GEOLOGICAL SURVEY OF CANADA
OPEN FILE 5906

Review of National Geothermal Energy Program
Phase 2 – Geothermal Potential of the Cordillera

A. Jessop

2008

Natural Resources Canada   Ressources naturelles Canada

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 5906

Review of National Geothermal Energy Program Phase 2 – Geothermal Potential of the Cordillera

A. Jessop

2008

Available from
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

Jessop, A.
2008: Review of National Geothermal Energy Program; Phase 2 – Geothermal Potential of the Cordillera; Geological Survey of Canada, Open File 5906, 88p.

Open files are products that have not gone through the GSC formal publication process.

The Meager Creek Hot Springs

22 February 1974

CONTENTS

REVIEW OF NATIONAL GEOTHERMAL ENERGY PROGRAM

PHASE 2 - THE CORDILLERA OF WESTERN CANADA

APPENDICES

1 - Expenditures of the Geothermal Energy Programme
2 - Federal participants in the Geothermal Energy Programme
3 - Industrial participants
4 - University participants
5 - List of contracts, with performer, cost, date, etc

These are to be found in Volume 1 of this report and are not repeated here.

FOREWORD

The purpose of this report is to set down a record of the work done, the contracts let, and the knowledge gained during the Geothermal Energy Program of 1976 to 1986. Small projects, both before and after the Program, are also included. A brief review of subsequent progress at Meager Creek, carried on by entirely commercial interests is also included. It is hoped that this will provide a base on which to build further research into geothermal energy in Canada and that will stimulate the use of geothermal energy as hydrocarbon resources decline, as environmental concerns grow, and as economic conditions change.

This report is the second volume and contains details of the work in the volcanic belts, the thermal springs, and areas of potential for hot dry rock exploitation in the Cordillera of British Columbia and the Yukon. Resources in the Cordillera are likely to be much more locally variable than in the Western Canada Sedimentary Basin of Alberta and Saskatchewan, but they are more likely to be of high potential for conversion to electrical power. This is the only part of Canada where high-temperature resources, capable of generating electrical power through steam turbines, are likely to be found. It is the location of most of the Canadian thermal springs. It is also the location of most of the intrusive rocks holding residual volcanic heat or containing sufficient radioactive heat generation to provide the potential for useful hot dry rock in the foreseeable future. The concept of “heat mining”, in theory possible anywhere on the surface of the earth, is still in relative infancy. In many parts of Canada this will require very deep drilling, and it will be many years before this energy source is available in tectonically stable parts of the earth’s crust.

The corresponding report for the Western Canadian Sedimentary Basin, the Atlantic Provinces, and all other parts of Canada east of the Rocky Mountains appeared in 2007, and is available from the NRCan web site as Open File 5690.

CHAPTER ONE

NATURE AND USE OF GEOTHERMAL RESOURCES

INTRODUCTION

Geothermal energy comes from the solid earth in the form of heat. The Earth's heat is a combination of the original heat resulting from formation and layering of the earth and of the heat generated since the formation by the decay of radioactive isotopes. Both depend on the finite amount of energy associated with the formation and original content of the earth, and so this is not, in principle, a renewable energy resource. However, the total heat of the earth is so great that it may be regarded, for human practical and economic purposes, as inexhaustible.

On a scale limited by human development and technology or by the individual geothermal system the heat is drawn from a limited volume of the Earth's crust, and so it is finite. In systems associated with recent volcanic plutons the heat may be renewed by natural hydrothermal circulation, but ultimately the resource is finite. In other systems, notably in sedimentary aquifers, the heat is drawn down much faster than it can be renewed, and so any individual production system must be regarded as non-renewable.

Heat energy is in all material on the earth, since the only matter without heat is at a temperature of absolute zero. The temperature of the earth's surface is controlled by the level of radiation from the sun, the filtering and insulating effects of the atmosphere, the local vegetation cover and the annual cycle of seasons. The annual average temperature of the surface of the earth normally lies between -15 ^{O}C, in regions near the poles, and 30 ^{O}C, in equatorial regions. Apart from perturbations of up to 4 ^{O} C near the surface, due to rapid surface warming in the last 100 to 200 years, temperature in the solid earth increases with depth.

Heat energy needs a carrier. In geothermal exploitation the carrier is normally the water in the ground that has collected and concentrated the heat in reservoirs. The only exception to this is in the use of hot dry rock, where water must be introduced artificially. It is convenient to take the freezing point of water as a base temperature for energy content. Below that temperature water can be neither produced nor reinjected. Since temperature of the solid earth rises with increasing depth, geothermal energy is present below the entire surface of the continents. However, the mechanisms and economics of extraction mean that most of the earth's energy is not useful. Only in special circumstances is geothermal energy capable of being exploited. Conditions for utility are governed by the geological setting, the physical nature, the available technology of extraction, and the economic need for the resource. Of these, the first two are constant for any particular reservoir, the available technology improves with time, but economic conditions fluctuate. This report of research and development of geothermal energy thus focuses on the first three conditions. Exploitation depends on the level of knowledge of these three conditions and the economic conditions of the time.

TYPES OF GEOTHERMAL RESOURCE

The physical nature of the resource and the technology of extraction impose a system of classification of geothermal resources. The physical nature provides a division into steam, water, and hot dry rock resources, and the technology of extraction divides the water resources by temperature, according to the suitability for electrical generation, direct heat use, or conversion by heat pumps. Geological setting, including the geomorphological character of the surface, may affect the ease and economic feasibility of development. Human factors, such as population density, effect the potential uses and economic situation. However, in order to describe the nature of geothermal resources the most suitable classification is by physical nature, and this system will be followed in this chapter. These divisions have been described in more detail in Volume One of this report (Jessop, 2007)

It is possible that all types of geothermal resource will be found in the Cordillera. The types of major interest are the dry-steam, or vapour-dominated, reservoirs, the hot-water, or water-dominated, reservoirs, and the hot dry rock resources. However, warm water reservoirs are also of interest for local application and hot springs are of interest for recreational purposes. Since there are many old mines in the Cordillera, options for uses similar to the example of Springhill, Nova Scotia, should be considered.

The Tertiary volcanoes of the Cordillera are likely to have associated hydrothermal systems still active, providing both vapour-dominated or fluid-dominated systems if aquifer formations are present. The depth and nature of high-temperature reservoirs are governed by the boiling point of water under pressure, shown in Fig.1. The enthalpy-pressure relation also plays a role, and this diagram may be found in Jessop (1990).

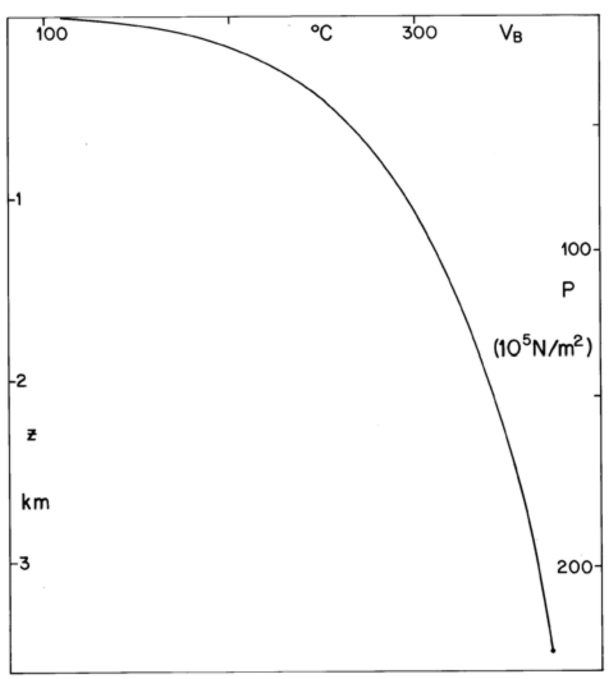

Fig.1 The boiling point of water plotted against pressure (right-hand scale), and depth (left-hand scale). The depth scale is calculated on the assumption that the confining pressure is the weight of a column of water at the ambient boiling point. The curve ends at the critical point, at a temperature of 374 ^{O}C and a pressure of 22.06 MPa, and a depth of 3400 m.

Vapour-dominated reservoirs

Vapour-dominated reservoirs are governed by the point of maximum enthalpy on the saturation curve of water. This temperature is 234 ^{O}C. Under conditions of hydrostatic pressure, this temperature is found at a depth of about 300 m, unless impurities in the water play a significant role. These are the best reservoirs for the production of electrical power because there is no need for separation of water and steam. On Fig. 1 they fall close to and to the right of the curve. Producing geothermal fields at Larderello, Italy and the Geysers, USA, are of this type, but none have been identified in Canada.

Fluid-dominated reservoirs

Fluid-dominated reservoirs show conditions that fall to the left of the curve in Fig.1, but they have no restriction on pressure or depth imposed by the enthalpy curve. They can thus be deeper, hotter and at a higher pressure than the vapour-dominated reservoirs. Temperatures may even be above the critical point of 374 ^{O}C.

Hot dry rock

Hot dry rock is solid rock at an unusually high temperature, but without a water reservoir. Since water is needed to carry heat to the surface, an artificial circulating system must be created. Rock sufficiently hot and within human reach may exist in volcanic zones or in batholiths with high concentrations of radioactive isotopes. Techniques for exploration and utilisation are still being developed.

PHYSICAL QUANTITIES USED IN THIS REPORT

Several scientific quantities will be referred to in this report. These have been presented in Volume One, but some are repeated here to assist the reader.

Terrestrial Heat Flow is the amount of heat conducted to the surface of the earth from below. It is a property of the heat generation in the crust and tectonic structure and age of the location. It is expressed in mW/m^2 (milliWatts per square metre). It is used as a geophysical indicator of the nature of the crust of the earth. The world average is 63 mW/m^2 and normal observed values are in the range 20 to 100 mW/m^2, but anomalous circumstances produce values well outside this range.

Temperature difference is expressed in K (Kelvin). This quantity has the same magnitude as a degree Celsius, but without the implication of a point on fixed scale of temperature. Temperature is expressed in ^{O}C (degrees on the Celsius scale)

Geothermal gradient is the rate of increase of temperature with depth. It is expressed in mK/m (milliKelvin per metre, the same as degrees Celsius per kilometre). Observed values range from 10 mK/m to over 100 mK/m. At any one location the geothermal gradient can vary with depth, being inversely proportional to thermal conductivity of the rocks so that heat flow remains uniform.

Heat generation is the amount of heat being generated continuously in the rocks by radioactive decay. It is expressed in ì W/m^3 (microWatts per cubic metre). Normal values range from undetectably low to the order of 10 ì W/m^3.

Thermal conductivity is the conducting property of rock through which heat is flowing. It is a property of the rock and depends on the conductivities of the component minerals in the rock. It is expressed in W/mK (Watts per metre Kelvin) and typical values range from 0.3 W/mK for coal, and 0.6 W/mK for water, 1.5 to 4.0 W/mK for most rocks, and 40 to 400 W/mK for metals.

Thermal diffusivity is a further property of materials, being the conductivity divided by the volumetric heat capacity. This property controls transient thermal changes in solid materials. It is expressed in m^2/s (square metres per second). Most rocks have a diffusivity of the order of 10^{-6} m^2/s, and since the prefix in a unit expression modifies the first unit quantity to the first power, this is usually expressed as 1 mm^2/s.

Table 1
Unit conversion

Energy - expressed in Joules (J)		
1 Joule	=	0.2338 Cal
1 Cal	=	4.187 J
1 kWh (kiloWatt.hour)	=	3.6 MJ
1 MWy (MegaWatt year)	=	31.56 TJ
1 BTU (British thermal unit)	=	1055 J
1 barrel of oil equivalent	=	5.7 GJ (approx)
1 tonne of oil equivalent	=	42 GJ
1 m^3 of natural gas	=	38 MJ
Power - expressed in Watts (W)		
1 W	=	1 J/s
1 W (Watt)	=	3.412 BTU/Hr
1 kW (kiloWatt)	=	1.341 horse-power
Heat flow - expressed in Watt per square metre (W/m^2)		
1 W/m^2	=	0.2388 $x10^{-5}$ cal/cm^2sec
1 cal/cm^2 sec	=	41.87 kW/m^2
Geothermal gradient - expressed in Kelvin/metre (K/m)		
1 mK/m	=	1 ^{O}C/km
1 mK/m	=	0.5486 x 10^{-3} ^{O}F/ft
Thermal conductivity - expressed in Watts/metre.Kelvin (W/mK)		
1 W/mK	=	2.39 $x10^3$ cal/cm sec ^{O}C

UNITS

All units in this report will be expressed in the Systeme Internationale des Pieds et Mesures (SI). Data introduced from old work using other systems have been converted to SI. Scientific publications from before about 1970 are usually expressed in an older metric system, based on grams and centimetres rather than the kilograms and metres of SI. Imperial and US systems, based on feet, pounds and degrees Fahrenheit, are occasionally still used by some engineers.

The main difference between the two metric systems is in the unit of energy. SI uses the Joule (J), whereas the older cgs system uses the Calorie. The Joule is directly derived from the fundamental units, whereas the Calorie depends on the properties of water and is subject to the inaccuracies of measurement. The Watt (W) is the power of one Joule per second. In terms of human energy use these are small units. To avoid the use of large numbers, larger composite units are often used, but because of the non-decimal time system, some of these are not simple multiples of powers of ten. Some conversions given in Table 1, with other important conversions. In this report energy is expressed in Joules.

Prefixes to quantities are used in SI to avoid repetition of powers of ten. The most common prefixes occur in steps of three, and they are shown in Table 2:

Table 2
Prefixes to SI units

k	kilo	3	m	milli	-3
M	Mega	6	ì	micro	-6
G	Giga	9	n	nano	-9
T	Tera	12	p	pico	-12
P	Peta	15			
E	Exa	18			

NB. There should be no confusion between m for “milli” and m for “metre”. Prefixes denoting scale come only at the beginning of a unit expression. Thus, in the unit mm the first “m” denotes “milli” and the second “m” denotes “metre”, and this unit will not appear anywhere but at the beginning of a unit expression.

CHAPTER TWO

THE GEOTHERMAL ENERGY PROGRAM

INTRODUCTION

Geothermal energy research by the Government of Canada was initiated as part of a major new approach to the problems of future energy supply, prompted in October1973 by the sudden rise in the price of oil and the subsequent popular perception that the supply of oil was approaching a serious decline. In the winter of 1974 the Geological Survey of Canada (GSC) and the Earth Physics Branch (EPB), both branches within the Department of Energy, Mines and Resources (EMR) began a small-scale investigation into the potential for geothermal energy in Canada. The formal task structure of the Geothermal Energy Program and the funding for the Program did not come into operation until 1 April 1976.

The price of oil remained high until 1985, but the public fears of future declining supply had disappeared by about 1980. Most of the Renewable Energy Task was eliminated in November 1984, when the Division of Energy of the National Research Council (NRC) was eliminated. The remaining part of the Geothermal Energy Program, located in EMR was reduced. The Program was eliminated entirely on 31 March 1986, when the EPB was combined with GSC, under the name Geological Survey of Canada.

During the years since 1986 popular concern with global environmental problems has grown substantially. The combustion of oil, gas and coal has been recognised as a producer of gaseous oxides, resulting in acid rain in areas down-wind from industrialised countries. The emission of these gases, in company with methane, has also been recognised as most probably responsible for "global warming", a long-term change in climate that it is predicted will eventually result in increase in severity of extreme weather conditions, changes in ocean circulation, migration of animal, insect and plant species, and some melting of polar ice-caps and subsequent rise in sea level. Observation shows that these effects are already occurring.

THE GEOTHERMAL ENERGY PROGRAM

During the ten years of the Geothermal Energy Program a series of unpublished internal reports was written by the participant in the program, and even before the formal Program began there had been a written discussion of the Canadian geothermal potential and the scientific expertise available to the Program. A copy of most of these reports has survived with the author of the current report, and they have provided much of the data of planning, costs, and operational sequence that has been included in this report. They contain little or no technical material, and since they are not accessible to readers, they are not referenced further.

Objectives

Research into geothermal energy in Canada from 1974 to 1986 can be divided roughly into four phases, with considerable overlap.

Phase one consisted of the examination of the accumulated geological knowledge and was directed towards two main questions. Where are the Canadian resources? How large are they? During the first phase, which lasted from about 1974 to 1977, objectives became focussed towards two specific sites and four geological regions.

The examination of these sites and regions constituted the second phase. What is the geothermal potential for electrical generation at the Meager Creek site? What is the geothermal potential at Regina, and how can it be integrated into the energy supply of the University campus? What parts of the Tertiary and Holocene volcanic areas of Canada offer geothermal resources? What parts of the western mountains, not of recent volcanic origin, offer geothermal resources, and of what type? What is the potential for low-temperature geothermal energy from Canadian sedimentary basins? What is the geothermal potential of the Atlantic Region, where costs of conventional energy are higher than the national average?

The question of shallow (<100 m) resources and the use of ground-coupled heat pumps was not raised and was not included in the mandate of the Geothermal Energy Program.

About 1980 the Program entered a third phase, in which the emphasis changed from the application of earth sciences to the assessment of the resources and to the application of engineering to assess the technology and economics of utilisation. The questions asked in this third phase were: What is the available technology, to be learned from other countries, for development in Canada? What are the economic facts governing the use of geothermal energy in Canada? What are the institutional, legal, and economic factors governing the use of geothermal energy in Canada?

From about 1983 the fourth phase of the Program produced a series of requests for advice and assistance, mainly from municipalities concerned with the cost of energy supply for public buildings within their jurisdiction, or with novel ways of reducing costs. These purely local questions developed into studies of feasibility, drawing on the developed experience in earth sciences, engineering and economics, each one directed at a specific location. By March 1986 the Geothermal Energy Program had established that there was a demand from the public for advice and assistance in the examination of geothermal resources, but at this point the Program was cancelled.

Scientific base.

The Geothermal Energy Program of EMR formally began on 1st April 1976, when the first funds generated by the Panel on Energy Research and Development (PERD) became available. Scientific Programs on which the Geothermal Energy Program was based had been in existence for many years. Volcanology had long been a part of the activities of the GSC, mainly in the Vancouver office. Volcanic centres of the four major volcanic belts of the Canadian Cordillera had been mapped and an inventory of hot springs had been maintained for many years. A geothermal research group had been set up in 1962 at the Dominion Observatory, Ottawa, later renamed Earth Physics Branch. Heat flow and heat generation had been measured and interpreted in many areas of Canada: the thermal regime of the crust was known in a broad regional manner, and equipment was available for detailed surveys of specific localities.

Scientific staff of EPB and GSC had worked together on projects of scientific geothermics since 1965, and they began to cooperate on projects related to geothermal resources in early 1974. They were having informal meetings, both among themselves and with consulting companies by the summer of 1975. As the start of the formal Geothermal Energy Program was put back from April 1974, to 1975, and finally to 1976, small projects were undertaken as regular funds were diverted.

Thus, when the Geothermal Energy Program of EMR began in 1976, energy studies had already begun in sedimentary basins and volcanic terrains, and a strong scientific base was in place on which to build. Without these scientific programs there would have been no readily available scientific management for the new Geothermal Energy Program. This is an excellent example of how long term scientific studies within government laboratories have provided an operational base at a time of national need.

Starting the Geothermal Energy Program

Scientific staff of EPB and GSC were working on projects related to geothermal energy from early in 1974. This was possible only by the use of funds from ongoing scientific programs. The Ottawa and Sidney offices of EPB and the Vancouver and Ottawa offices of GSC all made contributions. Meanwhile, the preparations for the Renewable Energy Program took two more years to produce funds for their support. 1975/76 was a year of uncertainty as to whether funds and additional manpower would be made available, and it eventually emerged that the Geothermal Energy Program would receive $100,000 on 1 April 1976, but there would be no manpower to perform the necessary field operations, contract supervision, program administration and clerical work. By early in 1977 it had already been decided that, in view of the fact that EPB and GSC personnel could not handle all the work of managing multiple contracts, EMR and the British Columbia Hydro and Power Authority (BCH) should share in the cost of a contracted project manager for work at Meager Creek. Unfortunately this turned out to be impossible in 1977/78.

MAJOR PROJECTS

During the course of the Geothermal Energy Program two major projects developed, one in the volcanic terrain of the Cordillera and one in the sedimentary terrain of the Western Canada Sedimentary Basin. These became the two foci of much of the research.

Meager Mountain

The first considerations were focussed on the western mountains, where hot springs and recent volcanism were well known. At the same time BCH began to consider geothermal steam as one of their options for future power developments and employed Nevin Sadlier-Brown Goodbrand Ltd. (NSBG) as geological consultants. Based on hot-spring water chemistry and geothermometry, compiled by the GSC, both EMR and BCH chose the Mount Meager Volcanic Complex as the first target of examination. Thus was started a project of cooperation, at times formal and at other times informal, that was to last for most of the life of the EMR Program.

Research and exploration at and around Meager Mountain occupied a substantial part of the work in the Cordillera, and consequently will occupy a substantial part of this report. The first drilling at the Meager Creek Hot Springs occurred in March 1974, a brief seismic survey was conducted during the winter of 1974/75, before funds were available for geothermal energy studies.

Details of the sequence of exploration at Meager Creek are to be found in Chapter 4.

Regina

The second area of interest to EMR scientists was the geothermal potential of sedimentary aquifers. It was known that such resources were in use in Hungary and France. In 1975 a contract was let for a study of the data set known as the Geothermal Survey of North America (Conolly, 1972) and analysis in terms of its use as an indication of the potential for geothermal development in Canada. This first contract was let to Sproule Associates Ltd., of Calgary. The principal investigator was H.A.Gorrell, who took a keen interest in the topic from that time until his death in 1985, providing an extremely valuable industrial perspective to the course of the research.

Early in 1977 the University of Regina approached EMR with the question of a geothermal demonstration project of geothermal water from sedimentary aquifers at the University. A feasibility study, funded by the Geothermal Energy Program, showed that the prospects for geothermal water were good, and a well was drilled in the winter of 1979 to a depth of 2214 m. Tests showed that the geothermal potential was excellent, the potential flow rates being higher than predicted, but the temperature being slightly lower than expected. The water was saline, roughly four times as saline as sea water, and a reinjection well would have been required.

Unfortunately, the large sports building that was intended to be the load for the well was not built, and the remainder of the campus uses a steam heating system, and so the well has never been used for its intended purpose. However, it has been used as a research facility, for temperature logging, hydrofracture testing, water level monitoring and corrosion testing. It has thus been of great value to the Geothermal Energy Program, in a manner that was not originally intended. A full account of the Regina project and of the data obtained from the well has been provided in Chapter 3 of Volume 1.

ENGINEERING AND ECONOMIC STUDIES

In the year 1981/82 an engineering component was added to the Geothermal Energy Research and Development Program, in order to provide information on the technology and economics of use of the resources being investigated by the earth scientists. This responsibility was assigned to the National Research Council. Early contracted studies were very general in nature, but after the first two years the emphasis shifted to specific feasibility studies associated with the growing demand from potential users. In 1984 a comprehensive report on the "Regulatory and Commercial Aspects of Geothermal Energy Development" (Acres Consulting services Ltd and Nevin Sadlier-Brown Goodbrand Ltd., 1984) was produced under contract, which examined the current state of Canadian law regarding geothermal development, provincial assistance programs, taxation, incentives, and institutional factors.

GROWTH OF OUTSIDE INTEREST

Starting in 1983, participants in the Geothermal Energy Program received a growing number of enquiries from outside agencies interested in the use of geothermal resources at specific locations. In addition to the projects at Meager Creek and Regina, which received substantial assistance from the Program, there were several that involved a municipality and commercial consultant, notably Springhill, Nova Scotia, Moose Jaw, Saskatchewan, and Summerland, British Columbia. Details of these enquiries are given in Chapter 5 and in volume one of this report.

THE GEOTHERMAL COMMUNITY

One of the tasks perceived by the managers of the Geothermal Energy Program was to build up a core of expertise in government and industry, to carry on the exploration for and development of geothermal resources after the end of government involvement. Of the core group of five scientists and engineers that steered the Geothermal Energy Program from 1976 to 1986, four are now retired (2008) and none remains in a scientific role. All university participants whose location is still known have retired. Consultants who developed a strong interest and expertise in geothermal resource exploration and development have necessarily moved on to other things and we can reasonably assume that much of the experience is dissipated. However, the author has found that an interest in geothermal exploration survives in Vancouver. Details are to be found in Chapter 2 and Appendices of Volume 1.

