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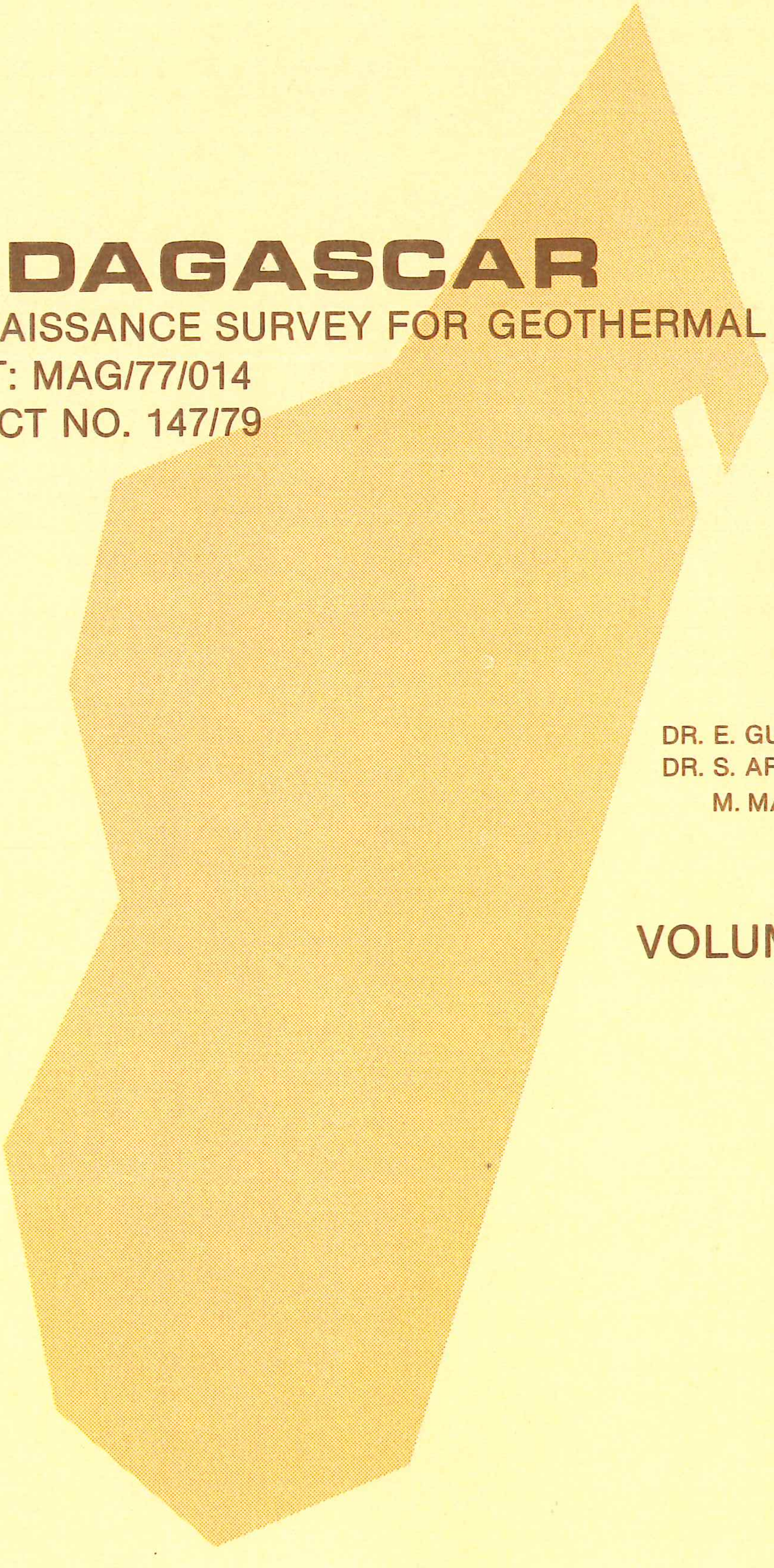

MADAGASCAR

RECONNAISSANCE SURVEY FOR GEOTHERMAL RESOURCES
PROJECT: MAG/77/014
CONTRACT NO. 147/79

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VOLUME 1 OF 2
TEXT

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CONSULTING GROUP LTD
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MAY 1981

SUMMARY OF RESULTS

During the present geochemical reconnaissance survey of geothermal resources in Madagascar 116 samples of thermal and cold water were sampled and analysed. Evaluation of the chemical composition of these waters indicates that about 30% of them have not reached equilibrium with alteration minerals and for this reason chemical geothermometry cannot be applied on these waters to predict subsurface temperatures. These non-equilibrated waters which are cold or slightly thermal are assumed to be surface waters or waters of relatively shallow subsurface circulation. Most ot them are located in sedimentary rocks in western Madagascar.

Chemical geothermometry results for waters which have apparently equilibrated with alteration minerals indicate subsurface temperatures which are most frequently in the range of 90-130°C. In some areas they reach 150-180°C and in several areas there are indications of temperatures exceeding 180°C and possibly as high as 240°C. Sulphate-water oxygen thermometry results in selected samples compare favourably with the quartz geothermometry results and lie in the range of approximately 130-150°C.

Eight areas are considered favourable prospects for further investigations. The areas of first priority include Antsirabe and Itasy (170 km and 125 km from Antananarivo respectively) where underground temperatures are inferred to reach 150-160°C and 170°C respectively, and they may be as high as 240°C in both areas. Four areas in northern Madagascar are considered to be of second priority. They include Ambilobe, Nosy Be, Ambanja and Andapa-Donay. Here subsurface temperatures are predicted to be in the range 140-180°C but they may be somewhat higher (200°C) at Ambanja. The two areas of third priority include the Morandava and Miandrivazo Areas west from Antsirabe.

Here, evidence for temperatures higher than 120-140°C (quartz temperature) is not convincing. The cation geothermometers, however, yield higher values and as much as 250°C.

The six areas of first and second priority are all closely associated with Pleistocene volcanism. They incorporate, with the exception of the Antseranana Area, all thermal manifestations that occur near Pleistocene volcanic rocks. This strongly suggests that the highest temperatures gradient in Madagascar are to be expected in areas of young volcanism.

Where geothermometry results indicate high subsurface temperatures there is always a large difference between measured temperatures in springs and the geothermometry temperatures. This suggests that strong conductive cooling has occurred in the upflow which in turn is indicative of a relatively poor permeability. It does not necessary follow that permeability is also poor at deep levels below the upflow zones.

Many of the geothermal waters in Madagascar are rich in carbon dioxide. Where such waters issue at the surface it is expected that waters rich in carbon dioxide will also be encountered at depth and will feed eventual boreholes. Problems with calcite scaling and corroison are expected to be associated with the exploration of waters rich in carbon dioxide.

RECOMMENDATIONS FOR FURTHER GEOTHERMAL INVESTIGATIONS

In view of the results of this study it is considered advisable to continue the geothermal investigations in Madagascar in order to seek further evidence for the existence of high subsurface temperatures.

The present report identifies 8 areas of interest which have been singled into three priority groups according to the geothermometer results. It has not been possible, on the basis of the findings of this report only, to distinguish clearly between priorities of areas within each group. During the course of further geothermal investigations it is considered necessary to assign priority to individual areas. In order to do so it is recommended that the second phase of the investigations involves as a first step a study dealing with the most promising areas only, involving.

1. Additional sampling and analyses, including isotopes, of groundwater and all existing thermal springs.
2. Regional geological mapping with special emphasis on volcanism and tectonic structures.
3. Collection and evaluation of all existing relevant work on geology, geochemistry, geophysics and hydrology.
4. Collection and evaluation of all relevant data concerning economi, geography and environment.

Having determined the priority of areas on the basis of the above study it is recommended that the following steps involve the writing of a report, with a detailed investigation programme for the selected areas. Such a programme should take into account not only the possibility of geothermal exploitation for power production, but also other utilization possibilities, in case the subsurface temperatures may not be sufficiently high for an economic power production.

The report should, besides including the above mentioned items, cover the following aspects.

5. Detailed geological mapping.
6. Resistivity surveys; Schlumberger and Wenner soundings would probably be most useful.
7. Drilling of thermal gradient holes in order to verify predicted underground temperatures.
8. Investigation of multi-purpose uses of geothermal energy and study of the advantages of specific uses in Madagascar.
9. Time plan and cost analysis for the proposed investigations.

LIST OF CONTENTS

Page

SUMMARY OF RESULTS

RECOMMANDATIONS FOR FURTHER GEOTHERMAL INVESTIGATIONS

1. INTRODUCTION 1.1
1.1 Antecedents 1.1
1.2 Scope of purpose 1.1
1.3 Execution of work 1.2
1.4 Acknowledgement 1.5

2. DISTRIBUTION OF GEOTHERMAL MANIFESTATION 2.1

3. SAMPLING TECHNIQUES AND ANALYTHICAL PROCEDURES 3.1

4. CHEMICAL GEOTHERMOMETRY 4.1

5. ISOTOPE GEOTHERMOMETRY 5.1
5.1 Background information 5.1
5.2 Results of the $\delta^{18}O$ water-sulphate geothermometer 5.2

6. WATER CHEMISTRY CHARACTERISTICS 6.1

7. RESULTS 7.1
7.1 Antseranana Area 7.3
7.2 Ambilobe Area 7.4
7.3 Nosy Be 7.6
7.4 Ambanja Area 7.7
7.5 Andapa-Doany Area 7.12
7.6 Saint Marie 7.15
7.7 Andasibe 7.16
7.8 Maintirano Area 7.17
7.9 Fenerive Area 7.18
7.10 Ranomafana Est (Brickaville) 7.20
7.11 Fenorivo/Ikopa Area 7.21
7.12 Itasy Area 7.23
7.13 Antisrabe Area 7.28
7.14 Morondava Area 7.33
7.15 Miandrivazo-Malambandy-Idalamavony Area 7.34
7.16 Ambatofinandiakana Area 7.39
7.17 Fianorantsoa Area 7.43

Page
7.18 Fandriana Area 7.44
7.19 Mangoky Area 7.45
7.20 Tulear Area 7.47
7.21 Fourth Dauphin Area 7.49
8. PROSPECTIVE AREAS - DISCUSSION 8.1
REFERENCES
APPENDIX 1 LOCATION OF GEOTHERMAL MANIFESTATIONS
1.1 List of maps made available to Virkir
1.2 Map showing location of geothermal manifestations
1.3 Simplified geological map
1.4 Location of geothermal manifestations
1.5 Description of sample sites
1.6 Estimated flow rate of springs
1.7 Geological time scale
APPENDIX 2 GUIDE TO THE TECHNIQUE OF COLLECTING THERMAL WATER. THE TREATMENT OF SAMPLES AND ANALYTICAL PROCEDURE OF FIELD ANALYSIS
APPENDIX 3 METHODS OF CHEMICAL ANALYSIS
APPENDIX 4 CHEMICAL ANALYSIS
APPENDIX 5 CHEMICAL GEOTHERMOMETRY RESULTS
APPENDIX 6 COMPUTER CALCULATIONS
6.1 Computer calculations at measured temperature
6.2 Computer calculations at quartz temperature

LIST OF TABLES

3.1 Analytical methods and mean % deviation 3.3
3.2 Samples for which large discrepancy in ionic balance was observed. 3.4
4.1 Equations for chemical geothermometers 4.6
5.1 Results of the $\delta^{18}O$ water-sulphate geothermometer in °C 5.3
6.1 State of saturation with respect to selected geothermal minerals 6.5

Page

7.1 Chemical geothermometry results in °C for the Antseranana Area 7.4

7.2 Chemical geothermometry results in °C for the Ambilobe Area 7.6

7.3 Chemical geothermometry results in °C for the Nosy Be Island 7.7

7.4 Chemical geothermometry results in °C for the Ambanja Area 7.10

7.5 Chemical geothermometry results in °C for the Andapa-Doany Area 7.14

7.6 Chemical geothermometry results in °C for the Saint Marie sample 7.15

7.7 Chemical geothermometry resluts in °C for the Andasibe sample 7.16

7.8 Chemical geothermometry results in °C for the Maintirano Area 7.18

7.9 Chemical geothermometry results in °C for the Fenerive Area 7.19

7.10 Chemical geothermometry results in °C for the Ranomafana Est sample 7.21

7.11 Chemical geothermometry results in °C for the Fenoarivo/ Ikopa Areas 7.23

7.12 Chemical geothermometry results in °C for the Itasy Area 7.28

7.13 Chemical geothermometry results in °C for the Antsirabe Area 7.32

7.14 Chemical geothermometry results in °C for the Morondava Area 7.34

7.15 Chemical geothermometry results in °C for the Miandrivazo-Malambandy-Ikalamavony Area 7.39

7.16 Chemical geothermometry results in °C for the Ambatofinondiakana Area 7.42

7.17 Chemical geothermometry results in °C for the Fianarantsoa Area 7.44

Page

7.18 Chemical geothermometry results in °C for the Fandriana Area 7.45

7.19 Chemical geothermometry results in °C for the Mangoky Area 7.46

7.20 Chemical geothermometry results in °C for the Tulear Area 7.48

7.21 Chemical geothermometry results in °C for the Fourt Dauphin Area 7.50

8.1 Estimated subsurface temperature in different geothermal areas in Madagascar 8.5

LIST OF FIGURES

2.1 Histogram of the measured temperature distribution 2.2

6.1 State of calcite-saturation in selected waters 6.6

6.2 State of fluorite-saturation in selected waters 6.7

6.3 State of anhydrite-saturation in selected waters 6.8

6.4 Na^+/K^+ ratios in thermal waters in relation to equilibrium with Na- and K- feldspars 6.9

6.5 The temperature dependance of $\sqrt{Ca^{++}}/H^+$ 6.10

6.6 Comparison between $T_{Na\text{-}K\ feldspar}$ and T_{quartz} 6.11

7.1 Areas dealt with in Chapter 7 7.2

7.2 Mixing model for sample 790015, Ambobaka 7.11

7.3 Andapa-Doany Area. Location of thermal springs 7.13

7.4 Itasy Area. Location of thermal springs 7.24

7.5 Mixing model for the Itasy Area 7.27

7.6 Antsirabe Area. Simplified geological map showing youngest volcanism 7.29

7.7 Ambatofinandiakana. Location of thermal springs 7.41

8.1 Histogram of subsurface temperature evaluated from the quartz geothermometer 8.2

1. INTRODUCTION

1.1 Antecedents

This report has been made as a sequel of a response of the VIRKIR Consulting Group Ltd to the United Nations' request for a proposal for a Reconnaissance Survey for Geothermal Resources MAG/77/014 dated February 27, 1979. The Virkir proposal was accepted by the United Nations and a contract was signed on July 5, 1979.

1.2 Scope of Purpose

Article 1.00 in the Contract between the United Nations and the Virkir Consulting Group Ltd. describes the approach to be adopted for the reconnaissance survey of the geothermal resources:

> "As a first step in assessing the geothermal energy potential of Madagascar, a reconnaissance survey will be undertaken which will include the location, sampling and chemical analysis of the major hot springs, followed by interpretation of the chemical data in order to identify areas which may be underlain by high temperature geothermal resources. The recently developed technology of using spring chemistry to evaluate reservoir temperatures (chemical geothermometry) will be the basis for interpretation..."

At the beginning of the project the Virkir Consulting Group Ltd. was to provide the service of Dr. E. Gunnlaugsson, geochemist, for making a preliminary three weeks' visit to Madagascar in order to instruct counterpart staff of the Malagasy Service of Energy (Division of Geology) on the techniques of collecting water samples, on sample preparation, documentation and shipping. Beyond that the Malagasy Service of Energy was responsible for the collection and shipping of samples.

The consitutents to be analysed included, sodium, potassium, calcium, magnesium, sulphate, chloride, carbonate, boron, and silica and where deemed necessary also sulphide and fluoride. Nitrate and ammonia was to be analysed only in samples where contamination with groundwater was suspected.

Mixing model were to be used, where appropriate, in conjunction with chemical thermometers to determine reservoir temperatures. Appropriate graphics were to be used to show local and regional chemical variations of samples.

1.3 Execution of work

The first part of the contract, a preliminary three week' visit to Madagascar, was carried out in the period September 13 to October 7, 1979 by Dr. Einar Gunnlaugsson,associate of Virkir. Mr. Emmanuel Randrianarisoa of the Ministry of Economy and Trade, Division of Industry, Service of Energy was in charge of the project on behalf of the Malagasy Government. During Dr. Gunnlaugsson's stay in Madagascar it became apparent that three teams were needed for collecting samples of thermal water in order to keep the time schedule in the Contract. Each team was to consist of a team leader, an assistant and a driver. The training of the three team leaders was carried out by visiting geothermal fields in the vicinity of the capital Tananarive, i.e. Antsirabe and Itasy and the Ambilobe-Ambajana areas in the north. A total of sixteen samples was collected during the visit of Dr. Gunnlaugsson. To be able to operate three teams simulataneously for collecting samples of thermal water in Madagascar, three sets of equipment were needed. One complete set was brought by Dr. Gunnlaugsson to Madagascar and left there at the request of the United Nations

Headquarters in New York. All the necessary additional equipment, except portable pH-meters and gas sampling bulbs, was assumed to be available in Madagascar. Two portable pH-meters, from Radiometer A.S., Copenhagen, Denmark, similar to the one left behind, were ordered upon request of the United Nations. Further eighteen (18) gas sampling bulbs (250 ml) from Gallenkamp, London, were dispatched directly to the United Nations office in Madagascar. Both orders were billed to Virkir and charged to the United Nations in New York according to agreement.

On May 29, 1980, the Counterpart representatives Messrs Emmanuel Randrianarisoa and Roger Rakotomalala visited the Contractor in Iceland in order to observe the analytical procedures, in accordance with Clause 6.03 of the Contract.

The first sixteen samples nos. 790001 to 790016 were collected during the visit of Dr Gunnlaugsson. They arrived in Iceland on October 15, 1979. Samles nos. 790017 to 790031 inclusive were collected from the time Dr Gunnlaugsson left Madagascat until the end of December, 1979, and arrived in Iceland on January 12, 1980. Samples nos. 800032 to 800051 arrived on March 15, 1980, samples nos. 800052 to 800078 on May 6, 1980, samples nos. 800079 to 800100 on May 29, 1980, samples nos. 800101 to 800115 on June 27, 1980 and samples nos. 800116 and 800117 arrived on August 6, 1980. Thus a total number of 117 samples was collected and shipped. One box with water samples containing 27 500 ml bottles and 4 100 ml bottles was lost in freight between Madagascar and Iceland. The total water analyses of 25 of these samples were carried out using only 2x100 ml samples and collection of two samples was repeated. Due to some unfortunate misunderstanding one of the lost samples was wrongly identified (sample 800054 instead of 800056) when sampling was repeated. Therefore analytical results are available.

for 116 samples and not for sample no. 800056.

All the chemical analyses were performed by the Geochemical Laboratory of the Science Institute, University of Iceland.

The results of all the chemical analyses and the geothermometry results were included in the bi-monthly reports submitted to the United Nations during the execution of the project.

As data accumulated it became apparent that many of the waters were of the carbonate type and in all cases the dominant gas constituent was carbon dioxide. On that basis, it was concluded that sampling and analysis of gases would not be useful for the main object of the survey, namely estimation of subsurface temperatures by geochemical techniques. In the second bi-monthly report it was therefore proposed to omit collection and analysis of gas samples.

During the interpretation of the analytical results in terms of geothermometry, discrepancy between the silica and the cation geothermometers was often observed. Therefore, a further study of equilibrium conditions between alteration minerals and dissolved aqueous constituents was carried out by making use of a special computer program. The results of this study are incorporated in the discussion on results in Chapters 6 and 7.

Seven samples were selected for analyses of oxygen isotopes in sulphate and water in order to predict subsurface temperatures by the water-sulphate isotope thermometer and compare the results with those of chemical geothermometry. The isotope analyses were carried out at the United States Geological Survey, Menlo Park under the supervision of Dr A.H. Truesdell.

A Technical Review Meeting was held in New York during April 6 - 10, 1981 to discuss the results of the geochemical reconnaissance survey as presented in the final draft report. Mr. A. Svanbjornsson and Dr. E. Gunnlaugsson from Virkir, Mr. E. Randrianarisoa from the Government of Madagascar and Dr. J.R. McNitt, Dr. A.H. Truesdell and Mr. S. Einarsson on behalf of the United Nations attended this meeting. The final report, presented here, incorporates comments and some minor modifications to the draft report made by the participants of the meeting.

