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GEOTHERMAL RESOURCES WITHIN AUSTRALIA - BMR SURVEY PROPOSALS

by

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SUMMARY

The development of geothermal resources is seen in many parts of the world as a partial alternative to the use of expensive petroleum products as the primary source for energy production. In Australia there are few surface expressions of thermal activity and consequently there have been few investigations of the economic potential of geothermal energy. There are, however, extensive reservoirs of warm water in artesian basins throughout Australia and, in addition, there are several warm springs associated with intrusive volcanics. With present technology the warm water in these areas can be used directly in many types of industrial processes. Alternatively, the energy can be extracted through heat exchangers in electricity schemes for isolated communities. It is proposed that the Bureau of Mineral Resources (BMR) initiate a program to investigate the extent of geothermal resources in Australia.

Apart from the thermal energy in artesian basins it is probable that many other areas of Australia contain hot dry rocks at relatively shallow depth. Continuing technological advances may enable large amounts of energy to be extracted from these rocks and consequently it is important to locate heat-flow anomalies in a program of regional mapping. Detailed measurements within anomalous regions could then be used to locate favourable sites for the establishment of artificial aquifers which are designed to tap the available energy.

Studies of regional heat-flow patterns are also important in theories concerned with gross surface features of the Earth. Many thermal anomalies can be associated with surface geology or deep crustal and upper mantle features, and consequently surface heat-flow data provide major constraints in geophysical and geological modelling. Interpretation of regional heat-flow data may for example explain some gravity and seismic velocity anomalies which at present are interpreted in terms of structural or chemical variations.

Provision should be made for accumulating heat-flow data as a matter of routine during all future BMR drilling projects, but in the short term regional data can be obtained from measurements in abandoned boreholes. It is recommended that BMR heat-flow programs should include provisions for:

(1) Collating all available thermal data in Australia (primarily indexing warm springs according to temperature, flow rate, and location) in order to emphasize any immediate economic prospects.

(2) Regional measurements of heat flow in deep holes (including abandoned water bores and exploration holes) as they become available.

(3) Detailed surveys in areas of high heat flow which may contain concentrated sources of energy.

(4) Routine thermal conductivity measurements requiring laboratory facilities and space for storage of samples.

Basic heat-flow programs can be conducted by a single geophysicist with assistance from a technical officer. A second geophysicist should be attached to the group at a later date to receive training in field procedures and to assist in thermal modelling. Capital outlay could be restricted to less than $9000 with recurring operational costs of about $7000 per year.

1. INTRODUCTION

As oil prices continue to rise, alternative sources of energy are becoming increasingly competitive. Among these alternatives, geothermal energy is particularly attractive. At present, two types of geothermal field can be defined: (1) hot water/steam systems suitable for generating electricity, and (2) warm water systems suitable for direct use. Both types have been developed, particularly in the regions of earthquake and volcano activity which are associated with the boundaries of tectonic plates (Fig. 1).

The technology required to generate electricity from hot spring sources of steam is well proven (notably in Italy, New Zealand, and the United States of America) and the necessary capital expenditure and running costs are generally less than in comparable hydro-electric or fossil fuel systems (Fig. 2, Meidav, 1974). In Australia, however, no steam fields are known, and consequently a more specialised technology would be required before the available geothermal fluids could be used for generating electricity. Of particular interest in this regard is a freon-based generator which has been developed in the Soviet Union; the energy from warm water (81°C) is sufficient in this case to drive two 340 kW turbines (Koenig, 1973).