Technical groups and symposia

During the period of the Geothermal Energy Program the subject of geothermal energy attracted considerable interest from technical groups and some special groups were set up to provide opportunities for dissemination of results. The Canadian Geothermal Energy Association (CGEA) was started in Vancouver at the end of 1976, by the efforts of NSBG and the federal and provincial geothermal scientists. A technical session was arranged in conjunction with the Canadian institute of Mining and Metallurgy in Vancouver in April 1978, and for some years the Association continued to hold a technical session with its annual general meeting in April, in British Columbia. CGEA has held sessions on sedimentary aspects at prairie locations. The Association has remained small and up to 2007 never exceeded about 60 people. During 2007 the Association was changed from Provincial registration to Federal registration, and it has been revitalised by enthusiastic people who perceive the need for a strong voice that will be heard by all levels of government and by industry on the subject of geothermal development and the contributions that it has to offer to the national energy supply.

ASSESSMENT OF THE RESOURCE

Methods and definitions for the assessment of geothermal resources have been proposed by Muffler and Cataldi (1978), to follow the conventional terms for hydrocarbon or other mineral resources. The conventional definitions may be applied directly to geothermal resources, but the character of the resource introduces some peculiarities in the separation into the various categories. Differences generally result from the fact that most mineral resources are material, either solid, liquid, or gas, whereas the geothermal resources is heat - energy itself. For the purpose of definition these differences may be summarised as follows: 1 - the heat requires a carrier and cannot be recovered independently. The carrier is usually water, which normally is naturally associated with the heat. However, the fluid may be introduced artificially, including reinjection of spent fluid, and it need not necessarily be water. 2 - The resource of heat may be renewable, but not necessarily in an economic time-span. Thus the usable resource may be larger than the static resource estimated from present conditions, but with a time-factor that is not included in the conventional resource terminology. 3 - The size of the resource depends on the use to which it is to be put. Thus, water at 60 ^{O}C is a useful resource for space-heating, but is not useful for the generation of electrical power. This is in contrast with the conventional situation where one useful commodity is uniform in its application.

A more detailed description of the resources assessment process has been given in part 1 of this report (Jessop 2007).

The geothermal resource base is very large, but the difference between the resource base and the usable resource is also very large. Geothermal resources are found in different geological settings, at different temperatures, and in different market options. The uses to which they may be put are so diverse that the assessment of useful reserves and resources can have meaning only if done in the context of the local conditions.

CHAPTER THREE

TECTONIC AND THERMAL STRUCTURE OF THE CORDILLERA

TECTONIC HISTORY

The Cordillera are highly complex, stretching from the southern national boundary at 49 ^{O}N, through British Columbia and western Alberta, the Yukon and Northwest Territories, to the western national boundary at 141 ^{O}W and the Beaufort Sea at 69 ^{O}N. The total area is about 1.5 x 10^6 km^2, or about 15% of the area of Canada.

The Cordillera are made up of five morphological belts, as shown in Fig. 2 (Gabrielse et al., 1992). These belts have combined into the present single land-mass by a process that has lasted from Proterozoic to Tertiary time. In the process the margin of ancestral North America was compressed and uplifted to form the Rocky Mountains. Some contacts between the individual components have been distorted by north-westward movement along major fault zones, but the nature of the individual blocks is still generally maintained.

Proceeding from east to west, the first belt is the Foreland Belt consists of mainly Paleozoic rocks, deposited on the passive margin of western North America in Paleozoic time, and folded, faulted and uplifted in Mesozoic time. In the south the Rocky Mountains are roughly 200 km across, but in the north the Foreland Belt is wider and includes several mountain ranges.

Next to the west, the Omineca Belt is an uplifted region of mainly metamorphic and granitic rocks, which lies between the accreted terranes to the west and the original North America to the east. In the south it is clearly bounded on the east by the Rocky Mountain Trench. It includes the Purcell and Monashee Mountains and many bodies of intrusive rock. In the Yukon it is much wider than in the south.

The Intermontane Belt is generally of lower elevation, and it comprises an amalgam of accreted terranes. It includes the Okanagan Valley and its small basins and volcanic features of Tertiary age. In central and northern areas amalgamation has generated uplift and consequent sedimentation, including the Bowser and Sustut Basins.

The Coast Belt is rugged and of high relief. It is composed mainly of granitic and metamorphic rocks of the Coast Plutonic Complex. The Coast Belt is believed to have been created by a combination of subduction and accretion of the Insular Belt to the west.

The Insular Belt includes the continental margin of Vancouver Island, the Queen Charlotte Islands, southern Alaska and the St.Elias Mountains.

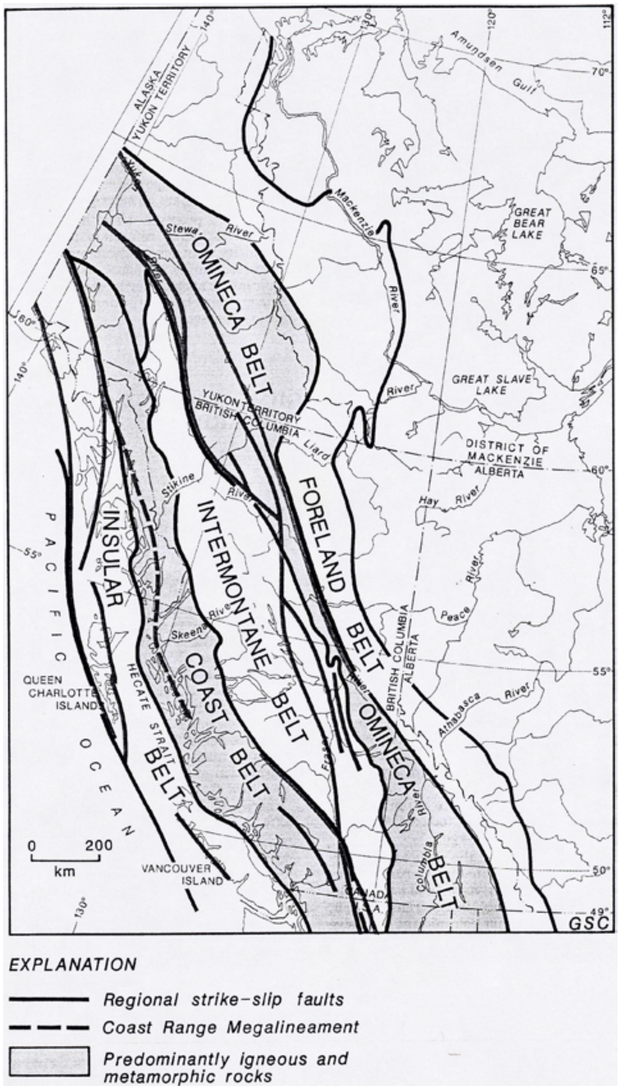

Fig. 2 The morphological belts and regional strike-slip faults of the Canadian Cordillera. Figure from Gabrielse et al. (1992)

In the Foreland Belt the low heat flow has been interpreted as being the result of water recharge on high terrain, followed by deep movement to the north-west beneath the Western Canada Sedimentary Basin, as described on p.36 of the first volume of this report (Jessop, 2007). However, heat flow is not well known throughout the Foreland Belt, because of the absence of wells or boreholes and the difficulty of avoiding disturbance to the thermal field by water flow or topographic contrast. Elsewhere water recharge and discharge acts mainly over much smaller distances, sometimes resulting in thermal springs, as at Banff and Miette. Elsewhere, to the west of the Foreland Belt both heat flow and heat generation are varied and very high in places.

HEAT FLOW AND HEAT GENERATION

Volume 1 of this report included a discussion of the measurement of heat flow and heat generation and the relation between the two. Heat flow is the factor that best describes the thermal state of the earth's crust at any location. Heat flow, when purely conductive, is an indicator of the nature of the crust as a whole and its radioactive content, of the depth to the mantle beneath it, and of the nature of mantle.

Heat flow is the product of the geothermal gradient and the thermal conductivity of the rock. Thus geothermal gradient can vary within areas of uniform heat flow, depending inversely on the conductivity of the rock through which the heat must pass.

Heat flow is measured by observing temperature gradients in boreholes and thermal conductivity of the rocks penetrated and by combining the two observations by the equation

$$Q = -K\frac{dv}{dz}$$

Where Q is terrestrial flow, K is thermal conductivity, v is temperature, and z is depth. The minus sign indicates that heat flows down the thermal gradient, or from the hotter zone to the cooler. Conductivity is not usually uniform in any rock, and may vary substantially between different rock layers, so the combination of temperature gradient and conductivity is not always a simple multiplication. Details may be found in Jessop (1990).

For exploration into geothermal energy the temperature and temperature gradient are more important than the heat flow. At any one site geothermal gradient may vary vertically as the conductivity of the rocks varies, or it may also be distorted by water flow, as will be shown in examples in this report.

Heat generation is caused by the decay of uranium-238 and thorium-235. These two isotopes are found in amounts of a few parts per million in most rocks. There is also a contribution from potassium-40, which comprises only about 0.01% of natural potassium. The heat generated by these three isotopes is usually in the range zero to 10 ì W/m^3. This seems like a small amount but, in a layer of thickness 10 km, it is sufficient to provide more than half of the total heat flow at the surface.

As described in Volume 1, the relation between heat flow and heat generation is of the form:

$$Q = Q_0 + bA_0$$

where Q is surface heat flow, Q_0 is "reduced" heat flow at the base of the layer of variable heat generation, b is the thickness of the layer of variable heat generation, and A_0 is the heat generation observed at the surface, measured from surface samples or diamond drill cores. This equation is satisfied by a layer of thickness b of uniform heat generation, or by a deeper layer of exponentially declining heat generation given by

$$A(z) = A_0 \exp(-z/b)$$

Values of Q_0 b d vary throughout the world, and they define several “heat flow provinces”. Lewis et al (1992) have shown that the value of b is 10.5 km for the area above the subduction zone of the Juan da Fuca Plate. Values of about 10 km are found in most parts of the world. Lewis et al (1984) and Lewis and Bentkowski (1988) have published sets of heat generation data that may be used in conjunction with the above equation to reveal zones of high heat flow and thus probable high geothermal gradient. However, as described in Volume 1, it may not be assumed that observations of heat generation at or near the surface are always representative of depths to 10 km.

Temperature deep in the crust below the depth of measurement, may be calculated from the formula:

$$v = v_s - Qz - Az^2 / 2K$$

which us based on the assumption of a uniform heat generation. Some examples are shown in Chapter 6 in the description of research in intrusive rocks of the Cordillera.

Fig 3 shows part of the “Geothermal map of North America”, edited by Blackwell and Richards (2004). Large parts of the Cordillera show high heat flow, above the world average of about 63 mW/m^2, as indicated by zones of red and orange colour. Zones of yellow, green and blue indicate below average heat flow. The contours of heat flow indicated by this map may depend in part on the distribution of the data, the gaps in coverage, and occasionally on unrealised distortions to heat flow, either by extreme topographic distortion, by refraction by bodies of contrasting conductivity, or by hydrological disturbance. However, the larger features are supported by multiple measurements and are reliable.

Zones of particular interest are in south-western British Columbia, in and around the Garibaldi Volcanic Belt, in south-eastern British Columbia, around large bodies of intrusive rock of high heat generation, and in northern British Columbia, around the Stikine Volcanic Belt and extending into the Yukon. There is also a large zone of elevated heat flow extending from the Cordillera of the Yukon eastwards across the MacKenzie Corridor, into the Precambrian Shield towards Great Slave Lake. The reasons for this anomaly are not entirely understood (Lewis et al., 2003). Its relevance to geothermal energy is limited by the fact that it is generally in an area of very low population density.

VOLCANIC ZONES

Volcanism has occurred from the beginning of continental accretion to recent times. Some volcanism occurred as a part of the process of accretion, and some has been superimposed later. As a result, some Tertiary volcanic belts lie within the morphological belts describe above, while others cut across belts. Intrusive rocks, plutons, and batholiths are found in all morphological belts. Most are too old to have any residual heat, but may have significant heat generation from radioactive isotopes. Terrestrial heat flow is generally high throughout the Cordillera, except in the Foreland Belt, indicating a crust that is generally hotter than in older and more stable areas.

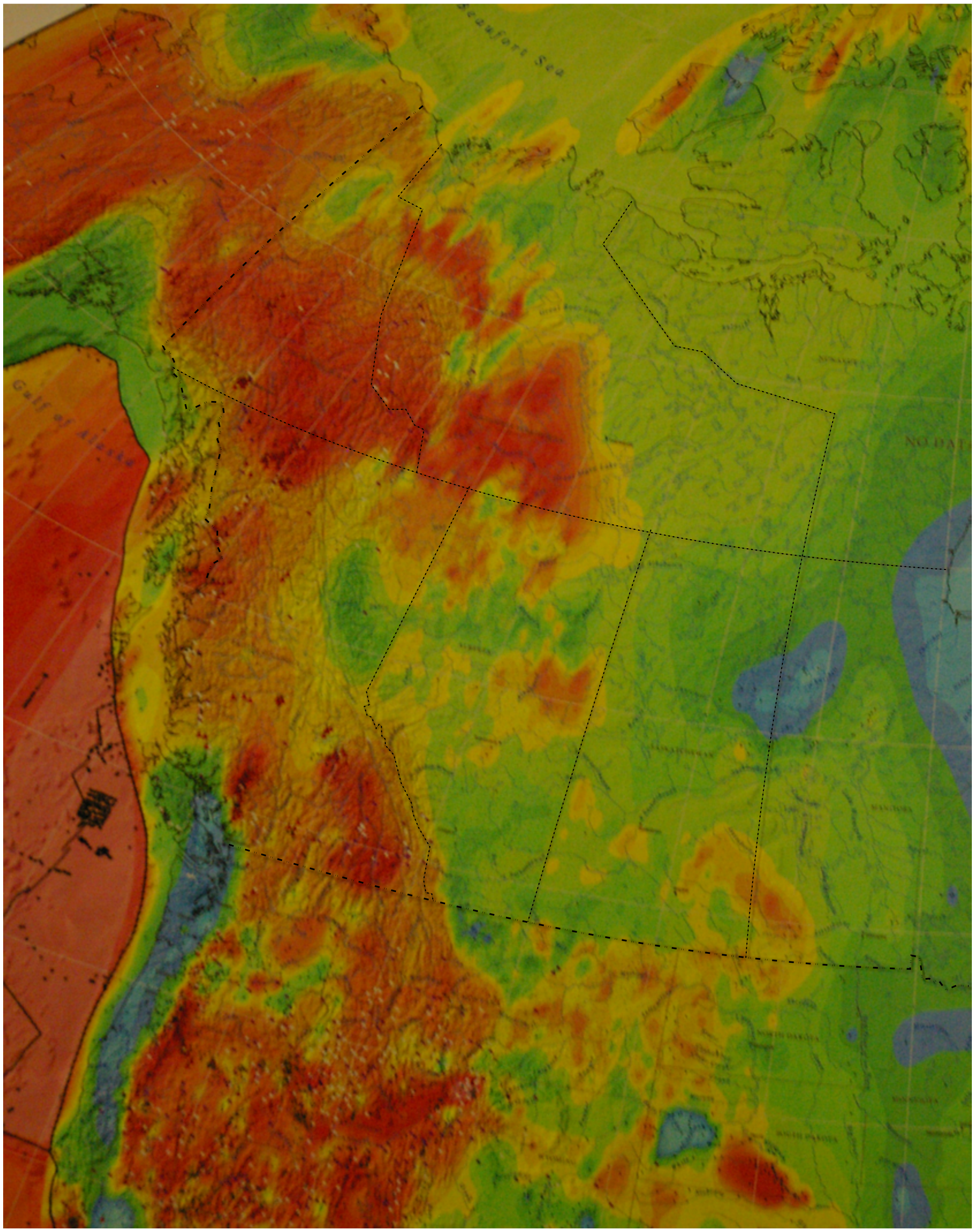

Fig. 3. Heat flow in western Canada. Much of the Cordillera has heat flow above average, as shown by red and orange colour. Figure taken from the Geothermal Map of North America (Blackwell and Richards, 2004)

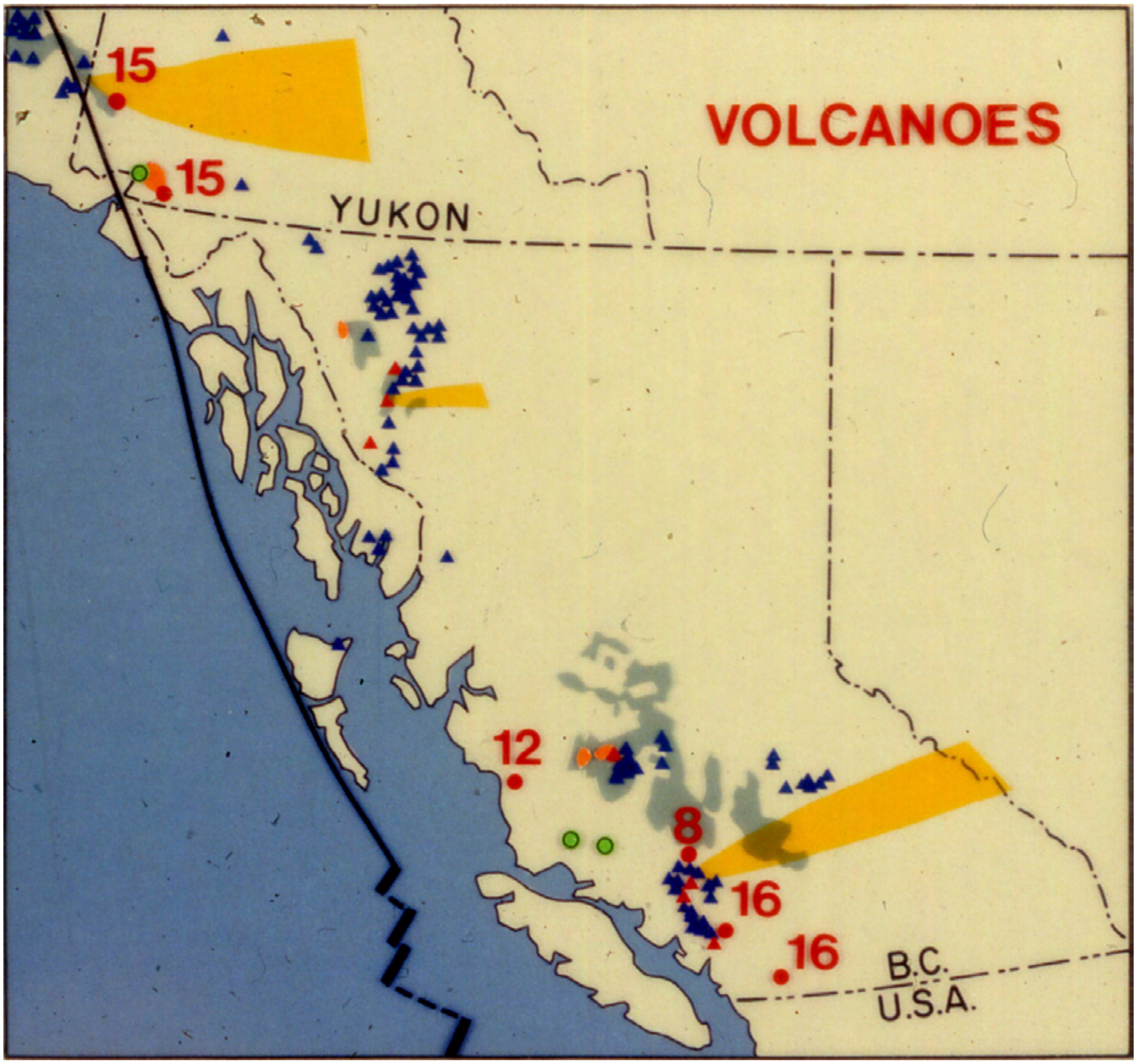

Fig. 4. Volcanic centres of the Cordillera. Blue triangles show individual volcanoes. Red circles show subvolcanic plutons with age in My. Green circles show major caldera. Grey patches show areas of flood basalt. Yellow zones show identifiable ash plumes of ages less than 2500 years. Diagram redrawn from Souther, 1975.

Figs. 4 and 5 show the volcanic centres of the Canadian Cordillera (Souther, 1975). The Pemberton Volcanic Belt runs south-east to north-west, parallel to the coast. It is of late Miocene related to an early stage of spreading from the Juan de Fuca - Explorer Plate system. Potassium-argon dates from some of the plutons range from 18 to 7.8 million years before present.

The Garibaldi Volcanic Belt runs north to south and crosses the Pemberton Volcanic belt at approximately 45 degrees, and is related to recent spreading of the Juan de Fuca Ridge. It contains approximately 32 volcanic features, most of them clustered around the main groups of, from south to north, Mount Garibaldi, Mount Cayley and Mount Meager. Activity is believed to have taken place between 10,000 years and 2,500 years before present. The youngest activity was an explosive eruption of dacite pumice that produced the Bridge River Ash, which has been identified over a wide area of southern British Columbia., as far as the Alberta border, and has been dated at 1440 years before present.

The Anahim Volcanic belt runs east-west between latitudes 52 and 53 ^{0}N, from the west coast to the Interior Plateau near Quesnel It includes 37 Quaternary volcanic centres and a large number of earlier centres. The Quaternary centres have produced small pyroclastic cones and thin lava flows. The volcanoes generally get younger from the coast to the interior. And they are interpreted as a result of the North American continent sliding westward over a small "hotspot". Near the centre of the belt there are three large shield volcanoes of Tertiary age, the Rainbow, Ilgachuz, and Itcha ranges. Near the eastern end is the Nazko cone, the most recent activity of which is only 7200 years old.

On Tuesday October 9, 2007, a swarm of small earthquakes commenced in the upper Baezaeko River region, about 100 km west of Quesnel, British Columbia. More than 100 tremors, mostly of less than magnitude 2 have occurred. Analysis of these seismic data indicated that the earthquakes were occurring about 20 km west of Nazko Cone, at approximately 25 km beneath the earth’s surface. Analysis of the seismic data suggests that magma (liquid rock) is intruding deep within the earths crust in the general region of Nazko cone, and is the probable cause of the seismic activity. Based on the number and size of the seismic events, there is no evidence at this time to suggest that a volcanic eruption is likely. It is possible that magma intruding at depth may stall without immediately rising towards the earth’s surface, and swarms of small magmatic earthquakes may occur at volcanoes without being followed by eruptive activity (NRCan, 2008) This episode of seismic tremors shows that the crust below the eastern end of the Anahim Volcanic Belt is still hot and that small magma movements are still possible.

In northern British Columbia, the Stikine Volcanic Belt runs north-south, and cuts across older north-westerly trending structures of the northern Coast Mountains. It contains more than 50 post-glacial eruptive centres and a similar number of late Miocene to Pliocene age. The belt includes some very large volcanic piles, such as the Edziza complex, which shows an eruptive record from Pliocene to recent time. The lava from the youngest eruption is clearly visible in the Nisga'a Memorial Lava Beds Provincial Park, about 60 km north of Terrace. The park contains cinder cones and lava flows of the Aiyansh - Tseax River volcano. The most recent cinder cone is about 290 m in diameter at the base and produced the most recent lava, which flowed 22.5 km from the vent to the Nass River where, according to legend of the Nisga'a people, it blocked the flow of the Nass River.

In the south-western Yukon the Wrangell Volcanic Belt is associated with subduction at the eastern end of the Aleutian Arc. The White River ash has been dated at 1500 years before present. Most of the eruptive centres lie on the continuation of the belt into Alaska.

Detailed information about Canadian volcanoes may be found on the web site:
http://gsc.nrcan.gc.ca/volcanoes/index_e.php

HOT SPRINGS

The study of hot springs is part of the background science that leads to exploration for geothermal resources. Many of these springs are used for recreational purposes, but this form of utilisation was not part of the mandate of the Geothermal Energy Program. The descriptions here thus describe the springs as indicators of high temperatures and aquifers that may form exploitable geothermal resources.

Elworthy (1925) presented one of the early compilations of mineral and thermal springs in Canada, including the measurement of radioactivity, which was of importance to the tourist industry but is of no other commercial value. Souther,J.G. and Halstead,E.C. (1969 and 1973) have published compilations of mineral and thermal springs in all parts of Canada, with information of geological setting, flow volume, temperature, and chemical composition. These compilations include data on 58 thermal springs of the Cordillera as well as springs in Manitoba and the eastern provinces. Fig. 5 shows the locations of the thermal springs of the Canadian Cordillera (Souther, 1975). Van Everdingen (1972) has provided a detailed description of springs in the southern Rocky Mountains.