1.4 Acknowledgements

The consultant wishes to express his sincere appreciation of the support and assistance given by the staff of the Ministry of Economy and Trade, Division of Industry, Service of Energy, especially to Mr. Emmanuel Randrianarisoa who was in charge of the project, and to the three team leaders, Bernand Rakotovad, Edmond Rabeatoandro and Luis Rakotoazanany who carried out the collection of water samples. Mr. Roger Rakotamalala at "Service des Mines ou Service Geologiques" supplied geological maps and geological information. Thanks are also extended to the staff of UNDP in Madagascar Mr. Ellis Cacouris, Mr. Macro Hartmann and Mr. David Whaley for their assistance during the visit of E. Gunnlaugsson to Madagascar.

Dr. J.R. McNitt and Dr. A.H. Truesdell are thanked for very useful discussions in New York during the Technical Review Meeting of April 6 - 10 and Dr. Truesdell especially for performing the isotope determinations.

2. DISTRIBUTION OF GEOTHERMAL MANIFESTATIONS

Geothermal manifestations are widely distributed in Madagascar. Between 120 and 140 thermal water springs are known but no fumaroles. The temperature of the water ranges from little above ambient mean temperature (18-20 °C) to 78 °C. A histogram of the temperature distribution is shown in Fig. 2.1. Of the 117 waters sampled for this study 87 have temperatures lower than 50 °C, and only 5 have temperatures above 60 °C.

Previous to this study all hot springs had been listed and located by the Service of Energy, Division of Industry of the Ministry of Economic and Trade of the Malagasy Government. During sampling each thermal spring was plotted on 1:100.000 topographical maps (these maps are kept in Madagascar) and on a 1:500.000 map to be used by the Consultant for evaluating the results. A map showing the distribution of thermal manifestations is included in Appendix 1, together with a table giving the coordinates of all the sample sites. A simplified geological map and a description of each site where samples of thermal water were taken are also included. The description was originally written in French during the collection of samples, but has been translated into English. The table in Appendix 1 was constructed using the 1:500.000 map. Appendix 1 also contain geological time scale.

The thermal springs occur in geological formations of widely different ages. In Antsirabe and in Itasy, in the central part of Madagascar, and in the northernmost part of the country, these thermal areas are associated with Pleistocene volcanism and young fractures. In these areas of young volcanism, the highest underground temperatures are predicted by chemical geothermometry as will be discussed in Chapters 7 and 8.

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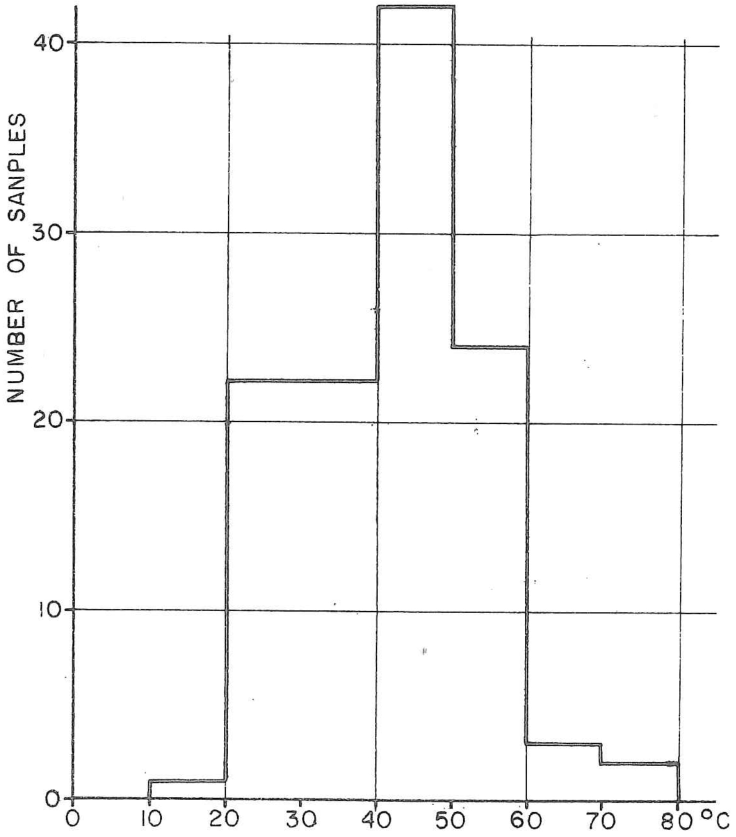
HISTOGRAM OF THE MEASURED TEMPERATURE DISTRIBUTION.



3. SAMPLING TECHNIQUES AND ANALYTICAL PROCEDURES

Sampling of thermal waters was mostly performed by the Service of Energy of the Ministry of Economic and Trade in Madagascar under the direction of Emmanuel Randrianarisoa. At the beginning of the project, a geochemist from the Consultant supervised the sampling and trained Malagasy personell in collecting and in analysing pH, total carbonate and hydrogen sulphide of water samples on site. A guide in English on the technique of collecting thermal water, on the treatment of samples and analytical procedure of field analysis (see Appendix 2) was provided at the beginning of the training. The UNDP office in Madagascar translated the guide into French.

The following procedure was adopted at each sampling site:

a) an untreated sample was collected into a 500 ml polythene bottle.

b) 250 ml of water was cooled, using a stainless stell cooling spiral, and collected into a glass sampling bulb. Within 36 hours this part of the sample was used for the determination of pH, CO_2 and H_2S.

c) 100 ml were acidified with hydrochloride acid for the determination of cations and stored in a polythene bottle.

d) 100 ml were treated with $Zn(CH_3COO)_2$ and stored in a polythene bottle for subsequent determination of sulphate. This was done to eliminate interference from sulphide which upon storage may be oxidized into sulphate.

e) the temperature was measured, the flow rate estimated, and the sample site briefly described.

The polythene bottles were shipped to Iceland for analysis. One box containing 27 500 ml bottles and four 100 ml bottles of water samples was lost in freight between Madagascar and Iceland. The total water analysis of 25 of those samples was carried out using only 2 x 100 ml samples, and two samples were recollected. Unfortunately one of the lost samples was wrongly identified (sample 800054 instead of 800056) when sampling was repeated.

Chemical analysis of the 116 samples was performed at the Geological Laboratory of the Science Institute, University of Iceland. The analytical methods used are summarized in Table 3.1. A detailed description of the analytical methods used is given in Appendix 3.

Chemical analyses of all samples are listed in Appendix 4.

The method adopted for checking the overall quality of the chemical analysis involved comparison of balance of cations and anions. A few samples show a larger difference than anticipated. These have been re-analysed and the new results were found to compare well with the older ones. Table 3.2 lists these samples giving a probable explanation of the discrepancy in the ionic balance.

TABLE 3.1 Analytical methods and mean % deviation.

Component	Method	Mean % deviation of duplicate analysis
SiO_2	Colourimetric-molybdate green	4.5
B	Colourimetric-methylene blue fluoroborate	4.8
Na	Atomic absorption spectrography	2.1
K	Atomic absorption spectrography	4.1
Ca	Atomic absorption spectrography	2.6
Mg	Atomic absorption spectrography	3.0
SO_4	Titration with $Ba(ClO_4)$ using thorin indicator	2.03
Cl	Mohr titration	1.80
F	Fluoride-ion sensitive electrode	2.90
pH*	pH-meter	
CO_2*	Titration with 0.1 N HCl	
H_2S*	Titration with $Hg(CH_3COO)_2$ using dithizone as indicator.	

* Carbon dioxide (CO_2), pH and hydrogen sulphide (H_2S) were analysed in field. The analytical procedures are given in the manual on sample collection techniques provided by Virkir.

TABLE 3.2 SAMPLES FOR WHICH LARGE DISCREPANCY IN IONIC BALANCE WAS OBSERVED

SAMPLE NO	DIFFERENCE %[1]	POSSIBLE REASON FOR DISCREPANCY
800054	+ 48	Possibly too low CO_2.
800066	-135	Chloride too high possibly due to contamination from pipette used for a) acidifying the sample b) and for precipitation of sulphide by addition of zinc acetate
800067	- 75	
800077	+ 93	CO_2 is apparently low in field determination. Upon acidification of the samples for SO_4-determination, strong degassing occurred as was the case for many waters rich in CO_2.
800085	+ 28	Probably low CO_2.
800086	+ 44	
800090	23	Probably high CO_2.
800094	- 61	Cold groundwater to which CO_2 has been added. The ionic balance of these low salinity waters is very sensitive to the precision of the pH and CO_2 determination.
800098	+ 34	
800100	- 73	
800101	- 26	
800102	-131	
800103	-132	
800104	- 74	
800105	- 52	
800111	+ 20	Sample similar to thermal water from Antsirabe, except for CO_2. Low CO_2 suspected.
800112	- 92	Same explanation as for samples 800094 to 800105.

[1] $$\% \text{ difference} = \frac{\Sigma\text{cations} - \Sigma\text{anions}}{\frac{\Sigma\text{cations} + \Sigma\text{anions}}{2}} \cdot 100$$

4. CHEMICAL GEOTHERMOMETRY

The chemical geothermometers that have been quantitatively calibrated and are used in this study include the silica, the Na-K, the Na-K-Ca and the Na-K-Ca-Mg geothermometers. Below, a brief summary is given on the assumptions and limitations involved when using these geothermometers to predict underground temperatures in geothermal systems.

There are two kinds of silica geothermometres. One assumes equilibrium with quartz and the other equilibrium with chalcedony. The temperature functions used for these geothermometers are based on experimentally determined solubilities of the mentioned minerals (Fournier, 1973; Kennedy, 1950; Morey et al., 1962). The functions used in this report are those recommended by Fournier (1977) (see table 4.1).

The cation geothermometers are all empirically calibrated, i.e. by relating the concentrations of the respective cations in thermal waters issued from drillholes with the measured temperature of these waters. For the Na-K geothermometer the temperature function, however, fits well with that of equilibrium between sodium- and potassium feldspars and solution. It is therefore beleived that these minerals control the concentrations (or better, the activities) of sodium and potassium ions in solution. It is not known what minerals are involved with respect to the Na-K-Ca and the Na-K-Ca-Mg geothermometers.

The calibration used for the Na-K geothermometer is from White and Ellis (see Truesdell, 1975) and Arnorsson (1980). White and Ellis considered that its function was not valid below 100 °C, but the temperature function proposed by Arnorsson (1980) holds in the range 25-250 °C. The calibration for the Na-K-Ca and the Na-K-Ca-Mg geothermometers is from Fournier and Truesdell (1973) and Fournier and Potter (1978).

The basic assumption involved in the application of chemical geothermometers is that a chemical equilibrium between solution and the relevant minerals is attained at depth and that these equilibria are quenched in the upflow where cooling may take place. Experience in many geothermal fields of the world has indeed shown that underground temperatures, predicted by chemical geothermometry are actually encountered at depth by drilling. This experience has largely been gained in fields of volcanic terrain, which, due to intense surface thermal manifestations and the results of exploratory work, were obvious as favourable prospects for geothermal development.

Much care has to be taken in transferring this experience to other geothermal areas in a different geological setting, both with respect to equilibrium conditions and secondary minerals which could control water compositions. This limitation must be kept in mind throughout the reading of this report. Non-critical analysis of the water compositions may lead to erroneous predictions of underground temperatures. Surface waters which have not equilibrated with secondary minerals may have very low Na-K ratios giving high Na-K temperatures. Sometimes such waters may also attain metastable equilibrium with amorphous silica, yielding false and too high geothermometry temperatures.

The geothermal waters in Madagascar are mostly of the carbon dioxide type but non-thermal carbon dioxide waters also occur. Waters with these chemical features are known in many other parts of the world (Barnes et al., 1978). These waters are not necessarily linked to underground geothermal reservoirs. They may have formed by dissolution of carbon dioxide of deep seated origin in ground water or surface water (Arnorsson, 1979; Arnorsson and Benjaminsson, 1980). Non-thermal carbon dioxide waters and sometimes also those of a relatively low temperature show typically chemical characteristics that reflect non-equilibrium conditions with secondary minerals. This experience emphasises the need for a critical evaluation of the water chemistry data, since it has a bearing or judging whether or not equilibrium is attained for the geothermometry minerals. If equilibrium is not attained, the chemical geothermometers are of course not applicable.

The temperatures calculated by the Na-K geothermometer agree better with quartz equilibrium temperatures than chalcedony equilibrium temperatures. This indicates that the geothermal waters in Madagascar equilibrate with quartz, and not with chalcedony. This relationship may, however, not be without exception.

The main approximation made in applying the chemical geothermometers is that the analytical concentrations of silica and the respective cations are representative of the activities of $H_4SiO_4^{\circ}$, Na^+, K^+, Ca^{+2}, Mg^{+2}. For the Na-K-Ca and Na-K-Ca-Mg geothermometers this approximation is circumvented by their empirical calibration. In the case of the Na-K and silica geothermometers these approximations cause no significant deviation for the Madagascar waters. It is only at high temperatures and for saline waters that errors are significant for the Na-K geothermometer. For high pH waters (more than 9.0, referring measurements at 20 °C) the analytical silica concentrations need to be corrected by calculating and substracting the fraction of silica which is dissociated in solution. Only a few of the waters sampled from Madagascar have that high pH. For those waters the mentioned correction was made when calculating the silica temperatures.

Paĉes (1975) pointed out that cool (less than 75 °C) carbon dioxide waters often yield high Na-K-Ca temperatures and recommended the use of a correction factor to be added to the temperature function of Fournier and Truesdell (1973) for the Na-K-Ca geothermometer. The correction factor recommended by Paĉes consists of two terms. The term involving carbon dioxide does not influence the calculated Na-K-Ca temperature much. The data that were used to derive this correlation factor show large scatter, and evidence that the respective waters had attained equilibrium is not convincing. For that reason no weight is given to the Na-K-Ca temperature results including the CO_2 correction factor in discussing the results in Chapter 7. For the sake of completeness, however, the respective temperatures have been calculated and are tabulated in Appendix 5.

The correction factor for the Na-K-Ca geothermometer that was proposed by Fournier and Potter (1979) involving magnesium is entirely empirical. It assumes that magnesium concentrations affect the potassium and calcium concentrations in the water. From a theoretical point of view this would not be expected at low temperatures. At low temperatures magnesium will neither replace calcium nor potassium in alteration minerals. Upon cooling of ascending thermal waters the small divalent magnesium ion appears to change rapidly in concentration towards a new equilibrium. For this reason, application of the magnesium correction factor will involve a conservative estimate for underground temperatures, assuming of course, that the other cations (Na-K-Ca) have equilibrated with alteration minerals. In Chapter 7, which incorporates the geothermometry results, Na-K-Ca-Mg temperatures are omitted although the respective temperature values have been calculated and incorporated in Appendix 5.

In upflow zones draining geothermal reservoirs, the hot water may mix with cold ground water or surface water. Since boiling hot springs do not occur, the only mixing model applied is the silica-enthalpy plot. (Truesdell and Fournier, 1975; Fournier 1977). Since surface waters and cold ground waters are lower in silica than thermal waters, mixing will lower the silica content of the water and give low estimates for the silica temperature. Mixing may also give low values for the Na-K-Ca and Na-K-Mg geothermometers if the cold waters are relatively high in Ca and Mg which is often the case. The Na-K geothermometer is usually insignificatnly affected by mixing. The exceptions include mixing with waters that have been concentrated by evaporation or other processes.

Mixing models cannot be successfully applied unless there is an independent evidence that mixing has occurred. Here large discrepancy between the silica and Na-K geothermometers is assumed to be the main evidence for such mixing, and high flow from springs with large difference between measured temperatures and geothermometry temperatures. An erroneous assumption of mixing, and the application of mixing models, will rend high results if cooling by conduction has taken place in the upflow.

TABLE 4.1 Equations for chemical geothermometers

---

(1) chalcedony (0-250 °C)1)

$$t\ °C = \frac{1032}{4.69 - \log SiO_2} - 273.15$$

(2) quartz (0-250 °C)1)

$$t\ °C = \frac{1309}{5.19 - \log SiO_2} - 273.15$$

(3) amorphous silica 1)

$$t\ °C = \frac{731}{4.52 - \log SiO_2} - 273.15$$

In all these three equations SiO_2 is in mg/l and represents unionized silica.

(4) Na-K (100-275 °C)2)
Na and K in mg/l

$$t\ °C = \frac{855.6}{\log (Na/K) + 0{,}8573} - 273.15$$

(5) Na-K(25-250 °C)3)
Na and K in mg/l

$$t\ °C = \frac{933}{0.993 + \log Na/K} - 273.15$$

(6) Na-K-Ca (4-340 °C)4)

$$t\ °C = \frac{1647}{\log Na/K + \beta \log(\sqrt{Ca}/Na) + 2.24} - 273.15$$

Na, K and Ca in moles/kg
$\beta = 4/3$ for $\sqrt{Ca}/Na > 1$ and $t < 100$ °C
$\beta = 1/3$ for $\sqrt{Ca}/Na < 1$ and $t > 100$ °C
Paĉes 5)correction for Na-K-Ca geothermometer for water less than 75 °C and partial pressure of CO_2 above 10^{-4} atm is:

$$I = 1.36 + 0.253 \log P_{CO_2}$$

References:

1)Fournier (1977), 2)Truesdell (1975), 3)Arnorsson (1980), 4)Fournier and Truesdell (1973) and 5)Paĉes (1975).

5. ISOTOPE GEOTHERMOMETRY

5.1 Background information

Several isotopic fraction reaction may be used as geothermometers. The rates of the reaction determine whether equilibrium exists or not. The most suitable isotope geothermometer for thermal systems is the sulphate/water geothermometer. It is based on the fractionation of oxygen isotopes between sulphate ion and water which depends on temperature. The isotope geothermometer appears to equilibrate in most geothermal reservoirs but undergoes little reequilibration during passage to the sampling point (Truesdell and Frye, 1977). The most suitable temperature range for the sulphate geothermometer is 140 - 350 °C (McKenzie and Truesdell, 1977). In low temperature systems, slow rate of isotopic exchange may prevent that equilibrium is attained, in which case the calculated temperatures are meaningless.

The experimental fractionation factor for the sulphate/water system has been determined by various authors. It is in good agreement between 100 - 200 °C. The equation used here for equilibrium fractionation between dissolved sulphate and water is from Mizutani and Rafter (see McKenzie and Truesdell, 1977)

$$1000 \ln\alpha_{SO_4-H_2O} = 2.88\ (10^6/T^2) - 4.1$$

where

$$\alpha_{SO_4-H_2O} = \frac{(^{18}O/^{16}O)\ SO_4}{(^{18}O/^{16}O)\ H_2O} = \frac{1000 + {}^{18}O\ (SO_4)}{1000 + {}^{18}O\ (H_2O)}$$

This isotope geothermometer allows an independant check of the reservoir temperature obtained by the chemical geothermometers, but, as with other geothermometers, it must be used with caution because various external conditions may affect the estimated temperature.

5.2 Results of the $\delta^{18}O$ water-sulphate geothermometer

Seven samples were analysed for their ratio of $^{18}O/^{16}O$ in water and sulphate at the United States Geological Survey, Menlo Park under the supervision of Dr. A.H. Truesdell, for estimation of subsurface temperatures by the respective isotope geothermometer. The results are shown in Table 5.1. They compare rather well with those of the quartz or chalcedony geothermometers but are considerably lower than temperatures estimated by the Na-K and Na-K-Ca geothermometers. The $\delta^{18}O$ water-sulphate isotope geothermometer yields on the average for the seven samples, temperatures that are higher by 18 °C and lower by 3 °C for the chalcedony and quartz geothermometers respectively. A corresponding difference for the Na-K geothermometer is 70 °C, the isotope geothermometer yielding lower values. For the Na-K-Ca geothermometer the difference relates to the selected beta-value. If it is 4/3 the chemical geothermometer yields lower values by 38 °C on the average. If, on the other hand, a beta-balue of 1/3 is selected according to the procedure recommended by Fournier and Truesdell (1973), the isotope geothermometer yields on the averager temperatures which are higher by 62 °C.

