperature observations and chemical analyses by various investigators shows large variation in Cl^- whilst temperature remains around 50°C: this may reflect the difficulty of sampling. Concentrations of Na^+ and K^+ plotted versus chloride show a linear relationship between these data except at low Cl^- (Figure 3); it is possible that a low Cl^- component distinct from river water and with high K^+ is present (e.g. W71, W79). However the anomalously high K^+ found by Giggenbach (1977) is above these K^+ vs Cl^- trends and might be in error.

The Na/Cl ratio (Table 4) is very close to that found at Lower Teuma and the value for seawater, however large depletion of Mg^{2+} and reduction of $SO_4{}^{2-}$ are reflected in very high Ca/Mg and Cl/SO_4 ratios. These depletions and particularly the virtual elimination of Mg are very characteristic of high temperature alteration reactions. The Cl/Br ratios (Table 4) are significantly higher than the seawater value (288), as with values found at Lower Teuma

The $\delta^{18}O$ and δ^2H values for the Mid Teuma spring samples are similar to values found for the more saline samples from the Lower Teuma springs (Table 3). Therefore there is some chemical and stable isotopic evidence for the Mid and Lower Teuma springs having common source water with varying mineralisation, probably due to complex mixing with limestone groundwater. However, in the case of Mid Teuma this source water has clearly been subjected to higher temperatures and is also mixing with shallow alluvium groundwater or river water at the point of discharge. The higher temperatures are indicated by elevated K^+, SiO_2 and B whilst Mg^{2+} and $SO_4{}^{2-}$ are strongly depleted and pH is raised; these are all typical of alteration reactions with silicate minerals.

Some of the samples from this study (W41, 70, 79) and from previous investigations (Lavigne & Marinelli, 1970; Williamson, 1980) show a fairly linear relationship of SiO_2 to Cl^- which is due to the mixing with shallow groundwater or river water (Figure 7). However there are several analyses from previous investigations which do not lie on this trend but are strongly enriched in SiO_2 up to 165 mg/l. In the absence of evidence to the contrary, it must be assumed that a separate source of water with different characteristics to W41 is discharging at this location; W71 may be derived from this and river water. The base temperatures predicted by quartz solubility are 167°C and 155°C respectively for the two high SiO_2 components (Goguel (1977), Giggenbach (1977) and W41). However if it is assumed that the high-SiO_2 spring waters observed are themselves the products of mixing a deeper hot component with cold groundwater then it is possible to estimate the SiO_2 concentration in this deep hot component and thence its temperature. The model applied to this assumes that the deep hot component is buffered by quartz and that, if over 100°C, it has undergone steam loss and adiabatic cooling in addition to mixing with cold water. The graphical estimation (Truesdell and Fournier, 1977) predicts 205°C and 185°C respectively for the two waters (Figure 8). The applicability of this extrapolative method depends on a simple model for spring water evolution, including for instance the absence of any conductive cooling which would lead to an overestimation of temperatures. The elevated K^+ concentrations lead also to high base temperature prediction with the Na-K-Ca geothermometer (Fournier & Truesdell, 1973). If it is assumed again that there are two separate high temperature water

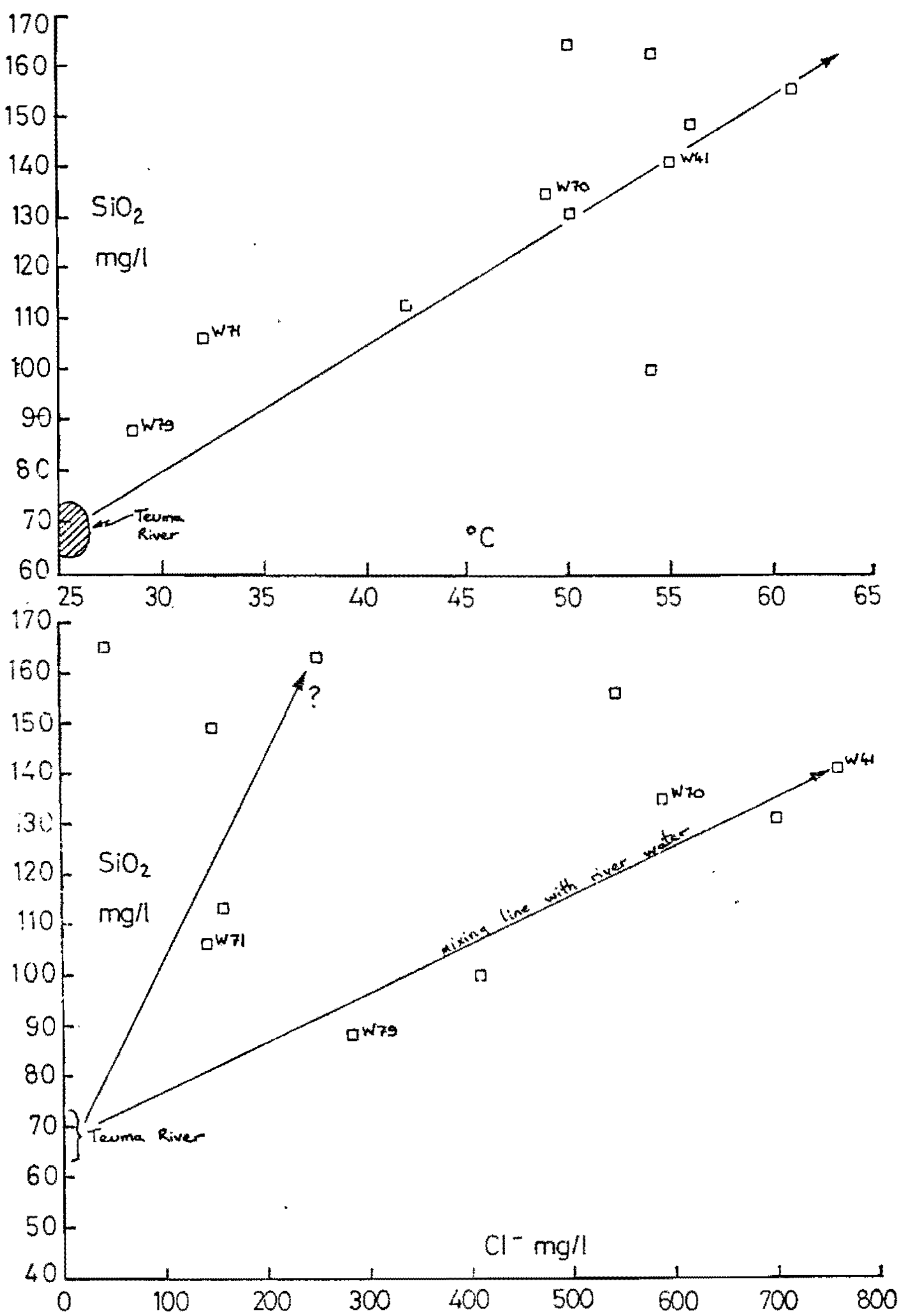


Figure 7. Dissolved Silica versus (a) Temperature and (b) Chloride for Mi Teuma Springs (data from previous studies included).

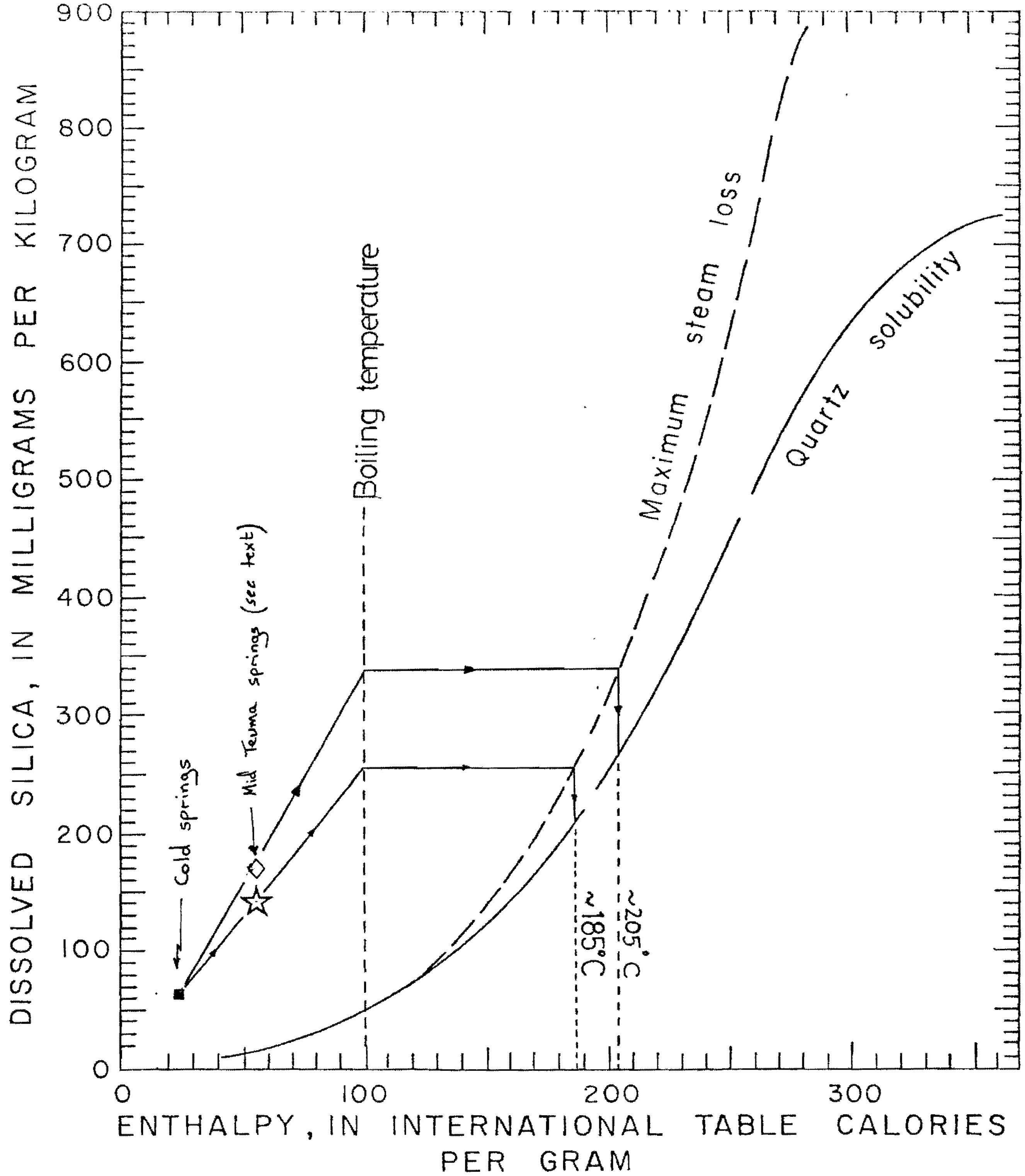


Figure 8. Graphical Estimation of Base Temperature at Mid Teuma from SiO_2 (Quartz) Solubility assuming Dilution due to Mixing with Cold Water before Discharge.

sources represented by data given by Giggenbach (1977), Goguel (1977), and Williamson (1980; NHØ1) and this investigation, then these sources have similar predicted base temperatures in the range 200-215^{o}C (Table 6).