McDonald, et al (1978) published a handbook entitled “Hotsprings of western Canada - a complete guide”. This book was written as the result of visits under contract to obtain water samples for geothermometry analysis. It describes the springs, the development, if any, and the means of access. It is written for the tourist or visitor, and it has been available in book stores, including those on British Columbia Ferries.

There are no boiling springs, geysers, fumaroles or mud pots such as are to be found in more active areas like Iceland, Rotorua, New Zealand and Yellowstone Park, USA. The hottest springs, at Lakelse, have a temperature of about 85 ^{0}C. Springs have been divided into three main types, 1- springs associated with deep flow systems in layered carbonate rocks, 2 - springs issuing from fractures in granitic or metamorphic rocks of non-volcanic regions, and 3 - springs located within or near belts of Quaternary volcanism. The chemical content of the waters reflects these origins.

Generally, springs in the Rocky Mountains, such as Banff, Miette and Fairmont, of are of the first type. Springs of the second type, such as Ainsworth and Lakelse, are associated with Tertiary plutons that have relatively high radiogenic heat generation. These may indicate a crust that has temperatures higher than average. Springs of the third type are found within the volcanic belts described above. The hottest of these are found at several points around the Meager Mountain Volcanic Complex. The exploration program that began at the springs on Meager Creek is described in Chapter 4.

The chemical content of dissolved minerals in the water of thermal springs gives some indication of the temperature at which it was in chemical equilibrium with surrounding rocks. There are two

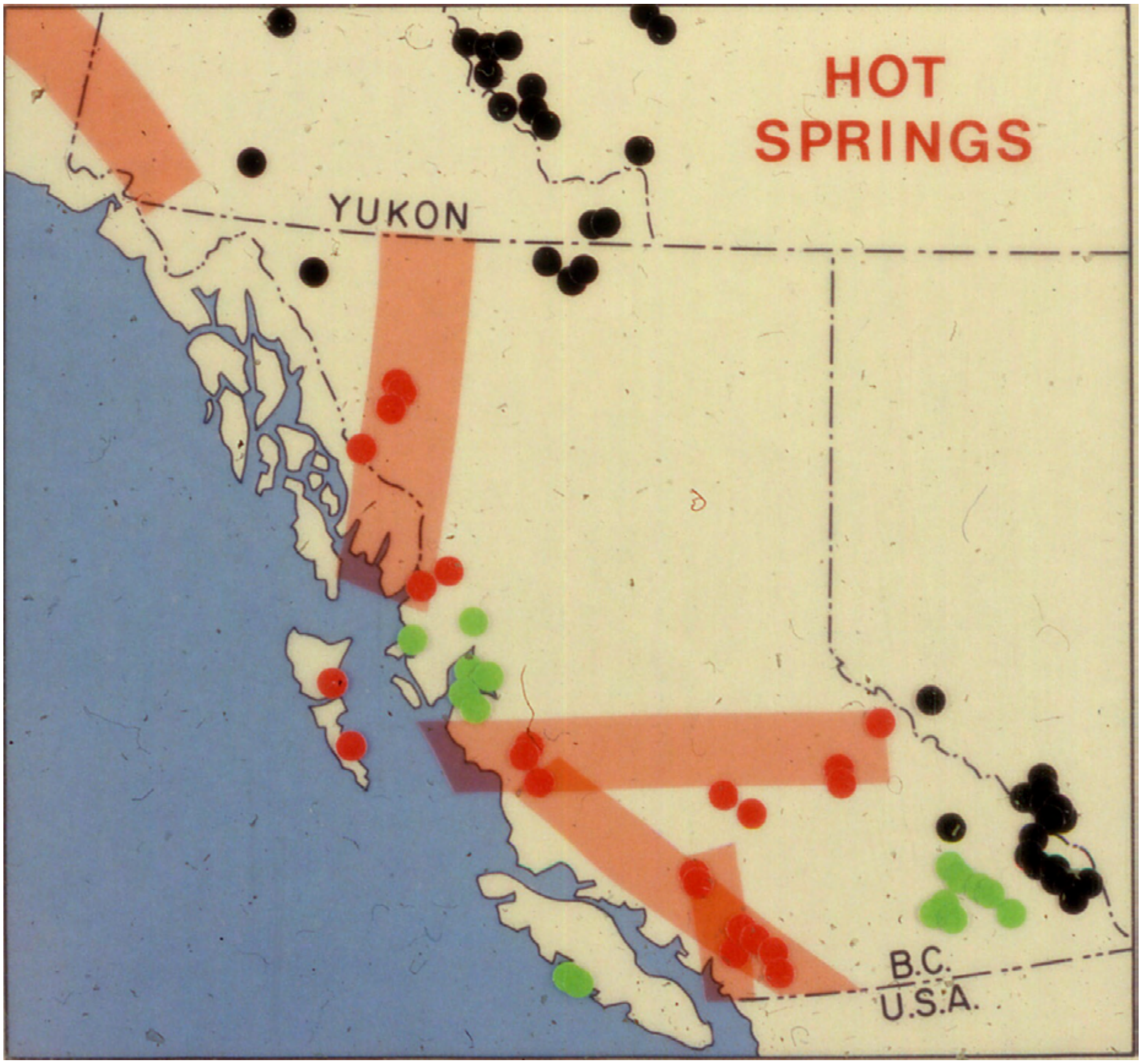

Fig. 5. Hot springs in the Cordillera, as known in 1975. Black circles show springs associated with deep flow systems in layered carbonate rocks, green circles show springs from fractures in granitic or metamorphic rocks in non-volcanic regions, and red circles show springs in belts of recent volcanism. Trends of the major volcanic belts are also shown. Diagram redrawn from Souther, 1975.

main chemical indicators, the quartz content and the ratios of the contents of potassium, calcium and magnesium. Fournier and Rowe (1966) showed that the concentration of silica of many boiling or near-boiling springs is controlled by the solubility of crystalline quartz at depth, rather than by the solubility of amorphous silica near the surface, so that water in equilibrium with crystalline quartz can be cooled considerably before the deposition of silica begins. This preserves an indication of the temperature of the reservoir from which the spring water has come. Fournier and Truesdell (1973) showed how ratios of the content of sodium, potassium and calcium are related to temperature at which the hot spring water was in equilibrium with host rocks. Since the relation depends on ratios, it is little affected by dilution with relatively dilute surface waters.

Chemical analyses of all known thermal springs have been compiled, and the implications in terms of temperature of the rocks through which the water has passed have been examined.

It has been estimated that there are over one hundred hot or warm springs in British Columbia Ghomshei and Sadlier-Brown (1996), and there are more in the Yukon territory. The same publication included a map of known hot springs. Many of these springs occur within two broadly-defined elongated zones. One zone coincides roughly with the Coast Range and into the Stikine and Yukon Plateau areas. The second zone includes the Kootenay and the southern and northern parts of the Rocky Mountains.

REVIEW OF INTERNAL AND OTHER STUDIES

Elworthy,R.T., 1925. Hot springs in western Canada; their radioactive and chemical properties.

This report reviewed the hot springs then known in the Cordillera, their chemical and radioactive content. The most radioactive waters in Canada were at Radium Hot Springs and Fairmont, but these were substantially lower than in some springs in Austria, Germany, France and Japan. It was recognised that the radioactive content of the spring water was of no economic value other than its attraction to the tourist.

Souther,J.G. and Halstead,E.C., 1969. Mineral and thermal waters of Canada.

This report listed thermal and mineral springs in all parts of Canada. It included tables of temperature, flow rates, dissolved solid content and chemical constituents for 58 thermal springs in the Cordillera and 28 mineral springs in all parts of Canada.

Everdingen,R.O.van., 1972. Thermal and mineral springs in the southern Rocky Mountains of Canada..

A booklet containing a detailed description of springs in Banff, Kootenay and Jasper National Parks, and the Rocky Mountains south of the national parks. Includes data on dissolved mineral content, Ph, and Eh. Deals only with springs associated with deep circulation in carbonate rocks.

Souther,J.G. and Halstead,E.C., 1973. Mineral and thermal waters of Canada.

This paper is a revised version of the paper of 1969 by the same authors. Gives tables of temperature, flow rates, chemical content and references.

McDonald,J., Pollock,D. and McDermot,B.,1978. Hotsprings of western Canada - a complete guide.

This guide book was written for the tourist as a result of a contract from the Geological survey to visit springs to acquire samples for further tests of chemical content and indications of subsurface thermal equilibrium. The book describes the springs, the means of access and the suitability for bathing. It is written for the non-scientific visitor or tourist.

CHAPTER FOUR

GEOTHERMAL RESOURCES IN ZONES OF RECENT VOLCANISM

INTRODUCTION

Geothermal resources in the Cordillera have several possible forms. They may occur in any of the forms outlined in the first chapter of Volume 1 of this report. In the volcanic zones the main interest is in vapour-dominated reservoirs or fluid-dominated reservoirs, but hot dry rock is also a possibility. Visible hot springs are also plentiful in volcanic zones.

Visible hot springs were mostly known before 1974, and those in accessible locations had been exploited for recreational pools and spas. Chemical analyses of the spring water can indicate the equilibrium temperature of the reservoir from which the spring flows, and such data had been collected by Souther and Halstead (1969 and 1973). These data were a valuable tool in the early years of the Geothermal Energy Program.

Hydrothermal systems were expected to be associated with geologically recent volcanic features, which were well known before 1974 as a result of geological mapping and research. Intrusive magmas in the cores of volcanic centres can hold their heat for a few million years. While cooling these intrusive bodies usually generate hydrothermal systems that can be exploited. These are often, but not always, indicated by the presence of visible hot springs, and their low electrical resistivity is easily detected by geophysical surveying.

Young intrusive masses may not always generate hydrothermal systems, and they acquired the name of “Hot Dry Rock”. They are much more difficult to detect, as they do not necessarily generate hot springs, and the low electrical resistivity associated with hydrothermal systems is not present. Hot dry rock may also result from anomalously high heat generation by the decay of radioactive potassium, uranium and thorium in large plutons of felsic rocks. No bodies of hot dry rock were known before 1974.

The Geothermal Energy Program in the Cordillera was immediately supported by a great deal of information gathered by routine activities of the scientific agencies concerned.

REVIEW OF INTERNAL STUDIES

Souther,J.G., 1975. Geothermal potential of western Canada.

An early paper on the background geological information leading to estimates of geothermal potential in Canada. Includes descriptions of the volcanic belts and thermal springs of the

Cordillera

Lewis,J.F., 1978. Preliminary field report of drilling near Mt. Meager and Mt.Cayley volcanic centres - 1977

The details of the drilling of four diamond drill holes in the Lillooet and Elaho Valleys for measurement of thermal gradient and heat flow near the meager and Cayley volcanic complexes.

Lewis,T.J and Souther,J.G, 1978. Meager Bountain, B.C. - a possible geothermal energy resource

An account of early work at the hot springs of Meager Creek. Details are to found in the section on Meager Mountain, below.

Souther,J.G., 1979. Canadian Geothermal Research Program.

A review of the Geothermal Energy Program to that date, including projects in both volcanic and sedimentary terrains.

Bentkowski,W.H. and Lewis,T.J., 1984. Preliminary results from shallow drilling in the Alert Bay Volcanic Belt.

An account of shallow drilling for the measurement of heat flow in the Alert Bay Volcanic belt of Vancouver Island. It was concluded that the heat flow in the area is about 64 mW/m^2 and that there is no potential for geothermal development resulting from the late Tertiary volcanic activity

Souther,J.G., 1991. Geothermal Energy

A summary of current knowledge in a large review of geological knowledge of Canada.

REVIEW OF CONTRACTED AND OTHER STUDIES

Work contracted by EPB and GSC was often in cooperation with, or in parallel with, work by the BCH. Federal agencies and BCH worked in close consultation and cooperation for the early part of the exploration program. Eventually BCH engaged in a major program of drilling deep exploration and potential production wells, at a level of cost that excluded federal agencies. All contracted studies, whatever the funding agency are listed here.

Since it is now more than 20 years since the end of the Geothermal Energy Program and of involvement of BCH at Meager Mountain, these reports have had time to be scattered and lost. The library of the Geological Survey in Vancouver seems to have only reports released as Open Files by either GSC or EPB, which are available in all libraries of the Geological Survey. More importantly, the Vancouver library has a collection of transactions of the geothermal Resources Council, containing written versions of papers presented at their annual meetings. These papers summarise some of the more important discoveries at Meager Mountain. NSBG no longer exists. T. Sadlier-Brown is still working as an independent consultant, and he was able to lend a box of reports for examination. M.Ghomshei, of the University of British Columbia, has a collection of reports, but not complete. He was able to lend these for examination for one evening only. B.C.Hydro has an extensive collection in their library at Burnaby, but permission from a high level would have been required before I could have had access to these. Such permission was not thought likely to be withheld, but the time factor prevented such an attempt while the author was in Vancouver. From the description, it seems that they may have preserved a complete collection of reports, at least of their own sponsorship, on all aspects of the work at Meager Mountain and elsewhere in British Columbia.

Many of the reports listed below have not been available for examination. Many of them contain detailed accounts of work that need not be reported here. Their titles and the fact of their existence is enough for present purposes. Where reports have been examined a brief description of contents has been added. Reports are listed in date order, by year only.

> *Nevin,A.E. and Sadlier-Brown,T.L., 1973. Exploration and economic potential of geothermal steam in western Canada.*

Drawing attention to the hot springs, observable thermal alteration of rocks and recent volcanic activity, all of which indicate the possibility of geothermal resources. Predicts that potential developers will face problems from high exploration risks, lack of governing legislation, and environmental questions.

> *Navis Sadlier-Brown,Goodbrand,Ltd., 1974. Investigation of geothermal resources in southwestern British Columbia.*

> *Navis Sadlier-Brown,Goodbrand,Ltd., 1975. Preliminary investigation of the geothermal resources of western Vancouver Island.*

> *Deep Grid Analysis Ltd., 1975. Deep resistivity surveys and supplementary geophysics at Meager Creek selected area, Pemberton, B.C.*

> *Navis Sadlier-Brown Goodbrand,Ltd., 1975. Detailed geothermal investigation at Meager Creek., Rept. to B.C.Hydro and Power Authority.*

> *Navis Sadlier-Brown Goodbrand,Ltd., 1975. Interim report on Meager Creek selected area geothermal investigations phase 2.,*

> *Read,P.B., 1975. Drill core alteration and sinters, Meager Creek, British Columbia.*

An examination of the cores from four holes drilled by NSBG and two holes drilled by EPB and GSC investigators. Recommended that investigation of the timing of alteration and fracture filling is important to the geothermal investigations. Also recommended hydrological studies of the thermal waters.

> *Pham van Ngoc., 1976. Magneto-telluric reconnaissance survey in the Lillooet Valley,*

British Columbia.

Hammerstrom,L.T. and Brown,T.H., 1977. The geochemistry of thermal waters from the Mount Meager Hotsprings area, B.C.

Navis Sadlier-Brown Goodbrand Ltd., 1977. Report on 1976 geothermal investigation at Meager Creek - north and northeast flanks of the volcanic complex.

Navis Sadlier-Brown Goodbrand,Ltd., 1977. 1976 geothermal investigation at Meager Creek.,

Read,P.B., 1977. Meager Creek Volcanic Complex, southwestern British Columbia.

Report on detailed geological mapping of the Meager Mountain Volcanic Complex.

Crandall,J.T. and Sadlier-Brown,T.L., 1978. Data on geothermal areas - cordilleran Yukon, Northwest Territories, and adjacent British Columbia, Canada. Earth Phys.Br., Open File 78-1, 23pp+append+diagr.

Report on the examination of 42 thermal and mineral springs in the Yukon and northwest Territories. Samples were collected for chemical analysis and self-potential traverses were run over some of the springs.

Geoprobe Ltd., 1978. Report on the Maxi-probe EMR-16 test survey around Meager Creek area (B.C.).

Nevin,A.E., Crandall,J.T., Souther,J.G. and Stauder,J. 1978. Meager Creek geothermal system, British Columbia, part 1 - Exploration and research programme.

A conference paper at an early stage of the exploration program at Meager Creek.

Mark,D.G., 1978. Seismic refraction study in the Meager Mountain geothermal region, Lillooet River Valley, B.C.,

Navis Sadlier-Brown Goodbrand Ltd., 1978. Progress report for 1977 Meager Creek geothermal project investigations for 1977-1978.

Navis Sadlier-Brown Goodbrand Ltd., 1978. Report on 1977 geothermal investigation at Meager Creek principally on the northeast flank of the volcanic complex.

Pham van Ngoc., 1978. Magneto-telluric prospecting in the Mount Meager geothermal region (British Columbia).

An extension of work done in 1976, showing significant anisotropy in rock resistivity. It also indicated a crustal thickness of 18 to 21 km.

Noel,G.A., 1978. Cenozoic rocks in the western Canadian cordillera of British Columbia.

A compilation of data on Cenozoic rocks in the Cordillera. plotted on 1:1,000,000 map sheets. Included some plutonic intrusions of the Omineca Crystalline Belt, the widespread extrusive basalt of the interior plateau, and lavas from numerous vents in south-western and north-western British Columbia.

Shore,G.A., 1978. Meager Creek geothermal system, British Columbia, part 3 - Resistivity methods and results.

Changing from a dipole-dipole system to a multiple pole-pole array, because of the steep and irregular terrain.

Combs,J., 1979. Review of the proposed 1979 exploration program for the Meager Creek geothermal project.

Fairbank,B.D., Shore,G.A., Werner,L.J. and Nevin,A.E., 1979. Report on 1978 field work Meager Creek geothermal area upper Lillooet River, British Columbia.

A report on the work done in the field season of 1978 under the first joint contract of B.C.Hydro and DEMR. Includes shallow diamond drilling and resistivity surveys in the areas of both the south and north reservoirs.

Michel,F. and Fritz,P., 1979. Isotope hydrology of the Meager Creek thermal waters.,

Reid, Crowther and Partners Ltd.,1979. Environmental reconnaissance report Meager Creek geothermal area.

Clark,I.D., Fritz,P. and Michel,F.A., 1980. Isotope hydrogeology and geothermometry of the Mount Meager geothermal area.

A study of the chemical composition of waters from the area of mount Meager, and analysis fo some radioactive isotopes.

Fairbank,B.D., Reader,J.F. and Sadlier-Brown,T.L., 1980. Report on 1979 drilling and exploration program Meager Creek geothermal area upper Lillooet River, British Columbia.

Michel,F. and Fritz,P., 1980. Isotope hydrology of the Meager Creek geothermal waters.,

Navis Sadlier-Brown Goodbrand,Ltd.,1980. Report on 1979 drilling and exploration program Meager Creek geothermal area upper Lillooet River, British Columbia.

Pham van gnoc,1980,Etude magneto - tellurique de la region du Mont Meager et de la Vallee de Squamish, Colombie Britannique. magneto-telluric survey of the Mount

Meager region of the Squamish Valley (British Columbia).

An extension of earlier magnetotelluric surveys to higher regions of the Mount Meager Volcanic Complex and to the valley of the Squamish River near Mount Cayley.

Reid, Crowther and Partners, Ltd., 1980. Meager mountain geothermal project status of environmental studies baseline data collection program.

Vtn consolidated,Inc., 1980. 1979 slope stability study - Meager mountain geothermal area.

Anderson,J.M., 1981. Report on seismic refraction survey of B.C. Hydro and Power Authority South Reservoir Meager Creek area, B.C.

A report into a survey to determine the depth to bedrock, to be used when locating sites for shallow diamond drilling in the geothermal area. Overburden ranged in depth from 12 to 340 m.

Geotronics Surveys Ltd., 1981. Summary report on a seismic refraction survey on the geothermal studiesMeager Creek area, B.C.

A report into a survey to determine the depth to bedrock, to be used when locating sites for shallow diamond drilling in the geothermal area.

Navis Sadlier-Brown Goodbrand,Ltd., 1981. Meager Creek geothermal area MC-1 geological summary, July 1981 - October 1981.

Navis Sadlier-Brown Goodbrand,Ltd., 1981. Meager Creek geothermal area slim hole drilling summary, volume 1: south reservoir area.

Navis Sadlier-Brown Goodbrand,Ltd., 1981. Meager Creek geothermal area slim hole drilling summary, volume 2: Lillooet River valley.

Navis Sadlier-Brown Goodbrand,Ltd., 1981. Report on 1980 drilling and exploration program Meager Creek geothermal area, upper Lillooet River, British Columbia.

Nevin Sadlier-Brown Goodbrand Ltd., 1981. Meager Creek Geothermal Project: Preliminary report on soil geochemistry of the South reservoir area

A brief report on soil sampling for mercury and arsenic in the soils in the Meager Creek Valley. Ity was concluded that these elements are an indicator of geothermal activity and of faults that may act as conduits for the escape of geothermal water. Observed that the geochemical indications agreed well with the results of resistivity surveys.

Openshaw,R.E., 1981. Hg and As soil geochemistry of the Meager Creek Geothermal Area.

Similar in content and conclusions to the above.

Scintrex Ltd., 1981. Report on magnetometric resistivity (MMR) survey Meager Mountain geothermal resource British Columbia.,

Shore,G.A., 1981. Report on a resistivity survey in the vicinity of Mt. Cayley, August 1980.

A report on the application of dipole-dipole resistivity surveying to the flanks of Mount Cayley. Two lines were completed for a total of 12 km.

Ward,S.H., 1981. Report on analysis of dipole-dipole resistivity data, Meager Creek, British Columbia.

Werner,L.J., 1981. Report on preliminary magnetometer survey Mt.Cayley area southern B.C.

Apex Airborne Surveys Ltd., 1982. Report on a helicopter E.M. and magnetometer survey in the Meager Creek area, British Columbia.

B.C.Hydro,Power Authority, 1982,. Meager Creek mapping program - 1981.

K.R.T.A.Ltd., 1982. Geothermal project Meager Creek well completion report MC-1.

Details of the deep well MC-1

K.R.T.A.Ltd., 1982. Geothermal project Meager Creek well completion report MC-2.

Details of the deep well MC-2

K.R.T.A.Ltd., 1982. Review of geochemical data from the Meager Creek geothermal area.

Navis Sadlier-Brown Goodbrand,Ltd., 1982. Interpretation of an airborne electromagnetic survey over the Meager Creek geothermal area.

Navis Sadlier-Brown Goodbrand,Ltd., 1982. Report on 1981 drilling and exploration program Meager Creek geothermal area upper Lillooet River, British Columbia.

Openshaw,R.E., Britton,J.M., Fairbank,B.D. and Reader,J.F., 1982. Report on 1981 drilling and exploration program, Meager Creek geothermal area upper Lillooet River, British Columbia.

Shore,G.A. and Schlax,M.G., 1982. Report on coordination and review of resistivity survey results from the Meager Creek geothermal area, 1974 to present.

The steep and variable terrain of the Meager Mountain area provided difficult conditions for the use of resistivity methods. Both north and south reservoirs were identified by these methods.

Navis Sadlier-Brown,Goodbrand,Ltd., 1982. Report on geothermal reconnaissance exploration of selected areas in southwestern British Columbia.

Phoenix Geophysics Ltd., 1982. Magnetotelluric survey data North Thompson Valley area British Columbia.

B.C.Hydro,Power Authority, 1983. Meager Creek geothermal project summary report for 1982-83.

A review of the work done in 1982 and 1983, including details of the three deep wells. It was concluded that there are two reservoirs of 190 to 200 ^{O}C, both of which were penetrated by one or more of the deep wells. The results were considered to be encouraging, but more exploration and testing were required before a successful commercial installation would be possible.

K.R.T.A.Ltd., 1983. Geothermal project Meager Creek well completion report MC-3.,

K.R.T.A.Ltd., 1983. Geothermal project Meager Creek, summary report for 1981-82.,

K.R.T.A.Ltd., 1983. Report on Meager Creek geothermal project 1981-1982.

Navis Sadlier-Brown Goodbrand,Ltd., 1983. Report on 1982 geological mapping program, north reservoir area, Meager Creek, B.C.

Navis Sadlier-Brown Goodbrand,Ltd., 1983. Report on 1982 temperature gradient drilling on Shovelnose Creek at Mount Cayley, southwestern British Columbia.

Navis Sadlier-Brown Goodbrand,Ltd., 1983. Report on a reconnaissance hydrogeochemistry survey of the south-western drainage of Mount Cayley, British Columbia.

An examination of surface waters on the south-west side of Mount Cayley.