The selection of samples for the ^{18}O analysis aimed mainly at comparing the isotope and the chemical geothermometry where results from the silica geothermometer on one hand and the Na-K and Na-K-Ca geothermometers on the other showed great discrepancy and when the latter were indicative of subsurface temperatures exceeding 200 °C.

The isotope geothermometry results for the seven samples selected do not indicate subsurface temperatures exceeding 180 °C. They compare rather well with quartz equilibrium temperatures and are lower than Na-K temperatures. This result indicates that equilibrium for quartz and for oxygen isotopes between water and sulphate is attained but not between feldspar and solution.

Table 5.1 Results of the $\delta^{18}O$ water-sulphate geothermometer in °C

Location	Sample no	$T_{meas.}$	$T_{SO_4-H_2O}$ oxygen isotopes
Antsirabe, source de l'hospital	790002	45	137
Itasy, Andranomafana Soavinaudriana	790008	45	129
Itasy, Andranoriangotraka	790010	28	149
Itasy, source d'Ambaraky	790011	24	152
Andranomafana Migioky	790016	72	139
Itasy, Sahasarotra	800110	41	140
Malailay	800114	36	84

6. WATER CHEMISTRY CHARACTERISTICS

The water samples collected in Madagascar are all of a dilute character. The samples can be divided into two groups on the basis of carbonate concentrations. About half of the samples have a carbonate concentration higher than 100 ppm, and 22 samples have a concentration higher than 500 ppm. All the areas with the highest underground temperatures, as computed from the silica geothermometer, belong to the high carbonate type. The thermal water in Antsirabe and Itasy have a carbonate concentration of 2000 - 3000 ppm and 1000 - 4000 ppm respectively.

The chloride concentration can be used to illustrate that waters are relatively dilute. Ninety of the samples have a chloride concentration lower than 200 ppm and only 7 samples have a concentration higher than 1000 ppm. The highest chloride concentration is 4250 ppm at Tabalahoriko on the island of Nosy Be.

An overall chemical equilibrium between solutes and alteration minerals is very often attained in geothermal systems for all the components which are incorporated in these minerals. Thus, geothermal waters are, as a rule, saturated with calcite and often saturated with anhydrite and fluorite. Mineral solute equilibria also fix the $\sqrt{\mathrm{Ca}^{+2}}/\mathrm{H}^{+}$ activity ratios at a particular temperature. If degassing occurs in hot springs the waters may become significantly supersaturated with respect to calcite solubility.

Surface waters and shallow groundwaters are typically calcite undersaturated and have a very low $\sqrt{\mathrm{Ca}^{+2}}/\mathrm{H}^{+}$ ratio. Relatively short underground residence time seems to be needed for cold groundwaters to attain equilibrium with calcite. Waters of mixed origin have low $\sqrt{\mathrm{Ca}^{+2}}/\mathrm{H}^{+}$ ratios for their temperature but are usually calcite-saturated.

It is considered that evidence indicating chemical equilibrium conditions for components other than silica, sodium, potassium, and calcium, gives improved confidence in the geothermometry results. For this reason, a computer program has been used to calculate the state of saturation for selected samples with respect to calcite, anhydrite, fluorite, Na- and K-feldspars as well as the $\sqrt{Ca^{+2}}/H^{+}$ activity ratio. The calculations were performed at measured water temperature and at quartz equilibrium temperature. The results are shown in Figs. 6.1 to 6.5. They show that most of the Madagascar waters are calcite-saturated or somewhat supersaturated at the measured water temperature (Fig. 6.1). For some waters fluorite saturation is observed whether reference is made to the measured temperature or to the quartz equilibrium temperature. Other waters are undersaturated (Fig. 6.2). For many samples anhydrite saturation occurs at quartz equilibrium temperature, but with a few exceptions the waters are undersaturated at the temperatures existing in the springs (Fig. 6.3). Over 50% of the waters are in equilibrium with Na- and K-feldspars at quarts equilibrium temperature, the rest is supersaturated. It is anticipated that the Na^{+}/K^{+} ratios show good correlation with the quartz equilibrium temperature (Fig. 6.4) but systematically they yield somewhat higher Na-K temperatures. This could be due to a slower re-equilibriation between feldspar and solution upon cooling in the upflow as compared with quartz and solution. It is, however, also possible that the differences are due to crystal structural differences in the assumed feldspars as compared with those occurring in the geothermal systems used in calibrating the Na-K geothermometer. If the latter explanation is correct the Na-K calibration function used yields on the average higher Na-K temperatures, probably by some 25°C.

It has been shown that as a rule there is an evident temperature dependence of $\sqrt{Ca^{+2}}/H^{+}$ activity ratios in geothermal reservoir waters (Arnorsson et al., 1978; Palmason et al., 1979). It is not known however which minerals are involved. The Madagascar waters selected for computer analysis all shown low $\sqrt{Ca^{+2}}/H^{+}$ activity ratios at measured water temperature, but many of them display "equilibrium" ratios at quartz equilibrium temperature (Fig. 6.5).

Comparison of the chemical composition of samples permits deductions to be made as to the equilibrium control of the overall chemistry of samples not run through the computer program.

The following rules have been adopted to strengthen or impair the geothermometry results:

(1) Calcite-undersaturated waters (at measured water temperature) with very low $\sqrt{Ca^{+2}}/H^{+}$ ratios, especially if they are of low temperatures and low in dissolved solids, are assumed to be non-equilibrated waters. Chemical geothermometry is not applicable to such waters.

(2) Geothermometry results are uncertain if $\sqrt{Ca^{+2}}/H^{+}$ ratios are low, even if equilibrium exists with respect to calcite, anhydrite, and fluorite, especially when there is large discrepancy (more then 50 °C) between the quartz and Na-K geothermometers. The low $\sqrt{Ca^{+2}}/H^{+}$ ratios and the difference between the two above mentioned geothermometry temperatures may have resulted from mixing of cold water with geothermal water in the upflow.

(3) When waters show calculated equilibrium ratios for $\sqrt{Ca^{+2}}/H^{+}$ and the quartz and Na-K temperatures differ by less than about 25 °C, the geothermometry results are belived to be reliable in the sense that they reflect true underground temperature conditions.

(4) If waters are calculated to be anhydrite and/or fluorite-saturated at quartz equilibrium temperature, in addition to fullfilling the requirements in item (3) above, this is assumed to give further confidence in the geothermometry results.

Table 6.1 summarizes the results for the samples selected for the computer analysis. Individual analyses are dealt with in chapter 7.

The chemical geothermometry temperatures have been calculated for all the collected samples. The results are listed in Appendix 5. Fig. 6.6 shows comparison between the quartz temperature and the temperature based on feldspar equilibrium. Some samples yield "unreasonably" high Na-K temperatures and have a low or relatively low silica concentration. All these samples fall under the first category, previously mentioned. Here they are grouped as cold ground waters or surface waters. The majority of these cold waters are located in a similar geological environment; sediments of Mesozoic to Quaternary age in western Madagascar.

Table 6.1
State of saturation with respect to selected geothermal minerals. The reference temperature was taken to be that of equilibrium with quartz, except for calcite where measured temperature was used.

Sample no.	Calcite	Anhydrite	Fluorite	Feldspar	$\sqrt{Ca}/H$ 1)
0001	s	u	u	s	e
0005	e	u	u	e	e
0006	u	u	u	s	u
0010	s	e	u	s	e
0011	e	u	u	s	u
0012	s	e	u	e	e
0014	s	e	u	e	e
0016	s	u	u	s	e
0017	e	u	u	e	e
0018	e	u	e	e	e
0021	s	u	u	s	u
0022	e	u	u	s	e
0024	s	u	u	e	e
0030	e	u	u	e	e
0032	s	u	u	e	u
0037	e	u	u	s	u
0043	e	e	u	s	u
0044	e	e	e	s	u
0050	e	e	e	e	e
0052	e	s	u	e	e
0059	e	e	e	s	e
0065	e	u	u	e	e
0067	u	u	u	s	u
0068	e	e	e	e	e
0072	s	e	e	s	e
0073	e	u	e	s	e
0080	e	u	u	e	s
0083	e	u	e	e	e
0085	u	u	u	e	u
0089	s	e	e	e	e
0091	e	u	u	e	e
0093	u	u	e	e	u
0094	e	u	u	s	u
0096	e	u	u	u	u
0099	e	u	u	u	e
0107	s	u	u	e	e
0109	e	u	u	s	e
0110	s	u	u	s	e
0114	s	e	u	s	u

s, e and u indicate supersaturation, equilibrium, and undersaturation respectively. Supersaturation for feldspar is taken to exist, if the Na-K temperature exceeds the quartz equilibrium temperature by more than 25 °C. 1) Significant departure from equilibrium is taken to be ± 0.5 log $\sqrt{Ca}/H$.

Fig. 6.1

The state of calcite saturation in selected waters referring to measured temperature (A) and quartz equilibrium temperature (B)

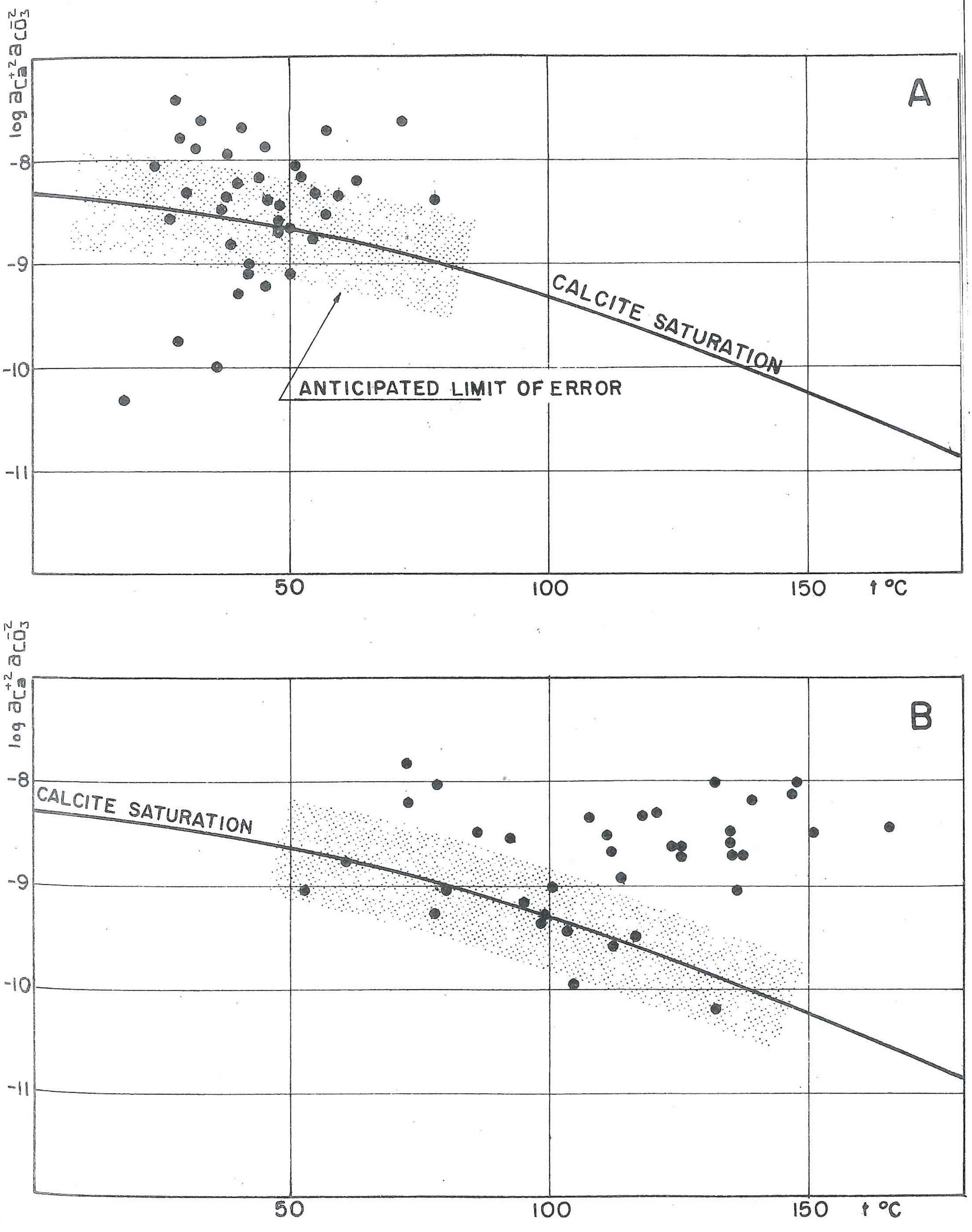
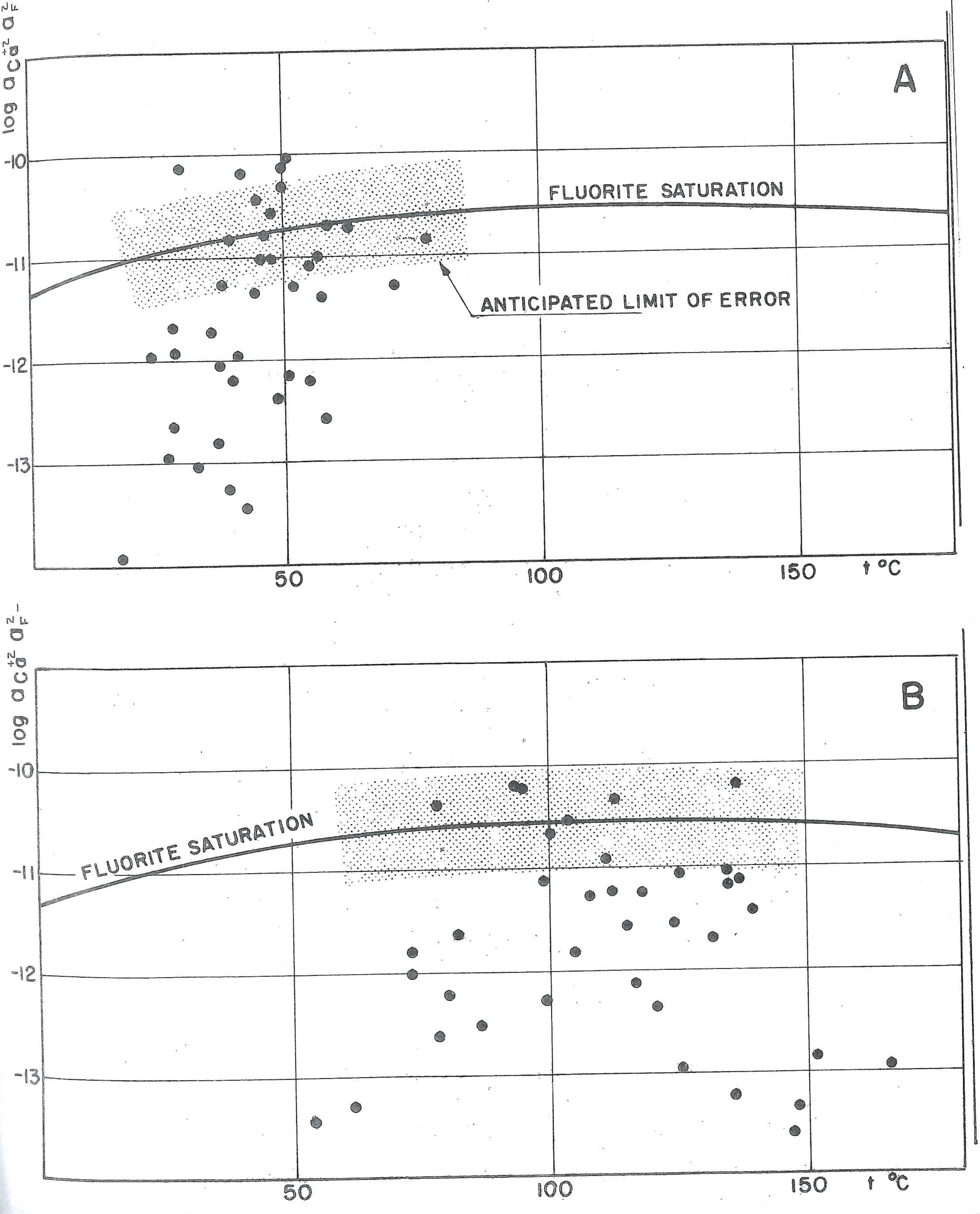


Fig. 6.2

The state of fluorite saturation in selected waters referring to measured temperature (A) and quartz equilibrium temperature (B)



The state of anhydrite saturation in selected waters referring to measured temperature (A) and quartz equilibrium temperature (B)

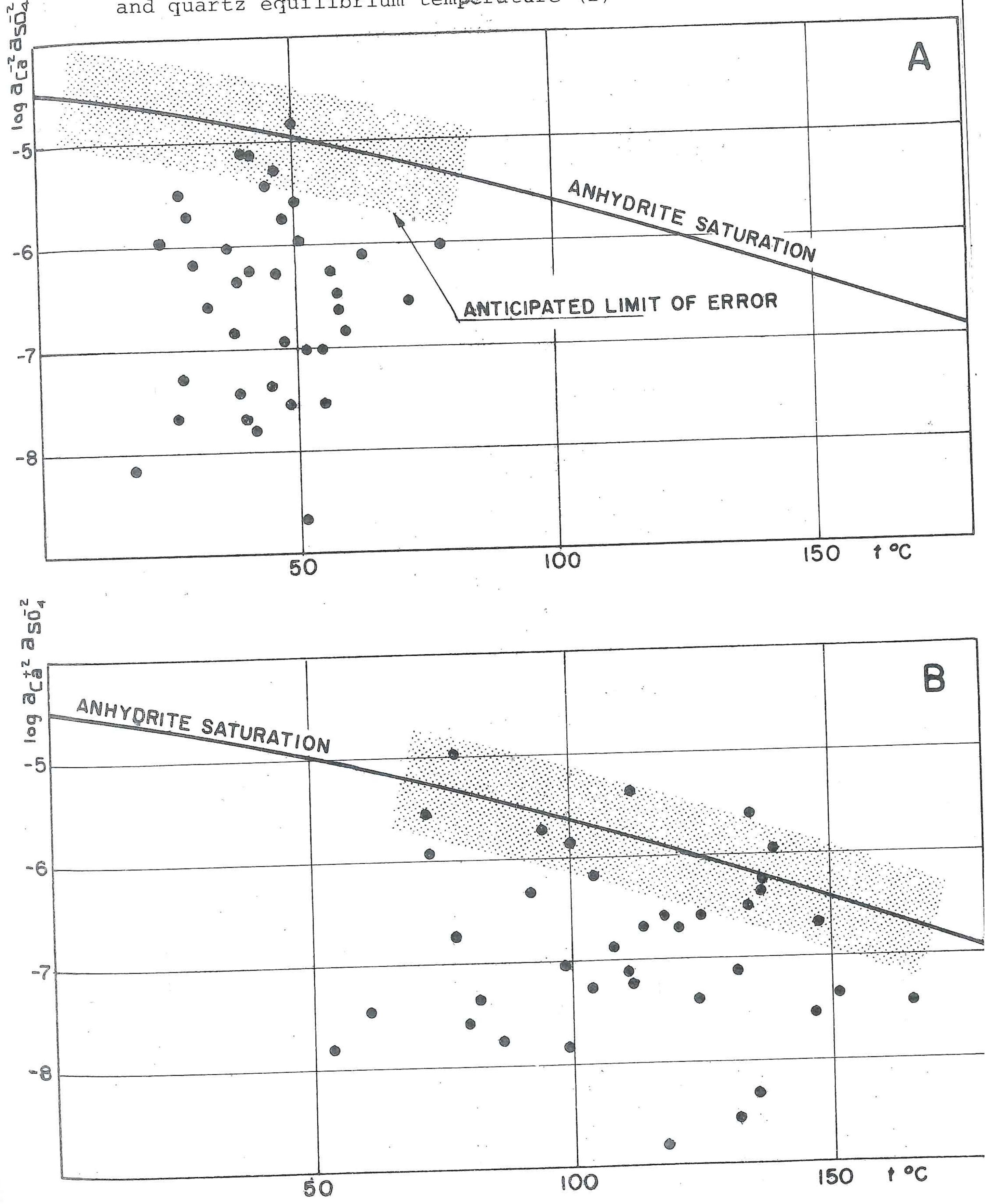


Fig. 6.4

Na^+/K^+ ratios in thermal waters in relation to equilibrium with Na and K-feldspars referring to measured temp (A) and quartz equlibrium temp (B)