3.3 Upper Teuma.

The Upper Teuma springs comprise an area of seepage on the bank alluvium and in the bed of the Teuma River (Figure 9). The large extent of the overall seepage is demonstrated by the raised mineralisation (Appendix 2) of the river downstream of the area. The temperatures of the seepages are lower than the springs at Mid Teuma although the Cl^- values are similar (Table 3). Ca/Mg, Cl/SO_4, Cl/Br and Cl/B ratios are also similar to the Mid Teuma springs (Table 4) although Na/Cl is significantly lower (∿0.4), suggesting a loss of Na^+. The loss of Na^+ is balanced by higher Ca^{2+} with lower pH. K^+ is not enriched as at Mid Teuma and falls close to the K^+ versus Cl^- trend of the Lower Teuma springs (Figure 3). The $\delta^{18}O$ and δ^2H data are similar to data for both Lower and Mid Teuma springs (Figure 4).

It is concluded that the Upper Teuma seepages have a similar origin to the Mid Teuma springs but have a different flow path which has concluded in movement through fine-grained sediments resulting in the diffuse seepage pattern; this might also account for relative depletion of Na^+ by ion exchange and also raises the possibility of K^+ having been lowered by the same process. A higher original K^+ concentration would be consistent with the very depleted Mg^{2+} and Cl/B similar to conditions at Mid Teuma. Therefore predictive cation geothermometry may give a minimum estimate in this case: the Na-K-Ca geothermometer gives a base temperature estimate of 90-100^{o}C using a value of 4/3 for the β factor and 174^{o}C for β = 1/3 (see Fournier and Truesdell, 1973). SiO_2 concentrations in samples collected in September 1982 (W59,68) are lower than in the more mineralised sample collected in February 1982 (W3; see Table 3); presumably this reflects the difficulty of representative sampling and the probable complexity of mixing before discharge of the spring. It is not possible to apply an extrapolation to correct for cold water mixing since the high SiO_2 concentration coupled with low measured temperature strongly suggests that conductive cooling has already occurred. Therefore minimum temperatures predicted from quartz solubility alone range from 145^{o}C down to 125^{o}C (Table 6).

3.4 Northern Springs.

These two groups of seepages (Figure 10), upstream of the Upper Teuma springs, were reported by Carney (1982). Although separated by about 1 km and discharging on opposite banks of the river, they have similar characteristics and will be described together.

Measured temperatures range up to 35.5^{o}C and conductivities up to 460 $\mu S\ cm^{-1}$ (EC_{25}). Chloride concentrations reach 28 mg/l at the northern group. Na/Cl ratios are between 1.8 and 3.5 and are therefore considerably enriched in Na relative to Na/Cl in the other springs or in seawater. The pH values are relatively high, particularly those of the northern group (W61, 62; Table 3) which are >8, whilst HCO_3^- concentrations are fairly low (115 mg/l).

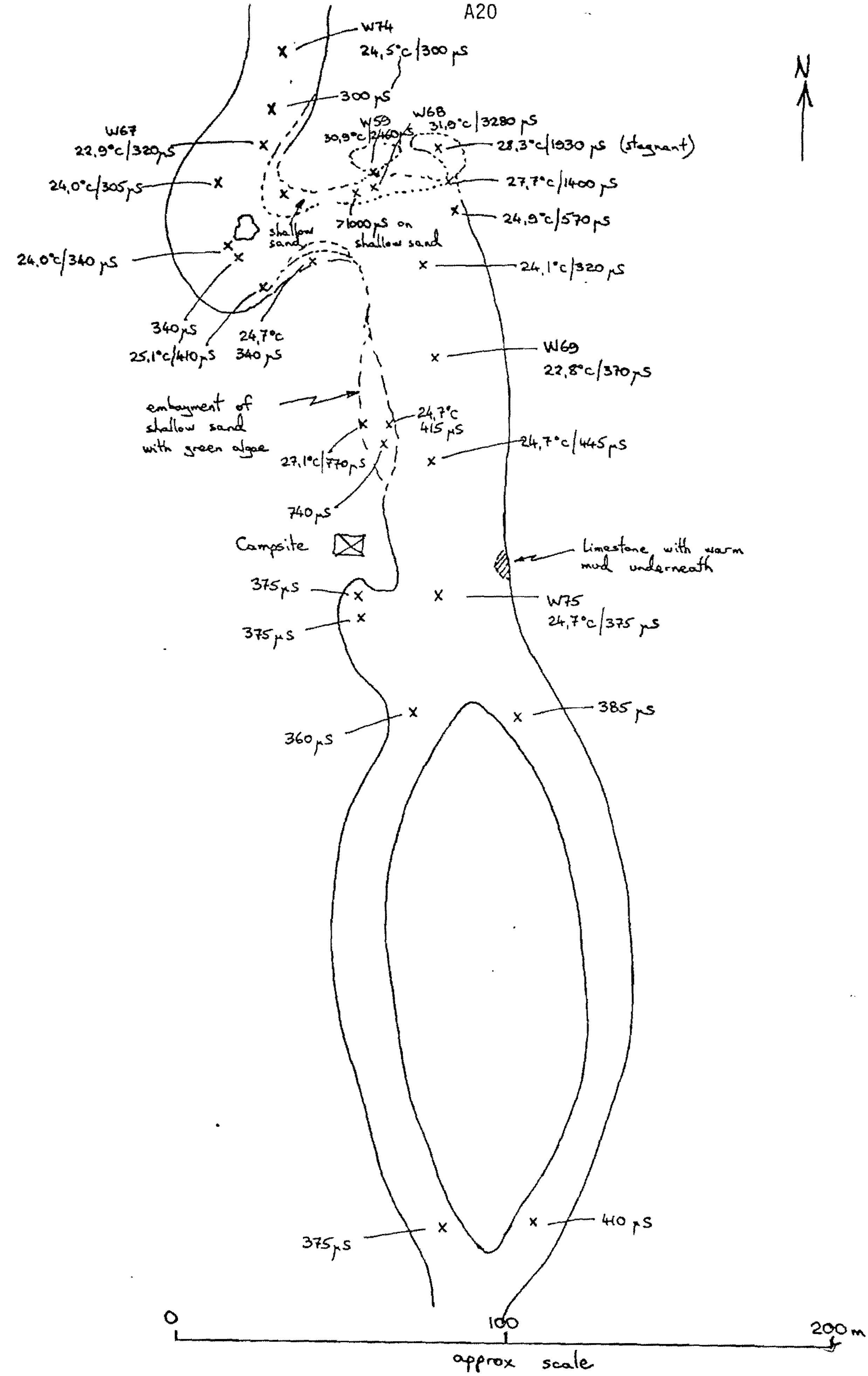


Figure 9. Sketch Diagram of Upper Teuma Springs and Associated River Measurements of Conductivity and Temperature (data collected on 10th, 13th and 14th Sept., 1982).

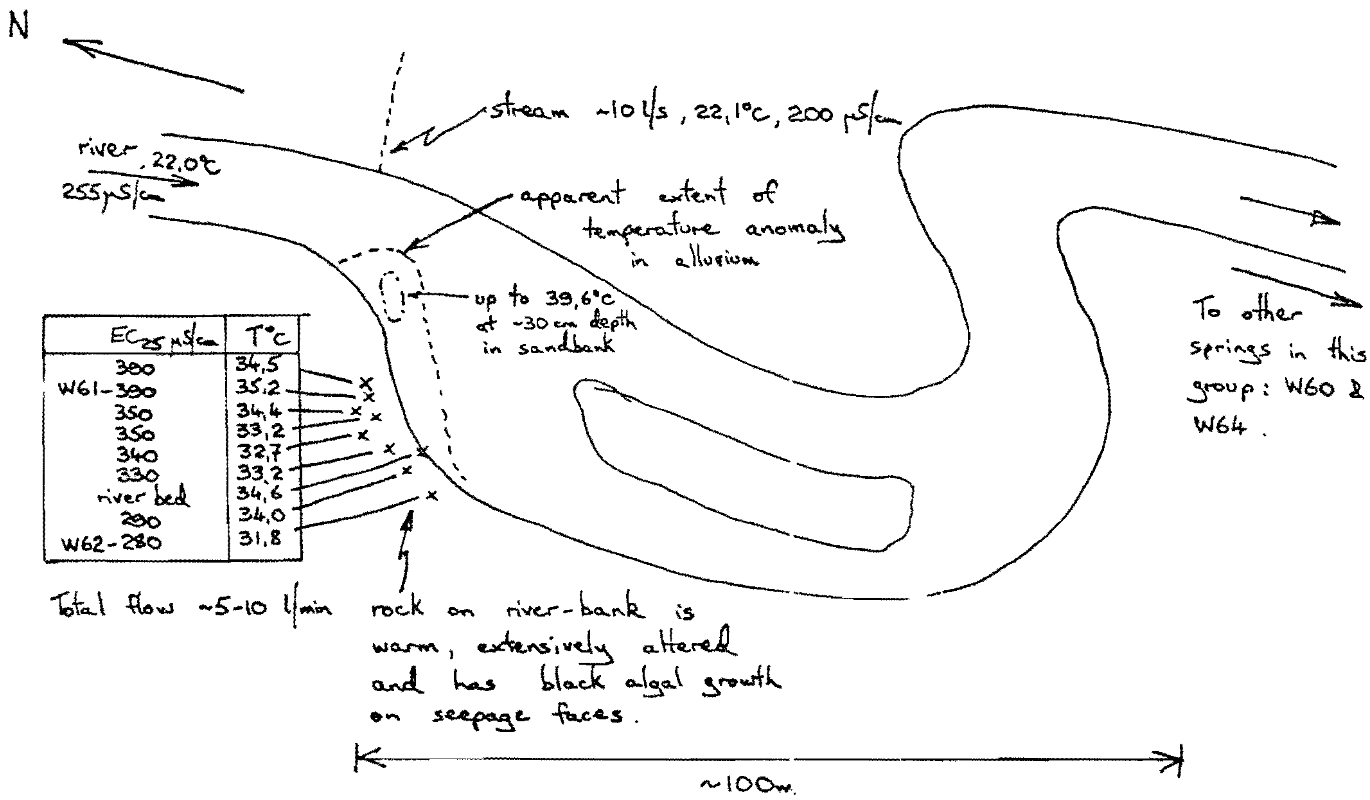


Figure 10. Sketch Diagram of Locations of some of the Northern Springs in the Teuma Graben.