Reader,J.F. and Fairbank,B.D. ,1983. Heat flow in the vicinity of the Meager Volcanic Complex, southwestern British Columbia.

The use of heat flow measurement as an exploration tool for the delineation of geothermal anomalies, rather than as a tool for detailed for well siting.

Shore,G.A., 1983. Application and interpretation of multiple pole-pole resistivity survey, Mt. Cayley, B.C.

A conference paper on the application of pole-pole techniques at Mount Cayley.

Shore,G.A., 1983. Electrical resistivity results from the Anahim Volcanic Belt, B.C.

Univ.Utah,Res.Inst., 1983. Multielement geochemistry of the Meager Creek geothermal system.

Nevin Sadlier-Brown Goodbrand Ltd., 1983. Report on thermal conductivity and heat flow in diamond drill holes, Meager Creek geothermal area, southwestern British Columbia

Contains values of temperature gradient, thermal conductivity, and heat flow from boreholes in the Mount Meager area.

Navis Sadlier-Brown Goodbrand,Ltd., 1984. Report on preliminary evaluations of three potential geothermal sites in southern British Columbia.

Navis Sadlier-Brown Goodbrand,Ltd., 1984. Report on a temperature gradient drill hole at Silt Lake (SL-1), ipper Lillooet River Valley, B.C.

An account of the drilling and logging at a hole near Silt Lake, about 4 km north-west of the Meager Mountain Volcanic Complex.

Navis Sadlier-Brown Goodbrand,Ltd., 1984. Report on: Bella Bella temperature gradient drilling, Denny Island, B.C.

A report on the drilling supervision of two experimental diamond drill-holes on Denny Island and data acquisition.

Phoenix geophysics Ltd., 1984. Magnetotelluric survey data, Mount Cayley area, British Columbia.

Report of megnetotelluric survys at five sites around Mount Caylet.

Navis Sadlier-Brown Goodbrand,Ltd. 1984. 1982 temperature gradient drilling on Shovelnose Creek at Mount Cayley, southwestern British Columbia.

Supervision of and temperature measurement in the diamond drill hole at Shovelnose creek, near Mount Cayley.

Shore,G.A., 1984. Report on E-Scan multiple pole resistivity survey at Mt. Cayley, British Columbia.

The application of E-SCAN, a multiple pole-pole resistivity survey method to the flanks of Mount Cayley. Defined an anomaly of potential geothermal significance

Kelley,S. And Blackwell,D., 1984. Fission-track geochronology of the Meager Creek geothermal system, British Columbia.

Measurement of fission tracks in apatite and zircon from two boreholes show that temperatures are now lower than in the past, but have never been above about 200 ^{O}C at shallow depths at either location

Adams,M.C., Moore,J.N. and Forster,C., 1985. Fluid flow in volcanic terrains - hydrogeochemistry of the Meager Mountain thermal system.

Several fluid types were observed in the Meager Mountain area, of both low temperature and high temperature origins. Fluid flow is confined to fractures separated by impermeable rock. Fractures are commonly filled by calcite precipitation caused by subsurface boiling.

Unknown authors, probably Navis Sadlier-Brown Goodbrand,Ltd., 1985. Meager Creek Project: report on activities 1983/84 and 2984/85. Volume 1 - text.

Contains temperature records of the deep wells and records of flow testing etc.

Piteau and Assoc., 1988. Geochemistry and isotope hydrogeology of the Mount Edziza and Mess Creek geothermal waters.

Fairbank,B.D. and twelve others, 1992. Geothermal resources of British Columbia.

A comprehensive map of geothermal resources in British Columbia, including the volcanic belts, sites of radiogenic plutons, and the sedimentary basins of the north-east. Also shows lists of hot springs and boreholes for temperature measurement.

Shore,G.A. and Clearwater,R.P., 1992. Hidden anomalies: small near-surface resistivity anomalies can completely mask large, deeper anomalies.

A conference paper that illustrates problems of interpretation when there are multiple resistivity anomalies present in the area of a survey. Concludes that deeper anomalies can be masked by shallow anomalies, so that potential drill targets are missed.

Shore,G.A. and Clearwater,R.P., 1992. Linear E-Scan: a reconnaissance resistivity mapping system that evaluates its own anomalies en route

A conference paper describing the use of an automated multi-le-electrode potential-mapping traverse system. This system eliminates the need for line cutting and permits quick addition of electrode locations, thus accelerating the decision-making process.

THE MEAGER MOUNTAIN PROJECT

Souther (1977) has reviewed the history of volcanism in the Canadian Cordillera from Upper Paleozoic time to the present. Only Tertiary and Quaternary volcanic centres are likely to be still hot enough to hold geothermal resources, and these lie in four main zones, as shown in Figs.4 and 5. Because of favourable data from hot springs and proximity to large human settlements, the Mount Meager Volcanic Complex was selected as the first target of geothermal investigation.

The Meager Mountain volcanic complex is located in the Garibaldi Volcanic belt, as described in Chapter 3. It is made up of several eruptive centres, including Mount Meager itself, Plinth Peak, Pylon Peak, Mount Job, and Mount Capricorn. It is one of a chain of volcanoes of Quaternary age, one of six major andesite-dacite volcanoes that form the Garibaldi Volcanic Belt which runs roughly north-south to the north of Vancouver. Potassium-argon dates from rocks from the Garibaldi group of volcanoes range from 4 My to less than 100 kY, which means that they are of roughly the same age as the Cascade volcanoes of the United Sates. The older Pemberton Volcanic Belt, of age 8 My to 18 My, runs roughly north-west to south-east, and the two belts meet close to Meager Mountain, as shown in Fig. 6. Both volcanic belts ae believed to have been related to subduction of the Juan de Fuca Plate at different stages of its development. The two volcanic belts are superimposed on the Coast Plutonic Complex, an older granitic and metamorphic terrain that extends north-westward from Vancouver the length of the Canadian Cordillera. The youngest dated eruption produced a plume of air-fall pumice, known as the Bridge River Ash, that has been identified as far east as the Alberta border. Peat immediately below the Bridge River Ash has a carbon-14 date of 2440±140 years. The geology of the Meager Mountain Complex is shown in Fig 7.

Early exploration and climbing of some of the peaks in the Meager Mountain Volcanic Complex has been described by Carter (1932). He and his party climbed Mt Meager (2691 m), Plinth Peak (2708 m), Pylon Peak (2492 m), and they noted the volcanic rocks of which these peaks were formed.

Several major thermal springs are known in the two volcanic belts, as shown in Fig. 6. The silica and sodium-potassium-calcium geothermometers suggested that all of these springs may be associated with high temperature reservoir systems. The Meager Creek springs and the Pebble Creek springs were seen as the thermal areas most likely to be related to recent volcanic activity. However, the chemical content of the two sets of spring water were different and neither were in equilibrium with rock at a well-defined high temperature. The Meager Creek springs issue from coarse gravel deposits, over an area of about 1 hectare. The area remains free of snow for most of the year, in comparison with accumulations of up to 5 m in the surrounding area as shown in the photograph at the front of this report, taken in January 1974. Flow rates and temperatures of the springs suggest that the energy output of the springs, above the ambient temperature of 4^{O}C of the creek, is about 5.4 MW.

Initial exploration

Early work at Meager Mountain and in the Meager Creek valley has been described by Lewis and Souther (1978). The first contracted work aimed at evaluation of geothermal resources was the drilling of two short diamond-drill holes at the hot springs of Meager Creek in March 1974. Since this was done in 1974, it was not part of the Geothermal Energy Program, but was a scientific project aimed at preliminary investigation of the springs.

The first borehole was drilled in the snow-free area. The hole penetrated about 10 m of impervious gravel that was tightly cemented by deposits of travertine and opaline silica. Once

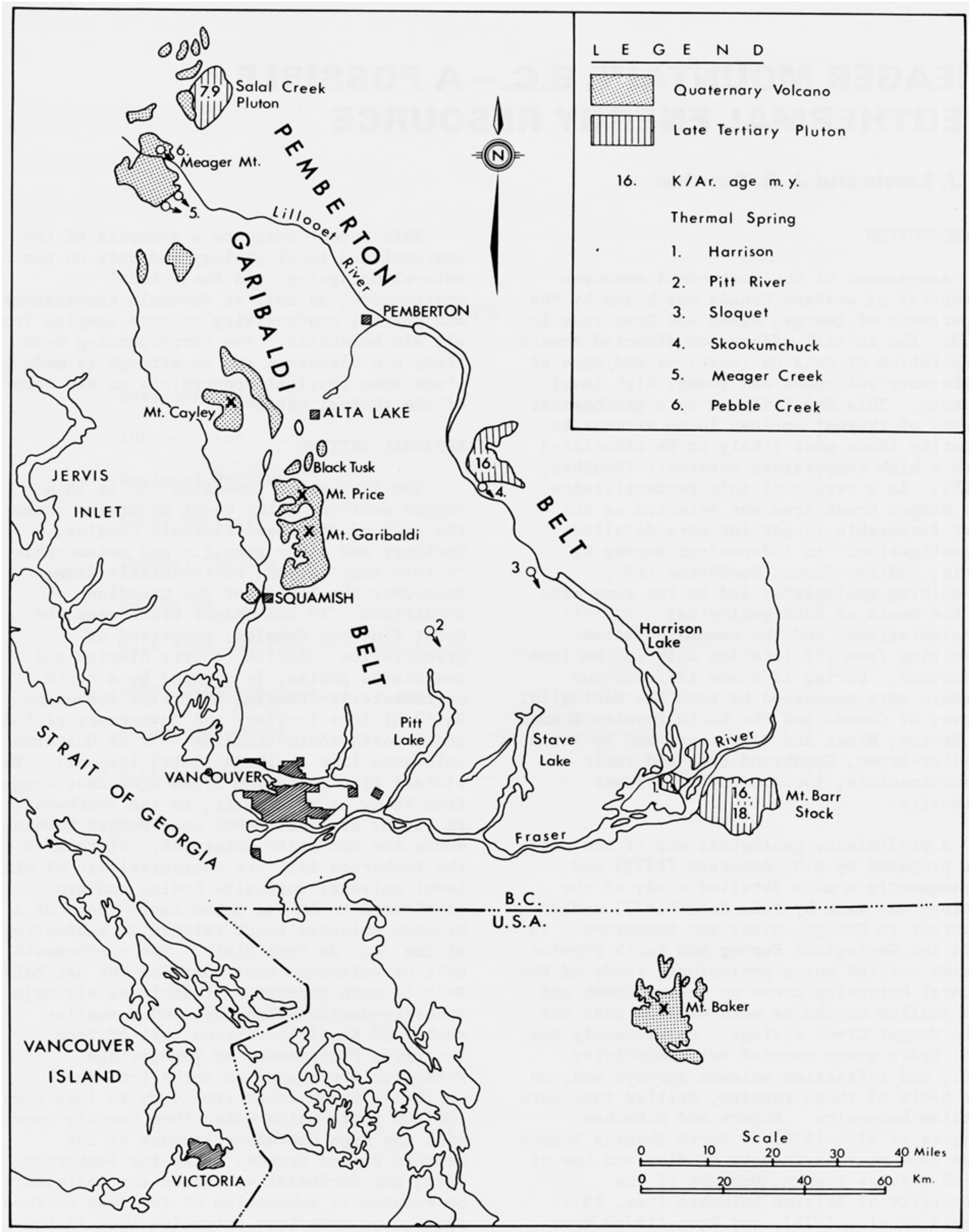

Fig. 6. The location of Meager Mountain and other volcanoes of the Garibaldi Belt, in relation to towns and cities in southern British Columbia. Diagram from Lewis and Souther, 1978.

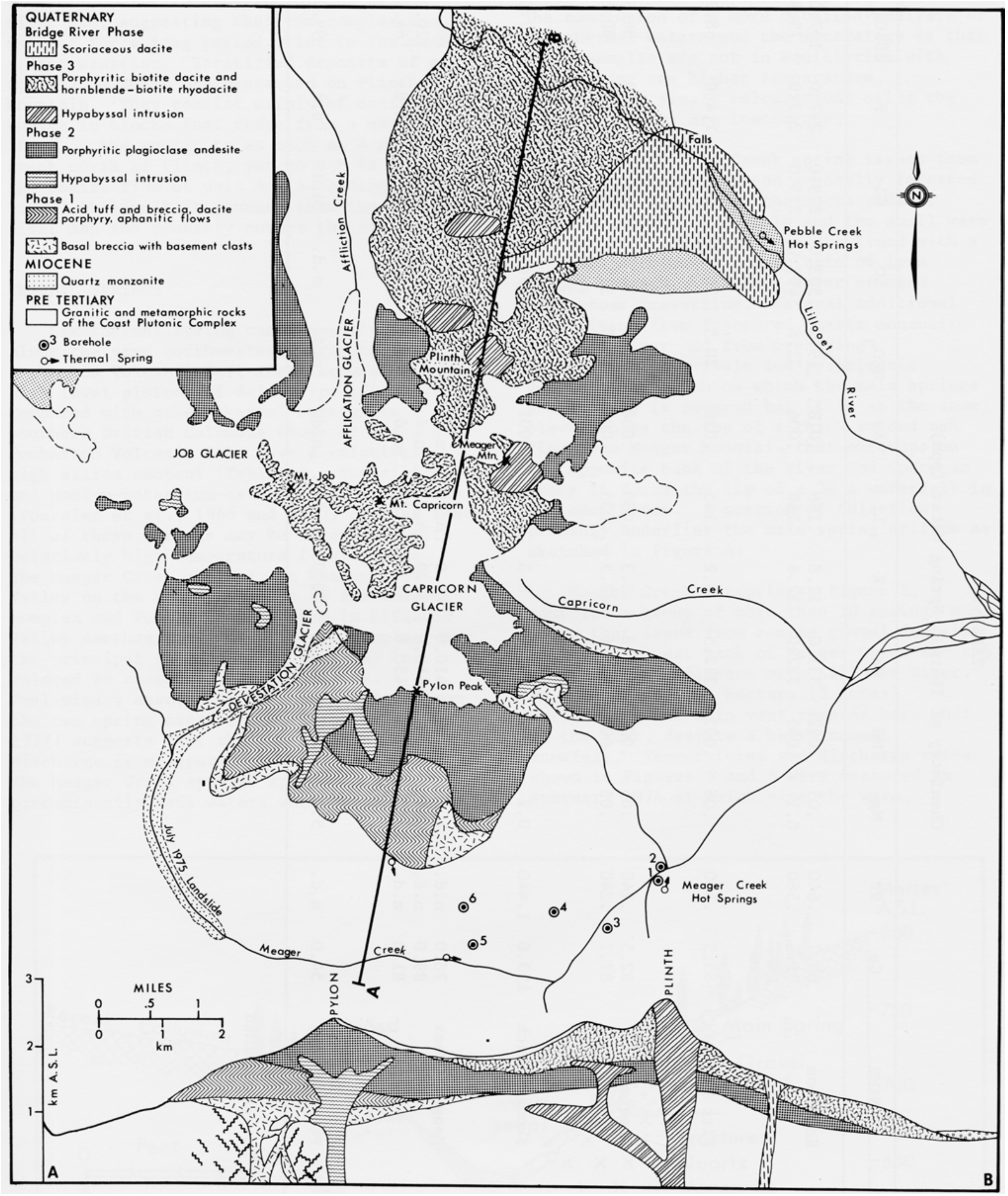

Fig. 7. Geology of the Meager Mountain Volcanic Complex. Locations of some of the early diamond drill holes are shown near Meager Creek. Diagram from Lewis and Souther, 1978.

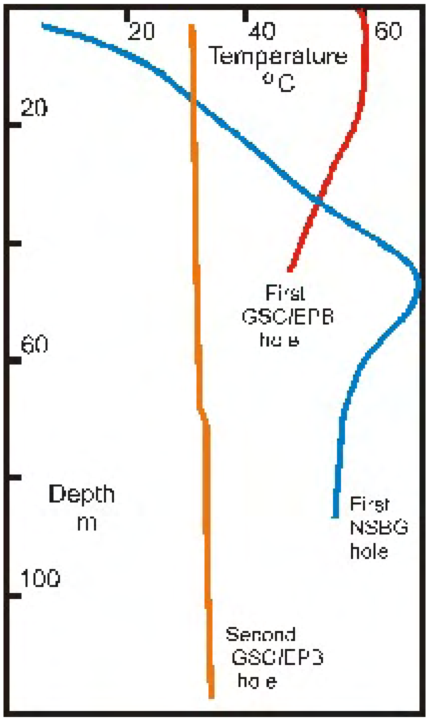

Fig. 8. Temperature profiles from the first two diamond drill holes at the Meager Creek Hot Springs and the first hole drill by NSBG for BC Hydro further up the valley.

the drill broke through into porous gravel hot water at about 59 °C began to flow from the collar. The temperature profile showed that the hot water, moving downstream in the gravels, had cemented a cap within the top of the gravels, and was escaping to form a major spring system where the cap was breached. Temperature logs for both holes are shown in Fig 8.

The second borehole was drilled on the flank of the hot spring area. The entire hole was drilled in quartz diorite gneiss. The temperature profile showed that warm water was entering the hole and was flowing to the surface in the new conduit. A third well was drilled by NSBG for British Columbia Hydro about a kilometre upstream from the springs, near an area of warm seeps. This hole had a temperature maximum at a greater depth and showed that the source of the hot water was further up the valley.

Eventually thirteen more diamond drill holes were drilled by NSBG for BCH further up the valley at sites within the area of a deep resistivity anomaly. Conductive temperature gradients, where it was possible to separate them from hydrological effects were in the range of 112 to 289 mK/m, from four to ten times normal values.

It was concluded that hot water circulates in fractures of the rocks of the Coast Range below the volcanic edifice, and emerges into the gravels of Meager Creek. A deeper much hotter zone, sealed with silica might reasonably be expected from the high silica content of the spring waters.

<u>Geophysical surveys and geological mapping</u>

By November 1975 EMR scientists had conducted magneto-telluric studies in the Lillooet Valley and a seismicity survey, based near the junction of Meager Creek and the Lillooet River. Many of the seismic events recorded were attributed to falling of clumps of snow from trees, but some events were clearly of seismic origin. Having only one recording station prevented the analysis of location of the events. NSBG had performed a resistivity survey in the Meager Creek Valley, and had traced a low-resistivity anomaly from the main hot spring upstream to the south-west and then due west in the gravels of the valley bottom for about 4 km. The anomaly was then seen to dip to the north beneath Meager Mountain.

From 1974 to 1978 EMR and BCH, through their contractors NSBG, worked in informal cooperation, with constant communication. EMR drilled the first holes at the hot springs, but after that concentrated on geological mapping, magnetotelluric surveys, trace-element soil and water surveys, and temperature logging in all available holes. BCH concentrated on further shallow drilling and electrical resistivity surveys.

In early June 1978 a new program of federal-provincial cooperation was set up. The author was asked at very short notice to go to Vancouver to negotiate with BCH. It was decided that work to the value of $500,000 could be done in 1978/79 and that the EMR share of this would be 60%. This Program was part of a series of cooperative ventures in alternative energies and conservation that was eventually to evolve into the Conservation and Renewable Energy Demonstration Agreements (CREDA).

The timing of these administrative moves took no account of the shortness of the field season at Meager Mountain. With longer notice and an earlier time in the financial year and field season, much more could have been achieved. Because of the lateness of the new program, the contract for the BCH part was already in preparation and EMR had to let a separate contract for its part. The NSBG camp was set up at Pebble Creek early in July. In mid-July 1978 multi-pole resistivity surveys were carried out and two new shallow holes were drilled, one to the north and one to the south of the volcanic complex, both of which gave very encouraging results. Audiomagneto-telluric studies showed low resistivity zones within10 km of the surface on two sides of the Meager volcanic complex. The AMT method sees much deeper than the standard resistivity methods, and there was perceived to be a gap in depth capability that prevented easy comparison of the two methods.

For 1979 a budget of $750,000 was prepared, including deeper drilling, further resistivity surveys, management costs, and a review by a panel of foreign experts. The cooperative Program lasted for two years, after which BCH continued with an expanded program of diamond drilling. One hole (M7) showed a temperature of 200^{O}C at a depth of 365 m, a result that demonstrated the presence of strongly convective hydrothermal systems and strongly suggested a significant geothermal resource.

Diamond drill holes

In the autumn of 1977 four diamond drill holes were drilled to depths of about 200 m for thermal studies. Sites were chosen for ease of access and proximity to Mount Meager and Mount Cayley. Observed thermal gradients were all in excess of 45 mK/m and heat flows were all 69 mW/m^2. The highest heat flow, at a site 7.3 km east of amount Meager was 132 mW/m^2, about double the world average (Lewis and Jessop, 1981).

In 1978 Lewis and Souther (1978) published a details of spring flow measurements and temperatures in the boreholes then existing. They found that the Meager Creek Hot Springs were producing about 5.4 MW of energy above a base temperature of 4 ^{O}C. They also reported on temperature gradients and heat flow in the six existing boreholes. The last three, all drilled by NSBG for BCH, showed temperature gradients of 112, 365 and 289 mK/m. Heat flows were 100 and 290 mW/m^{2} for boreholes 4 and 5, but the last one had not penetrated rock where conduction was the only heat transfer mechanism.

Drilling work in 1978 ran the risk of being curtailed by snowfall at the end of the field season, but it eventually produced valuable information. A hole on the north side of the mountain to a depth of 600 m showed a temperature of 103 ^{O}C.

In 1983 NSBG published a report of heat flow calculations from all diamond-drill holes in the Meager Mountain area. In active hydrothermal flow systems like this heat flow, which automatically assumes conductive heat transfer, is subject to disturbance by water movement, both in fractures and in the new conduit provided by the hole. As the report rightly says, heat flow "*must be used with caution due to the effects of convective fluid flow. Unseen deep convective systems can produce elevated heat flows which are difficult to interpret*." The temperature profiles, shown in Fig. 9, show that many of the temperature profiles are controlled, not by conduction alone, but by convective flow in fractures or by water flow in new paths provided by the drilling. As an exploration tool "*heat flow is most useful for modelling features of a system on a scale that describes the entire thermal anomaly, as opposed to defining local drill targets.*" Heat flow is more useful as a reconnaissance tool over a wide area, rather than as a means of deciding on specific targets. Temperature is much more appropriate in small-scale exploration.

Fig. 10 shows the sites of all the holes and wells drilled in the Mount Meager Volcanic Complex, on both south and north sides. The sites are shown on a background of the topographic map of the area.

The extent of the thermal anomaly is illustrated by the locations of wells of high temperature. Such values rarely occur outside zones of anomalous heat such as recent volcanic centres or mid-ocean ridges.

<u>Deep exploration wells</u>

Based on the encouraging results from the shallow, slim hole-drilling program, three deep, full diameter wells (20 cm at bottom) were drilled during 1981-82. The drill collars were close to each other, near the site of the diamond drill holes M4 and M10.

The first deep well, MC-1, was drilled to a length of 3038 m and a depth of 2,500 m below the collar elevation, at an azimuth of 335 ^{O}, approximately in the direction of Pylon Peak. Well MC-2 was drilled to a length of 3500 m and a depth of 3158 m at an azimuth of 30 ^{O}. Well MC-3 was drilled to a length of 3500 m and a depth of 3024 m at an azimuth of 295 ^{O}. Depths and directions were designed to test a substantial part of the known resistivity anomaly.