a

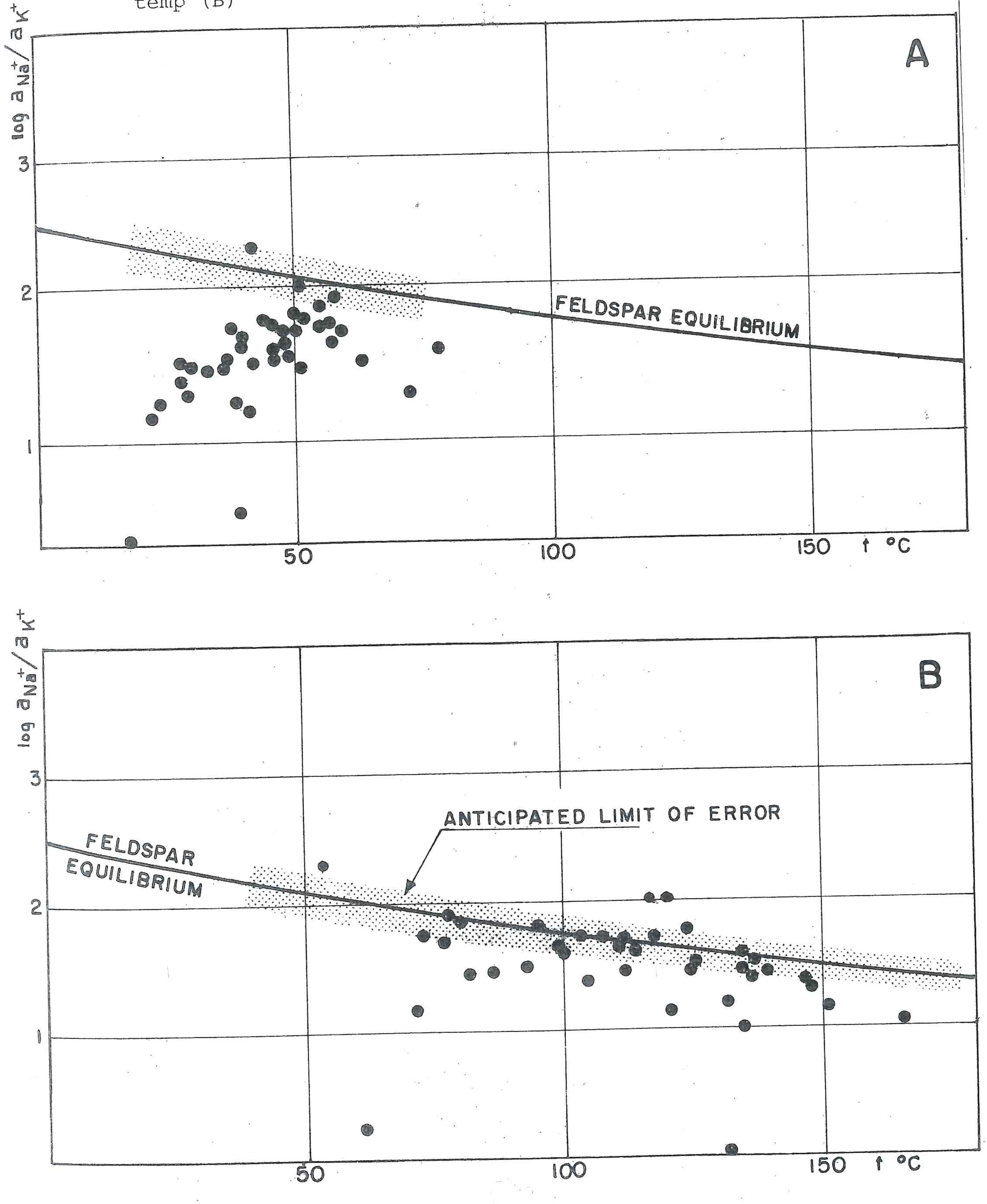
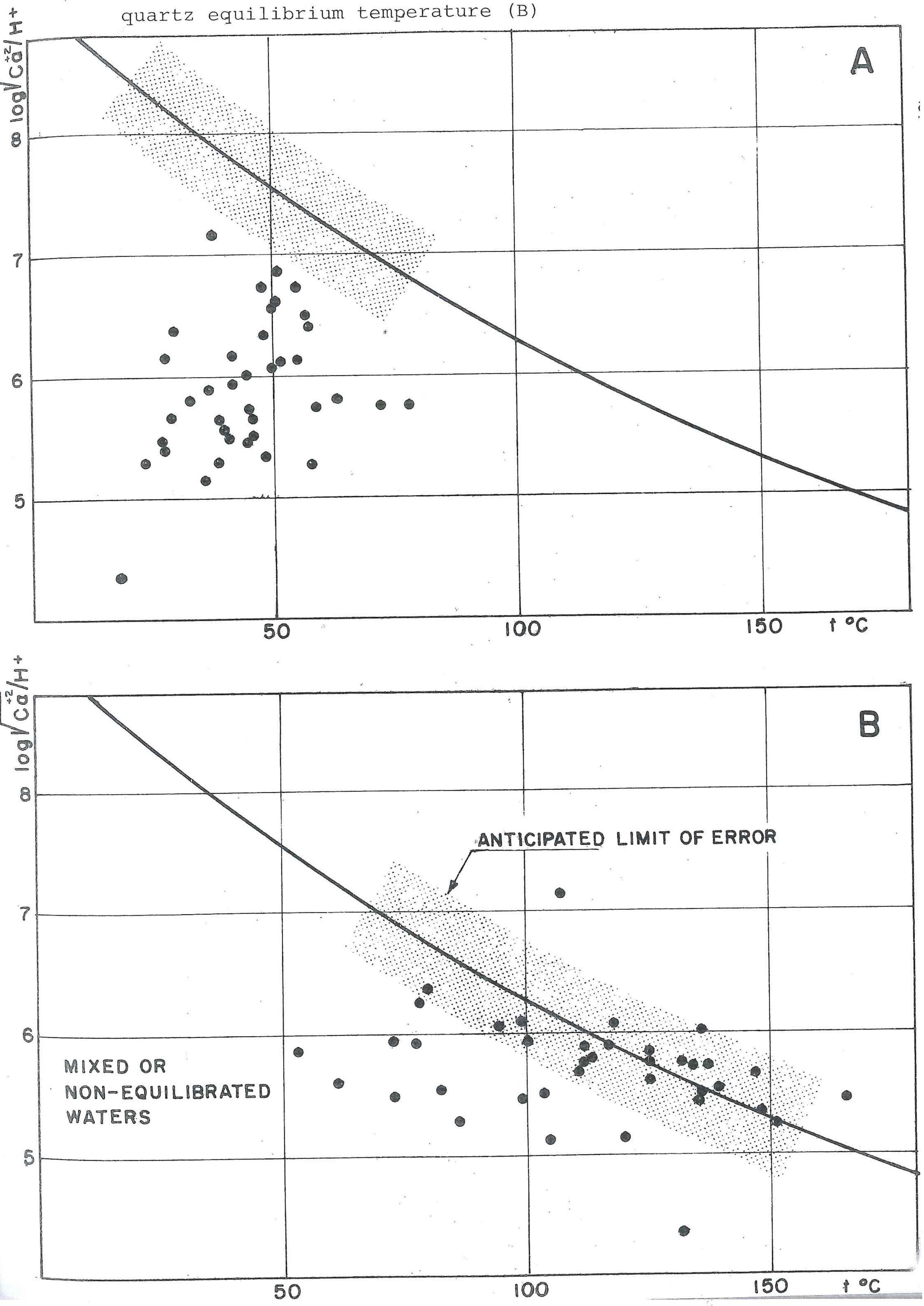
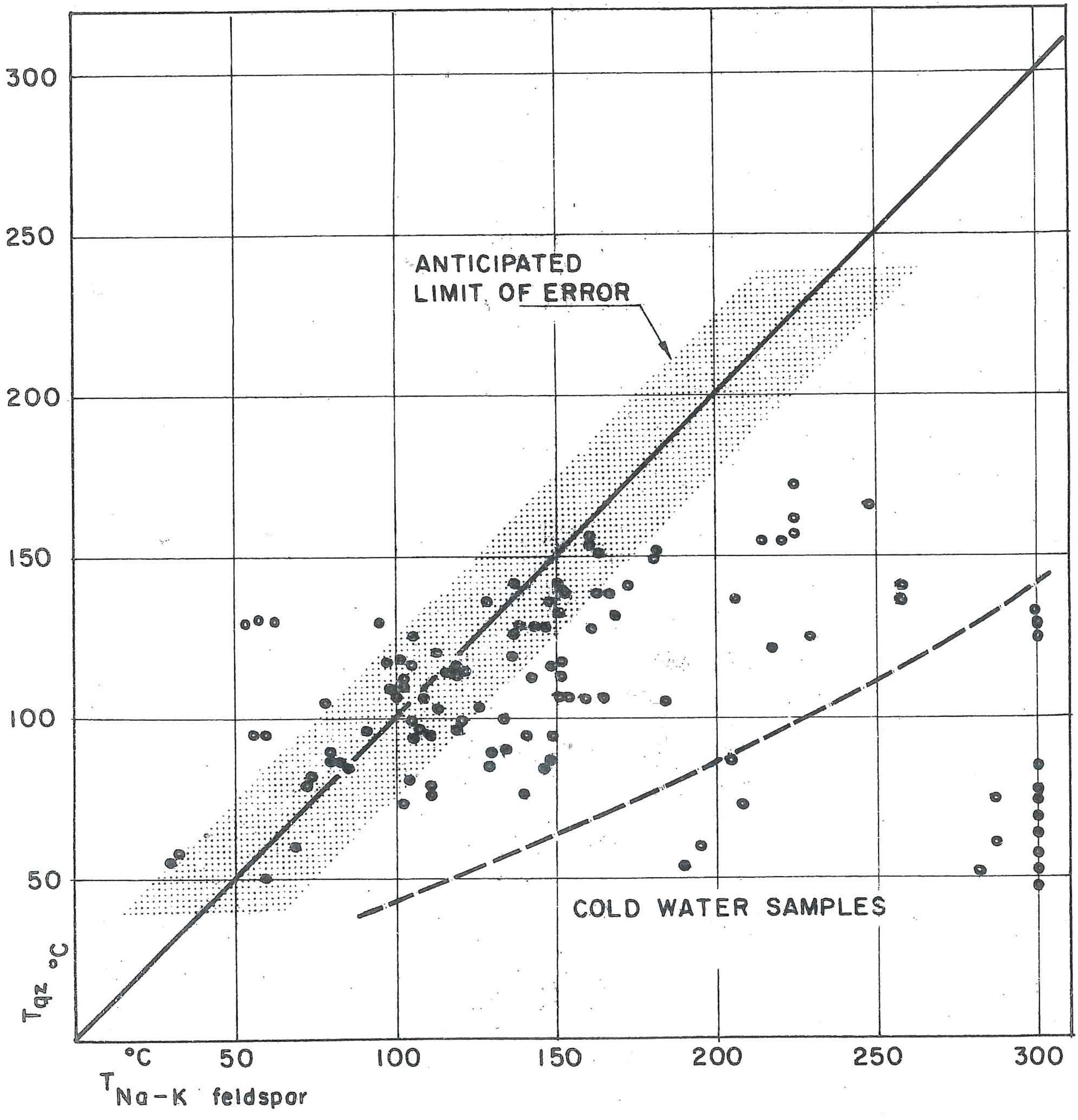


Fig. 6.5

The temperature dependence of $\sqrt{Ca^{+2}}/H^+$ referring to measured temperature (A) and quartz equilibrium temperature (B)



Comparison between $T_{Na-K\ feldspar}$ and T_{quartz}



7. RESULTS

In this chapter the results from each geothermal area will be discussed separately. It may be difficult to define what one thermal area is, especially in the lowest temperature regions. Here geothermal manifestations in Madagascar have been divided into 21 areas or regions. This division is based on geographical location, geological features and the chemistry of the waters. Figure 7.1 shows this division.

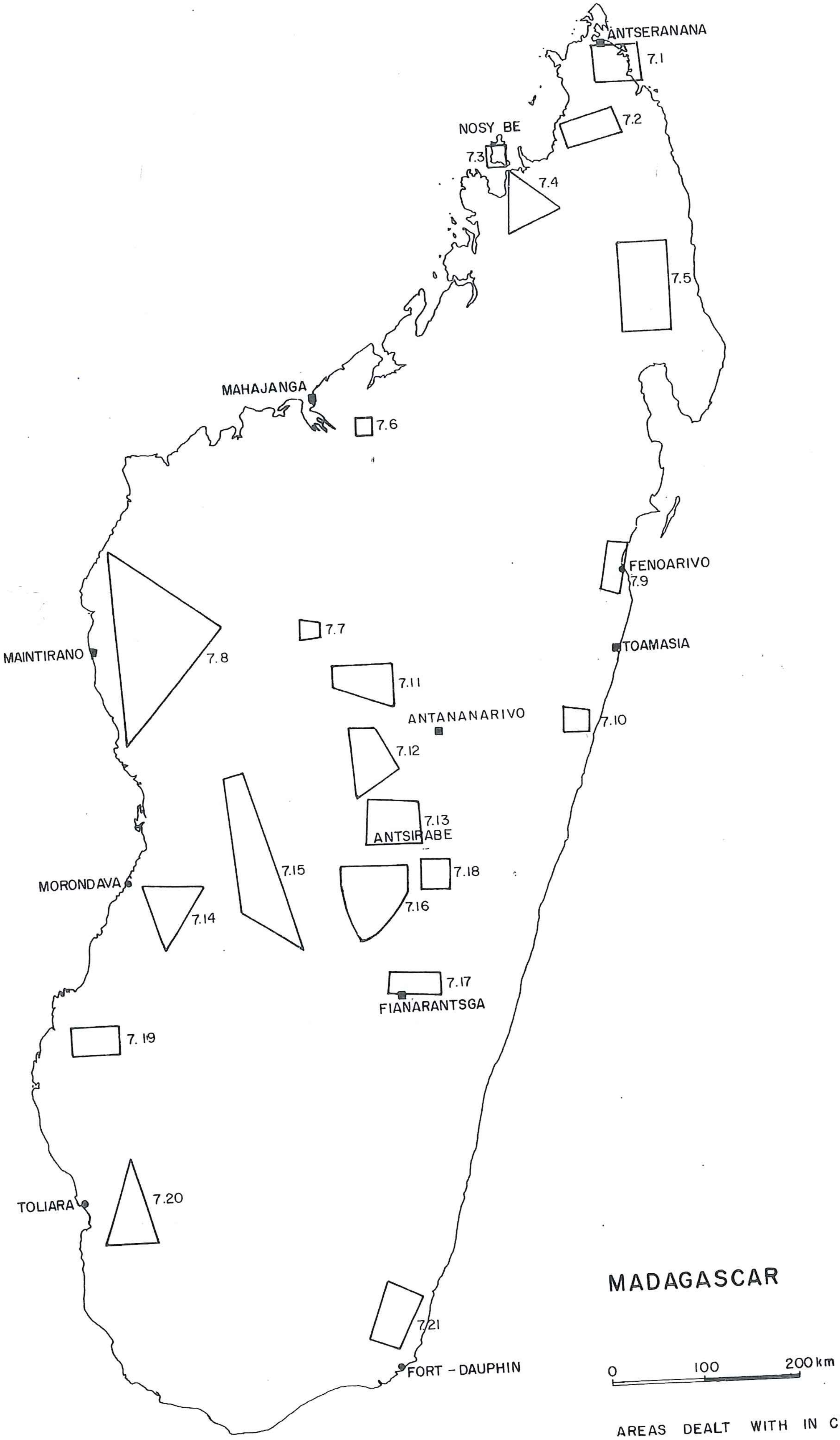
Each of the following sections is divided into three subsections:

a) Geology

b) Geothermal manifestations

c) Chemical geothermometry

The geological part is based on the general geological map of Madagascar in scale 1:1.000.000, on detailed geological maps (scale 1:100.000) where available, and on the report "Contribution á l'étude des sources minerales et des eaux souterraines de Madagascar" by Besairie (1959). The geological part does not deal with geological features in detail, but is, considered to be useful as it connects geothermal manifestations with geological features. Appendix 1 shows a schematic geological map of Madagascar with Quaternary and Createaceous igenous rocks, the main fracture zones, and the location of all known thermal manifestations. This map is based on the geological map (1:1.000.000), the geological map by G. Hottin (1:2.000.000) (Hottin 1976), and photographical maps (1:500.000) where the Service of Energy in Madagascar has located all thermal manifestations sampled. As discussed in Chapter 6 selected samples (40) have been run through a water chemistry computer program for the study of equilibrium conditions and the interpretation of the chemical geothermometry results. The geothermometry results for each area are summarized in tables at the end of each section of



AREAS DEALT WITH IN CHAPTER 7

Fig. 7.1

this chapter. These tables only incorporate those geothermometer results which are believed to be the most valuable for estimating underground temperatures (see discussion at the end of Chapter 4). A full tabulation of all geothermometry temperatures is incorporated in Appendix 5.

7.1 Antseranana Area

Samples: 790021 and 790022

7.1.1 Geology

The northermost part of Madagascar, the Ambre mountains, consists mainly of Quaternary and Pleistocene igneous rocks.

7.1.2 Geothermal manifestations

Two samples were collected from this area, from "Source de Sakaramy" (790022) and "Source d'Amranomandery" (790021). The temperature of both springs is low, 27 °C and 29°C, respectively. Flow rate of springs is low, less than 0.5 litres/sec. "Source de Sakramy" is located within the igneous rock formations but "Source d'Amranomandery" at their border.

7.1.3 Chemical geothermometry

The analyses of both these water samples were run through the computer program. The water at Andranomandery (790021) is assumed to represent a typical cold carbonate water, as equilibrium conditions are not identified with respect to any parameter (see Chapter 6). The high Na-K temperature results from non-equilibrium conditions and is not indicative of high underground temperatures. The other water (790022) is in equilibrium with calcite at measured temperature and the $\sqrt{Ca}/H$ ratio corresponds to equilibrium at quartz temperature. As a result the high Na-K temperature is thought to be due to non-equilibrium conditions with respect to feldspar. The high Na-K-Ca temperature when using β = 1/3 (see Appendix 5) results from low non-equilibrium Na-K ratio. In calculating the Na-K-Ca temperature, a β value of 4/3 is appropriate. The large difference between the quartz and the Na-K temperatures was in one of the progress reports for this study suggested to be due to mixing of the hot water with cold water. Mixing seems, however, an unlikely explanation since the $\sqrt{Ca}/H$ ratio fits equilibrium at the quartz temperature and a low $\sqrt{Ca}/H$ ratio is to be expected if mixing has occurred. It is concluded from quartz equilibrium and the Na-K-Ca geothermometer that underground temperature at Sakaramy does not exceed much more than 100 °C.

Table 7.1 Chemical geothermometry results in °C for the Antseranana Area.

Location	Sample no	$T_{meas.}$	T_{quartz}	$T_{Na\text{-}K}^{1)}$	$T_{Na\text{-}K}^{2)}$	$T_{Na\text{-}K\text{-}Ca}$
Andranomandevy	790021*	29	73	202	208	63
Sakaramy	790022	27	136	254	258	96

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1
* Cold non-equilibrated water.

7.2 Ambilobe Area

Samples: 790013, 790014, 790023, 790024, 790025.

7.2.1 Geology

The geology of this area is rather complicated. The exposed rocks are mainly Trias sediments and metamorphic rocks. They are cut by a few basaltic dykes. No other igneous rock seems to exist in the area. A NE-SW running fracture zone (the Andavahoere fracture zone) separates the metamorphic rock from sediments of Karroo and of later age.

7.2.2 Geothermal manifestations

Five samples of thermal water were collected in this area. These thermal areas are connected to the Andavahoere fracture zone. The temperatures range from 47 °C to 78 °C. The highest temperature measured in thermal water in Madagascar is at Betsiraka in this area. The total flow rate from this area appears to be low. For springs in the vicinity of the sampling sites it is estimated as 4 litres/sec.