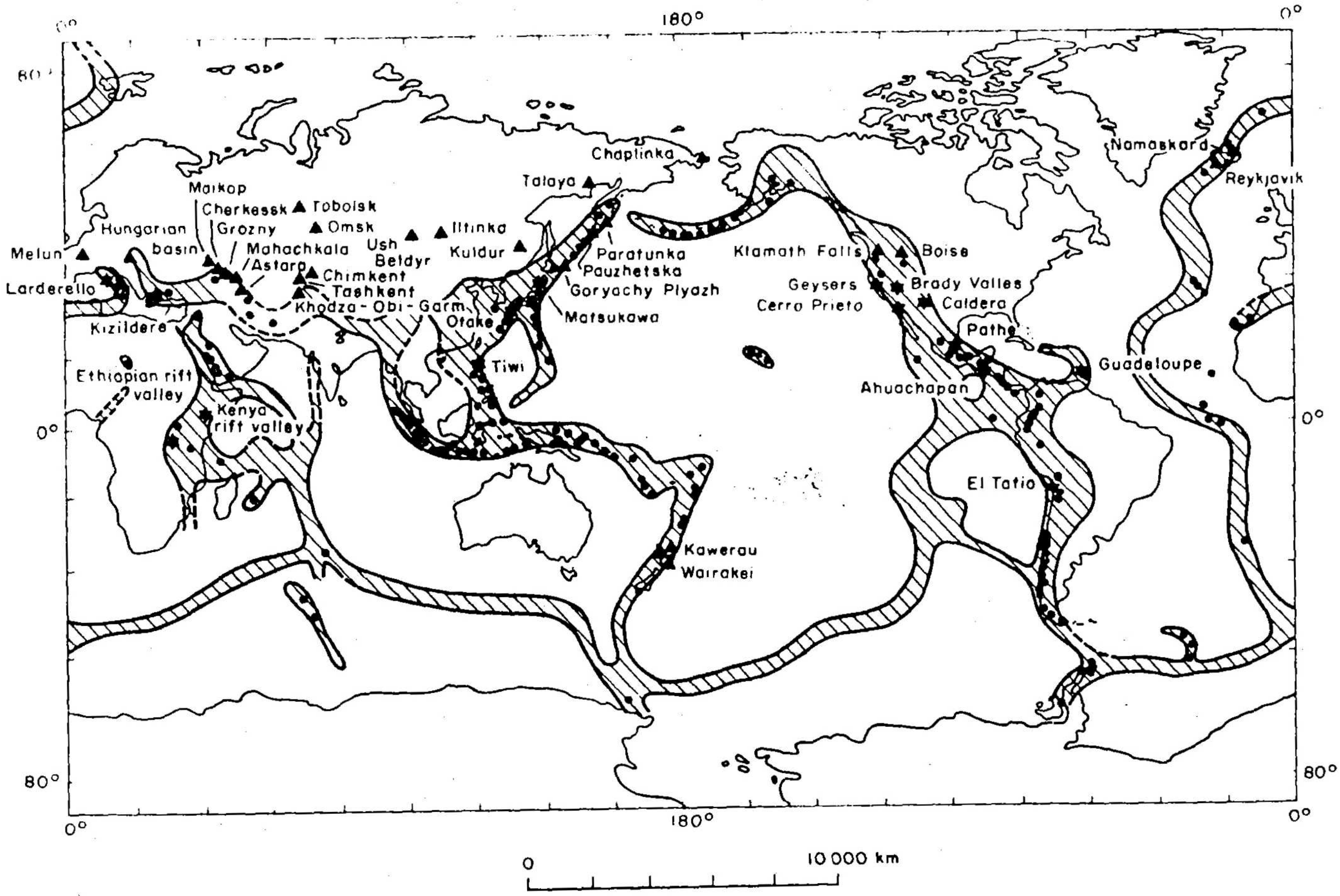
For "normal" continental areas, including Australia, subsurface temperatures are known to increase with depth by about 3°C for each 100 m. Consequently, the deep circulating artesian basins within Australia are ideal sources of low-grade heat. There are large volumes of water at depths less than 2 km which have temperatures near the surface boiling point (Ogilvie, 1955); these can be used for a variety of industrial and agricultural processes including wood pulping and greenhouse horticulture. In other countries, however, the single most important use has been for domestic space heating. Extensive heating grids have evolved in Iceland and are now proposed for Hungary, France, Germany, and the U.K. (where £250,000 has been allocated for feasibility studies - C.G.L.O., 1975). Reverse-cycle air-conditioning can also be included in such schemes and, for a hotel in Rotorua, the running costs are estimated to be less than five percent of conventional systems (Koenig, 1973).

In Australia natural hot water is used for bathing, but no commercial exploitation is known (BMR file 1975/1504). A proposal has been made for space heating in a Portland (Vic.) hospital but the project has not been pursued (BMR file 1974/582).

Successful development of any of the geothermal resources within Australia will depend on detailed knowledge of the artesian reservoir capacities and flow patterns together with regional and local data concerning surface heat flow (i.e. heat lost at the surface which has been generated mainly from radioactive elements in the Earth's crust). Maximum rates of heat extraction can then be defined so that the aquifers remain near their "native" temperatures and are not cooled by the relatively rapid and continuous introduction of recharge water. Near-surface heat-flow measurements will also be necessary in locating concentrated heat sources (such as volcanic intrusives) which may have associated steam fields directly suitable for generating electricity. Simple temperature gradients may not be sufficient to define these thermal anomalies since climatic conditions (including past glaciations) are the controlling factor for the first 100 m below the Earth's surface (highly variable thermal conductivities for different rocks affect temperature gradients at all depths).