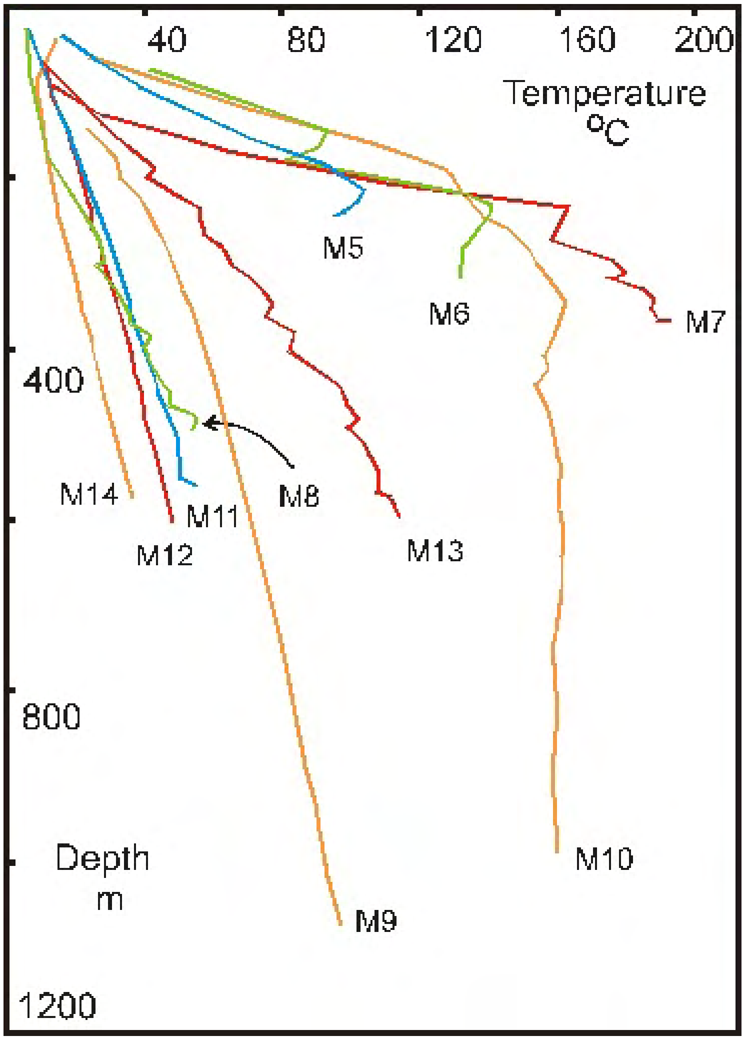

Fig. 9. Temperatures from all diamond drill holes in the area of the resistivity anomaly on the south side of Meager Mountain. These temperatures were taken daily at the bottom of the hole as it was each day, to minimise distortion caused by water movement in the hole. Later temperature profiles may be quite different from these.

Well MC-1 flowed unassisted, and from November 1982 until the summer of 1984, steam was provided intermittently to a 20 kilowatt demonstration plant provided to BC Hydro by the Electric Power Research Institute

Well MC-2 intersected a major permeable zone between 1600 and 1800 m, which was interpreted as being associated with the Meager Creek Fault, and a further permeable zone at 2600 to 3000 m. Some of the fracture permeability may have been damaged by invasion of lost drill fluid. A maximum bottom-hole temperature of 270 ^{O}C was observed, but the well was not proved capable of sustained discharge.

Well MC-3 encountered substantial fluid loss at a length of 3025 m, probably in the No-Good Fracture Zone. Tests indicated a maximum temperature of 290 ^{O}C, but this was not confirmed by reliable temperature logs. The well was not proved capable of sustained discharge. As in MC-2, permeability may have been damaged by drill fluid.

The high temperatures observed were quite adequate for a producing geothermal system. However, the water and steam flows indicated by testing were not sufficient for economic power

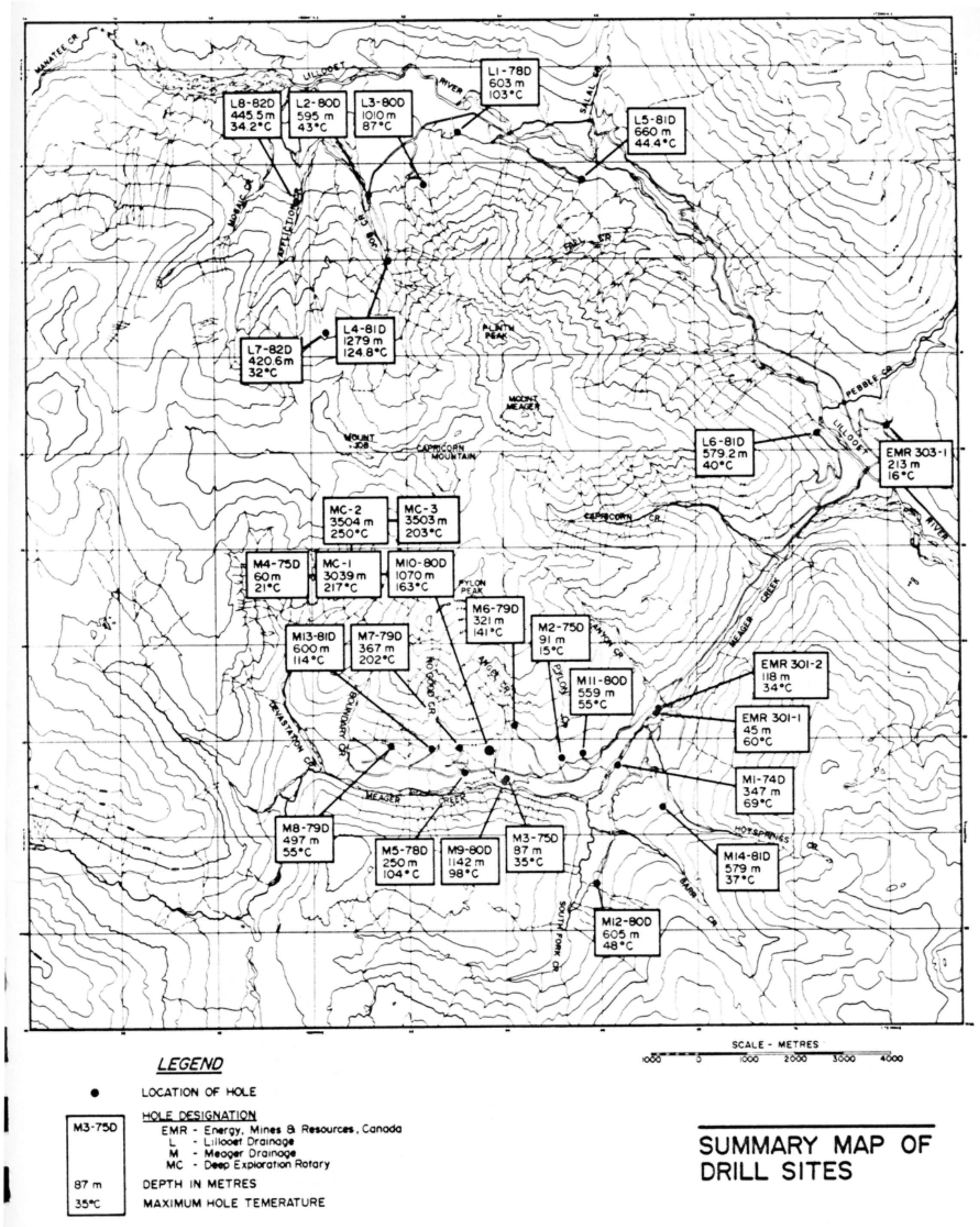

Fig. 10. Locations of drill holes in the area of the resistivity anomaly on the north side of the Meager Mountain Volcanic Complex. Diagram from B.C.Hydro, 1983.

production. Permeable zones were encountered in all three wells, but permeability was always in fracture zones or associated with dykes. Some permeable zones were damaged by being plugged with drill fluid, which must be avoided in any future drilling.

B.C.Hydro (1983) published a summary report showing many details of the completion of the deep wells, their setting in relation to exploratory work and the results obtained. Except for testing of the deep wells, geothermal exploration at Meager Mountain was suspended by B.C.Hydro in August 1982.

<u>The north reservoir</u>

A resistivity anomaly was identified on the north side of the Meager Mountain complex. Because geophysical surveys were prevented by the high rugged terrain in between, it was not possible to confirm that this was a continuation of the south reservoir

Eight exploratory diamond drill holes were drilled in the area of the north reservoir between 1978 and 1983. Sites are shown on Fig.10, and observed temperatures are shown in Fig.11. A further hole was drilled about 4 km to the north-west, near Silt Lake. Temperature gradient at this site was observed to be about 55 mK/m.

SUBSEQUENT DEVELOPMENTS AT MEAGER MOUNTAIN

In 1984 the whole geothermal Program of BCH was cancelled and the managing team was dispersed, because of the abundance of existing low-cost hydroelectric energy, the fall in price of fossil fuels, and the economic recession of the early 1980s. Similar considerations, plus political pressure to reduce federal government science expenditures, prompted the ending of the federal Geothermal Energy Program in 1986.

The large hot pool, set up by B.C.Hydro at the hot springs was destroyed for health and safety reasons, but users continued to go to the springs and to build new pools whenever possible.

Enough research and exploration has been completed at and around Meager Creek to show that there is a major geothermal anomaly associated with the volcanic complex. Although none of the three large wells was developed as a producer, there are many parts of the hydrothermal systems untested, and it seems very probable that there is a viable hot water, or even dry steam, resource present. A hot dry rock resource has been conclusively demonstrated. The development of this resource awaits a change in the economic or political forces governing power generation in British Columbia.

Ghomshei and Stauder (1989) wrote a brief review of the results of the deep wells, with encouraging forecasts of power plants, which have not yet been constructed.

In 1992 Andrew Nevin acquired geothermal tenure on 5,244 hectares of the Pebble Creek Geothermal Anomaly, previously referred to as the “north side of the Meager Mountain Volcanic Complex. He reviewed the known characteristics of the area (Nevin, 1992a) and added a section

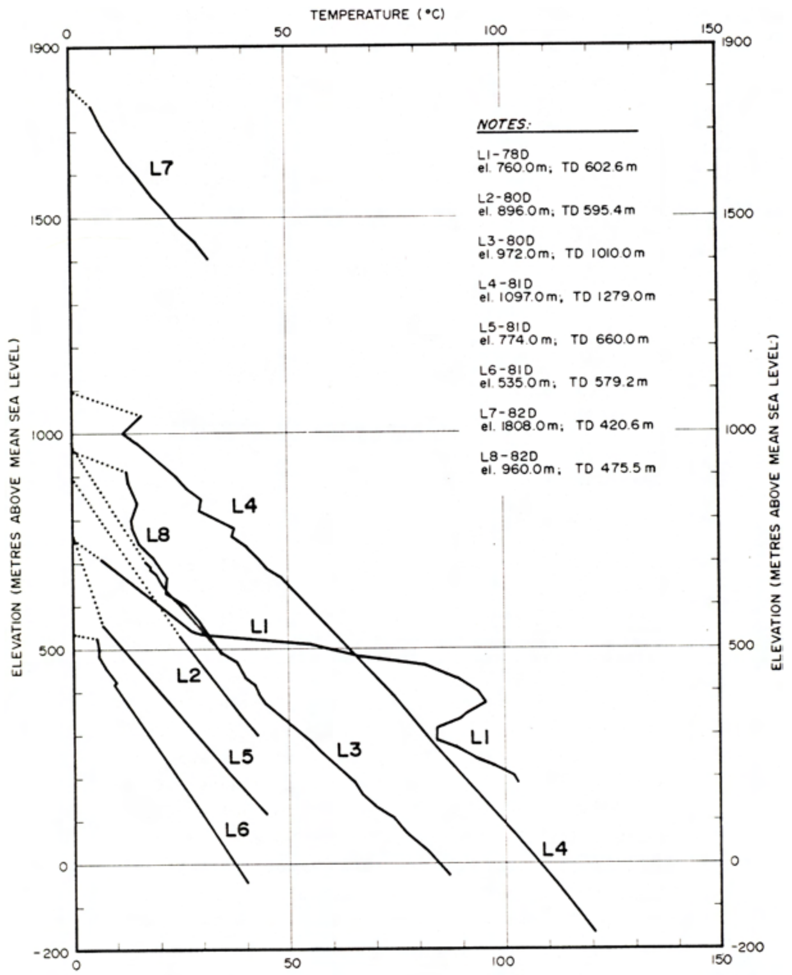

Fig. 11. Temperature profiles from diamond drill holes on the north side of the Mount Meager Volcanic Complex. These profiles are plotted against elevation above sea-level, rather than against depth of the hole, but connections to collar elevation are shown by dotted lines. Diagram from B.C.Hydro, 1983.

on economic factors and changes in government policies in British Columbia.

In another paper Nevin (1992b) reviewed the history of the investigations at Meager Creek, mainly from the organisational point of view. In 1987 the Meager Creek prospect was leased under the British Columbia Geothermal Resources Act of 1982 by Canadian Crew energy Corporation and Commonwealth Construction Company, which was a Canadian Subsidiary of Guy F. Atkinson Company

Ghomshei et al (2005) reviewed the Canadian geothermal situation. By this time the Meager Creek property was held by Western Geopower Corporation of Vancouver. Three further deep core-holes were drilled in 2001 and 2002, showing temperatures up to 224 ^{O}C at depths less that 600 m. Two deep rotary holes were planned for 2005.

Western Geopower Corporation

The remainder of this section is drawn from a document provided by Western Geopower Corp. (C. Aspinall, personal communication). The developments described here have been undertaken by commercial agencies, with no participation by BCH or federal or provincial governments.

In 1988, Meager Creek Development Corporation (MCDC) was formed and acquired the geothermal rights through the granting by the Government of B.C. of the first geothermal lease in Canada, Lease G1. Crew acquired MCDC that same year and funding was achieved by forming a Joint Venture with the Guy F. Atkinson Company of San Francisco. The original lease was expanded by the provincial government to the present size as lease 44507 in 1994 and 2003.

GeothermEx Inc. of Richmond, California, a consulting group with worldwide geothermal exploration and engineering experience and two other consulting groups, was commissioned to review the existing database and advise on an exploration plan. Against GeothermEx's advice, well MC-5 was licensed and spudded in late 1994. Temperatures measured at bottom were 240°C, but permeability was insufficient for commercial production. In 1995, the Joint Venture suspended further development because of the generally unfavorable market climate for independent power producers in B.C.

Well MC-5 was drilled at a new location about 1.5 km west of the drilling pad used for the MC-1, MC-2 and MC-3 wells. This well was directed to the north-north-east and designed to penetrate the fault at a point which would be at the same elevation but 1 km north of where the fault was thought to have been penetrated by well MC-3. Temperatures in MC-5 averaged about 65ºC, lower than those measured in MC-1 at comparable elevation, and again permeability was insufficient for production.

During 2001 and 2002, the Western Geopower carried out a technical program comprised of a magneto-telluric geophysical survey and three slim holes. The results provided strong evidence for the presence of a large, high temperature geothermal reservoir at relatively shallow depth, as earlier proposed by GeothermEx.

The MT survey, conducted by Frontier Geophysics of North Vancouver, which outlined a low-resistivity MT-anomaly under Pylon Peak and Angel Cirque on the mountain's southern slope. The three core holes, designated M-17, M-18 and M-19, were drilled across the southern flank of Pylon Peak. This anomaly is interpreted to represent the up-flow zone of the geothermal reservoir, leading into a shallow, tongue-shaped low-resistivity anomaly extending to the south, which was interpreted as an outflow plume. The drilling across this tongue-shaped anomaly fully supports this interpretation and provides strong evidence of a potentially substantial reservoir at depth feeding the outflow plume.

M-17 was drilled to a total depth of 1,186m and showed a maximum temperature of 197°C at a depth of 1,100m. M-18 was completed to 660m and showed temperatures over 200 ^{O}C between 550 m and bottom, with a maximum temperature of 212 ^{O}C at a depth of 551m. M-19 was drilled to a depth of 913m and showed temperatures over 200 ^{O}C between 660m and bottom, with a maximum temperature of 224 ^{O}C at the bottom. The temperature profiles of wells M-18 and M-19 both show strong convective components. Severe losses of circulation occurred while drilling and extensive fracturing and shearing is prominent in the cores. M-19 is located close to the southern margin of a large explosive volcanic vent mapped in the Angel Creek drainage area, and the high temperature fluids present in the wells are suggested to originate from deep penetrating fractures at the margin of this volcanic vent, or migrating southward along the vent margin from a source further to the north.

The results support the interpretation of the central reservoir or up-flow zone beneath Angel Cirque, with an estimated temperature of at least 250°C. The temperatures measured in the three core holes reflect the hydrology of the hot water system, which, for the most part, is controlled by the terrain, the distribution of permeability at depth, structures providing channels along which thermal fluids can migrate, and the thermodynamic properties of the thermal fluid. In a general sense, therefore, the temperatures measured in the core holes provide insight into the distribution of permeability.

Since 2004, Western GeoPower has drilled three deep, production-size wells to confirm the previously identified high temperatures and the ‘flow’ characteristics required for commercial production. Of the three wells, two are anticipated to be commercial (MC-6 and MC-8) and a third well (MC-7) will be utilized as an injector well to return the geothermal fluids to the reservoir.

Well MC-6 was completed in November 2004. It was drilled in a northeasterly direction to a depth of 2,662 m and following initial air lifting, the well flowed unassisted for more than seven hours. Survey results obtained in May 2005, demonstrated a maximum down-hole temperature of 260 ^{O}C at a depth of 2,632 m. Based on a preliminary injectivity test conducted at the time of completion, GeothermEx estimates the power capacity of MC-6 could be 4.8 MW.

Well MC-7 was completed in February 2005. It was drilled in a northwesterly direction to a depth of 3,291 m. GeothermEx coordinated the initial well testing for the well and reported high temperatures similar to MC-6. Temperature and pressure surveys of well MC-7 carried out in 2006 measured a maximum down-hole temperature of 260 ^{O}C. As the permeability of MC-7 is lower than the permeability in wells MC-6 and MC-8, well MC-7 will be used as an injector well for flow testing the other two wells.

Well MC-8 was drilled in an easterly direction to a depth of 2,380 m and completed in June 2005. Fractures were initially intersected between 2,092 and 2,175 m. At 2,345 m, the first major fracture was encountered and circulation of the drilling fluid was lost completely, following which drilling proceeded without any fluid returns to surface (‘blind’ drilling), to 2,347 m. The well was then drilled with aerated water to 2,380 m, with additional fractures intersected at 2,353 to 2,355 m; 2,363 m; 2,365 m; and 2,369 m.

Well-bore simulation carried out by GeothermEx on data provided by an injectivity test of well MC-8 during July 2005, indicates the well is commercial, with a projected generating capacity of up to 9.8 MW. GeothermEx estimates a minimum power potential for the well of 4 MW on the conservative assumption that the well will heat up to at least 240 ^{O}C and also a maximum power potential of 9.8 MW on the assumption that the well will heat up to 260 ^{O}C, the temperature of well MC-6.

Current plans include the construction of two 55 MW generating units and the time sequence is as follows (Western Geopower Corp. Web site):

Feasibility study	2008-2009
Permitting	2008-2009
Design and construction	2009-2011
Commercial generation	2011-2012

MOUNT CAYLEY

The initial exploration of Mount Cayley was by geological mapping of the Volcanic edifice.

Resistivity and magnetotelluric surveys have been carried out around Mount Cayley, as reported in publications listed above.

Several holes have been drilled for temperature observation. In 1977 two holes were drilled in the valley of the Squamish River on the west side of Mt Cayley (Lewis and Jessop, 1981). These showed high geothermal gradients of 51 and 65 mK/m.

In 1980 two holes were drilled above the valley on the west side of Mt Cayley, and in the following two years two more holes were drilled on the east side. Temperature profiles are shown in Fig. 12. Two of the holes showed geothermal gradients between 90 and 95 mK/m, while the others showed lower values of 45 to 50 mK/m, well above gradients in normal areas.

In 1982 a regional survey of geothermal gradient was performed by the drilling of several shallow holes of depth 100 m (Bentkowski and Lewis, 1983). Plastic casing was grouted into each hole to prevent water flow from masking the pre-drilling temperature. If the grouting works well and the flow of water in and around the casing is prevented, such holes give reasonable values of temperature, but are subject to distortion of the isotherms by topographic contrast or by recent change of temperature at the surface.

OTHER VOLCANIC BELTS

Continental volcanic belts are chains of volcanic structures. They are formed either as the result of subduction zones offshore, as in the Japanese and Indonesian volcanic arcs, by crustal movement over a hot spot or convective cell within the earth's mantle, as in Snake River Plain and Yellowstone Caldera. Canadian volcanic belts are thought to be mostly the result of subduction, either present or in the past, with the exception of the Anahim Volcanic Belt, which has been interpreted as the result of westward movement of the continent over a hot spot or convective plume in the mantle.

<u>Anahim Volcanic Belt</u>

The Anahim Volcanic Belt extends from the coast of British Columbia eastwards for about 500km, at a latitude of 52°N, with decreasing age eastward. It was postulated that this feature was the result of the North American Plate is moving westward over a hot spot or convective cell in the earth's mantle (Souther, 1977). If this theory were true, the crust within the Anahim

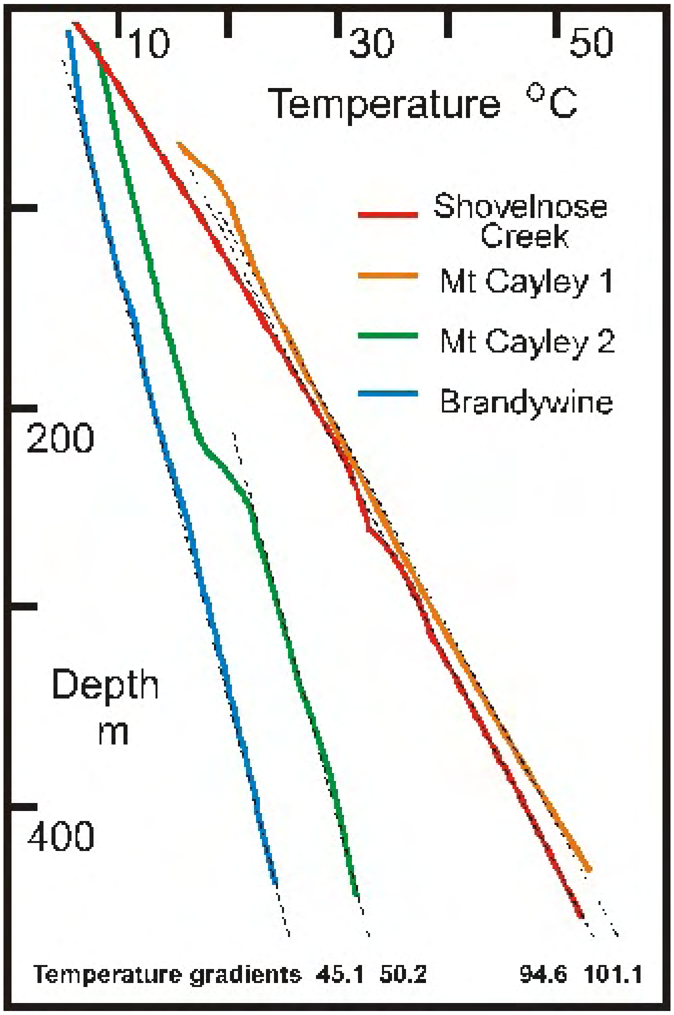

Fig. 12. Temperature profiles from the deep (approx. 400 m) diamond drill holes around Mount Cayley.

Volcanic Belt should show anomalously high heat flow, particularly towards the eastern end.

In order to test this concept, sixteen shallow holes were drilled in the volcanic belt. Holes in the eastern end, near Blue River, suffered from extreme drill deviation and results are unreliable. Eleven holes in the area of Hundred mile House showed geothermal gradients in the range 21.5 to 30.5 mK/m. These gradients, combined with thermal conductivity estimated by rock type, will give heat values at about the world average. Average observed heat generation was 0.90 ì W/m^3, not enough to make a significant contribution to the het flow.

About 60 km to the south, in the Raft Batholith temperature gradients at four drilling sites were observed to be between 27 and 36 mK/m, and heat flow, and heat flow is in the range 92 to 114 mW/m^2. Average heat generation by radioactive trace elements was observed to be 4.66 ì W/m^3, well above average. If the thickness of the heat producing layer is 10 km, the average reduced heat flow is 57 mW/m^2, approximately the same as the surrounding regions. Thus it has not been observed that the Anahim Volcanic Belt shows anomalous heat flow or temperature gradient, and it probably does not present geothermal energy potential greater than regions outside volcanic belts.

At the western end of the Anahim Volcanic Belt two holes were drilled near Bella Bella, on Denny Island. The first hole was drilled to a depth of 199 m and gave a temperature gradient of 27.4 mK/m, and the second was drilled to a depth of 381 m and gave 32.2 mK/m, both calculated from bottom-hole measurements during the drilling process. Nevin Sadlier-Brown Goodbrand Ltd., 1984)

Stikine Volcanic Belt

The volcanic structures of the Stikine Volcanic Belt are generally too far north and remote from human habitation or from electrical transmission lines to be of any interest in the years 1976 to 1986. Except for detailed geological mapping (Souther,1977) and a modest program of heat flow measurement, (Jessop et al, 1984) both undertaken before the Geothermal Energy Program, no geothermal exploration has been attempted.

CHAPTER FIVE

LOCAL AND MUNICIPAL PROJECTS

INTRODUCTION

In the later part of the Geothermal Energy Program several municipalities enquired about the geothermal potential below their land area. Only the Summerland project advanced to the stage of exploratory drilling.