7.2.3 Chemical geothermometry

The quartz, Na-K and Na-K-Ca temperatures compare rather well for four of the five water samples from this area. One sample, from Ambalobe (790013), shows a difference of 37 °C between the quartz and the Na-K temperatures the latter being higher. The overall chemistry of all the samples is very similar. Two of these samples (790014, 790024) were run through the computer program. These samples are considered to be representative for all samples from this area. They display equilibrium conditions for $\sqrt{Ca}/H$ and calcite at quartz and measured temperatures respictively, and one of them (790014) is anhydrate-saturated at quartz equilibrium temperature. It is concluded that underground temperatures in the Ambilobe Area are in the range 100-160 °C.

Table 7.2 Chemical geothermometry results in °C for Ambilobe Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
"Source de region d'Ambilobe"	790013	59	132	161	169	176
Betsiraka	790014	78	141	128	138	155
Ampahaka	790023	47	155	152	161	171
Andranomafanakely	790024	57	125		105	99
Andranomafanabe	790025	58	115	108	119	140

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1

7.3 Nosy Be

Samples 800107, 800108

7.3.1 Geology

The island of Nosy Be is mainly built up of igneous rocks, i.e. Quaternary volcanics and Cretaceous intrusions, but also of metamorphosed rocks (gneiss and schists) of Liassic age. The thermal springs are associated with the Quaternary volcanism.

7.3.2 Geothermal manifestations

Samples from two thermal springs in Nosy Be were collected during this project, from Tablahely and Tablahoriko, with temperatures of 33 °C and 28 °C respectively. Besairie (1959) mentions two hot springs on Nosy Be with temperatures of 30 °C and 44 °C but he uses different names to those adopted here. It is not clear if these are the same springs or whether there are more springs in Nosy Be than the two sampled for the present project. The flow rate is estimated to be 1 litre/sec in Tabalahely but about 10 litres/sec at Tabalahoriko.

7.3.3 Chemical geothermometry

The two water samples from the island of Nosy Be have a rather different chemical compositions. The water from Tabalahely (800108) has silica concentrations comparable to cold surface waters but the Na-K and Na-K-Ca geothermometry temperatures are similar for both samples, in the range 130-180 °C. The water represented by sample 800108 may have originated from sea-water mixing with the water represented by sample 800107. The high flow rate of the spring from which sample 800108 was collected supports this explanation. Sample 800107 was run through the computer program. The results indicate calcite-supersaturation at the measured temperature and $\sqrt{Ca}/H$ equilibrium at the quartz temperature. It is concluded that underground temperatures at Nosy Be are 150-180 °C.

Table 7.3 Chemical geothermometry results in °C for the Nosy Be island

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Tabalahely	800107	33	151	155	164	179
Tabalahoriko*	800108	28	77	129	140	178

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1
* Mixing with sea-water may have occurred.

7.4 Ambanja Area

Samples 790015, 790016, 790017, 790018, 790019, 790020, 800109.

7.4.1 Geology

The geothermal activity in this area is related to two fracture zones, the Andavakoera and Sambirano fracture zones. The first forms the boundary between Triasic sediments (sandstone) and metamorphic rocks (see also 7.2). The other zone has a NW-SE direction and runs parallel to the Sambirano Valley. Some outcrops of Quaternary volcanics occur parallel to this fracture zone.

7.4.2 Geothermal manifestations

Samples of geothermal water were collected from seven thermal springs in this area. Of these, three (790015, 790016 and 790017) are near the intersection of the two fracture zones. Another three samples were collected from springs which emerge near the Sambirano fracture zone (790018, 790019, 790020) in Sambirano Valley. The seventh thermal spring (sample 800109) lies further south, at the contact between sediments and metamorphic rock. It is probably linked to the Andavakoera fracture zone. The temperature of those springs ranges from 27° to 72 °C (hottest at Migiogy 790016). Some discrepancy exists between the temperature values listed by Besairie (1959) and those obtained when collecting the present samples. This may be due to changes in temperature with time or to the possibility that the two temperature measurements do not refer to the same spring.

The flow rate in the springs is low (0.1-4 litres/sec). Besairie (1959) quotes much larger flow rates in some of those springs.

7.4.3 Geothermometry

The waters in the Ambanja Area can be divided into two groups on the basis of their origin. Firstly, thermal waters which appear to have equilibrated at depth and cooled by conduction during passage to the surface, and secondly, mixed waters and non-thermal groundwater.

Four samples from this area have been run through the computer program. Three of these, Ankazohely (790017), Maevadoany (790018), also representing 790019 and Bejofo (800109) display equilibrium condition for the most important parameters tested. There is a satisfactory agreement between the quartz and the Na-K temperatures for these samples, the values lying in the range 105-150 °C. Na-K-Ca temperatures tend to be somewhat higher, or in the range 125-175 °C.

The water at Ampatamasina (790020) is considered to be cold groundwater or surface water which is indicated by its low content of dissolved solids, and supported by the description of the spring and its surroundings, where it is mentioned that the thermal water is in contact with cold water.

The sample from Migioky (790016) is in $\sqrt{Ca}/H$ equilibrium but supersaturated with calcite and feldspar referring to the measured and the quartz equilibrium temperatures, respectively. The Na-K and Na-K-Ca temperatures compare well, but the quartz temperature is significantly lower. Mixing may have occurred and be responsible for the low quartz temperatures, but it is also conceivable that mixing has led to a decrease in the Na-K ratio causing Na-K and Na-K-Ca temperatures to become high. If mixing has occurred, subsequent re-equilibration with respect to the $\sqrt{Ca}/H$ ratio has taken place. It has been attempted to use a mixing model for this sample (see Fig. 7.2). An intersept between the quartz solubility curve was not obtained. This may be the result of the cooling of the water by conduction after the mixing occurred.

The water sampled from Ambabaka (790015) yields quartz and Na-K-Ca temperatures of 86 °C and 91 °C, respectively, but the Na-K temperature is slightly above 200 °C. The measured temperature is 50 °C. The water emerges on the bank of the Ramena River only a few centimetres above water level, indicating that the mixing of the hot water with the river water is likely to have occurred. The silica enthalphy-mixing model has been used for this sample to estimate underground temperatures using the Ramena River water as the cold water component (Fig. 7.2). The application of the mixing model indicates a temperature of about 140 °C for the hot water component, which is comparable to the quartz equilibrium temperatures of the nearby Migioky and Ankazohely springs. The mixing model suggests that the ratio of cold water/hot water in the mixture is 3/1.

The quartz geothermometer indicates underground temperatures as high as 140 °C in the Ambanja Area. The Na-K and the Na-K-Ca geothermometers indicate higher temperatures for some of the samples. This may be misleading and due to mixing in the upflow.

One sample from this area, at Migioky (790016), was analysed for oxygen isotopes in water and sulphate. The result indicates subsurface temperature of 139 °C (Table 5.1) which substantiates the chemical geothermometry interpretation above.

Table 7.4 Chemical geothermometry results in °C for the Ambanja Area

Location	Sample no	$T_{meas.}$	T_{quartz}	$T_{Na-K}^{1)}$	$T_{Na-K}^{2)}$	$T_{Na-K-Ca}$
Ambobaka*	790015	50	86	207	214	91
Migioky	790016	72	136	200	206	198
Ankazohely	790017	55	116		104	77
Maevandoany	790018	46	128	129	139	150
Beangona amporiana	790019	48	132	141	151	156
Ampatamasina**	790020	27	85	>275	>300	25
Bejofo	800109	37	128	138	147	175

1) Equation (4) in Table 4.1

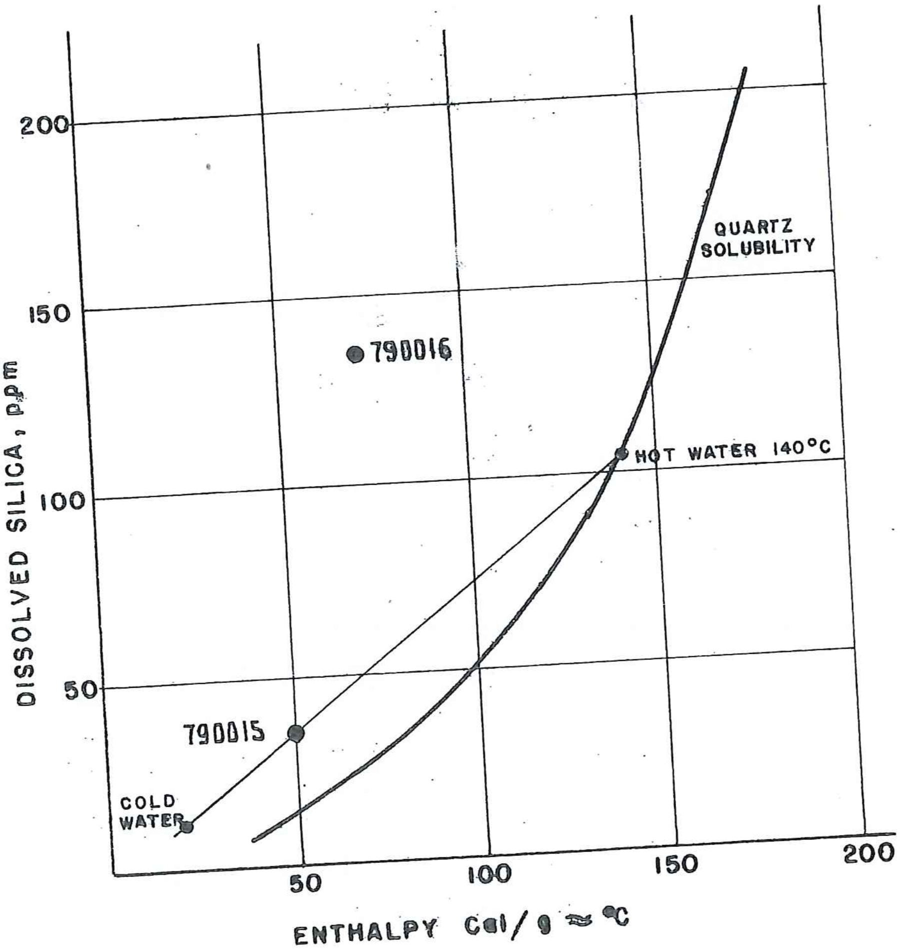
1) Equation (5) in Table 4.1

* Mixed water

** Cold non-equilibrated water.

Fig. 7.2

MIXING MODEL FOR SAMPLE 790015, AMBOBAKA



7.5 Andapa - Doany Area

Samples 800083, 800084, 800085, 800086, 800087, 800088, 800089, 800090, 800091, 800092.

7.5.1 Geology

Most of the rock in this area are metamorphic and of Precambrian or Cambrian age. Pleistocene volcanic rocks occur, however, in the southern part of the area, south of Andapa. The southernmost springs may be linked to this volcanism. Hottin (1976) shows a fracture zone with a NNW-SSE direction through the area. Most of the thermal springs are probably connected to this fracture zone. Besairie (1959) relates the thermal springs near Donay to the Andravory fracture zone, and the thermal springs near Andapa to the Anthala fracture zone.

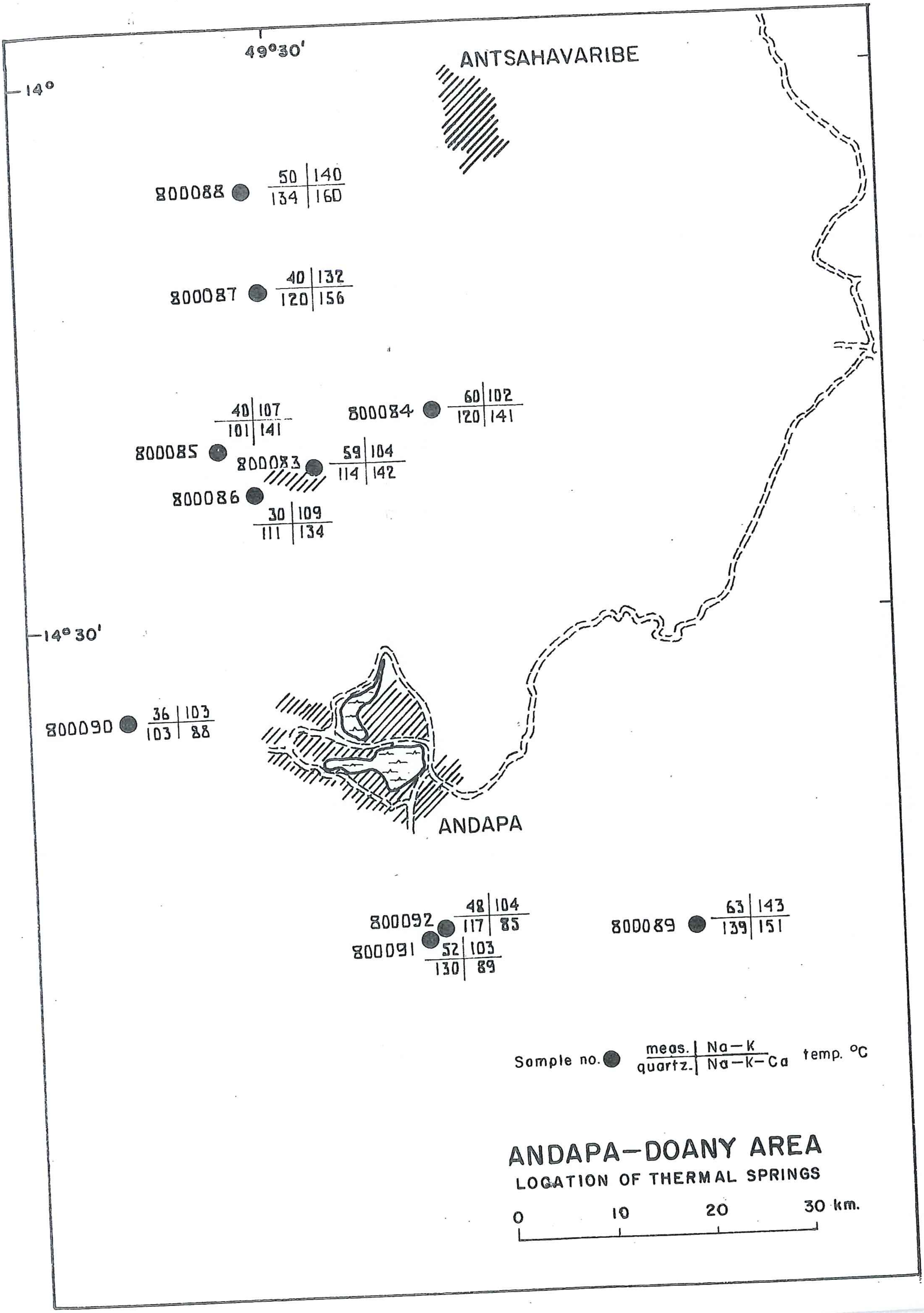
7.5.2 Geothermal manifestations

Ten samples were collected from this area. Their location is shown in Figure 7.3. The highest measured temperature, 63 °C occurs at Ambodiangezaka (800089) southeast of Andapa, but the lowest temperature is at Andranomafanahely Doany (800086), 30 °C. Estimated flow rate of individual springs ranges from 0.5 to 10 litres/sec.

7.5.3 Chemical geothermometry

Good agreement exists between the quartz and the Na-K geothermometers from this area. The Na-K-Ca temperatures are systematically somewhat higher except when the β value selected by the recommended calculation procedure becomes 4/3. Then the Na-K-Ca geothermometer yields lower temperatures than the quartz and the feldspar geothermometers. The highest underground temp-

Fig. 7.3



ANDAPA—DOANY AREA

LOCATION OF THERMAL SPRINGS

erature occurs at Ambodiangezaka (80089), 140-160 °C. Four of the samples from this area were run through the computer program for further study of equilibrium conditions. All of these samples except no. 800085 (which also represents 800086) display $\sqrt{Ca}/H$ equilibrium at the quartz temperature and calcite-saturation at the measured spring temperature. In addition, samples 800083 and 800089 are fluorite-saturated at quartz equilibrium temperature. Sample 800089 is also anhydrite saturated at this temperature. The coherence of the various mineral/solute equilibria substantiates the geothermometry results for samples 800083, 800089 and 800091.

Sample 800085 is near feldspar equilibrium at quartz temperature erature but fits with no other equilibrium, which in turn reduces the confidence in the geothermometry results for samples 800085 and 800086. In the light of the good overall conformity between the various geothermometers, it is considered that they truly reflect existing underground temperatures which may be as high as 160 °C in this area.

Table 7.5 Chemical geothermometry results in °C from the Andapa-Doany Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Ranomafana Doany	800083	59	114	104	115	142
Androranga	800084	60	120	102	113	141
Andranomlolo Doany	800085	40	101	107	118	141
Andranomafanahely Doany	800086	30	111		103	134
Ankiakabe	800087	40	129	132	142	156
Ranomafana Andranomadio	800088	50	134	140	149	160
d'Ambodiangezaka	800089	63	139	143	153	162
d'Andramonta	800090	36	103	103	114	88
de Marolakana	800091	52	130		95	89
Antsasaka	800092	48	117		97	85

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1

7.6 Saint Marie

Sample 800117.

7.6.1 Geology

Geologically this area belongs to the sedimentary sequences in Madagascar. The bedrock is mainly calcareous sandstone from Cretaceous age. According to geological maps, this thermal spring is close to Cretaceous volcanic rocks.

7.6.2 Geothermal manifestation

This thermal spring is southeast of Manjunga about 25 km SW of Manrovory. The temperature is 24 °C and the flow rate is 10 litres/sec.

7.6.3 Chemical geothermometry

The chemical composition of this water sample is similar to non-equilibrated cold groundwater. The chemical geothermometers are therefore not applicable. It is not possible to calculate the cation temperatures for this water because potassium is below detection limit. It should be kept in mind that higher Na-K ratio correspond to lower temperatures. Anomalous underground temperatures are not expected at this site.

Table 7.6 Chemical geothermometry results in °C for the Saint Marie sample

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Saint Marie	800117	24	85			

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1

7.7 Andasibe

Sample 800116.

7.7.1 Geology

This area is located in Precambrian bedrock. No volcanic rocks are known and the thermal spring cannot be related to any of the main fracture zones.

7.7.2 Geothermal manifestation

This 51 °C hot spring is located about 15 km south of Andasibe in the valley Antsahanavony. The flow rate is about 1 litre/sec.

7.7.3 Chemical geothermometry

The quartz equilibrium temperature for this sample is somewhat higher than the cation temperatures. The silica concentration is slightly higher than in most cold waters. It is possible that chalcedony equilibrium is attained but not quartz equilibrium; chalcedony temperature (75 °C) and the Na-K, Na-K-Ca temperatures compare well. It is not anticipated that underground temperatures much (by 25 °C) higher than those measured at the surface are to be expected.

Table 7.7 Chemical geothermometry results in °C for the Andasibe Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Andasibe	800116	51	105		68	74

1) Equation (4) in Table 4.1

2) Equation (5) in Table 4.1

7.8 Maintirano Area

Samples 800101, 800102, 800103, 800104, 800105, 800106.

7.8.1 Geology

This area belongs to the western sedimentary basins (Morondava basin). The sediments are of the continental type and are of Cretaceous, Jurassic and Pre-Jurassic age. In the western part of this area volcanic lavas of Cretaceous age occur. Two of the collected water samples (800104, 800105) flow through, or are located at the edge of, these lavas. Doleritic dykes (presumably Cretaceous) are common and three of the thermal springs sampled (800101, 800102, 800103) are linked to the dolerite dykes. A NNW-SSE running fracture zone (Bemaraha fracture zone) stretches through the area, and the thermal water of Bemonto (800106) seems to be connected with this zone.

7.8.2 Geothermal manifestations

The temperature of the six springs in this area ranges from 27 °C to 43 °C. The thermal springs of the lowest temperatures are linked to dykes but the highest temperature springs are near the Cretaceous volcanics. The estimated flow rate in individual springs is in the range 1-8 liters/sec.

7.8.3 Chemical geothermometry

The chemistry of the water samples is similar to that of groundwater to which carbon dioxide has been added. In only two of the six samples the silica concentration is higher than is usually the case for cold groundwater. Samples with similar composition have been run through the computer program. These reflect non-equilibrium conditions for their chemical compositon. Extremely high Na-K temperatures are typical for this type of water. The chemistry of these spring waters is not taken to be indicative of anomalous underground temperatures.