These hydrochemistries are typical of water which has circulated in basaltic lithologies and reacted with silicate minerals taking mostly Na^+ into solution. There is no evidence for reaction with limestone, and the slight enhancement in Cl^- over concentrations found in cold springs might be due to leaching of traces of residual Cl^- in the volcanic rocks.

$\delta^{18}O$ and δ^2H values are around -5.3‰ and -31‰ respectively which are slightly heavier than values for the low-Cl^- springs at Lower Teuma (Figure 4): this lends support to the suggestion that the isotopically-heavier, high Cl^- spring-waters at Lower Teuma might be derived from recharge in the centre of Efate followed by deep circulation. The SiO_2 concentrations, 80-118 mg/l, are similar to values at Upper Teuma, but it is possible that in this case they result from the inferred silicate alteration reactions rather than being buffered by quartz. Quartz buffering of these concentrations would imply deep temperatures up to 145°C, which is unlikely since Na-K-Ca geothermometry suggests a maximum temperature of only 65°C (Table 6). It is concluded that these seepages are not related to the deeper circulation responsible for the three larger groups of Teuma Graben springs.

3.5 Summary.

The Lower, Middle and Upper Teuma springs have similar characteristics which suggest they have a common source. However, important differences are also demonstrated which reflect the different extents of reaction and deep circulation.

The large flow at lower Teuma is inferred to represent a discharge of southwards and westwards regional flow in plateau limestone where the karstic flow paths are intersected by the graben boundary fault bringing fine-grained sediments adjacent to the limestone.

The springs at Middle and Upper Teuma are assumed to comprise predominantly the same water source which has circulated to greater depths, in the case of the Middle Teuma spring having probably penetrated underlying silicate lithologies (? basalt, pumice) and reacted at temperatures up to 200-215°C.

The Upper Teuma spring indicates temperatures up to only 100-150°C by chemical geothermometry although shallow modifications of the seepage water may be masking evidence of conditions similar to the Middle Teuma spring.

4. TAKARA AREA THERMAL SPRINGS

4.1 Takara.

Hot groundwater occurs at shallow depths in the reef limestone aquifer over an area of at least 4 km^2 at Takara. Evidence for this lies in the discharge of thermal springs at the intersection of water-table and general surface parallel to the coast; there is also thermal groundwater at ~3 m depth in a borehole on the Takara airfield and hot ground temperatures, reaching maximum ~100°C in the shallow subsurface, occur over a large part of this area (see section 5.3 of the main report).

TABLE 6. Summary of the Geothermometry Results.

	Ref.	T (^oC)	Cl (mg/l)	SiO_2 (mg/l)	Geothermometers*				
					T_{chalc}	T_{qtz}	$T_{Na-K-Ca}$ β 3/4	β 1/3	$T_{Mg-corr}$
Lower Teuma	W31	27.2	1180	42.6	62	95	137	175	65
	W32	27.2	43	48.3	68	100	38	160	-
	W55	26.3	30	40.2	60	92	36	170	-
	W54	25.1	89	16.5	22	57	37	139	-
	W52	25.2	112	18.0	25	60	39	137	-
	W53	24.3	160	18.8	27	61	54	147	-
	W56	26.5	169	47.7	68	100	73	165	-
	W58	28.4	600	64.2	83	114	113	169	76
	W81	28.0	781	42.4	62	94	119	171	80
	W57	27.1	860	52.0	72	104	125	170	67
Mid Teuma	W41	54.8	760	141	135	157	154	206	206
	W70	49.1	588	135	129	154	156	209	208
	W71	31.7	140	106	113	140	107	199	144
	W79	28.5	283	88	101	130	94	185	-
	WG**	54	250	163	142	166	130	209	203
	RG**	50	41	165	143	167	142	218	218
	W**	50	146	131	127	153	161	214	-
Upper Teuma	W3	30.6	465	114	118	145	92	175	175
	W59	30.9	680	80	96	125	101	176	176
	W68	31.9	850	88	101	130	99	174	174
Northern Springs (S)	W39	31.5	15	115	118	145	48	146	-
	W60	33.5	13	80	96	125	54	148	-
Northern Springs (N)	W38	35.5	25	118	120	147	62	143	-
	W61	35.2	28	99	109	137	66	137	-
	W62	31.8	14	91	103	132	63	149	-
West Takara	W17	40.8	3400	50.1	71	102	120	156	138
Central Takara†	W18	60	7000	75.7	93	123	134	159	157
	W50	60.5	9960	87.5	102	131	145	160	158
	W82	59.2	9950	92.6	105	134	145	161	159
East Takara	W19	70	11900	117	121	147	152	162	162
	W51	71.4	11170	112	118	145	151	164	164
Takara Beach	W20	41.2	8900	78.3	95	125	148	158	109
	W83	41.2	12280	58.8	80	111	177	160	44
Takara Pool	W21	39	11800	114	119	146	153	163	161
Takara Borehole	W87	88.1	14000	129	127	153	152	164	161
Siviri	W16	31.5	5000	53.9	74	106	205	167	-
	W49	30.2	3976	54.5	75	106	197	170	-
Emau	W40	38.8	13800	43.8	65	97	222	168	-
	W85	36.6	13410	46	52	85	238	169	-

* Geothermometry formulae of Truesdell (1975), Mg correction of Fournier & Potter (1979). See text for discussion of applicability.

† 'Takara West' of previous authors.

** WG : Giggenbach (1977) ** RG : Goguel (1977) ** W : Williamson (1980)

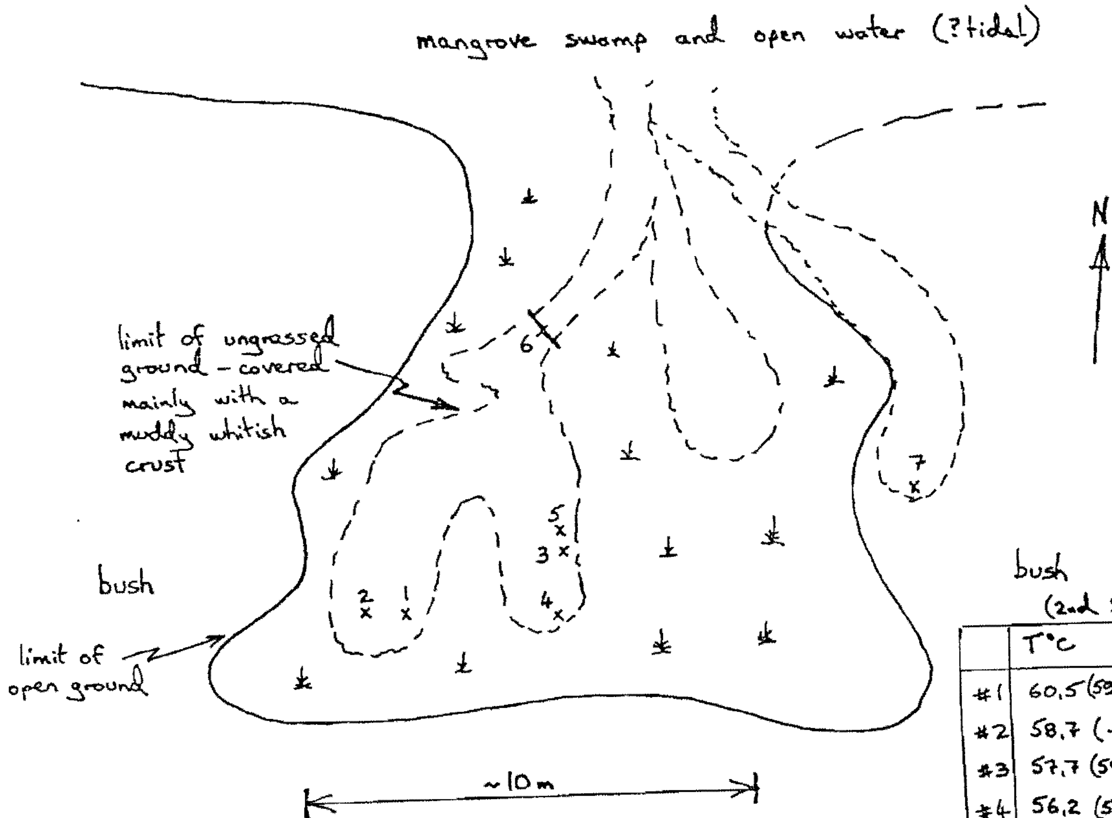
The spring line caused by discharge of this thermal groundwater has several foci which discharge perennially or almost perennially and have been described and sampled by several investigators. However it is clear that the discharge rates of these springs vary widely in response to seasonal rainfall which suggests either a direct component of infiltration water or an influence due to hydraulic loading up-gradient of the thermal groundwater. The major springs (Central and East Takara) occur several hundred metres apart (Figure 4 of main report) and temperatures up to 60°C and 71.4°C respectively were measured in 1982 (Table 7) though previously temperatures up to 63°C and 78°C have been reported. At each location, there are many dispersed points of discharge from alluvium overlying the limestone, having different temperatures and conductivities (Figures 11, 12): this may account for some variation in measurements reported by previous investigators (Table 6). The same flow at Central Takara gave identical chemical results when sampled over two weeks in September 1982 although the flow rate had diminished considerably (W50 and W82, Table 7). Greenbaum (1973) monitored this spring over almost a year during which flow varied threefold and temperature varied between 57°C and 63.5°C. There appears to be a loose correlation between flow rate and temperature and conductivity data at Central Takara. The East Takara springs occur over a smaller area and had virtually dried up on the second visit in September 1982. The chemical composition of this spring has remained remarkably constant since at least 1977 (Table 6), although temperature and flow rate are known to vary together (Greenbaum, 1973). Similarly, the higher temperature at East Takara is reflected in higher EC_{25} than at Central Takara.

A cooler, less saline flow was sampled west of Central Takara in February 1982 but by September this had ceased to flow (W17). Seepages occur along the shore in the north-east corner of the area, particularly at Takara Landing (Figure 13) at which the seepages occur in the inter-tidal zone and are therefore likely to be sea-water contaminated (W20,83). Further evidence of the distribution of the thermal groundwater under water-table conditions is the pool at the east end of the airfield (W21), which had mostly drained and was cool and stagnant in September 1982. Also, there is a 19 m deep borehole, drilled in 1980, just south of the airfield, in which water at 88°C was sampled from a water table at $\sim$3 m (W87). As expected from its high temperature this groundwater has the highest mineralisation of samples collected (Table 7).