REVIEW OF CONTRACTED STUDIES

Nevin Sadlier-Brown Goodbrand,Ltd., 1984. Report on preliminary evaluations of three potential geothermal sites in southern British Columbia.

Nevin Sadlier-Brown Goodbrand Ltd,1987. Feasibility study for direct utilisation of geothermal energy resources at Summerland, B.C.

Reported on the potential for the use of geothermal water in Summerland and the probable temperature of water within the basin. Gave three temperature forecasts: pessimistic, most probable and optimistic.

Piteau and Assoc.,1984. Summerland Basin hydrogeological study.

D.R.Piteau and Assoc.,1985. Summerland Basin hydrogeological study

A study of the hydrological nature of the Summerland Basin, concluding that the chance of geothermal water at the base of the basin was good.

Grant,M.B. and Michel,F.A., 1985. Study of the hydrogeology of the White Lake Basin, British Columbia.

A study of groundwater from diamond drill holes, domestic wells, springs and surface water in the White Lake Basin. Concluded that there is no evidence that water in the basin have been subjected to temperatures significantly higher than measured at the discharge points.

Michel,F.A. and Fritz,P.,1985. An initial study of the hydrology of White Lake Basin, B.C. Earth Phys.Br.

An analysis of the geological potential for warm water and the possible uses in the town of Summerland. Buildings considered for geothermal heating included greenhouses, schools, and municipal buildings. It was concluded that the geological conditions below Summerland were insufficiently known and that exploration was needed to confirm the magnitude and nature of the resource.

REVIEW OF INTERNAL STUDIES

Lewis,T.J. and Werner,L., 1982. Geothermal gradients on the west side of Okanagan Lake, B.C.

Details of measurements of the drilling of two boreholes, at Paynter Lake, north-west of Kelowna, and Trout Creek, close to Summerland, in or near small tertiary sedimentary basins, where warm water may be available. Includes details of the measurement of temperature, thermal conductivity and heat generation. The two holes were located in impervious rocks to ensure that measurements were not disturbed by water flow.

Lewis,T.J.,1984,. Geothermal energy from Penticton Tertiary Outlier, British Columbia.

An account of temperature logging in several holes in the White Lake Basin. Temperature gradients are in the range 40 to 70 mK/m. It was concluded that water at 80 °C was probable within basin aquifers, but that there was not enough data on aquifer properties to reach a definite conclusion about this particular basin

Jessop,A.M. and Church,B.N.,1991. Geothermal drilling in the Summerland Basin, British Columbia, 1990.

An account of the geological structure of the Summerland basin, the drilling of the first phase of the Summerland well and the observed temperatures. The borehole did not penetrate as far as the base of the Tertiary lavas, and so no reservoir of warm water was found.

THE SUMMERLAND PROJECT

Initial exploration

Early drilling in the Okanagan area showed a moderately high heat flow. Locations of sites described below are shown in Fig 13 and temperature profiles are shown in Fig 14. First heat flow measurements were made in 1963 in the White Lake Basin, 40 km south of Summerland. Temperature gradient was found to be 34.7 mK/m, when corrected for the effects of nearby hills, and heat flow was found to be 79 mW/m^2 (Jessop and Judge, 1971). Later measurements in the same basin gave gradients varying from 40 to 70 mK/m and heat flow varying from 69 to 109 mW/m^2 (Lewis, 1984). Lateral variations over a small distance were probably caused by water circulation in the lower strata of the basin or distortion of the temperature field by topographic features. It was concluded that small Tertiary basins in the Okanagan area showed a good probability of containing usable low-grade geothermal resources, suitable for space heating of homes, green houses, or other structures.   Lewis and Werner (1982) reported on the drilling and

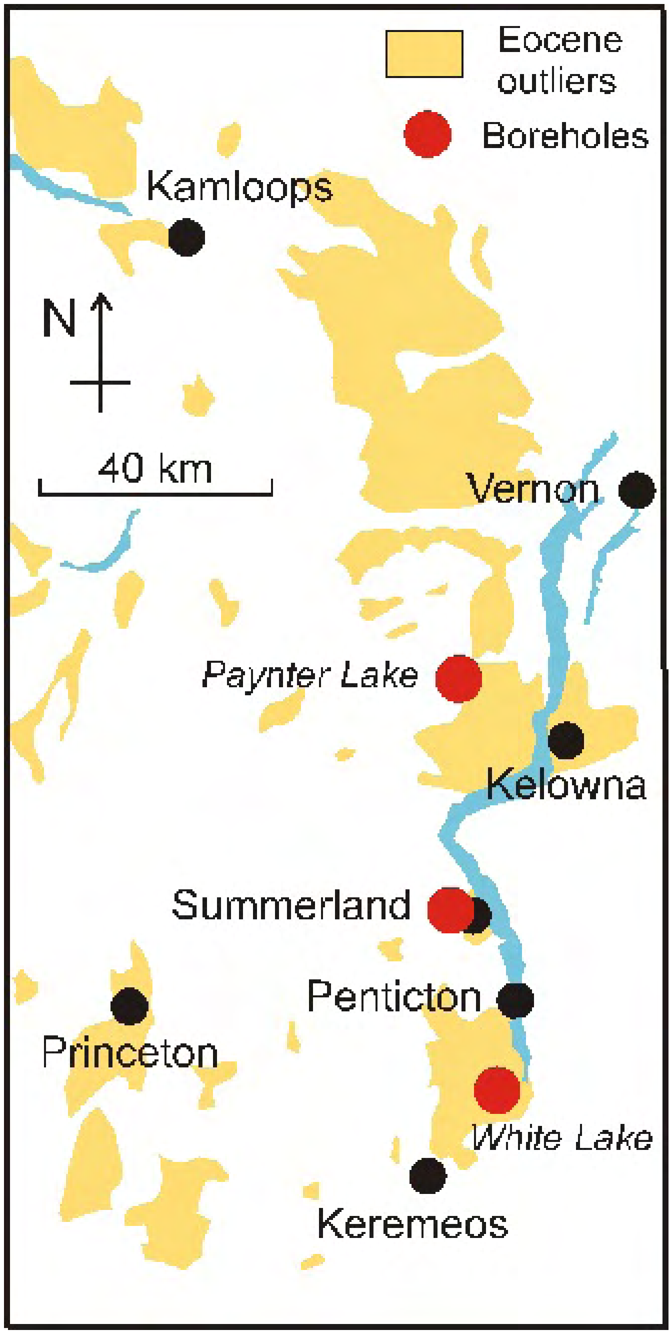

Fig. 13. Sites of drill holes in the Okanagan area. Indicated by red circles. Black circles indicate major towns. Yellow patches indicate Tertiary basins.

logging of two more holes, one at Paynter Lake, about 40 km to the north, where the geothermal gradient was observed to be 29.6 mK/m, and one at Trout Creek, about 5 km to the south, where the geothermal gradient was observed to be 30.0 mK/m. These holes were located near Tertiary basins, but they were located in granitic rocks in order to derive the best measurement of heat flow, free from disturbances due to water movement. These results were sufficient to encourage a direct search for geothermal water to provide heat for greenhouses in Summerland. These plots indicate an average surface temperature of about 10 ^{O}C, except for the plot from Paynter Lake, where the surface is at a higher altitude than the others and therefore cooler.

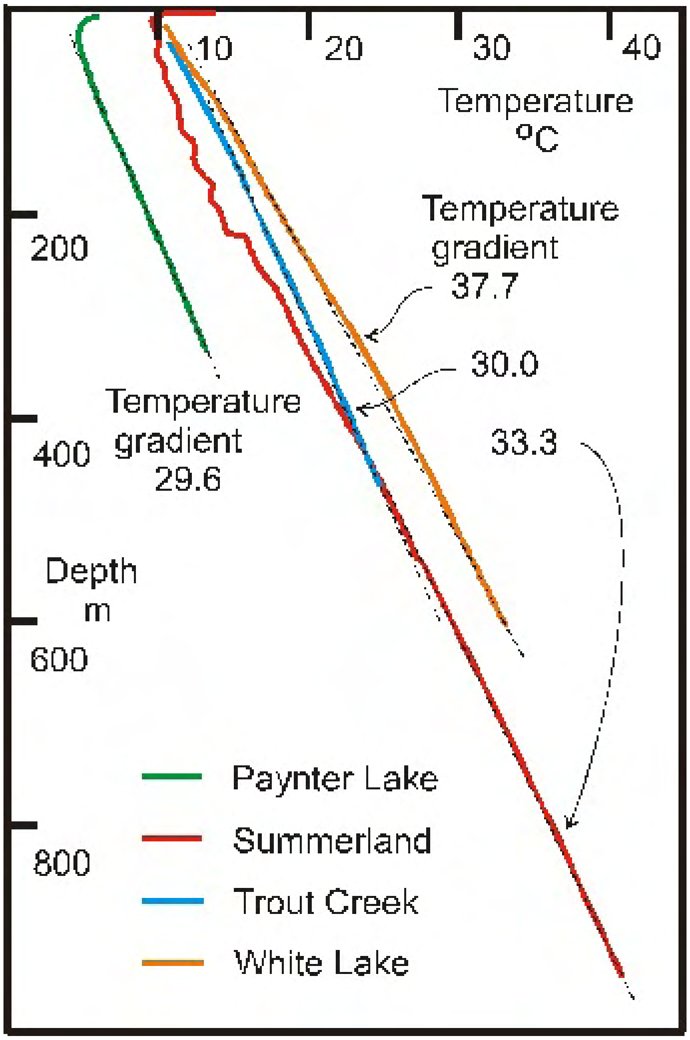

Fig. 14. Temperature profiles from diamond drill holes in the Okanagan area.

Piteau and Associates (1984) concluded that "a geothermal well drilled to the base of the Summerland Basin should have a reasonable chance of producing between 3 and 10 l/s of groundwater". A local natural spring was already flowing at a rate of 67.5 l/s and at a temperature of 11 ^{O}C. This water was the result of surface run-off. The water was being used for a trout hatchery, for which the constant temperature, with little seasonal variation, was a great advantage.

Nevin, Sadlier-Brown, Goodbrand Ltd (1987) concluded that there was a good chance of encountering water at temperatures between 50 ^{O}C and 65 ^{O}C beneath the town of Summerland, but that, while geothermal development was technically possible, economic factors needed to be carefully considered, including the present and future costs of conventional energy. Also, the nature and magnitude of the resource was not sufficiently known, and exploratory drilling was needed to confirm the resource.

Following this report, the Okanagan-Similkameen Community Association looked for ways to promote the use of geothermal resources. It was the practice of greenhouse operators in

Summerland to circulate water at 25 ^{O}C through tubes laid on the benches but beneath the roots of the plants, to provide warmth to the roots and encourage growth. Since the average temperature of the ground surface in the area is about 10 ^{O}C, the required temperature should be reached at a depth of only about 500 m, provided that the geothermal gradient is at least 30 mK/m. If water was available at that level it could be drawn on to provide the required heating. Mr. Boerboom, a farmer on the northwest side of Summerland, approximately 1 km from the centre of the town, was found to be willing to allow the drilling of an exploratory diamond drill hole on his property. Neil Church of the British Columbia Geological Survey provided a geological analysis of the site. The site was on the west limb of the basin and it was anticipated that the well would intersect the basal conglomerate of the Tertiary rocks, which were expected to provide an aquifer, at about the right depth.

Drilling

The Summerland well began as a 15.2 cm diameter rotary hole to a depthof 544 m, drilled between 10 March and 15 May 1990. This well penetrated 56 m of gravel and glacial till before entering bedrock. This hole was cased to 542 m and was continued by BQ diamond drilling to a depth of 712 m, from 21 to 31 July 1990. Samples were taken in the form of cuttings to 544 m and in cores from 544 m to 712 m. Rocks penetrated were mostly alternating ash flows and lava flows of the Marron Formation. A temporary water flow of about 100 litres per minute was reported at a depth of about 150 m. Water continued to flow very slowly from the collar whenever the cap was removed after the end of drilling operations.

Temperatures measured on 16 August 1990 showed temperatures of about 10.5 ^{O}C at the surface and 33.28 ^{O}C at a depth of 706 m. Temperature gradient in the lower part of the hole was 33.3 mK/m. The basal conglomerate was not reached, and no aquifer of sufficient capacity was intersected. Analysis of water from the upper part of the well showed low content of dissolved solids. The water was of a quality that permitted disposal in surface streams or for irrigation.

The well was deepened between 10 to 27 February 1992, to a total depth of 956 m. The angle between bedding and the core averaged 45 degrees, but showed a tendency to increase to about 50 degrees near the bottom of the well. This angle is greater than anticipated and probably accounts for the failure to intersect the basal conglomerate.

The final thermal profile of 21 July 1992 shows a series of breaks (Fig 16). These indicate small water flows, but none sufficient to provide the flow needed for the greenhouse application. Below 500 m the temperature gradient declines slowly from 35 to 32 mK/m. Thermal conductivities have not yet been measured, so the uniformity of heat flow over this depth interval has not been confirmed. The highest temperature observed was 40.985 ^{O}C at a depth of 946.5 m. This result may be extrapolated to a temperature of 42.7 ^{O}C at 1000 m depth, closer to the "pessimistic" forecast than to the "most probable" forecast of Nevin Sadlier-Brown Goodbrand Ltd (1987)

It was concluded that the prospects for low-temperature geothermal resources for use in greenhouses at Summerland was unlikely. Although temperatures were more than adequate for the system proposed, no usable water had been found, and the costs of deeper drilling would make geothermal water unattractive as a heat source. Given the high geothermal gradients, it is possible that warm water could be found in aquifers, if the aquifers can be located.

HOT SPRINGS COVE, VANCOUVER ISLAND

NSBG visited the village at Refuge Cove, often called Hot Springs Cove, in October 1984. Water and gas samples were collected and temperature measurements were made at three locations in the vicinity.

A major geological fault, running roughly north-south, runs through the middle of Hot Springs Cove, which may provide a conduit for water from deep below the surface. Temperature of the hottest of the springs were observed to be 50.5 ^{O}C. Chemical content of the water was used to provide estimates of the equilibrium temperature of the water before it rose to the surface. Results of the various geothermometer indicators range from 70.6 ^{O}C to 113.2 ^{O}C , with an average of 94.2 ^{O}C. The evidence was considered to favour a meteoric source for the water, and circulation to sufficient depth to attain the observed and implied temperatures.

It was concluded that an exploratory diamond drill hole, angled to intersect the Refuge Cove Fault was needed to gather more information about the local geothermal regime and the potential for exploitation. Potential uses suggested were space heating, aquaculture and silviculture, and the possibility of electrical generation by a binary cycle turbine. At that time the electrical generation would have required temperatures at least as high as those suggested by the geothermometry.

A cost estimate of $145,000 was provided. By 1984 the Geothermal Energy Program was already being reduced, and such funds were not available. The Federal-Provincial Agreement system also failed to provide the funds, and so the project proceeded no further.

KOOTENAY AREA

The towns of Kimberley and Riondel, with their abandoned mines, seem to be prime targets for research into the geothermal potential of mine water. So far I have found no indication that this is being considered.

YUKON TERRITORY

The City of Whitehorse uses water from wells, with a temperature of about 6 ^{O}C to mix with surface water to prevent the water supply system from freezing in the winter.

The Town of Mayo uses water from two wells to help heat some buildings in the community. This location was considered during the Geothermal Energy Program of 1976 to 1986, but federal interest was cut off with the closing of the Program.

At Haines Junction there is an artesian geothermal well that produces water at 16.9 ^{O}C. It is intended to use this water with heat pumps to warm the Haines Junction Community Centre. This will reduce carbon dioxide emissions by 87 tonnes per year. (Energy, Mines & Resources, 2008)

A report by Gartner Lee Ltd (2003) reviews the potential for groundwater and ground-coupled heat pumps in the Yukon territory. This report identifies the communities of Beaver Creek, Burwash Landing, Carcross, Carmacks, Haines Junction, Mayo, Pelly Crossing, Ross River, and Watson Lake as having above average potential for the use of groundwater with heat pumps for space heating. heat pumps.

CHAPTER SIX

POTENTIAL FOR HOT DRY ROCK RESOURCES

INTRODUCTION

The conventional use of geothermal energy depends on the presence of water as a carrier of the heat. In sedimentary basins the water is contained in extensive aquifers within porous strata. In volcanic zones the aquifers may be of irregular shape, but they must have a high porosity and permeability and they must be confined by impervious rocks above. The water is usually in liquid form, but in a few examples it is in the form of steam.

In contrast, the use of hot dry rock depends on the artificial injection of water to recover the heat in the solid rock. This requires the introduction of water into the hot zone and the recovery of the water after it has had time to acquire the temperature of the hot rock. This kind of geothermal development has been usually known as "hot dry rock", but the MIT report uses the term "Enhanced Geothermal System". Others use the term "Engineered Geothermal System" (MIT, 2006).

There are two possible settings for hot dry rock potential. The first is in recent volcanic edifices, where the subsurface rocks retain the heat of emplacement or are heated by recent magmatic events. Such sites may reasonable be expected in any of the centres of Holocene or late Tertiary volcanism in the Cordillera. The second is in intrusive bodies that have lost their initial heat but show a high radioactive heat generation, above about 4 ì W/m^3. For these locations the data sets mentioned above provide an invaluable first indication. As recounted in Volume 1, high values of heat generation may be misleading if the rocks sampled at the surface do not represent the rocks to a depth of up to 10 km. The inferred high geothermal gradient can be confirmed only by temperature measurements in a borehole.

CONCEPT AND MECHANISM

Of the few research projects so far undertaken, all have been aimed at bodies of hard intrusive rock. Such rocks are usually of very low porosity, and permeability is provided only by fractures. It is thus necessary to generate artificial channels for the movement of water. The technique so far used has consisted of the drilling of a well into the hot zone, the use of hydrofracture techniques to induce a vertical fracture, the injection of sand or some other "propping" agent, the drilling of a second well to intersect the fracture, and the establishment of water circulation from one well to the other through the fracture. It has been assumed that the thermal "shock" of the cold water would enhance the fracture system to provide more paths for the water from one well to the other.

The presence of a hot zone may be inferred from measurements of shallow temperature gradient or from measurements of heat generation by radioactive trace elements. Neither method, used alone, is capable of unequivocal results. Shallow temperature gradients may be distorted by water movements below the measurement zone, and heat generation may be confined to shallow surface layers only. Further combination with geological mapping and an analysis of the tectonic origins of the area help to prevent spurious interpretations. An example of apparently misleading heat generation data was given in the first volume of this report.

Hydrofracturing is the name given to the process of increasing the hydraulic pressure in a section of a well until it exceeds the pressure in the rock sufficiently to induce a fracture. The fracture always occurs in a plane perpendicular to the minimum principal stress. At shallow depths the fracture will be horizontal, but beyond a certain depth the fracture will be vertical. The direction of the fracture may be detected by seismic means. The fracture is often kept open by “propping”, or injecting sand into the fracture.

FOREIGN PROJECTS

The cost of such an experimental development is high, and few have been attempted so far. During the period of high oil price of 1973 to 1984, two experiments were undertaken, one at Fenton Hill, New Mexico, USA, and one in the Carnmenellis Granite of Cornwall, England. An exploration project was also undertaken at Marysville, Montana, USA. More recently a new project has been started at Soultz-sous-Forêts.

Meanwhile, experience in deep drilling has been acquired by the drilling of very deep holes on the Kola Peninsula, USSR, where the maximum depth reached was 12262 m, and in Bavaria, Germany, where the depth reached was 9101 m.

Fenton Hill, New Mexico, USA

The first such experiment, started in 1974 was at Fenton Hill, on the rim of the Valles Caldera in New Mexico, USA. Funds for this experiment came mainly from the Department of Energy of the USA. The operating agency was the Los Alamos National Laboratory, a branch of the University of California.

From 1974 to1978 wells were drilled to depth of 3000 m, where temperatures were about 185 ^{O}C, and circulation was established. From 1978 to 1980 experiments were conducted into circulation within the system. Beginning in 1980 a hotter and deeper reservoir was developed, at depth of about 3500 m and temperature of 220 to 240 ^{O}C. Flow tests were conducted in 1992 to 1995, in three periods with a total length of 11 months. Returns of 6.5 l/s at a temperature of 185 ^{O}C were established. Water loss was up to 14%, but it always declined after a period of use to about 1 to 2 %. (Duchane,D.V., undated, about 1996).

This rate and temperature of return imply an energy output of 5 MW thermal energy above 0 ^{O}C. The electrical generation capability will be less, depending on the design and efficiency of the turbines. The effective volume of the hot reservoir was estimated at 20 x 10^{6} m^{3}. At a uniform temperature of 230 ^{O}C, and assuming a specific heat of rock of 900 J/kgK and density 2.7 kg/m^3, this implies a heat content of about 11 x 10^{15} J above 0 ^{O}C. Production of this heat source at a rate of 5 MW implies a reservoir life of about 70 years, provided that all the heat can be recovered. Since a viable power plant would need to produce at a much higher rate, at least ten times greater, this is a short life span. However, this is a small volume of rock, amounting to no more that a thickness of 20 m over an area of 1 km^2.

Both Germany and Japan participated with funds and personnel in the Fenton Hill program. The pioneering work there demonstrated that energy from hot dry rock could be routinely extracted for practical use. Further programs have been started in Europe and Japan (Duchane and Brown, 2002).

Marysville, Montana, USA

Marysville is a small town in western Montana, in the foothills of the Rocky Mountains. In or before 1969 a region of high heat flow was observed. Further measurements were made and the anomaly was confirmed and geographically circumscribed. Heat flow values ranged from 134 to 812 mW/m^2 (Blackwell and Baag, 1973). Geophysical measurements showed an absence of the kind of electrical resistivity that would indicate the presence of an aquifer, and it was concluded that the heat flow anomaly was purely conductive. It was concluded that the thermal anomaly was the result of a cooling intrusive body a few kilometres below the surface. The data suggested a roughly spherical body, of age approximately 40,000 years, of diameter about 3 km, and with its top within 2 km of the surface. An exploratory well was drilled into the centre of the anomaly in 1974 to a total depth of 2070 m. From 450 m onward the hole intersected a series of fractures that contained large volumes of water at temperatures from 93 to 98 ^{O}C (Blackwell and Morgan, 1975). This result showed that large quantities of hot water can be present close to the surface without any surface indication in the form of hot springs, and that geophysical surveys can occasionally miss the low resistivity signals of water in fractures.

Carnmenellis granite, Cornwall, UK

From approximately 1975 to 1984 a hot dry rock experiment, funded mainly by the European Union, was located in the Cornubian Batholith of Cornwall, UK. The granites of south-west England form such distinctive features as Dartmoor, Bodmin Moor, Lands End, and the Scilly Isles. They were intruded in Permian time into Devonian and Carboniferous sedimentary and igneous rocks that were deformed and regionally metamorphosed during the Armorican Orogeny. Hydrothermal activity produced mineral deposits, notably of tin, which have been mined since the time of the Romans and the Phoenicians. It has also produced large deposits of China Clay, which were used extensively in the Industrial Revolution. The initial heat of emplacement has long dissipated, and any high temperature remaining depends on the high level of radioactive isotopes within the rocks. Temperature gradients were found to be about 35 mK/m.

The Weardale Granite, UK

A geothermal exploration hole was completed in 2004 at Eastgate, Durham, into the Weardale Granite, to a depth of 995 m. The Weardale Granite is of Devonian age. Results showed a heat generation in the granite of 4.1 ì W/m^3 and a temperature gradient of 38 mK/m. (Manning et al, 2007). The well encountered brines at about 46^{O}C in fractures in the granite, and it was concluded that the Eastgate borehole has significant exploitation potential for direct heat uses, and it demonstrates the potential for seeking hydrothermal vein systems within intrusive granites as geothermal resources.

Soultz-sous-Forêts

The project at Soultz-sous Forêts is supported by the European Union and several corporations. It was initiated in 1987, at a time when alternative energy was not an important concern, and so represents a remarkably far-sighted decision by the participants.

Soultz-sous Forêts is situated on the eastern side of the Rhinegraben, about 40 km north of Strasbourg. Five wells have been drilled to penetrate a large granite body overlain by 1400 m of sediment. Three of the wells have reached depths of 5000 m. The target zone lies between depths of 4500 m to 5000 m, where the temperature is about 200^{O}C.