Table 7.8 Chemical geothermometry results in °C for the Maintirano Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Folakara*	800101	28	126	>275	>300	272
Antanandava*	800102	38	68	>275	>300	38
Berohay*	800103	27	63	>275	>300	36
Ampoza Bebai*	800104	42	77	>275	>300	37
Ankilimahasoa*	800105	43	68	>275	>300	38
Benmonto*	800106	38	128	>275	>300	262

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1
* Non-equilibrated groundwater.

7.9 Fenerive Area

Samples 800079, 800080, 800081, 800082.

7.9.1 Geology

The bedrock in this area is composed of metamorphosed schists of Precambrian age. No volcanic rocks are known but Cretaceous dolerite dykes are common (geological map by Hottin 1976). A NNE-SSW running fracture zone cuts the area, and the thermal activity seems to be connected to it.

7.9.2 Geothermal manifestations

Waters from four thermal springs were collected during this project. The highest temperature is 65 °C at Marantsandry with an estimated flow rate of 10 litres/sec. Besairie (1959) reports temperatures in the range 60-70 °C for this spring site and a total flow rate of 18 litres/sec. The temperature in other thermal springs is lower (35-38 °C) and the flow rate is less than 1 litre/sec for individual springs.

7.9.3 Chemical geothermometry

The water chemistry of the springs in this area is rather uniform. A rather good agreement exists between the quartz temperature and the Na-K and Na-K-Ca temperatures. One of these samples, Vohitsara (80080) was run through the computer program, indicating equilibrium for calcite at the measured temperature, the $\sqrt{Ca}/H$ ratio is somewhat high but anhydrite- and fluorite- undersaturation is observed. It is concluded from the chemical geothermometry that underground temperatures of about 100 °C exist in the Fenerive Area.

Table 7.9 Chemical geothermometry results in °C for the Fenerive Area

Location	Sample no	$T_{\text{meas.}}$	T_{quartz}	$T_{\text{Na-K}}$ 1)	$T_{\text{Na-K}}$ 2)	$T_{\text{Na-K-Ca}}$
Marantsandry	800079	65	108		99	131
Vohitsara	800080	38	110		103	91
Ambilanifotsialana	800081	35	99		105	87
Vohibato	800082	36	106		108	72

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1

7.10 Ranomafana Est (Brickaville)

Sample 790026.

7.10.1 Geology

The bedrock in this area is Precambrian gneiss or migmatite. Pleistocene volcanic rocks occur 15-20 km south and southeast of the hot spring site but relation between the two seems improbable.

7.10.2 Geothermal manifestation

This hot spring is located about 28 km SW of Brickaville and about 2 km SE of the village Ranomafana Est. The temperature is 55 °C and the flow rate was estimated to be 4 litres/sec. Besairie (1959) mentions six other thermal springs in this area.

7.10.3 Chemical geothermometry

The water composition of this sample is similar to the composition of the samples collected from the Fianarantsoa Area (Chapter 7.17). One sample from that area was run through the computer program and showed that the water had equilibrated for $\sqrt{Ca}/H$ and feldspar at the quartz temperature and for calcite at the spring temperature. By comparison it is deduced that a similar state of equilibration has been attained for the water at Ranomafana Est. The chalcedony temperature for this sample is practically identical to the measured temperature in the spring. It is conceivable that this rather warm water has equilibrated with chalcedony and not with quartz. If not, geothermometry indicates underground temperatures of about 100 °C or even somewhat higher.

Table 7.10 Chemical geothermometry results in °C for the Ranomafana Est sample

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Ranomafana Est	790026	55	89	118	130	70

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1

7.11 Fenoarivo/Ikopa Area

Samples 800048, 800049, 800050, 800051, 800113, 800114, 800115.

7.11.1 Geology

The bedrock in this area is Cambrian granite and migmatite. No recent volcanic rocks are known to exist in the area. Besairie (1959) connects the thermal springs in the Ikopa Valley (800048, 800049, 800050, 800051) to a fracture which runs parallel to the river. Further west, at Fenoarivo the manifestations (800113, 800114, 800115) seem to be linked to a NW-SE running fracture which connects two N-S fractures, stretching south beyond the Itasy Area and 270 km towards north.

7.11.2 Geothermal manifestations

The thermal springs in this area can be divided into two groups, one includes thermal springs along the Ikopa Valley and the other springs near Fenoarivo. The temperature in the first group is in the range 42-51 °C, but 31-51 °C in the second group. The flow rate from individual springs is usually low (1 to 2 litres/sec) except for the hot spring at Malailay (800113) where the flow rate is estimated to be 10 litres/sec.

7.11.3 Geothermometry

The two groups of springs previously mentioned have a different chemical composition. One sample from each group was run through the computer program for evaluating equilibrium conditions. The composition of the sample taken to represent the samples collected in the Ikopa Valley is calculated to be anhydrite- and fluorite-saturated at quartz temperature with $\sqrt{Ca}/H$ equilibrium value and in equilibrium with calcite at the measured water temperature. The quartz and Na-K temperatures compare well for two samples but poorly for the other two. There is a good conformity between chalcedony and Na-K-Ca temperatures for all samples and Na-K temperatures also for two of them. From this it seems likely that underground temperatures may not exceed those measured in springs by more than 20 °C and accordingly be in the approximate range of 60-70 °C.

The computer analysis of sample 800114 from Malailay indicates calcite-supersaturation and a low $\sqrt{Ca}/H$ ratio at measured and quartz temperatures, respectively. This low $\sqrt{Ca}/H$ could originate from mixing which would explain the discrepancy between the quartz and the Na-K geothermometry results, in which case underground temperatures would be expected to be as high as 150-160 °C. This is, however, not convincing since Na-K-Ca temperatures are much lower (70-80 °C) and compare well with chalcedony equilibrium temperatures. A conservative estimate of underground temperatures in this area is therefore 70-80 °C and the optimistic estimate 150 °C.

The sample from Malailay (800114) was analysed for oxygen isotopes in water and in sulphate. The isotope distribution indicates subsurface temperature of 84 °C (Table 5.1). The result favours the concervative interpretation of the chemical geothermometry results.

Table 7.11 Chemical geothermometry results in °C for the Fenoarivo/Ikopa Areas

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Andranomafananandriana	800048	51	95		59	52
Antsira	800049	42	95		58	66
Anjohibe	800050	50	96		91	60
Sahalolo	800051	48	96		107	69
Malailay	800113	51	113	107	118	78
Malailay	800114	36	105	152	162	71
Ankohabe	800115	31	98	109	120	72

1) Equation (4) in Table 4.1

2) Equation (5) in Table 4.1

7.12 Itasy Area

Samples 790008, 790009, 790010, 790011, 790012, 800052, 800053, 800054, 800110.

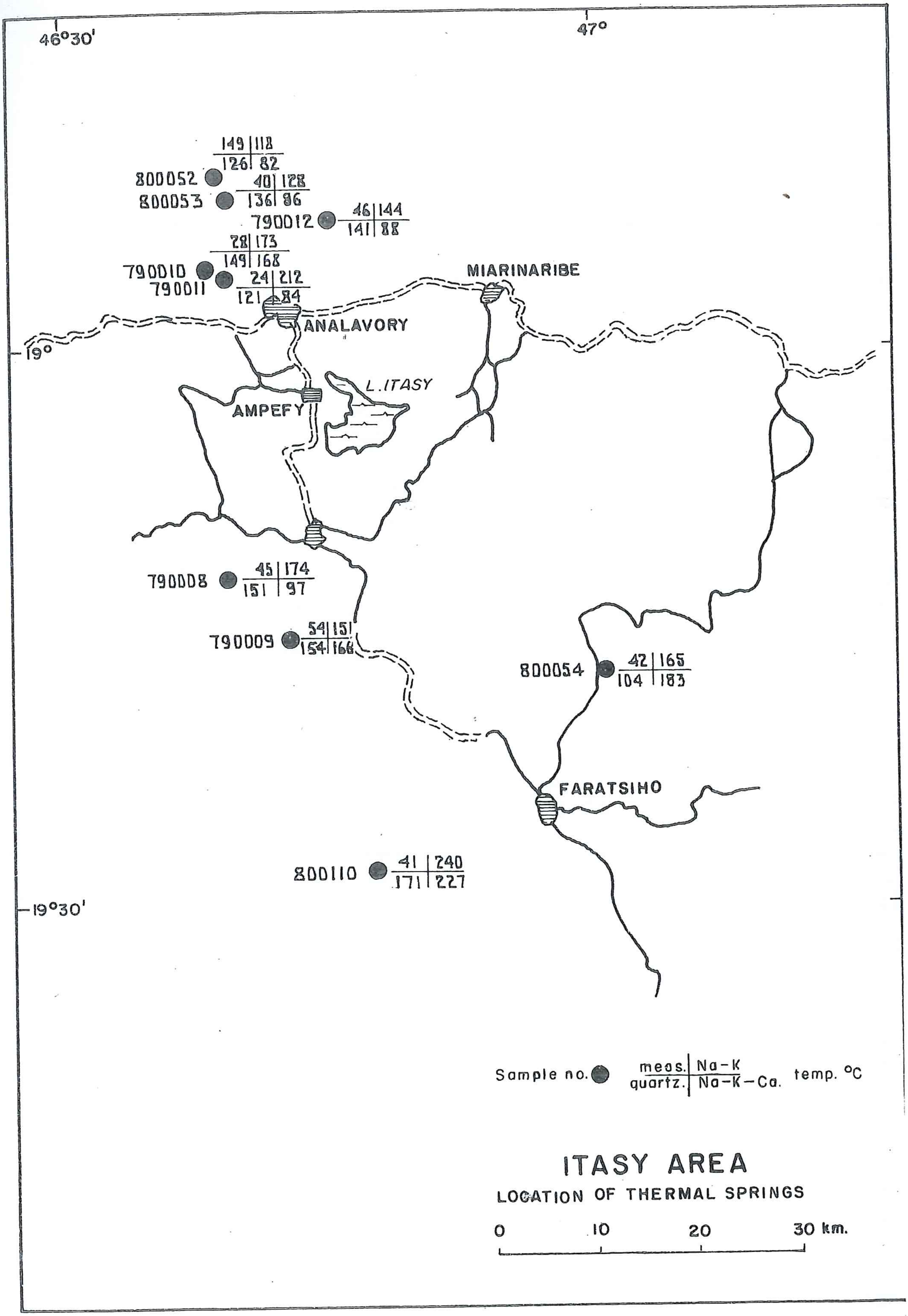
7.12.1 Geology

The area west of the Lake Itasy is covered with Pleistosene volcanic rocks (Itasy volcanism). Most of the thermal manifestations are connected to this volcanic rock series. The two thermal springs near Faratsio (800054, 800110) are, however, related with the Pleistocene volcanic rock of Ankararatra but they occur near the northwestern margin of this formation.

7.12.2 Geothermal manifestations

Nine thermal springs were sampled in this area. Their location

Fig. 7.4



ITASY AREA

LOCATION OF THERMAL SPRINGS

is shown in Fig. 7.4. These springs can be divided into three groups on the basis of their location. Five springs with temperature of 24-49 °C were sampled north of Analavary. They are all located near the margins of lava flows. The flow rate ranges from 2 to 10 litres/sec. The second group is south and west of Soavinadriana. In this group, water from two springs, with temperature of 45 °C and 57 °C was sampled. These springs emerge from gneissic bedrock although their location is within the volcanic region. Two springs were sampled from the third group which is near Faratsiho. Their temperatures are 41 °C and 42 °C. These springs are associated with the Ankaratra volcanics.

7.12.3 Chemical geothermometry

The chemistry of the samples from the Itasy Area indicates relatively high underground temperatures (Table 7.12). Six of the nine samples analysed show relatively good comparison between quartz equilibrium and Na-K temperatures but three samples show Na-K temperatures which are higher by 60-90 °C. The Na-K-Ca geothermometer does not conform well with the two other geothermometers. The calculatec value for the Na-K-Ca temperature is very sensitive to the β value selected by the recommended procedure. If a β value of 1/3 is assumed in all cases, a rather good conformity with the Na-K geothermometer is observed.

Five of the nine samples collected from this area were run through the computer program. Samples for which conformity between the quartz and Na-K geothermometers is observed also display equilibrium valued for $\sqrt{Ca}/H$ at quartz equilibrium temperature and calcite saturation or supersaturation at the measured temperature. This result is considered to strengthen the interpretation of the predicted high underground temperatures. A similar conformity is observed for samples where discrepancy occurs between quartz and Na-K temperatures, with the exception of sample (790011) which displays the largest difference. Here a low √Ca/H ratio is obtained. This is assumed to inditace mixing.

The waters from Andranoriangotraka (790010) and Sahasarotra (800110) are saturated with amorphous silica at the measured water temperatures in the springs. It is therefore possible that a deposition of this phase has occurred underground which would cause quartz temperatures to be low.

It has been attempted to use mixing models for those waters displaying large differences between the quartz and Na-K temperatures. An intersept between the quartz solubility curve and the mixing line is only obtained for one sample, 800054 (Fig. 7.5). This may be the result of cooling of water by conduction after mixing occurred. The mixing model indicates a temperature of 140-170 °C for the hot water component in sample 80054, the exact value depending on the assumed silica concentration in the cold water component.

The geothermometry results for the Itasy Area indicate underground temperatures as high as 170 °C. They may be higher as indicated by the Na-K and Na-K-Ca temperatures for samples 790011 and 800110, if sample 790011 is mixed water and amorphous silica precipitation has occurred underground for sample 800110. These results are however not substantiated by the mixing model and should for that reason be regarded as uncertain.

7.12.4 Oxygen water-sulphate isotope thermometry

Four samples were analysed for oxygen isotopes in water and sulphate. The results are similar for all the samples and lie in the range of 129-152 °C (Table 5.1). Thus the isotope results indicate subsurface temperatures slightly lower than the chemical geothermometry results.

MIXING MODEL FOR THE ITASY AREA

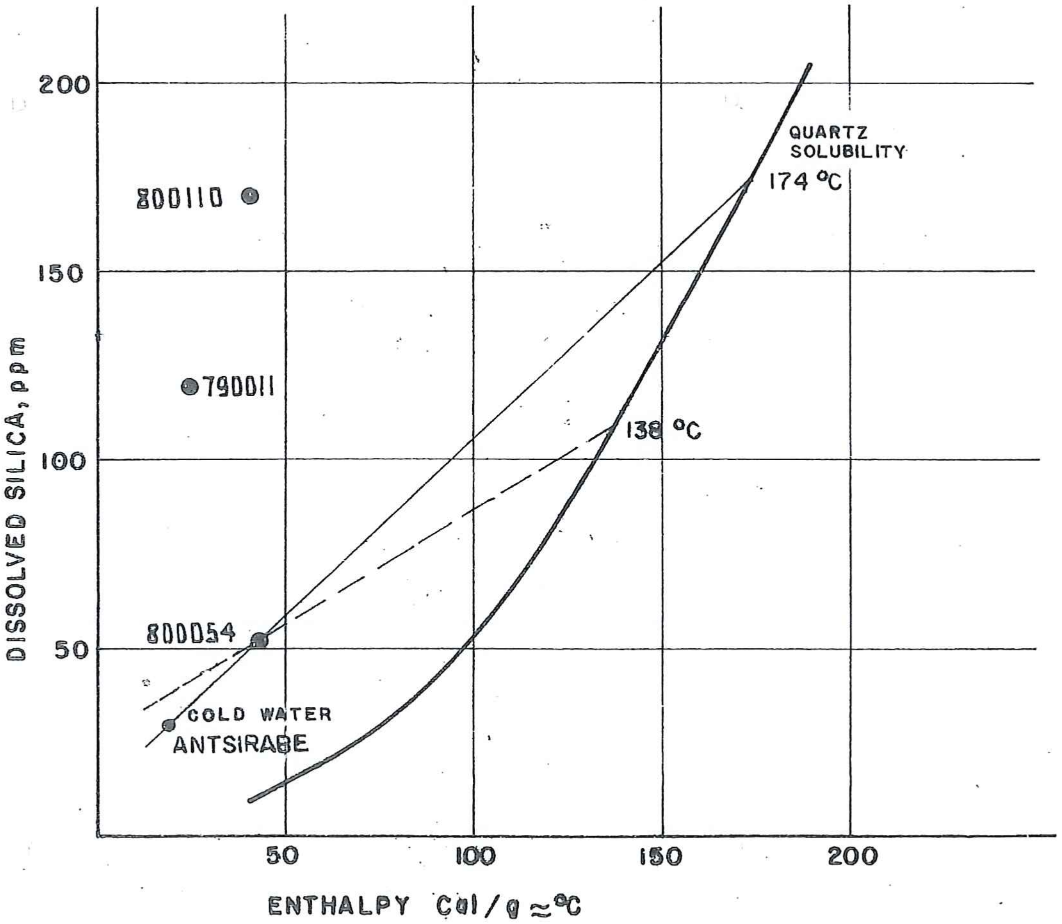


Table 7.12 Chemical geothermometry results in °C for the Itasy Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Soavinaudriana	790008	45	151	174	182	97
Mashoma	790009	57	154	151	161	166
Andranoriango-traka	790010	28	149	173	181	168
d'Ambaraky**	790011	24	121	212	218	84
Mocain d'Ifanja	790012	46	141	144	154	88
Mahtsinjs Ambohipano	800052	40	136	118	128	82
Anosibe	800053	49	126	128	138	86
Ramainandro*	800054	42	104	165	174	183
Sahasarotra**	800110	41	171	240	244	227

1) Equation (4) in Table 4.1

2) Equation (5) in Table 4.1

* Mixed water

** Probably mixed water

7.13 Antsirabe Area

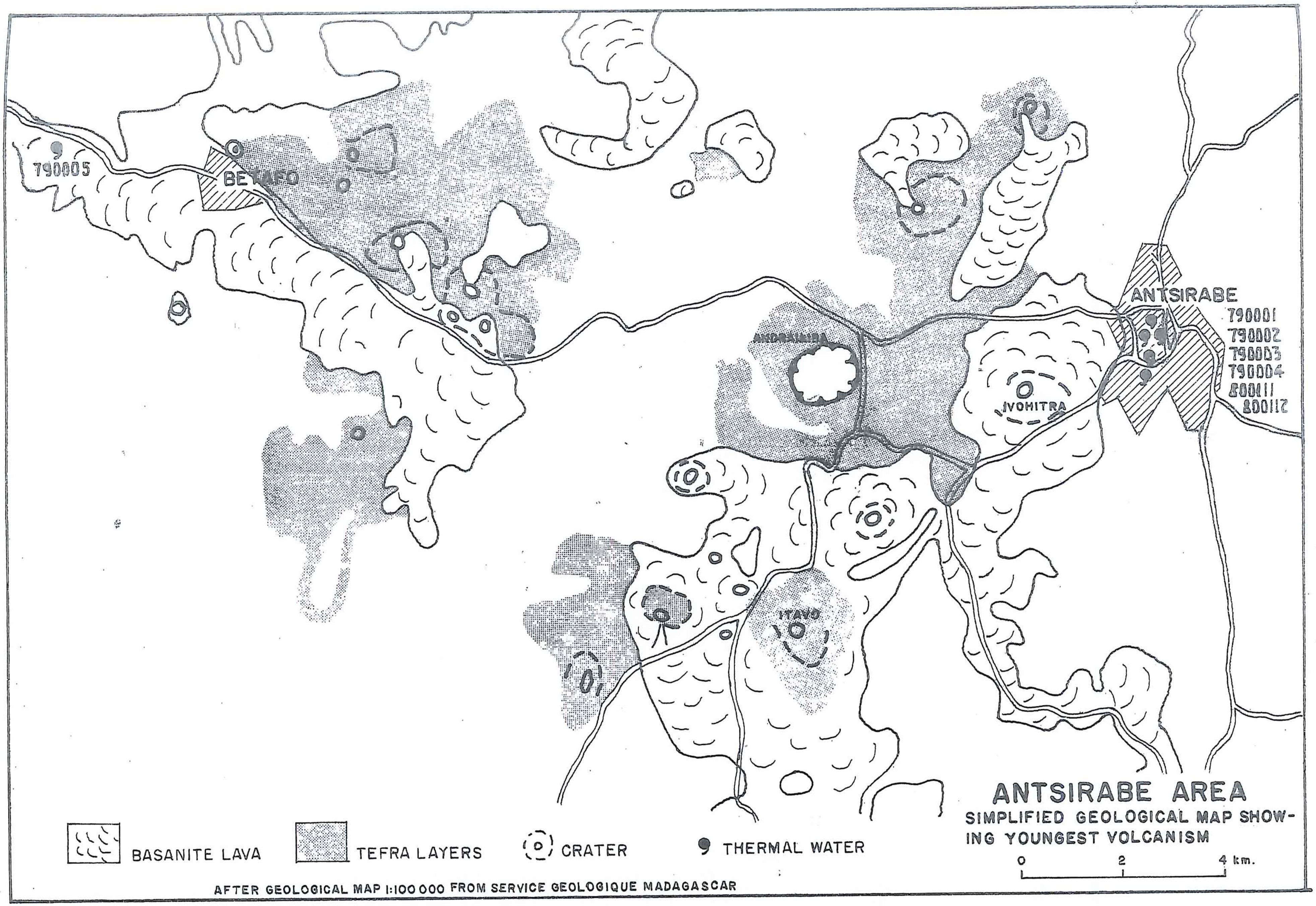
Samples 790001, 790002, 790003, 790004, 790005, 790006, 800111, 800112.