Measurements of heat flow throughout Australia would serve not only to determine prospective sources of energy but would also provide data useful for geological modelling. Several models have resulted from the throty of plate tectonics (or continental drift) and these have been successful in explaining most of the gross surface features of the Earth (Turcotte & Oxburgh, 1969). However, the forces that cause plate motion remain speculative. Many geophysicists consider that the thermal gradients within the Earth are sufficient to cause convective motion mechanisms of solid state creep. On this basis several convection theories have been formulated to explain the observed surface movements. The different theories imply distinctive heat flow patterns at the surface of the Earth and consequently they can be tested. Measurements of heat flow through the ocean floors do in fact conform to some of the predicted patterns (Turcotte & Oxburgh, 1969) but in continental areas there are insufficient data for a complete appraisal.

Observations of surface heat flow can also be used to compute local temperatures in the crust and upper mantle. Interpretations of other geophysical data can then be refined. Gravity anomalies of -25 mGal may, for instance, result entirely from thermal expansion in normal crust (30 km thick) which has been raised in temperature by 200^{o}C (e.g. by magmatic intrusions). Structural considerations based on gravity data may consequently be grossly inaccurate if the thermal regime is unknown. Similar difficulties exist in the interpretation of seismic data since the measured velocities depend not only on composition but also on temperature. The interpretation of seismic low-velocity zones is particularly complicated since these can be caused simply by high thermal gradients even when the actual temperatures are not sufficient to cause partial melting or changes in mineral phase. Detailed thermal data are also required in studies of electrical conductivity, remanent magnetism, isostatic adjustment, volcanism, rates of magmatic intrusion, and oil/gas maturation.



LEGEND

- Active volcanoes, historic times
- Ongoing geothermal power development
- Geothermal heat supply plants
- Geothermal regions

Fig. I World geothermal resource development (from Meidar, 1974)

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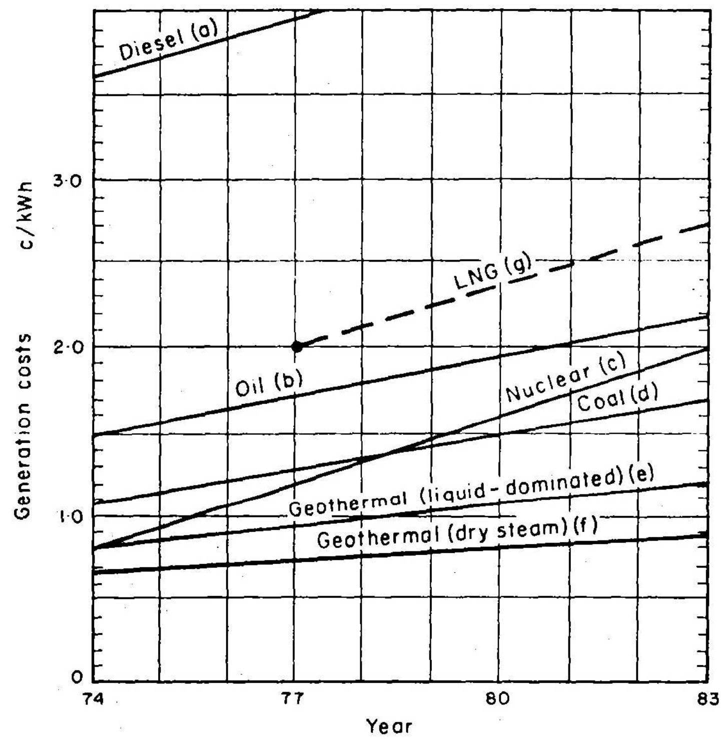

Notes:

(a) — Diesel-based power as determined by price of diesel fuel, assumed at $20/bbl.

(b) — Oil-fired plants: $7/bbl of residual fuel, $340/kW for an 880-MW installation start-up in 1978. (Wall Street Journal, 21 Feb, 1974).

(c) — Nuclear: plant cost $600/kW in 1980 for 1,000MW plants; fuel at 3 mills/kWh in 1973 escalated at 5%/year; waste disposal, enviromental protection 1 mill/kWh. No escalation in plant cost after ordering has been assumed, providing thus the least cost of nuclear power.

(d) — Coal: 11·3 mills/kWh for a plant going on stream in 1972. (Kaufman, PSC, personal communication).