DEEP DRILLING

There have been two attempts to drill very deep wells as research facilities. The first was the "Kola Superdeep Borehole" in what was then the USSR. The second was the KTB deep well in what was then the Federal Republic of Germany.

The Kola Superdeep borehole was drilled between 1970 and 1989 to a total depth of 12,262 m. Technical difficulties eventually forced the termination of the project. Temperature was observed to be 180^{O}C rather than the expected 100^{O}C.

Rocks at the bottom of the hole were about 2.7 Gy old. An observed change in seismic velocity, previously interpreted as marking the change from granite to basalt was found to be at the bottom of a layer of metamorphic rock that extended from about 5 km to 10 km depth. This rock was highly fractured and was saturated with water. This water was interpreted as having come from deep-crust minerals and had been unable to reach the surface because of impermeable layers.

The KTB drilling experiment in Germany reached a final depth of 9101 m, where the temperature was observed to be 265^{O}C. Again, large amounts of free fluids were found down to mid-crustal levels. So far, drilling to depths of 9 km or more in hard crystalline rock is an expensive and time-consuming venture. It is not a well-developed technology.

REVIEW OF INTERNAL AND OTHER STUDIES

> *Leroux,J.,1980. Geothermal potential of the Coryell Intrusions, Granby River area, British Columbia. Geol.Surv.Can., Paper 80-1b, 213-215*

An account of detailed geological mapping of the Coryell intrusions

Lewis,T.K., Allen,V.S., Taylor,A.E. and Jessop,A.M. 1979. Temperature observations during drilling of two 400 m wells in the Coryell intrusives north of Grand Forks, British Columbia, 1978. Earth Phys. Br. Open File 79-4, 24 pp.

This report gave the temperature observations in two boreholes in the Coryell intrusions, drilled to test hot dry rock potential, during and soon after drilling.

REVIEW OF CONTRACTED STUDIES

No studies of hot dry rock were undertaken under contract, as the topic had not advanced to a stage where such contracts were warranted.

CANADIAN POTENTIAL

Funding levels of the Geothermal Energy Program in Canada were quite inadequate to mount a hot dry rock experiment. However, it was possible to conduct some basic earth science research to provide information about possible sources.

Studies of both terrestrial heat flow and heat generation were the prime tools in this research. Heat flow measurement requires direct measurement of temperature and geothermal gradient, and so provides indications of where thermal gradients are above average. Measurement of heat generation of surface samples taken from batholith and intrusive bodies provides an indirect indication of heat flow, based on the assumption that the measured heat generation is representative of the rocks to a depth of about 10 km. The relation between heat flow and heat generation has been described in Chapter 3 of this report and in Volume One in consideration of hot dry rock options in the Maritime Provinces and Newfoundland. Some of the shortcomings of reliance on heat generation were also described, where measurement of surface samples are not representative of a thick sequence of rocks.

However, heat flow measurement depends on the availability of boreholes in which to make measurements, or the drilling of holes specially for temperature measurement. Unless there are mining operations nearby or funds to drill holes for measurements purposes, there will be no measurements. Further, in mountainous terrain temperature disturbance by water movement is a hindrance to the measurement of geothermal gradient. Measurement of heat generation is much easier and less expensive, provided the gamma-ray spectrometer is purchased and maintained.

In the Canadian Cordillera many surface exposures of intrusive rocks have been sampled and heat generation has been measured. Lewis et al (1984) and Lewis and Bentkowski (1988) have published compilations of heat generation data. The distribution of observed heat generation is shown in Fig. 15 and a list of granitic plutons and heat generation is given in Table 3 (Lewis et al, 1992). In Table 3 “n” denotes the number of samples measured, “A” the average heat generation in ì W/m^3, and”SD” the standard deviation in the same units.

Fig 16 shows a group of curves of temperature with depth, based on a heat flow province where the reduced heat flow is 50 mW/m^2 and the thickness of the radiogenic layer is 10 km. The curves correspond to heat generations ranging from zero to 8 ì W/m^3. The calculated temperature profiles show a decline of gradient with increasing depth because the heat flow is reduced by the amount of heat generation above each point, until the heat flow at depth is equal to the theoretical reduced heat flow and the curves are all parallel.

Table 3
Heat generation in granitic plutons

Name	n	A	SD
Insular Belt			
Island intrusions	65	0.78	0.25
Coast Plutonic Belt			
Chillwack	9	1.70	1.48
Coast Plutonic complex	87	0.82	0.61
Mt. Barr	5	2.05	0.38
Needle Peak	1	1.49	-----
Intermontane Belt			
Guichon	6	0.83	0.27
Pennask	3	1.75	0.43
Similkameen	12	1.31	0.22
Takomkane	32	0.95	0.27
Omineca Crystalline Belt			
Baldy	3	4.84	1.12
Battle Range	5	4.67	0.86
Bayonne	8	2.28	0.70
Bugaboos	18	6.15	1.33
Coryell	34	4.78	1.35
Crawford Bay	7	2.69	0.29
Fry Creek	18	4.85	1.17
Galena Bay	6	1.69	0.21
Horsethief	14	6.51	1.85
Kuskanax	4	1.15	0.11
Lost Creek	5	3.55	0.35
Nelson	32	2.12	0.98
Raft River	41	4.35	1.39
Salmon Arm	5	3.37	0.44
Shepphard	7	1.75	0.27
White Creek	20	3.60	0.87

The model of exponential decline of heat generation, described in Chapter 3, will give higher temperatures in the crust, but evidence from deep drilling is so far insufficient to support this model or these higher temperatures.

The curves of Fig. 16 can be recalculated for the parameters of any heat flow province, but they are not valid for volcanic zones where recent heating from volcanic activity has added to the heat generated by radioactive isotopes.

<u>The Coryell Syenite</u>

In the autumn of 1978 two holes were drilled in the Coryell intrusive rocks, to the north of Grand Forks, British Columbia. (Lewis et al, 1979) Temperature profiles are shown in Figure 18. Both holes penetrated water-bearing fractures and provided new paths for water flow. The first hole, shown by the red line in Fig 18, penetrated several fractures, each of which contributed a component to the upward water flow. The second hole, shown by the blue line, penetrated only one fracture that provided upward water flow. Below the water-bearing fractures temperature gradients were observed to be 51.2 and 54.0 mK/m respectively. These gradients, when multiplied by the average thermal conductivities of 2.13 and 2.18 respectively, imply a heat flows of about 109 and 117 mW/m^2, and indicate that the high heat generation does indeed extend for some depth.

The situation in the Coryell pluton is represented best by the orange line in Fig.16. It shows that the temperature of 200^{O}C is reached at a depths of 5000 m, about the same depth as at Soultz-sous Forêts.

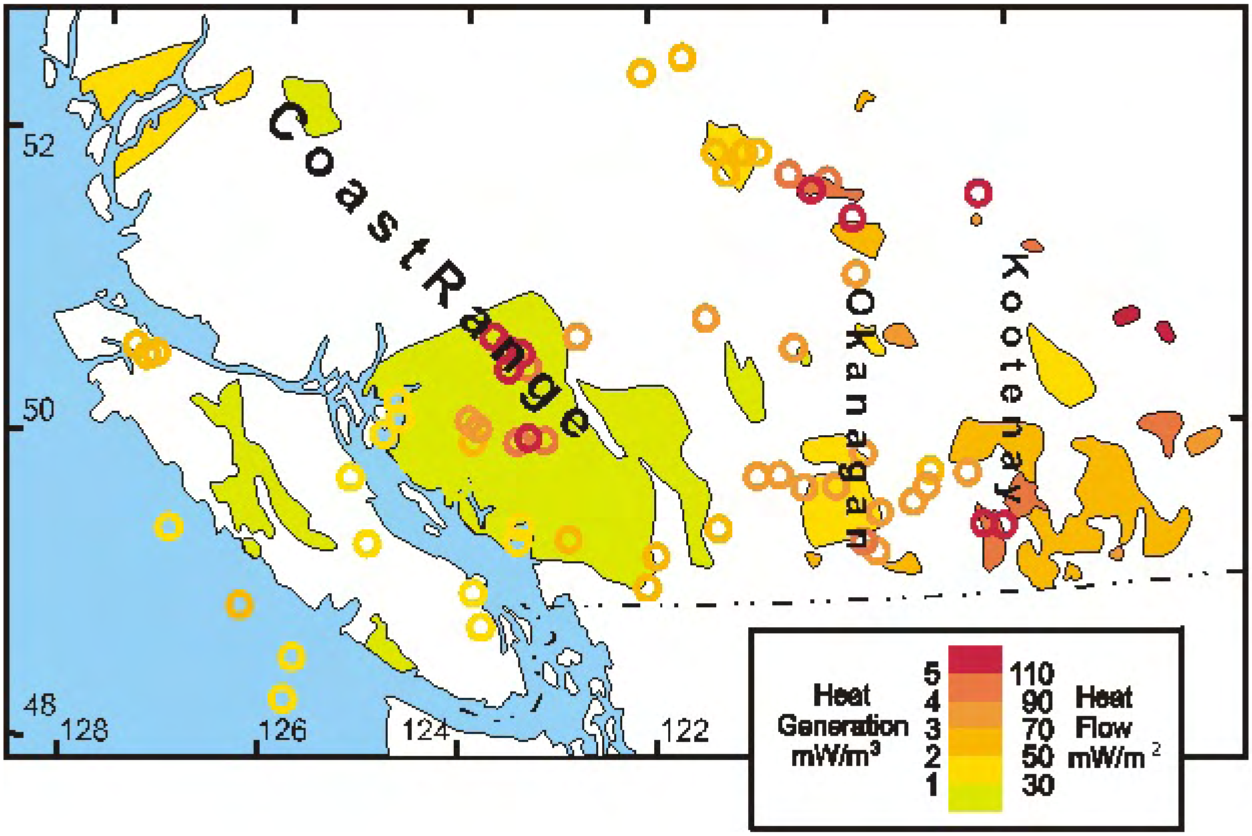

Fig. 15. Distribution of measured heat generation in intrusive bodies in the southern Cordillera. Heat generation is shown by coloured patches and heat flow is shown by coloured circles. Figure redrawn from Lewis et al., 1992.

The Raft Batholith

Four holes were drilled into the Raft Batholith in 1984, another rock body that showed a high value of heat generation. Temperature gradients were in range 27.2 to 36.2 mK/m, not as attractive as those observed in the Coryell intrusives, as shown in Fig 20. Average conductivities were 3.18, 2.77, 3.30, and 3.47 W/mK respectively, giving approximate heat flow of 110, 101, 90, and 108 mW/m^2.

CONCLUSIONS

There are certainly bodies of hot dry rock within the Cordillera of British Columbia. The very high temperatures and thermal gradients observed during the exploration at Mount Meager show that there is a large geothermal resource located below the volcanic edifice. If it is eventually decided that the resource cannot be developed as a hydrothermal system, the hot dry rock resource is proved, although the fractures already encountered may make artificial circulation difficult. There are probably similar hot dry rock resources below other volcanoes of the Garibaldi Volcanic Belt, Mount Cayley and Mount Garibaldi.

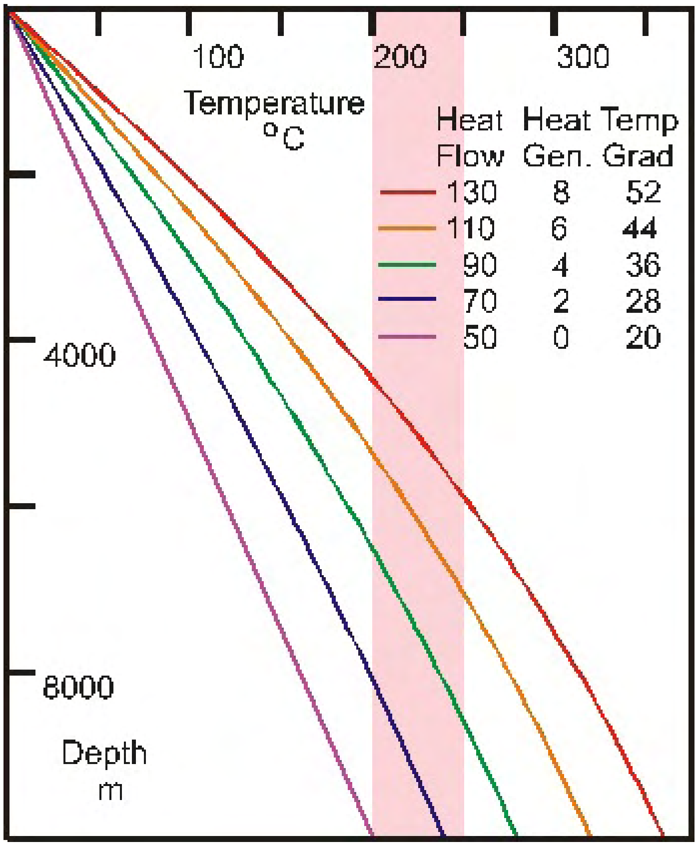

Fig. 16. Calculated temperatures in the crust of southern British Columbia. It is assumed that the heat generation and thermal conductivity remain uniform with depth.

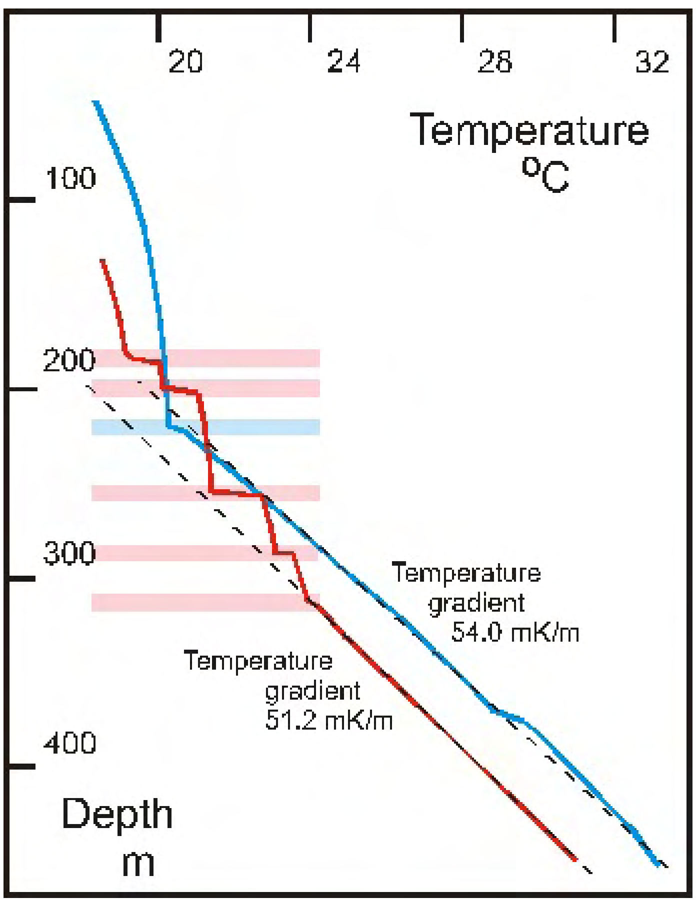

Fig. 17. Temperature profiles from two boreholes in the Coryell intrusive. Temperatures in the upper parts of both boreholes are disturbed by water flow from fractures flowing up the holes, and inflow zones are shown by coloured bars. Below the water bearing fractures thermal gradients are uniform

In the Anahim Volcanic Belt the Nazko Cone may be the most favourable location, as the seismic indication of moving magma at a depth of about 25 km suggests a high temperature gradient. In the Stikine volcanic belt there may be several volcanos that cover hot dry rock, including Mount Edziza and the Aiyansh - Tseax River Volcano..

Batholiths show promise of heat from continued radioactive decay of trace isotopes. There may be less problem with natural fractures at the depths of production, but this cannot be known until the experiment is tried. So far only two have been examined, and these only at shallow depths. The brief experiment in the Coryell intrusives showed that thermal gradients are high enough to be very encouraging.

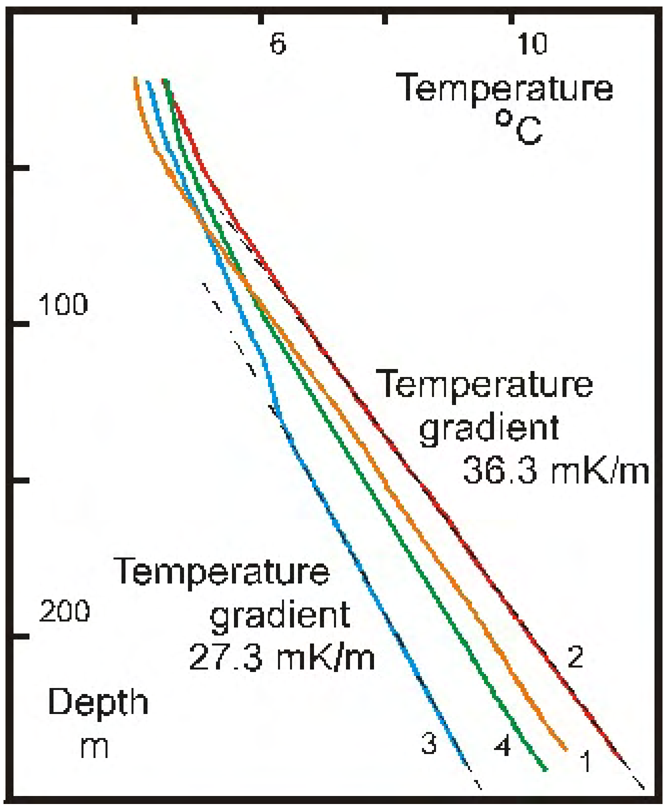

Fig. 18. Temperature profiles from four boreholes in the Raft Batholith. These profiles show no evidence of disturbance by water flow, except possibly in number 3.

In theory, hot dry rock is present beneath all parts of the earth's surface. However, economic concerns dictate that there must be an exploitable resource within reach by drilling at a reasonable cost. Whereas the experiment at Soultz-sous-Forêts and predictions for the Coryell syenite are aimed at a depth of 5 km, prospects in areas of lower heat flow or heat generation will need deeper drilling to reach temperatures of the order of 200 ^{O}C.

Depending on the use to which the heat is to be put, lower temperatures may be acceptable. However, parts of the world with old stable cratons, such as the Canadian Shield, have such low heat flow, temperature gradients and heat generation, that it is unlikely that hot dry rock will be an economic prospect for many years. This means that most of central and eastern Canada are ruled out from immediate development.

Exploitation of hot dry rock in engineered Geothermal Systems has been strongly promoted in the MIT report. There can be no doubt that the earth's crust contains a great deal of heat, but the extent to which it can be economically exploited has not been thoroughly explored. Programs of development in other countries have met with mixed success, but the present program at Soultz-sous Forêts seems to be encouraging. The costs of these experiments have been very high, but the resource is itself extremely large. If the resources can be exploited at a cost that is reasonable compared to conventional energy supply, this type of geothermal development could play a large role in the future.

The Cordillera clearly show the best potential for hot dry rock, because of the young tectonic and volcanic ages. Volume 1 has showed that potential in the Maritime Provinces, where intrusive bodies are of Silurian to Devonian age is much less. To extend such exploitation to tectonically old areas, such as central Canada, will take a good deal more time and expense, and this remains a project of the far future.

Even in the Cordillera, the form in which the energy could be developed and carried away, the economic factors of development, and the potential markets have not been examined. These studies await a growing interest in alternative energy sources and exhaust gas abatement.

CHAPTER SEVEN

SEDIMENTARY BASINS OF THE CORDILLERA

INTRODUCTION

The sedimentary basins of the Cordillera have not been examined for geothermal energy potential, and there are no internal or contracted studies on this subject. Some hydrocarbon exploration wells have been drilled, but there is not enough information on temperature, porosity, permeability and detailed sedimentary structure to provide a clear picture of the geothermal potential

Much of the area of the two major sedimentary basins of British Columbia and the basins of the Yukon is remote from human settlement, and the potential for economic geothermal potential is low, unless the value of space heating or commercial process heating in remote communities has value.

BASINS OF BRITISH COLUMBIA

There are two large sedimentary basins within the Cordillera of British Columbia, both mainly within the Intermontane Belt. The Bowser Basin, with the Sustut Basin, a smaller basin to the north-east, have an area of 65,000 km^2 and lies between approximate latitudes 54^{O} 50' and 57^{O} 40'. The Nechako Basin has an area of 75,000 km^2 and lies between approximately 51^{O} 10' and 54^{O} 30'. The locations of these basins are shown in Fig.19, on a background of heat flow distribution and with sites of the published heat flow data (Majorowicz and Osadetz, 2007). These authors describe the tectonic history and thermal state of the two basins in detail.

The Bowser Basin may be the result of back-arc spreading at a time when subduction was taking place, resulting in thinning of the crust and high crustal temperatures. Active subduction stopped about forty million years ago, as a result of changes in geometry of the plate movement. The Stikine Volcanic Belt is now superimposed on the west side of he Bowser Basin, possibly because of tensional forces related to the Queen Charlotte Fault Zone. Sediments of Jurassic to Cretaceous age are at least 6 km thick.

The Nechako Basin is probably similar in age and origin to the Bowser Basin. About one third of the Nechako Basin is covered by Tertiary plateau basalts, which obscure what lies below. The Anahim Volcanic Belt is superimposed on the southern end of the Nechako Basin.

Only 17 heat flow values have been determined in the Intermontane Belt, with an average of 73 mW/m^{2}. One value of heat flow has been measured in the Bowser Basin, in a hydrocarbon exploration well. The result was 93 mW/m^2 after correction for terrain and paleoclimate (Jessop et al, 1984). Temperature gradient, calculated from a combination of accurate measurements and corrected log-heading data is 31 mK/m. In the Nechako Basin accumulated log-heading data from seven wells give a temperature gradient of 32 mK/m.

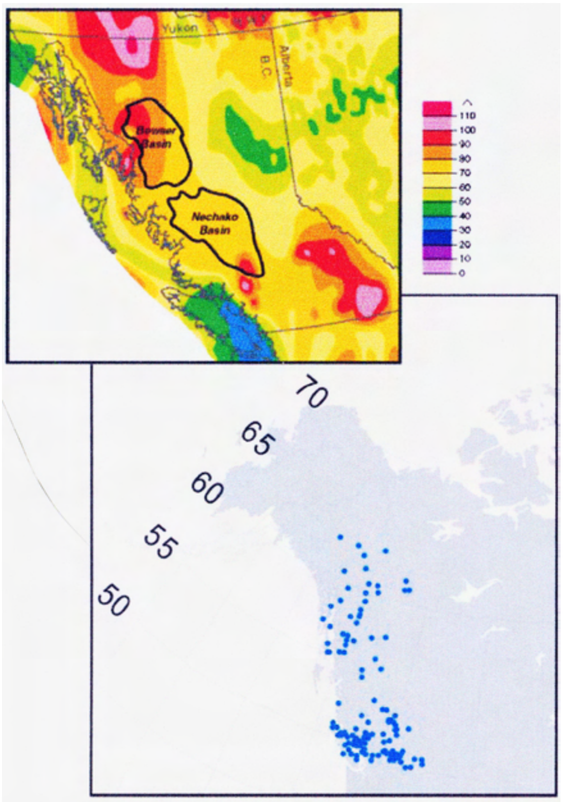

Fig. 19. The boundaries of the Bowser and Nechako Basins, superimposed on a part of the heat flow map (upper panel) and the locations of heat flow measurements in the Cordillera (lower panel). Diagram from Majotowicz and Osadetz (2007).

BASINS OF THE YUKON

There are some hydrocarbon exploration wells in the Yukon Territory, and the data of log-heading temperature have been collected. No interpretation in terms of geothermal resources has been attempted. Many of these wells are in remote areas.

ASSESSMENT OF RESOURCES

From the sparse data available the temperature gradients in both the Nechako Basin and the Bowser Basin are in excess of 30 mK/m. This gradient, if continued throughout the sedimentary strata of 6 km thickness, imply a temperature of about 180 ^{O}C in the lower levels of the basins. Alternatively, they suggest a temperature of about 65 ^{O}C at a depth of 2000 m, rather better than found in the well at Regina, which found water at about 59 ^{O}C at a depth of 2200 m. However, no study has been made of the possible aquifer formations, and no reliable forecast can be made of the geothermal potential.

There is probably a geothermal resource in place, but it is impossible to assess its magnitude at present, and the potential for economic use is limited by the general remoteness of the area.