7.13.1 Geology

Antsirabe is located at the southern boundary of the Ankaratro volcanic area, which is of Pleistocene age. The Ivahitra crater is at a distance of only 2 1/2 km from the centre of Antsirabe village.

Fig. 7.6 is a simplified geological map of the Antsirabe area, showing the distribution of the youngest volcanics in the area.

Fig. 7.6



ANTSIRABE AREA
SIMPLIFIED GEOLOGICAL MAP SHOWING YOUNGEST VOLCANISM

AFTER GEOLOGICAL MAP 1:100 000 FROM SERVICE GEOLOGIQUE MADAGASCAR

The figure is based on the geological map, scale 1:100.000, from "Service Geologique" in Madagascar. The thermal springs in Antsirabe have been studied by various authors and the stratigraphy in shallow drillholes has been worked out by Lenoble (see Besairie 1959). At the surface there are young sediments underlain by altered tephra layers (cinerite). The tephra has been altered into clays but the original structure is preserved. Clay sediments occur under the tephra and become sandy above the underlying basement gneiss. Besairie (1959) does not report thickness of individual strata.

The thermal water in Betafo issues from fissures at the margin of a lava flow.

7.13.2 Geothermal manifestations

The thermal springs in Antsirabe are mainly located at the center of the village around the lake Lac Ronomafana. This lake is an artificial one and was constructed to prevent thermal gas to escape from the ground into the atmosphere. The temperature of the thermal water in Antsirabe is 38 to 51 °C but the temperature in Betafo is 57,5 °C. It is difficult to estimate the total flow from springs in Antsirabe because of their large number. According to Besairie (1959) the total flow is less than 8 litres/sec excluding thermal manifestations at the bottom of the lake.

7.13.3 Chemical geothermometry

Four samples of thermal water, one of cold mineral water and one of domestic water were collected in Antsirabe. Two neighbouring springs sampled at Betafo and Andrantsara-Antsira are here grouped with the Antsirabe springs.

The chemistry of the four thermal waters and the cold mineral water is very similar. One of these samples was run through the computer program together with the two samples from the neighbourhood. All these waters are high in carbonate except that from Betafo. The water from Betafo (790005) shows a rather good agreement between the quartz, Na-K and Na-K-Ca temperatures, although the last yields somewhat lower values. The water is calcite-saturated at measured temperature and in equilibrium with $\sqrt{Ca}/H$ at quartz equilibrium temperature. The latter result substantiates the geothermetry results.

The samples from Antsirabe have rather uniform quartz equilibrium temperatures of 154-164 °C, if the domestic water is excluded. Na-K and Na-K-Ca temperatures are somewhat higher, or in the range of 208-244 °C and 215-232 °C respectively. The cold water (22 °C) yields the highest geothermometry temperatures in all cases.

The computer calculations of sample 790001 indicate that all the samples from Antsirabe have equilibrated with respect to $\sqrt{Ca}/H$ at quartz temperature. The discrepancy between the quartz and the Na-K and Na-K-Ca geothermometers might be due to mixing, but the mixing model involving the silica-enthalpy plot and the $\sqrt{Ca}/H$ indicates that the discrepancy cannot be explained solely by mixing. Some of the Antsirabe waters are near saturation with respect to amorphous silica, and precipitation of this phase would cause quartz temperatures to become lower than the cation temperatures.

The composition of the water sampled from Andronatsara-Antsira indicates that it has not equilibrated with any two minerals at a particular temperature. The geothermometry results can not therefore be taken to indicate anomalous underground temperatures.

It is concluded that underground temperatures at Antsirabe are 150-160 °C and may even exceed 200 °C. At Betafo it is expected that underground temperatures will be ca 100 °C.

7.13.4 Oxygen water-sulphate thermometry

One sample was analysed for oxygen isotopes in water and sulphate. An isotope geothermometry temperature of 137 °C was obtained which is slightly higher than the chalcedony equilibrium temperature and somewhat lower than the quartz equilibrium temperature. The isotope thermometry thus favours the conclusion derived from the silica geothermometry that subsurface temperatures at Antsirabe Area are in the range of 150-160 °C and accordingly the high Na-K and Na-K-Ca temperatures of more than 200 °C would be explained by non-equilibrium conditions between water and feldspar.

Table 7.13 Chemical geothermometry results in °C for the Antsirabe Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Antsirabe, lac	790001	38.5	154	208	215	215
- de l'hospital	790002	45	157	220	225	222
- de Ranovisy	790003	46	161	218	224	220
- Ranomafana II	790004	51	154	215	221	221
Betafo	790005	57.5	117	112	123	82
Andronatsara-Antsira*	790006	18	132	>275	>300	78
Antsirabe (Source froide)	800111	22	164	244	248	232
Antsirabe (eu domestique)*	800112	20	74	>275	>300	37

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1
* Non-equilibrated cold water.

7.14 Morondava Area

Samples 800074, 800075, 800094, 800095, 800096.

7.14.1 Geology

This area belongs to the sedimentary basins at the western coast of Madagascar with continental and marine sediments of Pre-Jurassic to Pliocene age. The area is dissected by a NNW-SSE running fracture zone. Thermal springs at Vangoho and Maharivo (800075, 800095, 800096) are connected to fractures but the spring at Bevaho (800074) is associated with a doleritic dyke.

7.14.2 Geothermal manifestations

Only five thermal springs are known in this area. The temperature is 39-42 °C. The flow rate from each spring is 1-2 litres/sec except the newly identified spring at Mahabo (800094) where the flow rate is estimated 8 litres/sec.

7.14.3 Chemical geothermometry

Chemically the water samples from this area can be divided into two groups. One includes samples from Bevoho on Antsrotsy (800075) and represents waters which have equilibrated with alteration minerals. The other group includes water samples from Mahabo (800094), Soatanana (800095) and Ambango (800096). The sample from Mahabo is in equilibrium with calcite at the measured temperature but the $\sqrt{Ca}/H$ ratio is low and the Na-K temperature exceeds 300 °C and is much higher than the quartz and the Na-K-Ca temperatures. This water is therefore suspected to be a non-equilibrium one and its chemistry cannot be taken to be indicative of anomalous underground temperatures. The waters from Soatanana and Ambango yield low, however, comparable quartz equilibrium and Na-K temperatures of 30-60 °C. These localities are not considered to be of interest because of the low predicted underground temperatures.

Quarts equilibrium and Na-K and Na-K-Ca compare rather well for the springs at Bevoho on Ansrotsy and Vongoho and lie in the range 138-173 °C. As deduced from the computer results for sample 800072, which has a comparable chemistry, these waters are in equilibrium with anhydrite and fluorite as well as for the ratio $\sqrt{Ca}/H$. These results strengthen the geothermometry results, and it is concluded that at these localities underground temperatures may be as high as 170 °C.

Table 7.14 Chemical geothermometry results in °C for the Morondava Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Bevoho on Ansrotsy	800074	39	138	159	167	173
Vongoho	800075	41	138	154	163	170
Mahobo*	800094	39	62	>275	>300	91
Soatanana	800095	40	58	21	33	98
Ambango	800096	42	56	18	30	96

1) Equation (4) in Table 4.1

2) Equation (5) in Table 4.1

* Non-equilibrated water.

7.15 Miandrivazo - Malambandy - Ikalamavony Area

Samples: a) 800047, 800076, 800078
b) 800070, 800071, 800072, 800073, 800077, 800093
c) 800067, 800068, 800069
d) 800044, 800045.

7.15.1 Geology

The area discussed in this chapter is very large. The distance between the southernmost thermal spring and the northernmost one is about 220 km. The thermal activity has been divided into four subgroups identified above by a) to d). Although the springs considered here are spread over a large area they are situated in a similar geological environment. The westernmost springs in this group are all near the contact of sediments and metamorphic basement. A fracture zone defines this contract and the thermal manifestations are closely associated with the fractures. Doleritic dykes control the ascent of the thermal water in at least two places, at Antsira (800072) and at Kiposa (800073). The springs belonging to groups c) and d) are located in metamorphosed rock of Precambrian or Cambrian age.

7.15.2 Geothermal manifestations

a) The northernmost springs are 20 to 35 km north of Miandrivazo. The temperature in these springs is 29 to 39 °C.

b) The second group is around Malambandy and associated with the fracture zone at the contact of sediments in the basins and Cambrium metamorphosed rocks. The temperature is 30 to 55 °C.

c) This group is East of Malambandy in Cambrian bedrock. The temperature is in the range 28-40 °C and the flow rate is low.

d) These springs occur in the southernmost part of this area and are located near Ikalamavony. They issue from Cambrian gneiss. Their temperature is near 50 °C.

7.15.3 Chemical geothermometry

a) The three springs in this area have quartz equilibrium temperatures in the range 119-128 °C. The Na-K and the Na-K-Ca temperatures are similar or somewhat higher, especially for sample 800078 from Amberobe. This water is higher in sodium than the waters from the other springs. It seems unlikely that the discrepancy between the geothermometers is due to mixing, although the composition of these waters is quite variable.

The composition of sample 800076 is very similar to that of sample 800072 but the latter was run through the computer program. This latter water sample is in equilibrium with anhydrite, fluorite and the $\sqrt{Ca}/H$ ratio at quartz equilibrium temperature. By comparison it is deduced that the same will hold for sample 800076 giving strong confidence in the validity of the predicted underground temperatures of 130-160 °C by geothermometry.

It is concluded that underground temperatures in this area are at least 120 °C but they might be as high as 220 °C. If this is the case partial re-equilibration with respect to anhydrite, fluorite and quartz has occurred during cooling in the upflow although this would not be the case for feldspar.

b) The quartz temperature for the six waters sampled from Malambandy lie in the range 84-140 °C. For some samples the Na-K and Na-K-Ca temperatures are significantly higher. They lie in the range 107-238 °C and 78-252 °C respectively. The composition of the waters classified under this group is variable and cannot be explained by simple mixing. Three of the six samples were run through the computer program and showed that they all had equilibrated with fluorite at the quartz temperature. One (800072) is also saturated with anhydrite and in equilibrium for the $\sqrt{Ca}/H$ ratio but calcite supersaturated at the measured water temperature. Sample 800093 is undersaturated with calcite and has a low $\sqrt{Ca}/H$ ratio. Yet the quartz and Na-K temperatures compare well. The fit with various mineral equilibria at quartz temperature is thus random and unpredictable. The use of such fitting is therefore limited in respect to supporting or devaluating the geothermometry results. The water with the highest salinity in this group shows the largest discrepancy between quartz and cation geothermometers. A satisfactory explanation of this cannot be given. The water is not amorphous silica saturated at the measured temperature in the spring so precipitation of this phase is not responsible for the difference. It seems possible that the difference is due to partial re-equilibration with quartz accompanying cooling in the upflow and slower re-equilibration with feldspar as a result of the relatively high water salinity.

The water from Mahasoa (800067) has not equilibrated with hydrothermal minerals. Its silica content is similar to that of cold ground waters. The chemical geothermometry results cannot at this locality be assumed to indicate anomalous underground temperatures

In conclusion it is predicted that underground temperatures in the various parts of the Malambandy Area are in the range of 100-140 °C, and they may be as high as 250 °C at Andranamandevy.

c) The waters from Mafana (800068) and Antsirasira (800069) have a very similar composition. Computer analysis indicates saturation with fluorite, anhydrite and the $\sqrt{Ca}/H$ ratio at quartz equilibrium temperature, and calcite-saturation at the measured water temperature. Na-K temperatures are somewhat higher than quartz temperatures for these two waters, but the Na-K-Ca temperatures are much lower. In view of the very low chloride content of the water (similar to rain water) it is deduced that underground temperatures may not be much higher than those measured at the surface and as indicated by the Na-K-Ca geothermometer. This is, however, to be regarded as a conservative evaluation.

d) The two waters from this group (800044 and 800045) have a very similar composition. They are low in chloride. The silica concentrations are similar to those of cold ground water or surface water. Chalcedony temperatures compare well with the measured temperatures in the springs (see Appendix 5). Na-K temperatures are considerably higher than the quartz equilibrium temperatures but the Na-K-Ca temperatures are much lower and lower than the measured water temperatures. Computer analysis shows equilibration for anhydrite, fluorite and the $\sqrt{Ca}/H$ ratio at quartz temperature. Integration of all the results indicates that underground temperatures are not to be expected to exceed 100 °C and may not exceed much those measured in the springs.

Table 7.15 Chemical geothermometry results in °C for the Miandrivazo - Malambady - Ikalomavony Area

Location	Sample no	$T_{meas.}$	T_{quartz}	$T_{Na-K}^{1)}$	$T_{Na-K}^{2)}$	$T_{Na-K-Ca}$
Angaradoa a)	800047	39,5	119	125	136	148
Analaba a)	800076	29	128	153	158	169
Amberobe a)	800078	29	122	224	229	222
Ambia-Quest b)	800070	46	90	123	135	146
Ambia-Sud-Est b)	800071	55	84	119	131	86
Antsira b)	800072	51	141	154	159	171
Kiposa b)	800073	30	94	131	140	80
Andranamandevy b)	800077	46	140	254	238	252
Soatanimbary b)	800093	45	107		107	138
Mahasoa* b)	800067	28	84	138	146	78
Mafana c)	800068	48	103	115	128	41
Antsirasira c)	800069	27	105	139	147	47
Tsiefa d)	800044	50	79	100	116	28
Fitampilo d)	800045	48	80		110	25

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1
* Non-equilibrated cold water.

7.16 Ambatofinandiakana Area

Samples: 790007, 800055, 800056, 800058, 800059, 800060, 800061, 800062, 800063, 800064, 800065, 800066.

7.16.1 Geology

The area under consideration is located south of Antsirabe. The bedrock is of Precambrian age and includes schists, quartzite but also granite and gabbro intrusions.

The granite intrusions belong to the Ambatofinandrahana intrusive complex which is 700 to 1100 MY old. Most of the thermal manifestations are located within the granite or at the contact of the granite intrusion with the enclosing metamorphic rock.

7.16.2 Geothermal manifestations

Twelve thermal springs belong to this area. Their location is shown on Fig. 7.7. The highest temperature (69 °C) and the highest flow rate (10 litres/sec) occur at Tsangandrano (800058).

7.16.3 Chemical geothermometry

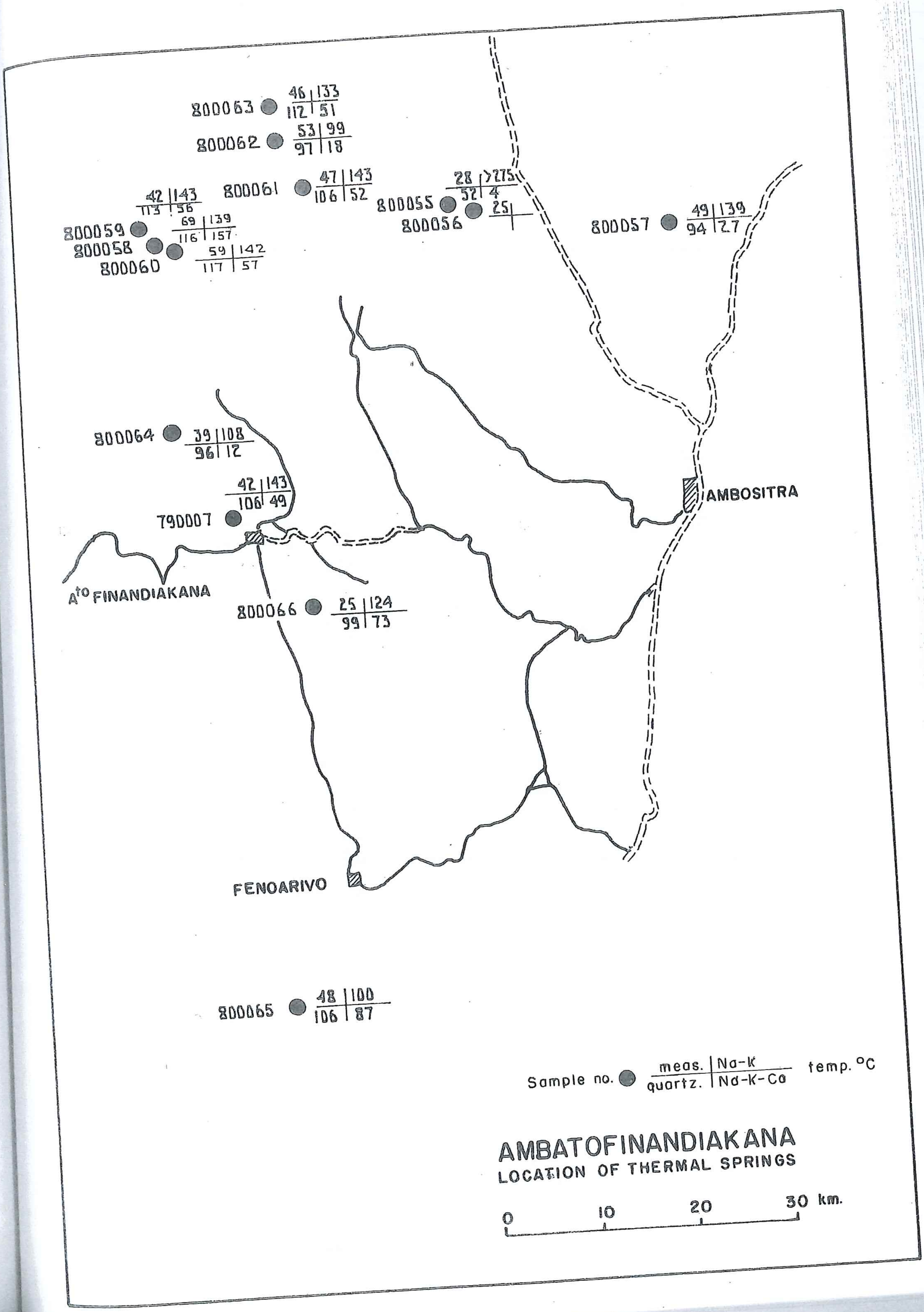
The waters from this area have a rather uniform composition. Most of them are sodium sulphate waters with very low chloride, similar to that of rain water. This composition is probably related with the granite rocks through which the thermal waters flow.

Water samples 800065 and 800066 are distinguished by their lower content of calcium and sulphate and also by high chloride in the case of sample 800066. The water at Henikenina Quest (800055) represents cold non-equilibrated water.

Quartz equilibrium temperatures for other samples lie in the range 96-117 °C. Na-K temperatures are similar for four samples but otherwise higher by 25-37 °C. Na-K-Ca temperature are very erratic, lying in the range 18-157 °C.

A computer analysis of sample 800059, which is also assumed to represent samples 800058 and 800060-64 shows that it is saturated with anhydrite and fluorite at quartz temperature and in equilibrium for

Fig. 7.7



AMBATOFINANDIAKANA
LOCATION OF THERMAL SPRINGS

the ratio $\sqrt{Ca}/H$. By contrast, sample 800065 is undersaturated with the above minerals but in equilibrium with the $\sqrt{Ca}/H$ ratio at quartz equilibrium temperature.

Underground temperatures in this area are expected to be 100 °C or slightly higher.