(e) — Geothermal, liquid dominated, Ahuachapan-type, estimated at 7 mills/kWh in 1971, start operation by end of 1974; escalated at 5%/year after design date.

(f) — Geothermal, vapour-dominated, Geysers California-type, reported at 6·2 mills/kWh in 1973, escalated at 5%.

(g) — LNG — liquefied natural gas: Assumed delivered cost of $1·50/1 000 ft^3 in 1977.

Fig 2 Comparison of costs in power generation (from Meidar, 1974)

2. THERMAL OBSERVATIONS WITHIN AUSTRALIA AND THE SURROUNDING SEAS

Geysers are the most obvious and spectacular expression of geothermal heating in water at depth. In many countries these phenomena have stimulated a general interest in geothermal resources and the energy potential has been quickly recognized. In Australia the lack of such spectacular thermal activity has resulted in general neglect of lesser surface manifestations and ignorance of the geothermal field. However, several warm springs (50°C to 100°C) are known (Fig. 3, and BMR file 75/1504) although their temperatures and flow rates are not well documented. There are probably many other warm springs, particularly on the margins of artesian basins. Complete documentation would serve to define immediate economic prospects; heat-flow measurements could then be used to locate any concentrated sources of heat and would assist with site location in development planning.

Although there are few data for springs, extensive and well-documented measurements of subsurface temperatures have been made in boreholes within the Great Artesian Basin (Fig. 3). Water temperatures of 110°C have been recorded at depths of 1700 m (Thomas, 1960) and these indicate good geothermal energy prospects. For depths less than 1000 m, however, the temperatures are generally less than 100°C. Temperature gradient maps have been produced from the data (Heyl & Thomas, 1961; Thomas, 1960) but no thermal conductivities were ascribed to the various rocks and consequently heat-flow calculations could not be attempted. A complete appraisal of the temperatures measured in the basin requires a careful examination of the water-flow patterns in each aquifer. For inclined aquifers there may be a significant vertical component of flow; measured water temperatures then become ambiguous and are not easily related to steady-state temperatures within the host rocks (temperatures measured in flowing bores are almost completely determined by the flow-rate and consequently it is difficult to derive actual thermal gradients from such data). In the central portion of the Great Artesian Basin, however, the aquifers are largely flat and consequently the temperatures should not be flow-dominated; measurements in non-flowing bores may, in these areas, permit some calculations of heat flow.

Heat flow observations

To obtain heat-flow data on land it is necessary to know both the thermal gradient in the Earth's crust and the thermal conductivity of the rocks in which the gradient is established. However, as near-surface thermal gradients are determined primarily by climatic conditions, temperatures must be measured at depths greater than 100 m to avoid perturbations caused by secular variations in the ambient air temperature. Routine exploration boreholes frequently penetrate to depths greater than 100 m and consequently, when abandoned, they are ideal sites for heat-flow measurements. However, the drilling process causes temperature fluctuations in the surrounding rock and equilibrium is not regained for up to one year after completion of drilling. Because of this time delay it is often necessary to insert casing to ensure that the hole does not collapse before the final temperatures can be measured. The cost of casing and the long-term nature of heat-flow programs have generally discouraged all but reconnaissance surveys in the continental regions of the Earth. In Australia the only measurements of heat flow have been made by the Australian National University (ANU) and much of the early data was obtained from mines and tunnels (Howard & Sass, 1964; Sass, 1964a & b; Sass et al., 1976). Four main regions are at present defined by the ANU data (Fig. 4). These are two areas of high heat flow, one in south-eastern Australia (including Tasmania) and one in the northern half of the Northern Territory (which presumably results from high concentrations of radioactive elements, particularly near Rum Jungle). A third region is defined by low values in the West Australian Shield corresponding to an area of crustal erosion and depletion of heat sources. Heat-flow measurements in eastern Queensland, the fourth region, are close to the world average but these may require an upward adjustment since it is possible that they are affected by recharge to the Great Artesian Basin.

The ANU coverage of Australia compares well with data distributions in other countries. Only in Japan and western USA is there a significantly greater density of land-based heat-flow results (W.D.C.A., 1976). In much of Africa, Asia, and South America there is no general coverage. The data in Australia (and other countries) do, however, come from anomalous areas since most measurements have been made on an opportunity basis in exploration boreholes which have been drilled to assess mineral prospects (Sass et al., 1976). There is consequently in all regions a need for specific measurements away from zones of mineralization, but more general reconnaissance surveys are required in the north of Western Australia and in central Queensland where no data are yet available. Little work has been done in Australia to pursue suggested correlations between surface heat flow and surface radioactivity (Bunker et al., 1975); additional coverage in the Northern Territory could provide a valuable exploration tool to define areas of high radioactivity.