The $\delta^{18}O$ and $\delta^{2}H$ values for the Takara samples are roughly colinear when plotted versus Cl^-, and the curves extrapolated through them from the fresh water isotopic composition for this area intersect the marine Cl^- concentration close to 0‰ in both cases (Figure 14). This is convincing evidence that sea-water is the thermal fluid. However, the chemical compositions of West, Central and East Takara springs when extrapolated to marine Cl^- concentration suggest a chemical composition different from that of sea-water: Mg^{2+} is heavily depleted, Ca^{2+} is enriched, Na^+ is slightly depleted, and SO_4^{2-} is also strongly depleted (Figure 15). These chemical alterations are very typical of sea-water which has reacted with basalt at elevated temperature.

TABLE 7. Hydrochemistry of Takara & Emau Thermal Springs.

			EC_{25} µScm^{-1}	T°C	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	Br	B	SiO_2	$\delta^{18}O$	δ^2H
						milligrammes per litre										‰ SMOW	
W16	Siviri	2/82	16680	31.5	7.30	2740	118	148	324	287	649	5000	19.5	1.3	53.9	-5.1	-31
W49	"	9/82	11000	30.2	7.20	2300	110	150	260	288	565	3976		1.2	54.5	-5.0	-29
W17	West Takara	2/82	10200	40.8	7.05	1330	74	669	36	120	89	3400		2.4	50.1	-5.0	-29
W18	Central Takara	2/82	22600	60	6.70	2650	144	1570	34	64	137	7000	22.5	5.5	75.7	-4.5	-25
W50	"	9/82	25100	60.5	6.25	3810	200	2140	53	63	195	9960	25	7.4	87.5	-3.0	-19
W82	"	9/82	31700	59.2	6.40	3820	202	2160	53	71	195	9950		7.5	92.6	-3.1	-20
W19	East Takara	2/82	34600	70	6.85	4790	247	2670	43	46	199	11900		9.5	117	-2.9	-13
W51	"	9/82		71.4	6.40	4420	243	2560	39	42	228	11170	32	8.9	112	-2.5	-12
W20	Takara beach	2/82	25700	41.2	7.15	3810	183	1710	180	82	382	8900		6.05	78.3	-3.1	-20
W83	"	9/82	40800	41.2	6.85	5990	250	1440	493	78	1050	12280	34	6.1	58.8	-2.0	-14
W21	Takara pool	2/82	32000	39	8.35	4670	250	2540	60	62	223	11800		9.1	114	-0.4	-11
W87	Takara b/h	9/82	39000	88.1		4910	272	3080	14.6	29	194	14000	38	10.2	129	-2.3	-13
W40	Emau beach	3/82	37000	38.8	7.75	7020	283	592	777	95	161	13800		3.6	43.8	-1.6	-12
W85	"	9/82	43000	36.6		7510	299	644	860	85	1740	13410	34	4.2	46	-1.4	-11
SEA WATER (Average)					8.2	11020	408	422	1320	145	2775	19800	69	4.6	4.4	0	0
W85	"Sea" at Emau	9/82	49000	31.6		6920	358	616	1050	107	2140	15780	57	4.6	33.2	-0.6	- 4



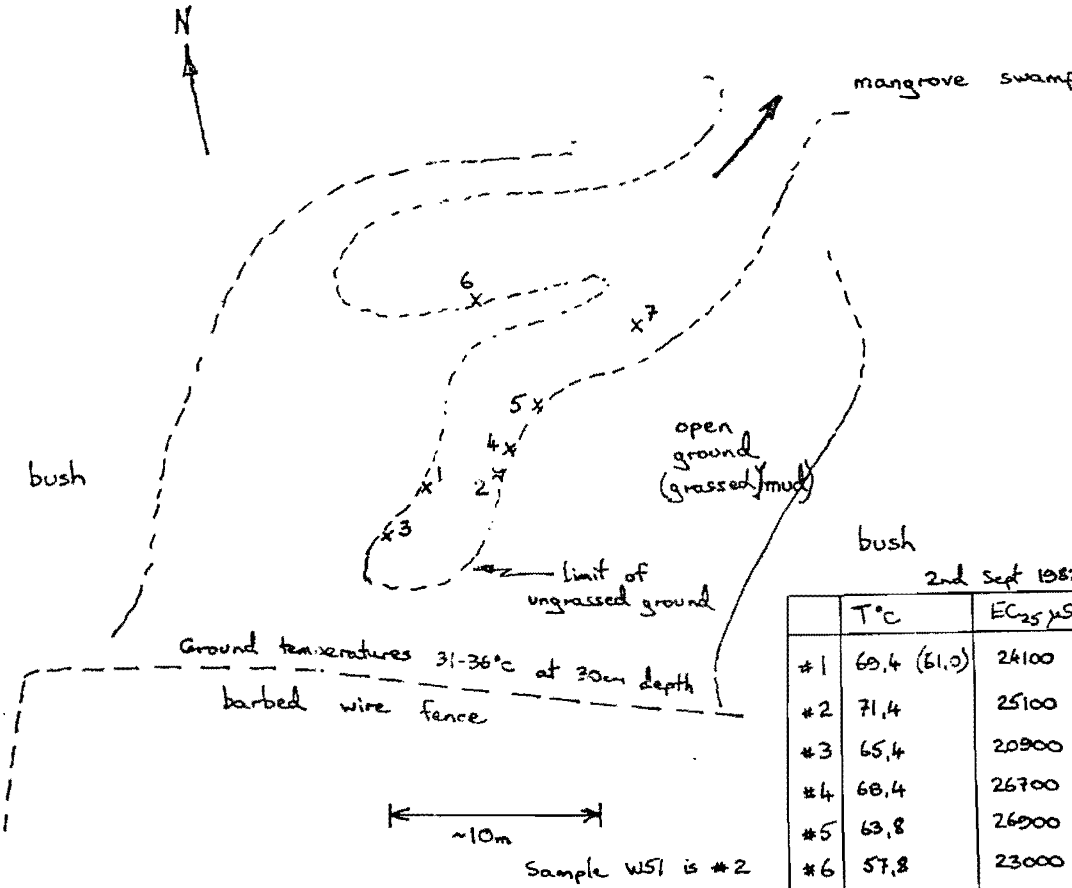
(2nd Sept 1982/16th Sept 1982)

	T°C	EC_{25} µS/cm	Q l/min
#1	60,5 (59,2)	25100 (31700)	20 (v. low)
#2	58,7 (-)	24100 (-)	
#3	57,7 (58,4)	24700 (31000)	
#4	56,2 (55,5)	19700 (32000)	20 (low)
#5	58,2 (58,4)	25600 (31000)	
total discharge → #6	56,5	25100	~40
#7	- (50,3)	(33500)	(v. low)

(measurements on 16/9/82 in brackets)

Samples W50 & W82 are #1

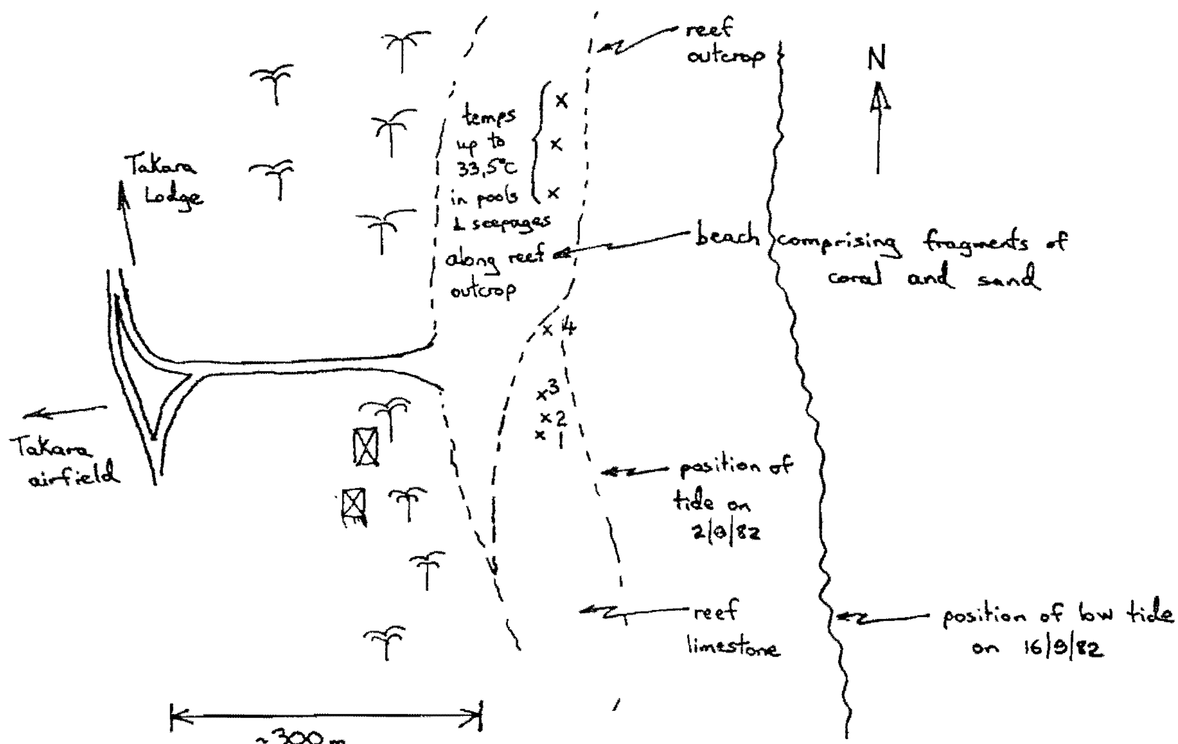
Figure 11. Sketch Diagram of Central Takara Thermal Spring Area (referred to by previous authors as Western Takara) showing Locations of Temperature and Conductivity Measurements.



2nd Sept 1982/16th Sept 1982

	T°c	EC_{25} µS/cm	Q l/min
#1	69.4 (61.0)	24100 (28900)	~1-2 (stagnant, on 16/9/82)
#2	71.4	25100	
#3	65.4	20900	
#4	68.4	26700	
#5	63.8	26900	
#6	57.8	23000	
#7	65.9	27800	

Figure 12. Sketch Diagram of East Takara Thermal Springs Area showing Locations of Temperature and Conductivity Measurements.