CHAPTER EIGHT

ENGINEERING AND ECONOMICS

INTRODUCTION

Much of the early work of the Geothermal Energy Program and before it was focussed on the volcanic belts of the Cordillera, drawing on the accumulated experience and data in the earth sciences. This was the part of Canada where geothermal resources were perceived to be the most likely. It was demonstrated quite early in the Program that there were indeed resources, whatever their eventual form and quality.

However, while BCH was one of the main partners in the research, with the intention of installing electrical generation plant , there was no need for the federal agencies to pay attention to the engineering and economic part of the process. It was only later in the program, as knowledge of the resource throughout the region and when interest was shown by municipalities and others, that the engineering and economic aspects grew in importance.

Whatever economic conditions existed in 1976 to 1986, they have long been modified and are now quite different. BCH no longer builds new generating plant, but solicits proposals from commercial agencies. Energy costs have changed substantially. The perceived future of energy supply, particularly of oil, is less changed, but now the awareness of limited supply is based on reality. Further, the awareness of the environmental effects of continued uncontrolled combustion of hydrocarbons has grown to the point where there is popular demand for reduction, even if there is no political will to make any meaningful changes.

REVIEW OF CONTRACTED STUDIES

Studies commissioned by federal agencies have been reviewed in volume 1 of this report, and will not be repeated here.

> *Nevin Sadlier-Brown Goodbrand Ltd and Canadian Resourcecon Ltd, 1981, revised and reprinted 1983. Geothermal energy resources in British Columbia, a study of factors affecting development and utilisation.*

This report began by reviewing the world-wide use of geothermal energy at the time. It then reviewed the federal research program up to that time and the use of geothermal resources by spas and recreational facilities. It included comprehensive tables of known hot springs. and volcanic centres of late Tertiary age. It included chapters on the economic analysis of electrical generation and space heating. Predictions of the market penetration of geothermal energy were invalidated by the fluctuations in the price of oil and other energy sources that followed. This report gives a detailed account of the conditions then existing, and would be a good model for future economic evaluations. publication of this report.

The report recommended that *"the provincial government should take the lead in fostering exploration and development of geothermal resources by encouraging participation by the private sector."* This was done in 1982 by the enactment of the Geothermal Resources Act. A second recommendation was *"to accelerate applied research and development. Certain government-sponsored scientific and engineering services are a traditional part of the economy of Canada."*

The Geothermal Resources Act of 7 June 1982 significantly changed many factors in the potential for development of geothermal resources. For the first time in Canada there was an act of a provincial government that set out to define and regulate geothermal resources and to control how they were to be explored and developed.

THE GEOTHERMAL RESOURCES ACT

The Geothermal Resources Act of British Columbia received Royal Assent on 7 June 1982. Like other acts controlling the development of mineral resources it defined the resource and provided regulations for the orderly exploration and exploitation of the resource.

It defined a geothermal resource as:

"the natural heat of the earth and all substances that derive an added value from it, including steam, water and water vapour heated by the natural heat of the earth and all substances dissolved in the steam, water or water vapour obtained from a well, but does not include (a) water that has a temperature less than 80^{o}C at the point where it reaches the surface, or (b) hydrocarbons".

This specifically excludes any spa or recreational facilities then in existence or likely to be built. The act goes on to define ownership of the resource, permits and leases, operation and conservation, and royalty and unitisation.

This act made it possible for the private sector to consider geothermal resources as a field into which they could venture with a definite understanding of the rules and regulations that would be applied, a condition that had not previously existed.

CHAPTER NINE

FUTURE RESEARCH AND DEVELOPMENT

INTRODUCTION

During the past year public interest in the question of alternate energy sources has been reawakened. During February and March 2008 the author has twice been interviewed by the CBC. The first occasion was for a section of "Quirks and Quarks" on CBC radio. The second occasion was for television news, when "The National" was presenting a feature on the use of heat from old mines at Springhill, Nova Scotia, to mark the fiftieth anniversary of the tragic incident that forced the final closing of the coal mines.

The reincarnation of the Canadian Geothermal Energy Association provides a national agency that can argue the benefits of geothermal energy before government agencies and the private sector. Any new technology or resource needs initial encouragement by government, in the form of research, either in the form of financial support of some kind or of in-house research. Unfortunately, scientific research in government laboratories has been severely cut back over the last fifteen years, and shows no sign of recovery.

During 1976 to 1986 the federal Geothermal Energy Program, the exploration program of B.C.Hydro, and provincial support at Regina and Springhill produced a great deal of information that has produced energy and emissions savings at Springhill and has the potential to produce similar benefits at Meager Mountain and Regina. The private sector is now using a broad base of knowledge provided by government agencies at Meager Mountain, and could do so at Regina and at many sites of abandoned mines throughput the country.

VOLCANIC ZONES

At Meager Mountain the time for government-sponsored earth science research is over. That resource is now in the hands of the private sector, and their plans are outlined in Chapter 4.

Other volcanic zones have not been examined, but many of them are remote from transmission lines or from centres of population. A major generating capacity would be required to merit the building of the transmission lines from areas as remote as most of the Stikine Volcanic Belt. However, since recent features at the southern end of the Stikine Volcanic Belt are found within 80 km of Terrace, there may be possible applications that would be within reasonable reach of markets..

Beyond projects of a magnitude to merit connection to an electrical grid, there is potential for smaller systems to feed local communities in northern British Columbia or the Yukon, such as

Telegraph Creek, Atlin, or Whitehorse.

HOT DRY ROCK

The potential for hot dry rock has been vigorously presented by the "MIT report" (Massachusetts Institute of technology, 2006). The resource undoubtedly exists, it is known to be very large, but the means of exploiting it are not yet in place. Chapter 6 has recounted the efforts of foreign countries to develop a technology to exploit this resource. The Geothermal Energy Program has shown that an accessible resource exists in the Coryell Syenite and probably in other intrusive rocks of southern British Columbia, but there is now no national laboratory that can do further work of this kind. No attempt has yet been made to use these resources, and it is probably wise to wait a few years to see what progress is made by the European Union at Soultz-sous-Forêts in France. However, that does not prevent further research into the existence and nature of our own resources.

BINARY TURBINES

Technology now exists for the generation of electrical power from water at temperatures as low as about 90 ^{O}C. The efficiency of such generation is necessarily low, according to the laws of thermodynamics, but it would be possible to supply some remote communities with electrical power by this means instead of by burning diesel fuel acquired at high costs for transportation. Germany, Austria, Australia and Alaska, USA are already using this form of electrical generation.

The town of Chena, Alaska, has installed a binary turbine system to take advantage of the water from their hot springs. Input temperature is 74 ^{O}C and river water at 3 ^{O}C is available for condensing, giving a conversion efficiency of 8 %. The project cost was about $1300 per kW installed, and the production cost is $0.07, rather than the previous $0.30 when using diesel generators. The average load is 130 kW.

SPACE HEATING

Geothermal water at any temperature above about 10 ^{O}C, provided that there is enough of it, can be used, with heat pumps, to provide space heating. This could be for domestic use or industrial. The Summerland project failed because the nature of the rocks within the Summerland Basin could not be predicted, but there is ample scope of similar projects in the Okanagan Valley and elsewhere.

ABANDONED MINES

There are many abandoned mines in the Cordillera. Any one of these might be able to provide enough water, at temperature above the ground temperature, that could be used for the heating of industrial or residential buildings. This is an aspect of geothermal research that should be vigorously promoted.

IMMEDIATE PRIORITIES

The Geothermal Energy Program of 1976 to 1986, and the scientific knowledge generated by long-term earth-science research within federal and provincial governments provide a good foundation on which to base site-specific studies and demonstration projects. The technology of geothermal development is generally available or under development in other countries. Canada does not need to develop new geothermal technology, but it would be good to see participation in work to begin to reduce our dependence on fossil fuels.

Only in the Provinces of British Columbia and Nova Scotia is there any acknowledgement, in the form of legislation, that geothermal resources exist. This omission discourages the private sector from any participation, since they have no rules within which to work and may have unpredicted rules forced upon them after the expenditure of considerable time and money.

<u>Specific priorities</u>

1. Examine towns in the Cordillera that grew up around mines and are now cut off from their main source of economic support. To be able to entice new industry into the town with the promise of low-cost energy supply could revive many towns. Springhill, Nova Scotia, has made a great success of this geothermal system. A consultant study of the potential for use of water from abandoned mines is therefore a high priority.

2. Examine the availability of water at about 100 ^{O}C for use with binary cycle turbines and the source of generators to make use of such water. This energy source could be valuable in remote communities or close to farming or other industrial users.

<u>General needs</u>

In addition to needs identified in the first volume, present needs in Canada are as follows:

1. Since there is now no national or provincial laboratory for the measurement of underground temperature, heat flow or heat generation, the establishment of such a facility is needed as a support to resource research and to industrial developers. The original Geothermal Service of the Earth Physics Branch was eliminated in 1986, including its laboratory, which had been built up to serve research into geothermal energy, permafrost, pipeline corridor monitoring, nuclear waste disposal and scientific geothermics. Most of the participants have now passed retirement age, and those still of working age will approach retirement within the next five years. There are a few people in universities, but they are not equipped or available to serve as a national laboratory.

2 A library of material related to geothermal energy, accessible to all. BCH probably has copies of all the reports that they commissioned in the period 1976 to 1984, but they are

not generally accessible. EPB made contractors' reports generally available as open files wherever possible. It is not clear that the GSC made all reports public to the same extent. The present GSC has copies of most reports available as Open Files, whether originating in EPB or GSC, open for purchase by all, or open for inspection at their libraries. This report, and the first volume, attempt to provide a list of all these publications. Some original copies of GSC and EPB reports exist on the shelves of the individual research personnel, but since these are mostly now retired, the continued preservation of these reports is at risk. Some contractors have maintained copies of their reports, but contracting agencies may change their purpose or their management personnel, and report preservation is not a high priority, particularly after twenty to thirty years.

3. Data from the exploration of 1974 and after should be carefully preserved. Data obtained by measurement of temperature, thermal conductivity, heat generation and other parameters in boreholes or on samples from holes drilled by EPB or GSC has been compiled into a large data base (Jessop,2006). Data relevant to geothermal exploration, such as heat generation from hand samples of rocks from batholiths of the Omineca Crystalline Belt has not been so compiled.

4. Both federal and provincial governments should consider further encouragement, by tax incentives or other financial measures, of the geothermal industry and of research into geothermal resources, other than those parts concerned with ground-coupled heat pump systems. Geothermal heat has the potential to contribute a fraction of the national need for space heating and electrical generation, but it is not known how large that contribution can be.

5. Legislation to regulate geothermal development is needed in all provinces, except British Columbia and Nova Scotia. Those provinces have put legislation in place because there was a geothermal industry within the territory under their jurisdiction. Other provinces and territories would encourage geothermal development by enacting similar legislation.

REFERENCES

Three lists of references are presented. The first is a list of all references cited in the text. The second is a bibliography of all known documents related to geothermal energy produced by Canadians or describing Canadian locations or conditions. The third is a similar bibliography of scientific geothermics.

Items in the first list may be repeated in either the second or third list. The second and third lists may be incomplete because the author does not know of all publications. Several items have been discovered since volume one of this report was produced in 2007, and they have been added to these bibliographies. They are also subject to the author's judgement as to whether any item belongs in the list, and a judgement as to which list it should be in. There are no clear boundaries by which these judgements may be made. Some items may be in both lists because they are relevant to both scientific geothermics and geothermal energy.

REFERENCES IN THE TEXT

Acres Consulting Services Ltd and Nevin Sadlier-Brown Goodbrand Ltd, 1984. Regulatory and Commercial aspects of Geothermal Energy Development.

B.C.Hydro,Power Authority 1983. Meager Creek geothermal project summary report for 1982-83. B.C.Hydro,Power Auth., 36pp

Bentkowski,W.H. and Lewis,T.J. 1983. Preliminary results of shallow drilling in the Garibaldi Volcanic Belt British Columbia,1982. Earth Phys.Br., Open File 83-23, 39pp

Blackwell,D.D. and Baag , C., 1973. Heat flow in a blind geothermal area near Marysville, Montana. Geophysics, 38, 941-956.

Blackwell,D.D. and Morgan,P., 1975. Geological and geophysical exploration of the Marysville geothermal area, montana, USA. Proc. U.N. Symp. Geothermal Resour., San Francisco, 895-902.

Blackwell,D.D. and Richards,M., 2004. Geothermal Map of North America. Am. Assoc. Petrol. geol., 1 map sheet, 1:6,500,000.

Carter,N.M., 1932. Exploration in the Lillooet River Watershed. Canadian Alpine Journal, Vol 21, 8-18.

Conolly,E.T., 1972. Geothermal Survey of North America progress report and associated data-gathering problems. Trans.Can. Well Logging Soc. Fourth Evaluation Symp. 37 pp.

D.R.Piteau and Assoc.,1985. Summerland Basin hydrogeological study. Earth Phys.Br., *Open File 85-29, 82pp.*

Duchane,D.V., undated, about 1996. Geothermal energy from hot dry rock: a renewable energy technology moving towards practical implementation. Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, USA.

Duchane, D. and Brown,D., 2002. Hot dry rock (HDR) geothermal energy research and development at Fenton Hill, New Mexico. GHC Bulletin, 13-19.

Elworthy,R.T., 1925. Hot springs in western Canada; their radioactive and chemical properties. Min.Br.Invest.Miner.Resour.Min.Indust., 1-33

Energy, Mines & Resources, 2008. www.emr.gov.yk.ca/energy/geothermal.html

Everdingen,R.O.van., 1972. Thermal and mineral springs in the southern Rocky Mountains of Canada.,Environment Canada, 151pp.

Fournier,R.O. and Rowe,J.J., 1966. Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells. Am.J.Sci., 264, 685-697.

Fournier,R.O. and Truesdell,A.H., 1973. An empirical Na-K-Ca geothermometer for natural waters. Geochim. Cosmochim. Acta, 37, 1255-1275.

Gabrielse,H., Monger,J.W.H., Wheeler,J.O. and Yorath,C.J. 1992. Chapter 2, Tectonic framework, Part A. Morphogeological belts, tectonic assemblages and Terranes. In - Geology of the Cordilleran Orogen in Canada, Ed.Gabrielse,H and Yorath,C.J., Geological Survey of Canada, Geology of Canada, No. 4.

Gartener Lee Ltd., 2003. Yukon groundwater and ground source heat pump potential inventory. Report to Energy Solutions Centre Inc.

Ghomshei,M.M., MacLeod,K., Sadlier-Brown,T.L., Meech,J.A. and Dakin,R.A., 2005. Canadian geothermal energy poised for takeoff, Proc. World Geothermal Congress 2005.

Ghomshei,M.M. and Sadlier-Brown,T.L., 1996. Direct use energy from the hot springs and subsurface geothermal resources of B.C., BiTech, Richmond, B.C. ISBN 0-921095-39-2

Ghomshei,M.M. and Stauder,J.J. 1989. Brief review of the Meager Creek Geothermal Project: a second look at the data. Geothermal Resources Council Bulletin, July 1989.

Jessop,A.M. 1990. Thermal Geophysics. Elsevier Publishing Co., 305pp.

Jessop,A.M. 2007. Review of National Geothermal Energy Program: Phase 1 - Geothermal Potential of Sedimentary Basins. Geol. Survey Canada, Open File 5690.

Jessop,A.M. and Church,B.N.,1991. Geothermal drilling in the Summerland Basin, British Columbia, 1990. Geol.Surv.Can., Open File 2348, 19 pp.

Jessop,A.M. and Judge,A.S., 1971. Five measurements of heat flow in southern Canada. Can.J.Earth Sci., 8, 711-716.

Jessop,A.M., Souther,J.G., Lewis,T.J. and Judge,A.S., 1984. Geothermal measurements in northern British Columbia and southern Yukon Territory. Can. J. Earth Sci. 21, 599-608.

Lewis,J.F. and Jessop,A.M. 1981. Heat flow in the Garibaldi Volcanic Belt, a possible Canadian geothermal resource area. Can.J.Earth Sci., 18, 366-375

Lewis,T.J.,1984,. Geothermal energy from Penticton Tertiary Outlier, British Columbia. Can.J.Earth Sci., 21, 181-188

Lewis,T.J., Allen,V.S., Taylor,A.E. and Jessop,A.M., 1979. Temperature observations during drilling of two 400 m wells in the Coryell intrusives north of Grand Forks, British Columbia, 1978. Earth Phys. Br. Open File 79-2,

Lewis,T.J., Bennetts,H., Allen,V.S. and Chan,F., 1984. Uranium, thorium and potassium concentrations and heat generated in samples of crustal rocks: a data file. Earth Physics Br., Open file 84-15.

Lewis,T.J. and Bentkowski,W.H., 1988. Potassium, uranium and thorium concentrations of crustal rocks: a data file. Geol.Survey of Canada Open File 1744.

Lewis,T.J. and Souther,J.G. 1978. Meager mountain, B.C. - a possible geothermal energy resource. Earth Phys.Br., Geothermal Ser.9, 17pp

Lewis,T.J., Bentkowski,W.H. and Hyndman,R.D., 1992. Crustal temperatures near the Lithoprobe Southern Canadian Cordillera Transect. Can. J. Earth Sci., 29, 1197-1214.

Lewis,T.J., Hyndman,R.D. and Fluck,P. 2003. Heat flow, heat generation, and crustal temperature in the Northern Canadian Cordillera: thermal control of tectonics. J.Geophys.Res., 108, B6, 2316

Lewis,T.J. and Werner,L., 1982. Geothermal gradients on the west side of Okanagan Lake, B.C. Earth Phys.Br. Open File 82-6, 37pp + append.

Majorowicz,J.A. and Osadetz,K.G., 2007. Cordilleran intermontane thermotectonic history and implcations for neotectonic structure and petroleum systems, British Columbia, Canada. Intl.J. Earth Sci., DOI 10.1007/s00531-007–215-x.

Manning,D.A.C., Younger,P.L., Smith,F.W. and Jones,J.M., 2007. A deep geothermal exploration well at Eastgate, Weardale, UK: a novel exploration concept for low-enthalpy resources. L. Geol. Soc., March.

MIT, Massachusetts Institute of Technology, 2006. The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century. http://geothermal.inel.gov

McDonald,J., Pollock,D. and McDermot,B.,1978. Hotsprings of western Canada - a complete guide. Labrador Tea Co., 161pp.

Muffler,P. and Cataldi,R., 1978. Methods for regional assessment of geothermal resorces. Geothermics, 6, 53-89.

Nevin,A.E., 1992a. Economic factors in future development of the Pebble Creek geothermal resource, B.C., Canada. Trans. Geothermal Resources Council, 16, 65-70.

Nevin,A.E., 1992b. Lessons from frontier exploration at Meager Creek and Pebble Creek, British Columbia, 1971-1992. Trans. Geothermal Resources Council, 16, 105-110.

Nevin, Sadlier-Brown, Goodbrand Ltd,1987. Feasibility study for direct utilisation of geothermal energy resources at Summerland, B.C. Report to Renewable Energy Branch, Energy, mines and Resources. 85pp.

Nevin Sadlier-Brown Goodbrand Ltd and Canadian Resourecon Ltd, 1981, revised and reprinted 1983. Geothermal energy resources in British Columbia, a study of factors affecting development and utilisation. Report to Ministry of Energy, Mines and Petroleum Resources of the Province of British Columbia. 282pp.

NRCan, 2008. http://earthquakescanada.nrcan.gc.ca/nazko/nazko_summary_e.php

Piteau and Assoc. 1984. Summerland Basin hydrogeological study. Earth Phys.Br., Open File 85-29, 49pp+append.

Souther,J.G. 1975. Geothermal potential of western Canada. Proc. U.N.Symposium on Geothermal resources, San Francisco, 259-267

Souther,J.G., 1977. Volcanism and tectonic environments in the Canadian Codillera - a second look. In Volcanic regimes in Canada, Ed. Baragar,W.R.A., Coleman,L.C. and Hall,J.M., Geol Assoc. Canada, Spec Paper 16, 3-24.

Souther,J.G. and Halstead,E.C., 1969. Mineral and thermal waters of Canada. 23rd.Int.Geol.Cong., Prague, 225-256.

Souther,J.G. and Halstead,E.C., 1973. Mineral and thermal waters of Canada. Geol.Surv.Can., Paper 73-18, 32pp

==

NEW BIBLIOGRAPHY

Adams,M.C., Moore,J.N. and Forster,C., 1985. Fluid flow in volcanic terrains - hydrogeochemistry of the Meager Mountain thermal system. Trans.Geothermal Resources Council, 377-382.

Anderson,J.M., 1981. Report on seismic refraction survey of B.C. Hydro and Power Authority South Reservoir Meager Creek area, B.C. Report to Nevin Sadlier-Brown Goodbrand Ltd.

Bechtel Canada Ltd, 1981, Preconceptual design and cost estimate for a 55 MWe power plant at the Meager Creek geothermal area. Report to BC Hydro.

Clark,I.D., Fritz,P. and Michel,F.A. 1980. Isotope hydrogeology and geothermometry of the Mount Meager geothermal area. Geol.Surv.Can. Open File 1015, 131pp

New access info

Geotronics Surveys Ltd., 1981. Summary report on a seismic refraction survey on the geothermal studiesMeager Creek area, B.C. Report to Nevin Sadlier-Brown Goodbrand Ltd.

Kelley,S. And Blackwell,D. 1984. Fissio-track geochronology of the Meager Creek geothermal system, British Columbia. Trans. Geothermal resources Council, 1984, 129-132.

Nevin Sadlier-Brown Goodbrand Ltd. 1981. Meager Creek Geothermal Project: Preliminary report on soil geochemistry of the South reservoir area. Report to unknown sponsor, 9pp plus diagrams.

Nevin,A.E., 1992. Economic factors in future development of the Pebble Creek geothermal resource, B.C., Canada. Trans. Geothermal Resources Council, 16, 65-70.

Nevin,A.E. and Sadlier-Brown,T.L., 1973. Exploration and economic potential of geothermal steam in western Canada.. Paper to Annual General Meeting of Can.Inst.Mining, Metallurgy, Vancouver, 18 April 1973.

Nevin Sadlier-Brown Goodbrand Ltd, Canadian Resource Con Ltd, Abraham,B.E., Scott,G.H., and D.W.Thompson and Associates Ltd., 1981. Geothermal energy resources in British Columbia: a study of factors affecting development and utilisation.. Report to Ministry of Energy, Mines and Petroleum resources, British Columbia.

Nevin Sadlier-Brown Goodbrand Ltd., 1984. Report on a temperature gradient drill hole at Silt Lake (SL-1) Upper Lillooet River Valley, B.C. Report to Geological Survey of Canada.

Read,P.B., 1975. Drill core alteration and sinter, Meager Creek, British Columbia. Report to unknown sponsor. 15pp plus charts.

Read,P.B., XXXX. Mount Meager Complex, Garibaldi Belt, southwestern British Columbia. Geoscience Canada, 17, 167-170.

Read.P.B., 1980. Petrography and alteration of samples from 79H1, Meager Creek geothermal area, British Columbia. Report to Nevin Sadlier-Brown Goodbrand Ltd.

Read.P.B., 1980. Petrography and alteration of samples from 79H2 and 19H3, Meager Creek geothermal area, British Columbia. Report to Nevin Sadlier-Brown Goodbrand Ltd.

Nevin Sadlier-Brown Goodbrand Ltd. 1983. Report on thermal conductivity and heat flow in diamond drill holes, Meager Creek geothermal area, southwestern British Columbia. Report to B.C.Hydro.

Ryder,A.J.D., 1983. A reconnaissance hydrogeochemistry survey of the southwestern drainages of Mount Cayley, British Columbia. Geol.Surv.Can. Open File 1016

Shore,G.A. and Clearwater,R.P., 1992. Hidden anomalies: small near-surface resistivity anomalies can completely mask large, deeper anomalies. Trans. Geothermal Resources Council, 16, 255-261.

Shore,G.A. and Clearwater,R.P., 1992. Linear E-Scan: a reconnaissance resistivity mapping system that evaluates its own anomalies en route. Trans. Geothermal Resources Council, 16, 263-272.

Souther,J.G., 1977. Volcanism and tectonic environments in the Canadian Codillera - a second look. In Volcanic regimes in Canada, Ed. Baragar,W.R.A., Coleman,L.C. and Hall,J.M., Geol Assoc. Canada, Spec Paper 16, 3-24.

Ward,S.H., 1981. Report of dipole-dipole resistivity data, Meager Creek, British Columbia. Report to Premier Geophysics Inc.

Unknown authors, 1985. Meager Creek Project: report on activities 1983-84 and 1984-85. Volume 1 - text.