Table 7.16 Chemical geothermometry results in °C for the Ambatofinondiakana Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Ambatofinondiakana	790007	42.5	106	143	152	49
Tsangandrano	800058	69	116	139	149	157
Ampasimihebo	800059	42	113	143	152	56
Kelipetaka	800060	59	117	142	151	57
Sahavatoana	800064	39	96	108	119	12
Ambohibato	800066	25	99	124	134	73
Antsira	800061	47	106	143	153	52
Laondany	800062	53	97	99	110	18
Langainony	800063	46	112	133	143	51
Henikenina Quest*	800055	28	52	>275	>300	4
Henikenina Est	800056	25				
Imody	800065	48	106	100	111	87

1) Equation (4) in Table 4.1

2) Equation (5) in Table 4.1

* Non-equilibrated cold water.

7.17 Fianorantsoa Area

Samples: 790028, 790029, 790030, 790031, 800046.

7.17.1 Geology

The thermal springs which are discussed here occur in two localities near Fianorantsoa. At both localities the bedrock is metamorphic and of Pre-Cambrian age. At Ifanadiana (790028, 790029, 790030, 790031) two fracture zones are known. One runs N40W to N60W and the second N50E. The thermal springs are located by the second fracture zone.

7.17.2 Geothermal manifestations

The thermal springs at Vohidiavina are about 15 km north of Fianarantsoa. Their temperature is 30 °C and the flow rate is 1 litre/sec. Besairie (1959) reports a temperature of 47 °C for this locality. In the second locality at Ifanadiana the waters, which are used for balneological purposes have temperatures of 55 to 56.5 °C. This is somewhat higher than recorded by Besairie (1959). The total flow rate from these four thermal springs is near 7 litres/sec which is similar to that given by Besairie (1959).

7.17.3 Chemical geothermometry

The quartz temperature and the Na-K and Na-K-Ca temperatures compare well for the samples from Ifanadiana. Computer analysis of one of these samples indicates $\sqrt{Ca}/H$ equilibrium at the quartz epuilibrium temperature and calcite equilibrium at the measured temperature. It is concluded that underground temperature will be in the range 70-90 °C. The sample from Mohicavina (800046) has evidently not equilibrated. Its chemistry is therefore not indicative of anomalous underground temperatures.

Table 7.17 Chemical geothermometry results in °C for the Fianarantsoa Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Ifanadiana (source S1b)	790028	55	85		84	66
" (source S1a)	790029	56.5	88		81	67
" (source 2a)	790030	55	86		83	66
" (source 2b)	790031	56	89		81	66
Mohicavina*	800046	30	74		287	36

1) Equation (4) in Table 4.1
2) Equation (5) in Table 4.1
* Non-equilibrated cold water.

7.18 Fandriana Area

Samples 790027, 800057.

7.18.1 Geology

The two thermal springs in this area are both located in Pre-Cambrian rocks. No young volcanism, dykes or fractures are known to which the thermal manifestations can be related.

7.18.2 Geothermal manifestations

The thermal water at Miarinavaratra (790027) has a temperature of 55 °C and the flow rate was estimated 2 litres/sec.

The water in Vohidambo has a temperature of 49 °C and the flow rate is about 4 litres/sec.

7.18.3 Chemical geothermometry

These two samples have a chemical composition similar to the samples from Ifanadiana. The quartz temperature is 94 °C for both samples. For the Miarianavaratra water, similar temperatures are indicated by the Na-K and the Na-K-Ca geothermometers. By contrast, the water at Vohidambo yields a low Na-K-Ca temperature of 27 °C and a high Na-K temperature value of 140-150 °C. For the latter equilibrium may only have been partial and it is not considered certain that the chemistry indicates anomalous underground temperatures. For Miarinavaratra it is expexted that underground temperatures will be 90-100°C.

Table 7.18 Chemical geothermometry results in °C for the Fandriana Area

Location	Sample no	$T_{meas.}$	T_{quartz}	$T_{Na-K}{}^{1)}$	$T_{Na-K}{}^{2)}$	$T_{Na-K-Ca}$
Miarinavaratra	790027	55	94		106	87
Vohidambo	800057	49	94	139	149	27

1) Equation (4) in Table 4.1
2) Eauation (5) in Table 4.1

7.19 Mangoky Area

Samples: 800032, 800033, 800037.

7.19.1 Geology

These three springs are located in the sedimetary rocks of Western

Madagascar. Some Cretaceous basalts occur near the thermal springs at Tsaripioka (800037).The thermal water at Andonaky and Amokoty (800033) emerges from the NNE-SSW fracture zone named Sikily by Hottin (1976).

7.19.2 Geothermal manifestations

All the three thermal springs mentioned in this chapter are near River Mangoky. The temperature is 44 to 58 °C, and the flow rate is among the highest recorded in Madagascar, 10 to 20 litres/sec in each spring.

7.19.3 Chemical geothermoetry

Two of the three samples were run through the computer program for further study of equilibrium conditions. The water at Tsaripicka (800037) may only have attained partial equilibration. Since the $\sqrt{Ca}/H$ is low, little weight is given to the high Na-K and Na-K-Ca temperatures. Underground temperatures are probably not much higher than those measured at the surface. The other two samples yield similar values for quartz, Na-K and Na-K-Ca temperatures (70-90 °C). Yet these samples show low $\sqrt{Ca}/H$ ratios. Underground temperature at these localities is therefore uncertain and it may not be significantly higher than recorded at the surface.

Table 7.19 Chemical geothermometry results in °C for the Mangoky Area

Location	Sample no	$T_{\text{meas.}}$	T_{quartz}	$T_{\text{Na-K}}$ 1)	$T_{\text{Na-K}}$ 2)	$T_{\text{Na-K-Ca}}$
Andonaky	800032	58	82		74	95
Amokoty	800033	44	79		73	93
Tsaripicka*	800037	48.5	87	138	148	174

1) Equation (4) in Table 4.1

2) Equation (5) in Table 4.1

* Non-equlibrated water.

7.20 Tulear Area

Samples: a) 800034, 800035, 800036
b) 800038, 800039, 800040, 800041, 800042
c) 800043.

7.20.1 Geology

The thermal springs which are discussed in this chapter are located in the sedimentary formations at the west coast of Madagascar. The sediments date from Pre-Jurassic time (Isalo formation) to Late Cretaceous time. Some Cretaceous volcanic rocks (basalts) exist in the area. NNE-SSW fracture zones stretch through the area. The thermal springs in the northern part of the area are partly connected to the Cretaceous volcanic rocks and partly to the Illova fracture zone. The thermal springs at Bezaha (800038, 800039, 800040, 800041, 800042) emerge through the Isalo sandstone along fractures (Teheza fracture zone).

7.20.2 Geothermal manifestations

The thermal springs in this area can be divided into three subgroups. The first includes the northernmost springs which are relatively cold (26-34 °C) and with a low flow rate (< 2 litres/sec). The second group contains the thermal springs at Bezaha with temperatures of 38 °C to 45 °C and a high flow rate (total 50 to 60 litres/sec). The third group includes the thermal spring at Tongobory, which has a temperature similar to the Bezaha waters and a high flow rate of 20 litres/sec.

7.20.3 Chemical geothermometry

The samples incorporated in this section all represent non-equilibrium waters. They all contain silica concentrations similar to cold ground water and surface water and the chloride concentrations are low with the exception of sample 800043. The chemistry of these waters is not considered to be indicative of anomalous underground temperatures.

Table 7.20 Chemical geothermometry results in °C for the Tulear Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K} 1)	T_{Na-K} 2)	$T_{Na-K-Ca}$
Miary*	800034	34	60	57	69	115
Andrambo*	800035	28	60	187	195	21
Andravidahy*	800036	26.5	54	181	189	19
Serp*	800038	42	47	121	>300	84
Devolimanga*	800039	38	52	>275	>300	83
Ranomofana (fiscine)*	800040	44	52	>275	281	73
Raingile*	800041	43	60	>275	286	76
Ambilanisabe*	800042	45	57	>275	>300	70
Tongobory Ranomay*	800043	44.5	74		102	137

1) Equation (4) in Table 4.1

2) Equation (5) in Table 4.1

* Non-equilibrated waters.

7.21 Fourth Dauphin Area

Samples: 800097, 800098, 800099, 800100.

7.21.1 Geology

This area lies in the southeasternmost part of Madagascar, north of Fourth Dauphin and is located in Pre-Cambrian rocks. 780 to 900 MY old granitic intrusions are common (Chaines Anosyennes). A NE-SW fracture cuts the area and some of the thermal springs may be associated with it.

7.21.2 Geothermal manifestations

Four thermal springs occur in this area. Their temperature ranges from 40 °C to 51 °C. The flow rate is low.

7.21.3 Chemical geothermometry

The geothermometry results for this area differ from those in other areas in Madagascar in the sense that Na-K and Na-K-Ca temperatures are lower than both chalcedony and quartz equilibrium temperatures. The Na-K temperatures are similar to the temperatures measured in the springs. The Na-K-Ca geothermometer yields somewhat lower and higher values. It may be that the dissolved silica has not equilibrated with chalcedony or quartz and that its concentration is controlled by the rate of leaching from the rock. This is known to be the case in other geothermal fields (Arnorsson, 1979). It is therefore concluded that underground temperatures at Fourt Dauphin are not much higher than those measured at the surface.

Table 7.21 Chemical geothermometry results in °C for the Fourt Dauphin Area

Location	Sample no	$T_{meas.}$	T_{quartz}	T_{Na-K}1)	T_{Na-K}2)	$T_{Na-K-Ca}$
Emitray	800097	40	130		62	39
Betaimboraka	800098	48	50		59	38
Marosanoa	800099	51	131		58	84
Sarongaha	800100	43	129		54	88

1) Equation (4) in Table 4.1

2) Equation (5) in Table 4.1

8. PROSPECTIVE AREAS - DISCUSSION

The maximum subsurface temperatures in the various geothermal areas in Madagascar as evaluated from chemical geothermometry are summarized in Table 8.1. Fig. 8.1 shows the distribution of subsurface temperatures as evaluated by the quartz geothermometer. No conclusive evidence indicates temperatures in excess of 180 °C. There are, however, indications that subsurface temperatures may exceed 180 °C in some areas and could possibly be as high as 240 °C. The following areas are considered to be favourable prospects for further investigations. They are put into three groups in order of priority.

Priority 1: Antsirabe and Itasy

Priority 2: Ambilobe, Nosy Be, Ambanja and Andapa-Doany

Priority 3: Morandava and Miandrivazo a) and b)

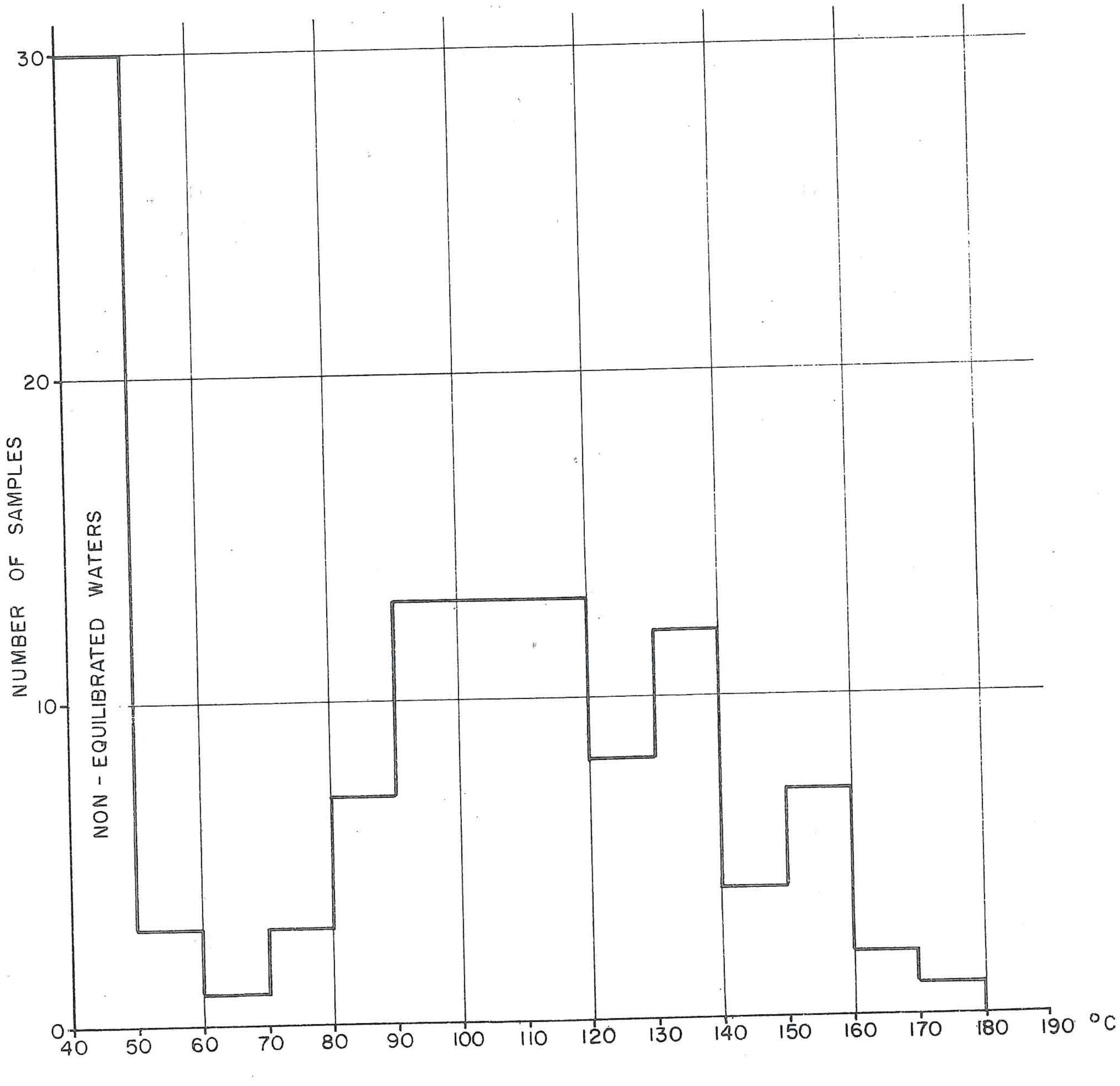
The six areas listed under priorities 1 and 2 are associated with Pleistocene volcanism, and with the exception of one area, Antseranana, they incorporate all the thermal manifestations which emerge in or near young volcanic rock. This suggests that high temperature gradients are to be related with areas of recent volcanism. The last two listed areas (under priority 3) occur in Pre-Jurassic and younger sediments west of Antsirabe and in old granites and gneisses. The first is associated with dolerite dykes of Cretaceous age and the latter with fractures separating the sediments from granitic rocks and gneisses. The areas in priority group 3 seem to be by far less favourable than those listed under priotities 1 and 2.

The waters at Antsirabe and Itasy are high in carbon dioxide. That is also expected to be the case for waters entering eventual boreholes. The salinity is moderato to low, being somewhat lower at Itasy. Corrosion and calcite scaling problems might occur in accosiation with the exploitation of these waters.

Fig. 8.1

MADAGASCAR

HISTOGRAM OF SUBSURFACE
TEMPERATURE EVALUATED
FROM THE QUARTZ GEOTHERMOMETER



In the prospective areas in northern Madagascar carbon dioxide concentrations are moderate to high but water salinity is relatively low as indicated by chloride concentrations which do not exceed 300 ppm, except for the waters at Nosy Be where they are a little above 4000 ppm. Here, sea-water mixing may have contributed to the high chloride concentrations. The high carbon dioxide concentration indicates that calcite scaling and corrosion problems might be encountered in association with the exploitation of these waters

The waters belonging to the Morandava Area (priority 3) are low in carbonate. The waters indicative of high subsurface temperatures are of moderate salinity as can be seen from their chloride concentrations of some 1000 ppm.

The waters from the Miandrivaza Area a) and b) (priority 3) are also low in carbonate and of rather low salinity. The chloride concentrations for those waters, are by far the highest, however, or 500-1200 ppm, which indicates high subsurface temperatures.

About 30 of the analysed waters have not equilibrated with alteration minerals and can for that reason not be used for chemical geothermometry interpretation. Most of these waters are located in sedimentary rocks in western Madagascar.

No fumarolic activity indicative of underground boiling of geothermal fluids is known in Madagascar. It is notable that large discrepancy always occurs between measured temperatures and geothermometry temperatures when the latter indicate high subsurface temperatures. This large difference suggests strong conductive cooling in the upflow and hence relatively poor permeability.

It should, however, be realised that low permeability in the upflow is not necessarily indicative of low permeability at deeper levels.

The observed difference between the results of the various chemical geothermemeters may be due to a number of reasons such as.

1. Slower re-equilibration between feldspar and solution upon cooling as compared with quartz and solution.
2. Structural difference in the assumed feldspars and those occuring in the geothermal systems used to calibrate the Na-K geothermometer.
3. Mixing of hot water with cold groundwater.
4. Non equilibrium conditions between water and feldspar and/or quartz.

In the two areas in priority group 1, mixing and underground precipitation of silica may have occurred as discussed in chapter 7, yielding low silica temperature. The discrepancy between the geothermometers in the Ambanja area may be due to mixing, yielding low silica temperature and possibly a too high cation temperature as seen in sample 790015. In priority group 3 re-equilibration between quartz and solution may have occurred, or, which is more likely, equilibrium between feldspar and solution has not been attained.

The thermal waters in Madagascar are characterized by high carbonate content. Such waters are known in many parts of the world, but have so far not been exploited on a large scale except in Hungary.

In Czechoslovakia, Hungary and France, high carbonate water from deep wells having temperatures lower than 100°C are being exploited. The chemical geothermometers indicate higher temperatures. In France, both the silica and the cation geothermometers yield temperatures exceeding 150°C. In Czechoslovakia the silica geothermometer yields low temperatures similar to the measured discharge temperature, but the cation geothermometer yields temperatures exceeding 150°C.

In Iceland, carbon dioxide waters are known in warm springs in several areas. Here chemical geothermometry indicates subsurface temperatures which are app. 100°C higher than the temperature measured at the surface (45-75°C). Drilling in two areas has verified the geothermometry results. In one of the areas the quartz geothermometer yielded 160°C where Na-K geothermometers yielded 105-120°C. A temperature of 160°C was reached at 1070 m depth. In the other area the quartz geothermometer indicated a temperature of 161°C-164°C for two samples and the Na-K geothermometers 163-166°C and 202-209°C for the two samples respectively. A temperature of 173°C was reached at 1800 m depth.

Aqueous speciation was calculated for 1/3 of the samples collected from Madagascar with the aim of studying overall mineral/solution equilibrium conditions in order to strengthen or impair the geothermometry results. In the case of the areas of the highest priority, equilibrium conditions appear to be prevailing at temperatures close to that of equilibrium with quartz.

Where temperatures in the range of 150-250°C are encountered in drillholes, calcite scaling problems are to be expected which might pose a severe problem if the hot water is rich in carbon dioxide and of a rather high salinity (over 2000 ppm dissolved solids appr.).

The high carbon dioxide content of many of the geothermal waters, and their relatively low pH, causes high concentrations of free carbon diocide which in turn could lead to corrosion problems in association with exploitation.

The lower geothermal reservoir temperature limit for economical power production by conventional techniques has generally been assumed to be around 180°C. Technically, power can be generated from water of a lower temperature. The economic feasibility of such power generation will obviously depend on local factors including production cost from other power resources.

Table 8.1 Estimated subsurface temperatures in different geothermal areas in Madagascar

Chapter	Area	Temperature °C
7.1	Antseranana	100
7.2	Ambilobe	160
7.3	Nosy Be	150-180
7.4	Ambanja	140 (possibly 200)
7.5	Andapa-Doany	160
7.6	Saint Marie*	24
7.7	Andasibe	51-75
7.8	Maintirano*	27-42
7.9	Fenerive	100
7.10	Ranomafana Est	55-100
7.11	Fenoarivo/Ikopa	70-80 (possibly 150)
7.12	Itasy	170 (possibly 240)
7.13	Antisrabe	150-160 (possibly 240)
7.14	Morandava	170
7.15	Miandrivazo	a) 120 (possibly 220)
	Malambandy	b) 100-140 (possibly 250)
	Antsirasira - Mafana	c) 50
	Ikalamavony	d) 50-100
7.16	Ambatofinandikana	100
7.17	Fianorantsoa	70-90
7.18	Fandriana	90-100 (possibly 150)
7.19	Mangoky	50-90
7.20	Tulear*	25-50
7.21	Fourt Dauphin	50

* Areas consisting of cold and weakly thermal non-equilibrated waters.

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