2nd Sept 1982 | 16th Sept 1982

	T°C	EC_{25} µS/cm	Q l/min
#1	32,7	30000	
#2	36,0 (36-37)	29000 (38400)	? < 1
#3	38,7	27100	
#4.	(41,2)	(40800)	

(measurements on 16/9/82 in brackets)
Sample W83 is #4

Figure 13. Sketch Diagram of Takara Beach showing Locations of Warm Seepages.

The Cl/Br ratio in these thermal waters (Table 8) is also higher than th of normal sea-water (Figure 16) which demonstrates that Cl^- enrichment or Br^- depletion or both is occurring. A plot of $\delta^{18}O$ and δ^2H versus Br^- suggests that this might be depleted (Figure 17) but the evidence is not conclusive, particularly since the borehole sample (W87) plots on the right of the $\delta^{18}O$ and δ^2H versus Cl^- trends in Figure 14. Cl^- enrichment, which could result from leaching of young basalts, would affect the validity of the extrapolation of cation concentrations in Figure 15: it is noteworthy that K^+ and Na^+ concentrations for the Takara borehole sample (W87) plot just below the Takara springs trend. A possible explanation is that the Takara springs samples are mixtures of 3 components: altered thermal sea-water, normal sea-water and fresh water, whereas the borehole sample comprises only the thermal fluid and fresh water. Certainly the minimum Mg^{2+} found in W87 suggests that this is the least contaminated and most representative sample of thermal fluid.

Na-K-Ca geothermometry predicts a base temperature of 165°C from W87 (Table 6), and the extrapolated composition corresponding to marine Cl^- (Figure 15) also leads to a prediction of ∿165°C; the question as to the absolute concentrations in the reservoir has little influence since the Na-K-Ca geothermometer is sensitive to the ratios Na/K and Na/Ca. SiO_2 concentrations also correlate roughly with Cl^- (Figure 18); since SiO_2 in cold sea water is very low, this gives an estimate of contamination in the shoreline springs (e.g. W20 & W83). Central Takara samples might be contaminated in September 1982 (W50 & 82) unlike February 1982 (W18). The SiO_2 versus Cl^- line intersects marine Cl^- at approximately 180 mg/l SiO_2 which corresponds to a base temperature of ∿174°C on the quartz solubility model. This is considered the best estimate of base temperature using the silica geothermometer. The Takara borehole sample, which contains 129 mg/l SiO_2 suggests a base temperature of 152°C on the basis of quartz solubility alone, and this is not appreciably affected by applying the dilution-mixing model and extrapolating to unmixed component after allowing for steam loss.

4.2 Siviri.

The seepages on the shore at Siviri (Figure 19) have relatively high Mg^{2+} (Figure 15) and marine Na/Cl (Table 8) and thus do not belong to the same mixing series as that forming the thermal groundwater at Takara. The absence of Mg^{2+} depletion suggests that these springs are a mixture between unreacted sea water and fresh water with ∿60-70 mg/l SiO_2 (see Figure 18); it is not possible to tell whether mixing has occurred before or after circulation, though the latter seems most probable.

4.3 Emau.

The seepage in the inter-tidal zone in Emau Island has a component which is slightly depleted in Na^+ and Mg^{2+} and strongly depleted in SO_4^{2-}, demonstrated by the sample taken in March 1982 (W40; Table 8). The sample taken in September 1982 (W84) is mixed with unreacted sea water although the temperature was only slightly lower than previously. A warm fresh water component for this flow is inferred; the SiO_2 concentration of this component could

TABLE 8. Chemical Features of Takara & Emau Thermal Springs.

			T^oC	Cl^- mg/l	Na/Cl	Ca/Mg	Cl/SO_4	Cl/Br	Cl/B	K/Cl
					wt/wt ratios					
W16	Siviri	2/82	31.5	5000	0.55	0.46	7.7	256	3846	0.02
W49	"	9/82	30.2	3976	0.58	0.58	7.04		3313	0.03
W17	W. Takara	2/82	40.8	3400	0.39	18.6	38		1417	0.02
W18	C. Takara	2/82	60	7000	0.38	46	51	311	1275	0.02
W50	"	9/82	60.5	9961	0.38	40.4	51.1	398	1346	0.02
W82	"	9/82	59.2	9950	0.38	40.8	51.0		1330	0.02
W19	E. Takara	2/82	70	11900	0.40	62	60		1253	0.02
W51	"	9/82	71.4	11170	0.40	65.6	49	349	1255	0.02
W20	Takara beach	2/82	41.2	8900	0.43	9.5	23		1471	0.02
W83	"	9/82	41.2	12280	0.49	2.9	11.7	361	2020	0.02
W21	Takara pool	2/82	39	11800	0.40	42	53		1301	0.02
W87	Takara b/h	9/82	88.1	14000	0.35	211	72	368	1373	0.02
W40	Emau beach	3/82	38.8	13800	0.51	0.76	86		3833	0.02
W84	"	9/82	36.6	13410	0.56	0.75	7.7	394	3170	0.02
SEA WATER				19500	0.56	0.32	7.1	288	4349	0.02
W85	"Sea" at Emau	9/82	31.6	15780	0.57	0.59	7.4	277	3460	0.02

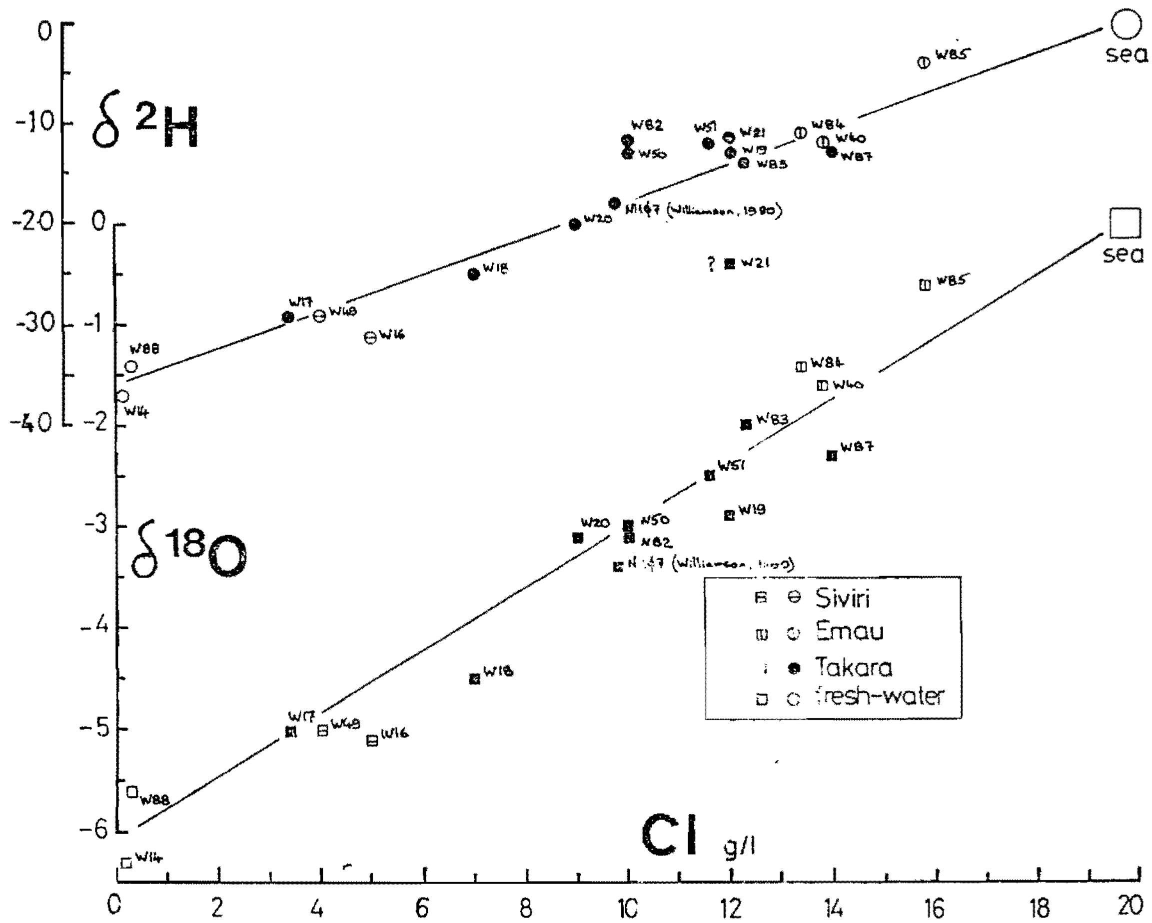


Figure 14. Relationship between Stable Isotope Compositions and Chloride in Takara Area Springs.

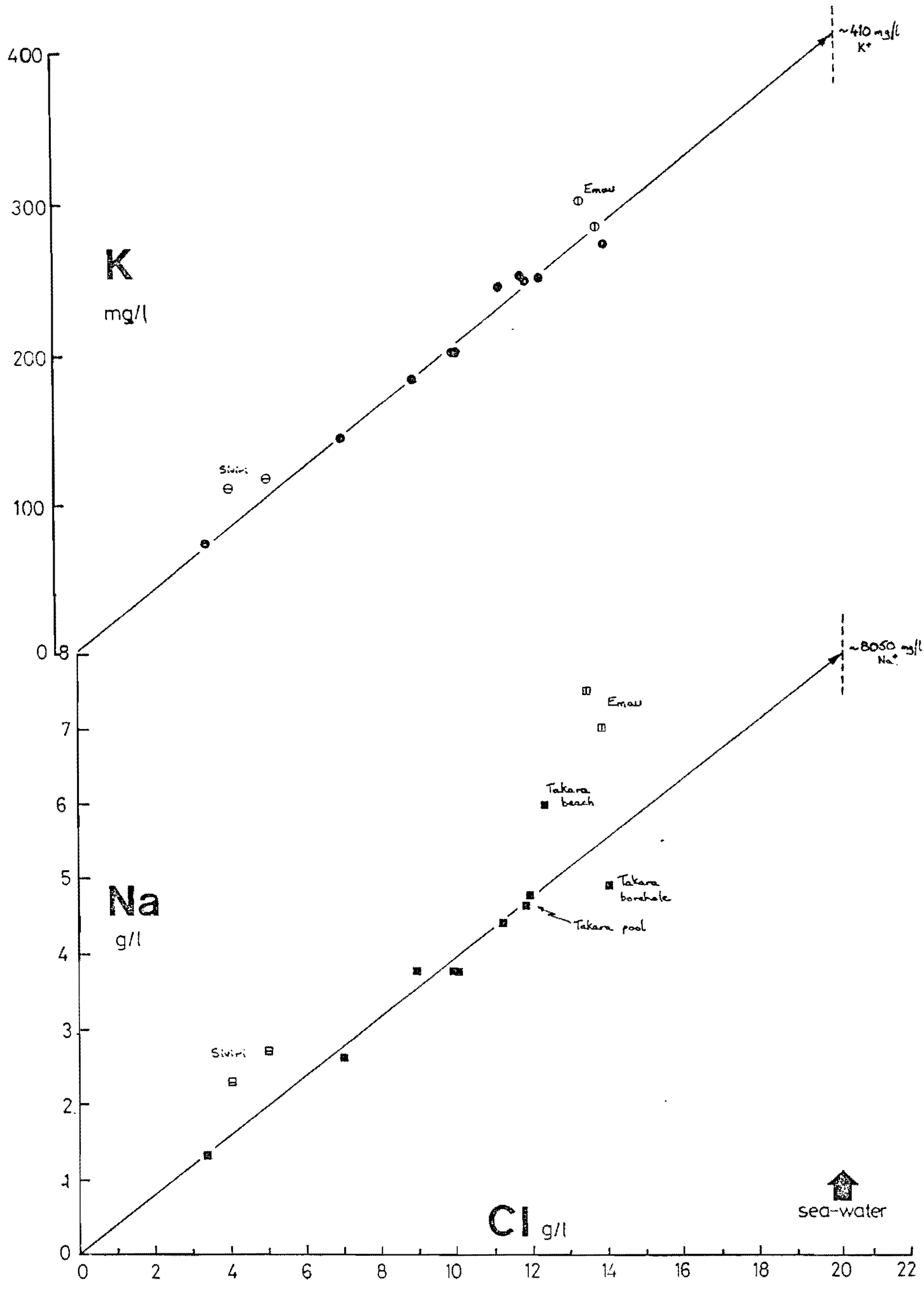


Figure 15a. Ion Concentrations (K^+, Na^+) versus Chloride in Takara Area Springs.

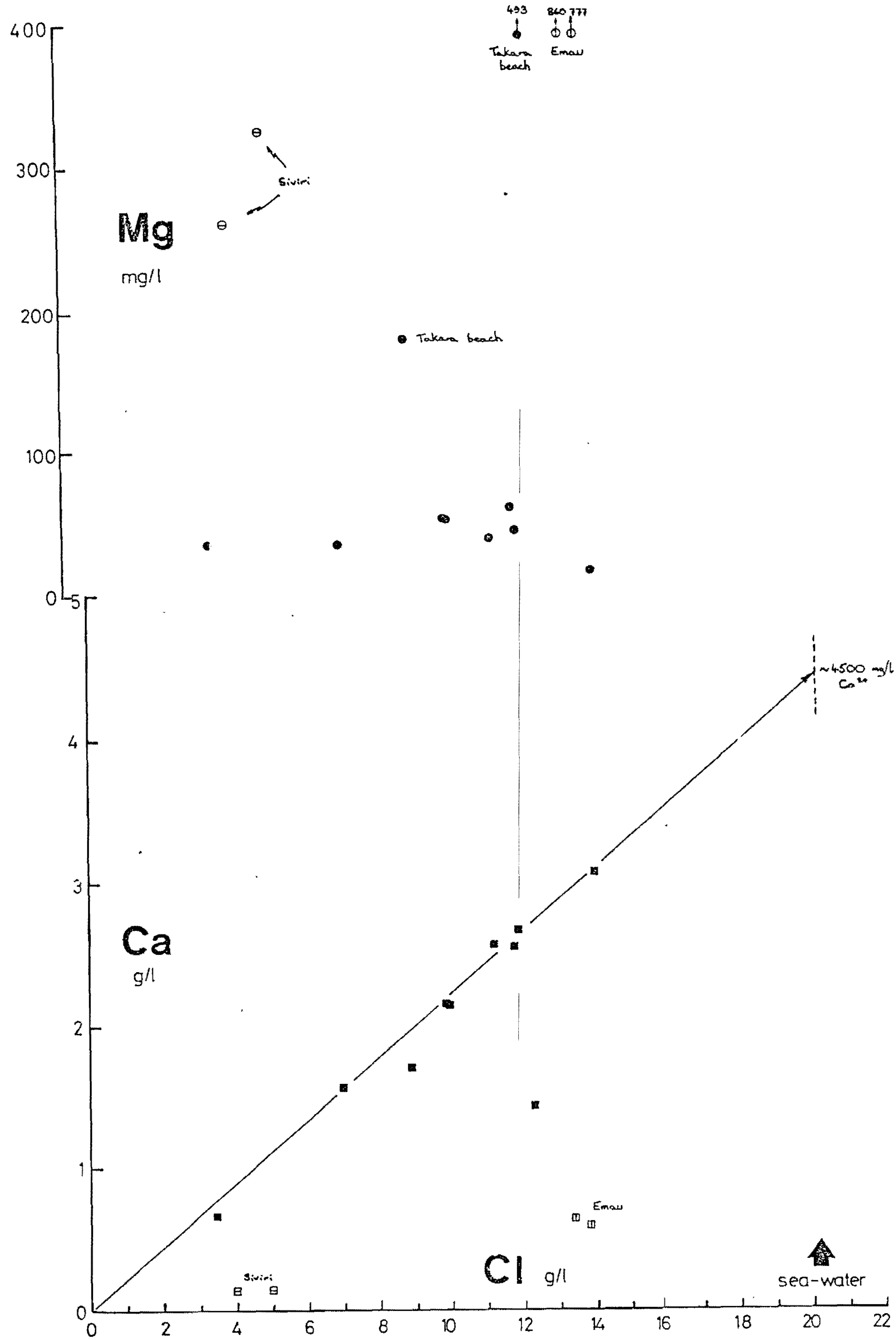


Figure 15b. Ion Concentrations (Mg^{2+}, Ca^{2+}) versus Chloride in Takara Area Springs.

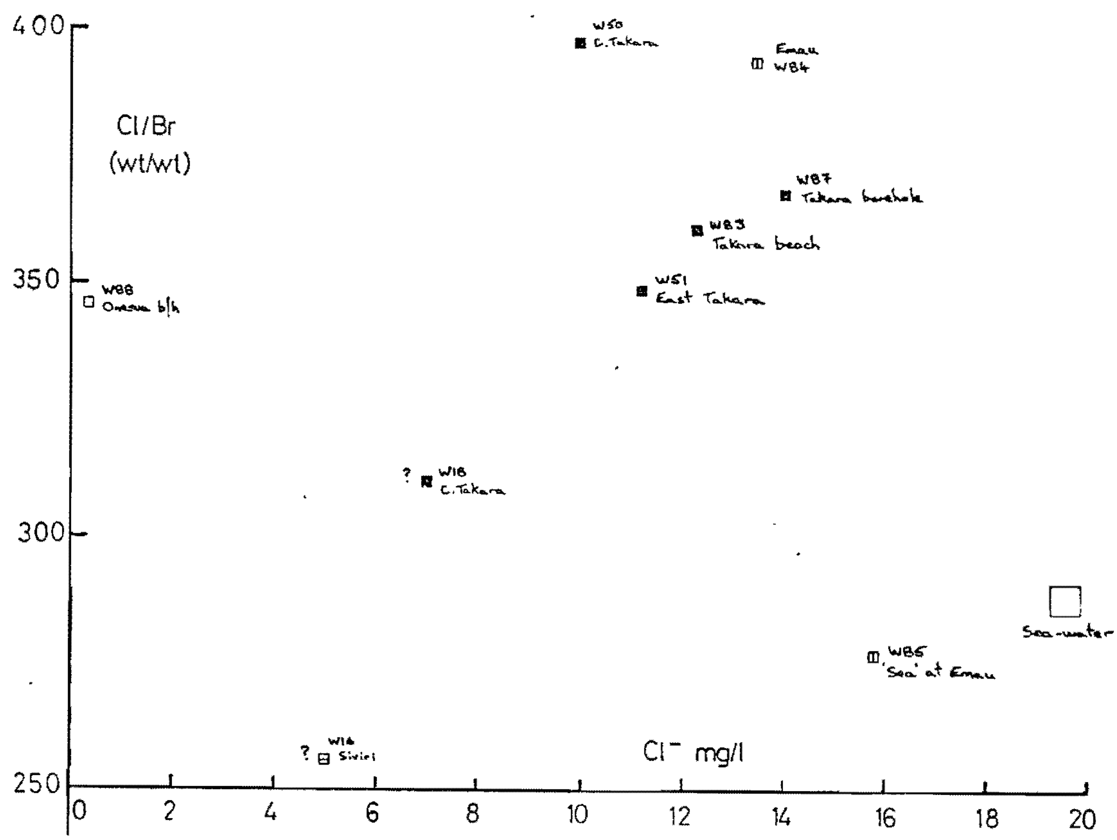


Figure 16. Cl/Br Ratios versus Chloride Concentrations in Takara Area Thermal Water.

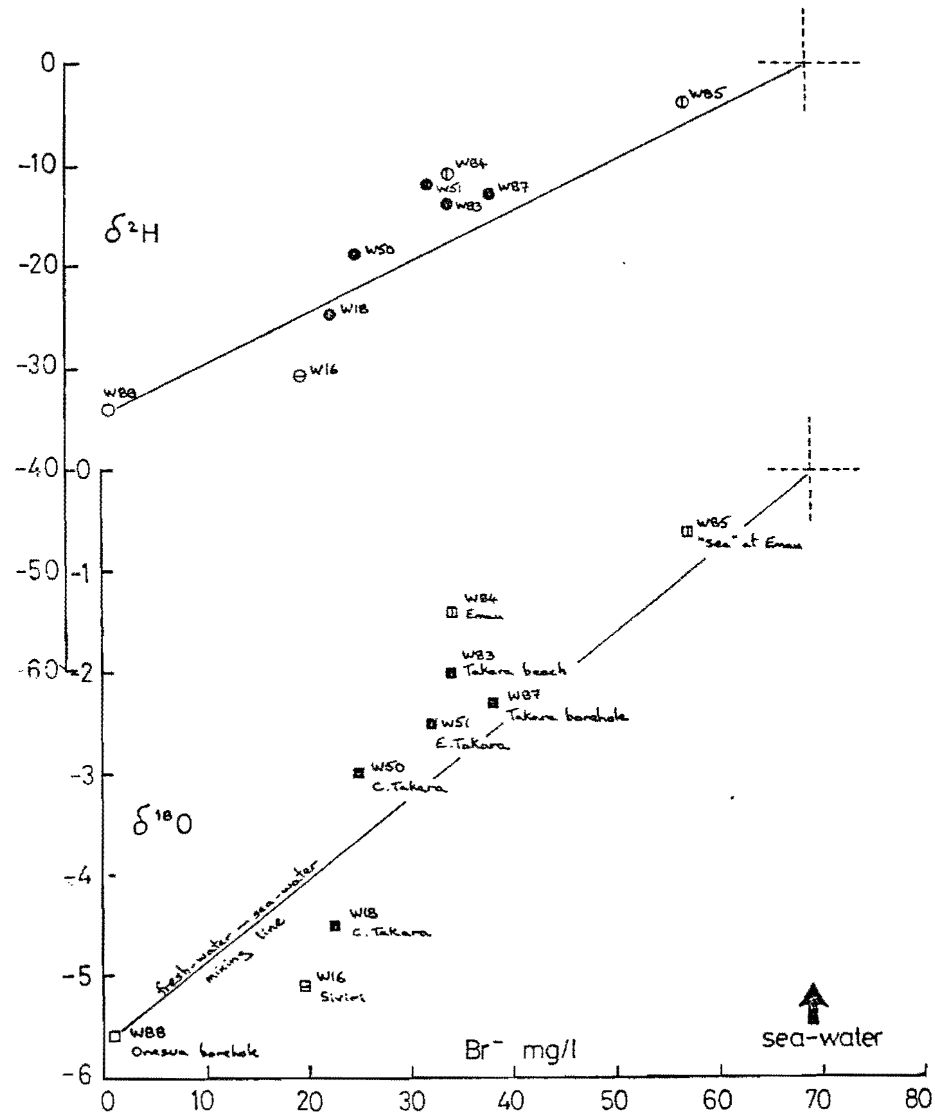


Figure 17. Stable Oxygen and Hydrogen Isotope Compositions versus Bromide Concentrations in Takara Area Thermal Water.

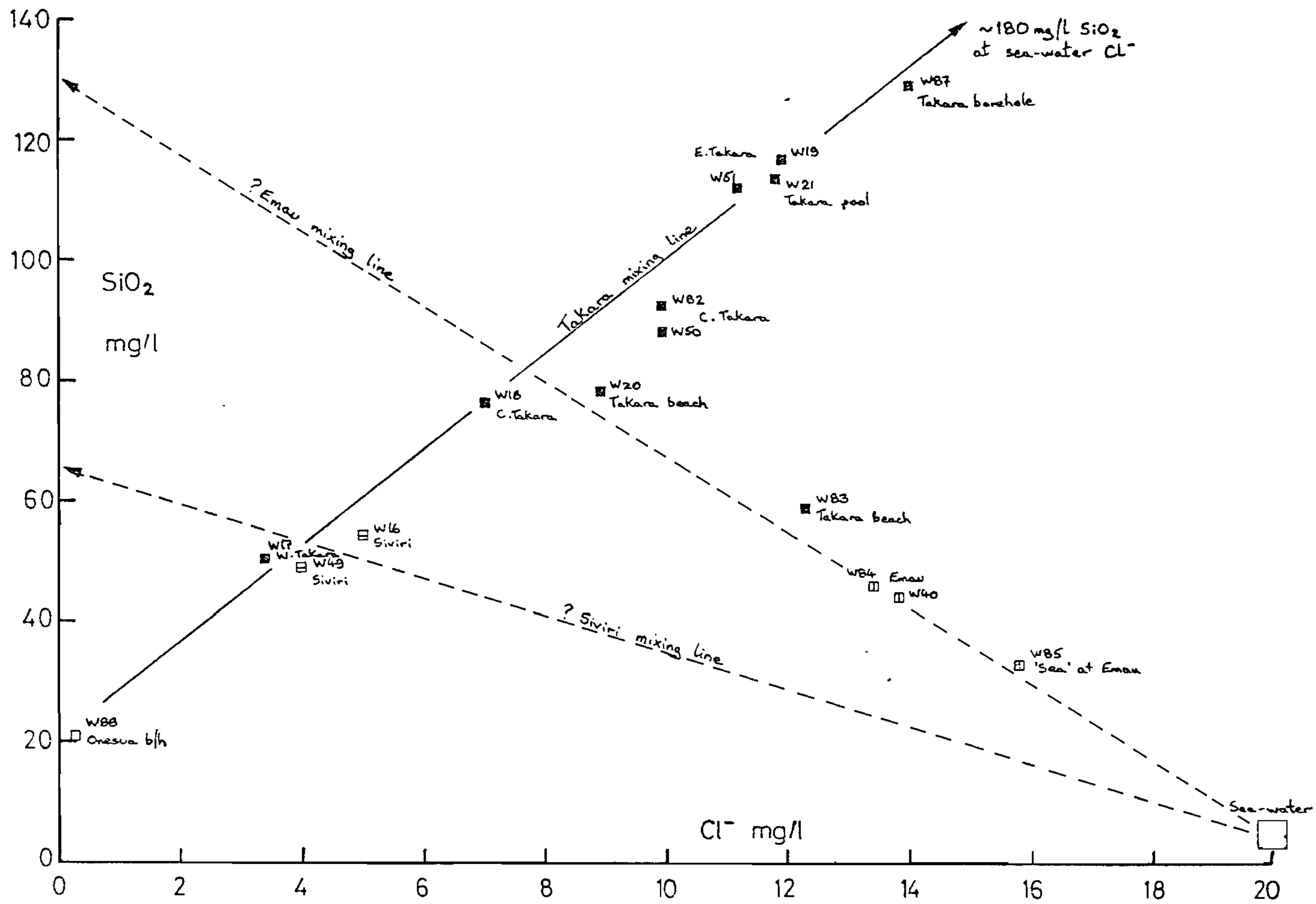
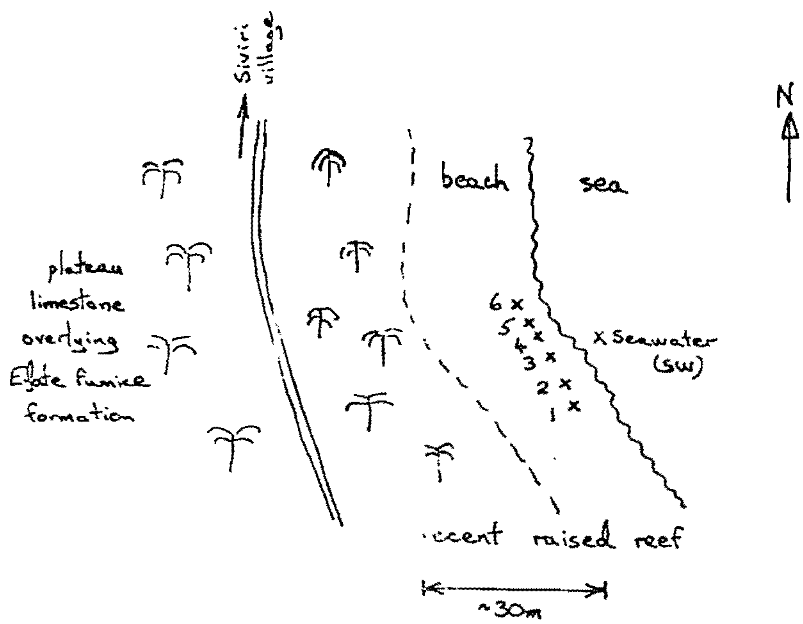


Figure 18. Silica versus Chloride Concentrations for Takara Area Thermal Waters, showing Inferred Mixing Trends.



(2nd Sept 1982)

	T°C	EC_{25} µS/cm	Q l/min
#1	31,1	10100	~5
#2	30,0	8450	~2
#3	30,1	12800	~10
#4	29,7	5700	~2
#5	29,4	5300	~5
#6	26,0	21000	~0
SW	26,2	35400	

Sample W49 is #1

Figure 19. Sketch Diagram of Siviri Beach showing Locations of Seepages.

be up to 130 mg/l (i.e. 150°C on quartz geothermometry) although it is unlikely that the simple linear mixing model shown in Figure 18 is valid since it is known that the saline component of the mixture also takes part in alteration reactions. However, a moderate-temperature source of fresh water percolating through the basalts of Emau Island is supported by the warm moist air rising from several 'vents' on the hill above this seepage. Contact between percolating water and a shallow dike or similar intrusion of recent age seems probable.

Of some significance is the diluted salinity of the sample (W85) taken from the incoming tide at the same location. The low salinity accompanied by raised Ca^{2+} and SiO_2 relative to seawater (Table 7) is clear evidence that there is an extensive sub-marine seepage of water similar to that found in W84.

4.4 Summary.

Hot groundwater occurs over an extensive area at Takara where the water table in the reef limestone approaches the surface. Flow rates and discharge temperatures of the springs increase as a response to seasonal increase in rainfall, suggesting that the reservoir of thermal water is to the south of the discharge area. The springs are a mixture of a thermal saline component and shallow fresh groundwater of the reef limestone. In places a cold sea water may also be involved in the mixing. The thermal component is sea water which has reacted with basalt at a temperature between 165 and 180°C.

Seepages on the shore at Siviri are a mixture between fresh water and sea water which has not reacted at a significantly elevated temperature.

The intertidal seepage at Emau represents a mixture, the thermal component of which is a fresh water which may have had a maximum temperature of 150°C.

APPENDIX 2

Calculation of Heat Losses to the Teuma River.

Increases in electrical conductivity of the Teuma River downstream of the Upper and Mid Teuma springs (Figures 1 and 2, Appendix 2, and Figure 5, main report) suggest discharges of mineralised thermal water to the river. The highest EC_{25} and Cl^- values from chemical analyses of river water (Table 1, Appendix 1) and an average chemical composition for each set of springs are used below to calculate the resulting total heat losses to the river.

If spring inflow = x l/s @ EC_{25} = y & Cl = z

and river flow upstream = a l/s @ EC_{25} = b & Cl = c

and river flow downstream = a+x l/s @ EC_{25} = m & Cl = n

$$\text{then } x = \frac{a\,(m-b)}{(y-m)} \quad \underline{\text{or}} \quad \frac{a\,(n-c)}{(z-n)}$$

(a) For Upper Teuma:

$$x = \frac{3900 \times (370-300)}{(3280-370)} \quad \underline{\text{or}} \quad \frac{3900 \times (27-13)}{(850-27)}$$

$$= 94 \text{ l/s (from } EC_{25}) \quad \underline{\text{or}} \quad 66 \text{ l/s (from } Cl^-)$$

(b) For Mid Teuma:

$$x = \frac{3900 \times (425-395)}{(3100-425)} \quad \underline{\text{or}} \quad \frac{3900 \times (46-34)}{(760-46)}$$

$$= 44 \text{ l/s (from } EC_{25}) \quad \underline{\text{or}} \quad 44 \text{ l/s (from } Cl^-)$$

The thermal springs are 8.9°C (Upper Teuma) and 31.8°C (Mid Teuma) above background temperature (∿ 23°C), and therefore these flows represent excess heat losses of approximately 3 and 6 megawatts respectively. The absence of any temperature anomalies in the river is not surprising, since it would require about 16 MW to raise the temperature of the river by 1°C.

APPENDIX 2

Figures

1. Summary of Conductivity Measurements in Teuma River South of Upper Teuma Springs, 13th-14th September 1982.

2. Summary of Temperature and Conductivity Measurements made in the Teuma Graben, 7-10th September and 13-14th September 1982.

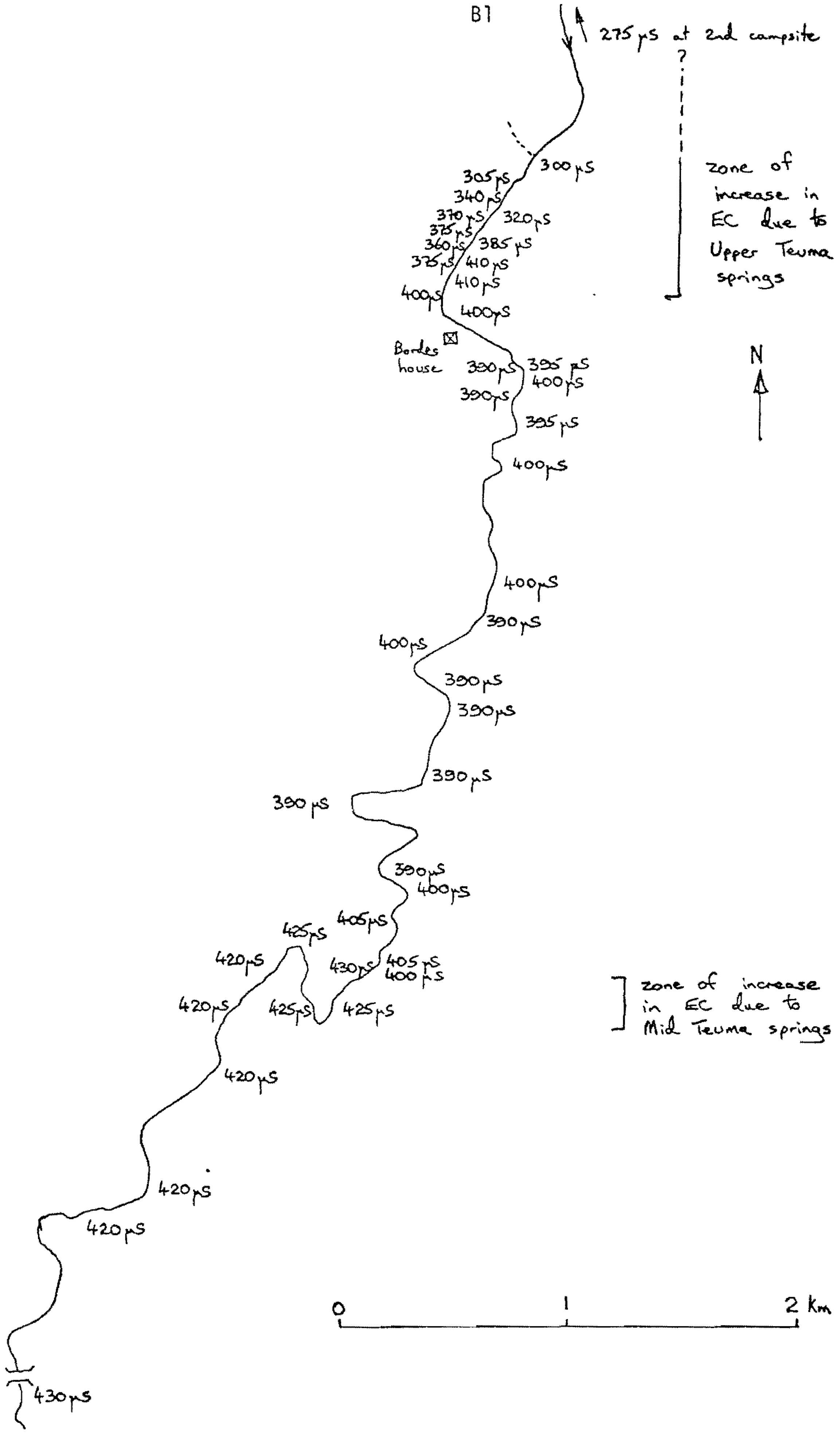


Figure 1. Summary of Conductivity Measurements in Teuma River south of Upper Teuma Springs, 13-14th Sept. 1982.

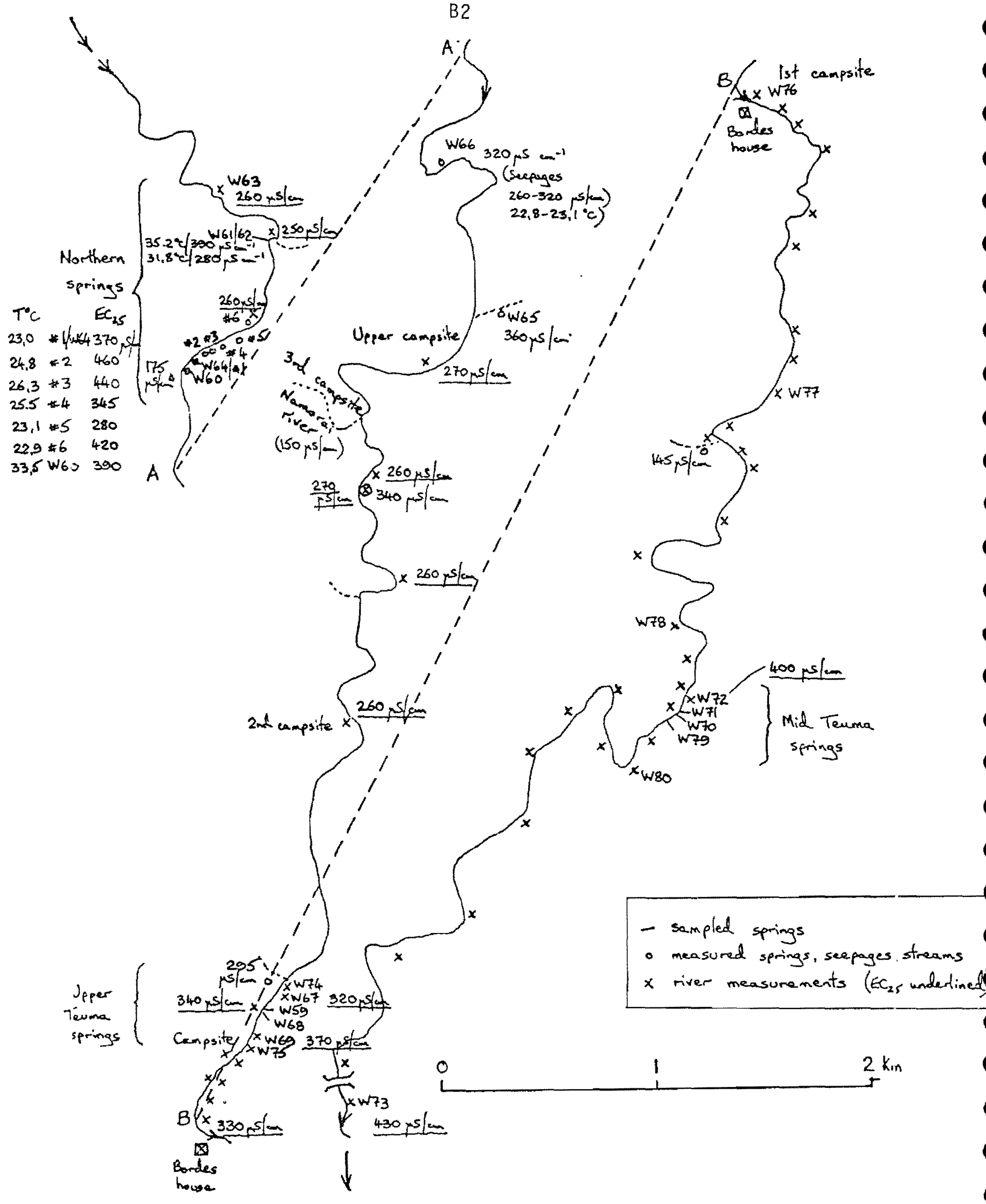


Figure 2. Summary of Temperature and Conductivity Measurements made in the Teuma Graben, 7-10th Sept. and 13-14th Sept. 1982.

APPENDIX 3

Estimated Costs for Phase 2, Efate Geothermal Project.

Cost Estimates.		Estimated Cost: (£)

Item:

1) Resistivity Reconnaissance

(a) Schlumberger traversing

IGS Staff : 2 (HSO + SSO) Preparation : 1 week Field Duration : 3 months (6 man months) Interpretation : 2 man months (SSO)	} 18 500	
Travel (Freight, 40 kg)	15 120	
Sub Total:		£ 33 620

(b) AMT survey

Approx. Contractor costs £100K for 50 stations	100 000	
IGS Staff : 1 (SSO) Field Duration : 9 weeks	} 5 350	
Travel	5 600	
Sub Total:		£ 110 950

2) Gravity Survey

IGS Staff : 2 (HSO + SSO) Preparation : 1 week Field Duration : 2 weeks (1 man month) Interpretation : 2 weeks (HSO)	} 3 810	
Freight : 20 kg	2 120	
Sub Total:		£ 5 930

3) Microseismicity Survey

IGS Staff : 3 (PSO, SSO, PTO2) Preparation : 1 man month (PTO2) Field Duration : 10 days (PSO + PTO2) 1 month (PSO) 2 months (SSO) 3 months (PTO2) Interpretation : 6 months (SSO)	} 30 760	
Travel (Return Flights, 5; Freight, 3 tons)	25 720	
Sub Total:		£ 56 480

Item:	Estimated Cost: (£)
4) Coordination and Reporting	
IGS Staff : 1 (SSO) Field Duration : 2 of 1 month visits Reporting : 2 months (SSO)	9 200
Travel (Return Flights, 2)	7 640
Sub Total:	£ 16 840
TOTAL	£ 223 820

Notes

The estimated total cost for the recommended resistivity reconnaissance, gra[illegible] microseismicity survey is approximately £225K.

The resistivity reconnaissance alone would cost approximately £145K. The gravity survey would be carried out by the same IGS staff on the same trip and its inclusion would increase the cost by £6K.

The contractor costs for the AMT survey are based on estimates given by commercial companies and the University of Edinburgh Department of Geophysics, and would include substantial home-based interpretation.