For offshore measurements of heat flow it is possible to obtain data with temperature sensing probes which penetrate the bottom sediments to depths up to 10 m when dropped overboard;

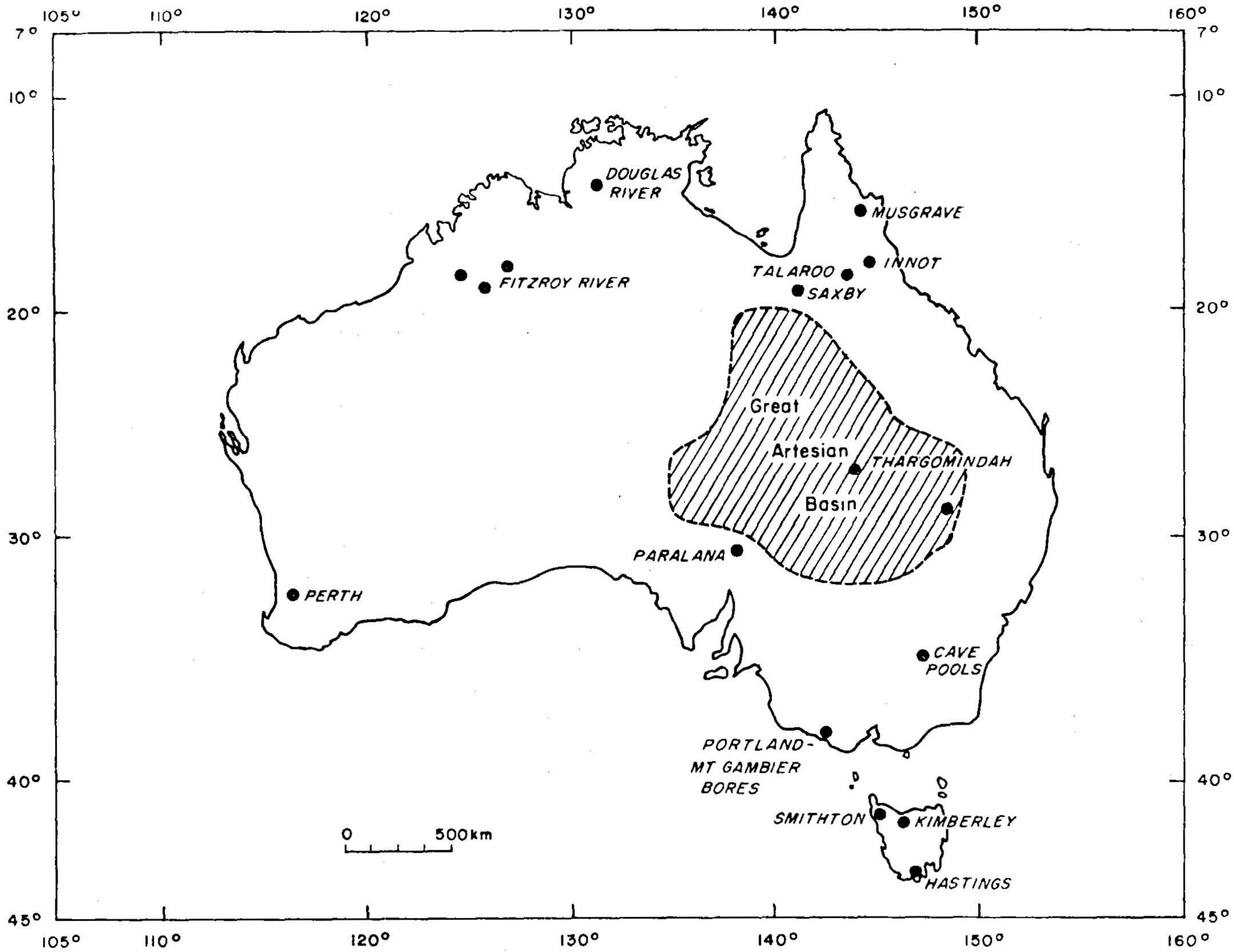

Fig. 3 Warm spring (50 – 100°C) locations in Australia (Hatched area represents the Great Artesian Basin containing many warm springs on the outflow margins and numerous boreholes which have been logged for temperature – Thomas, 1960. Paralana and Thargomindah may be associated with local granites.)

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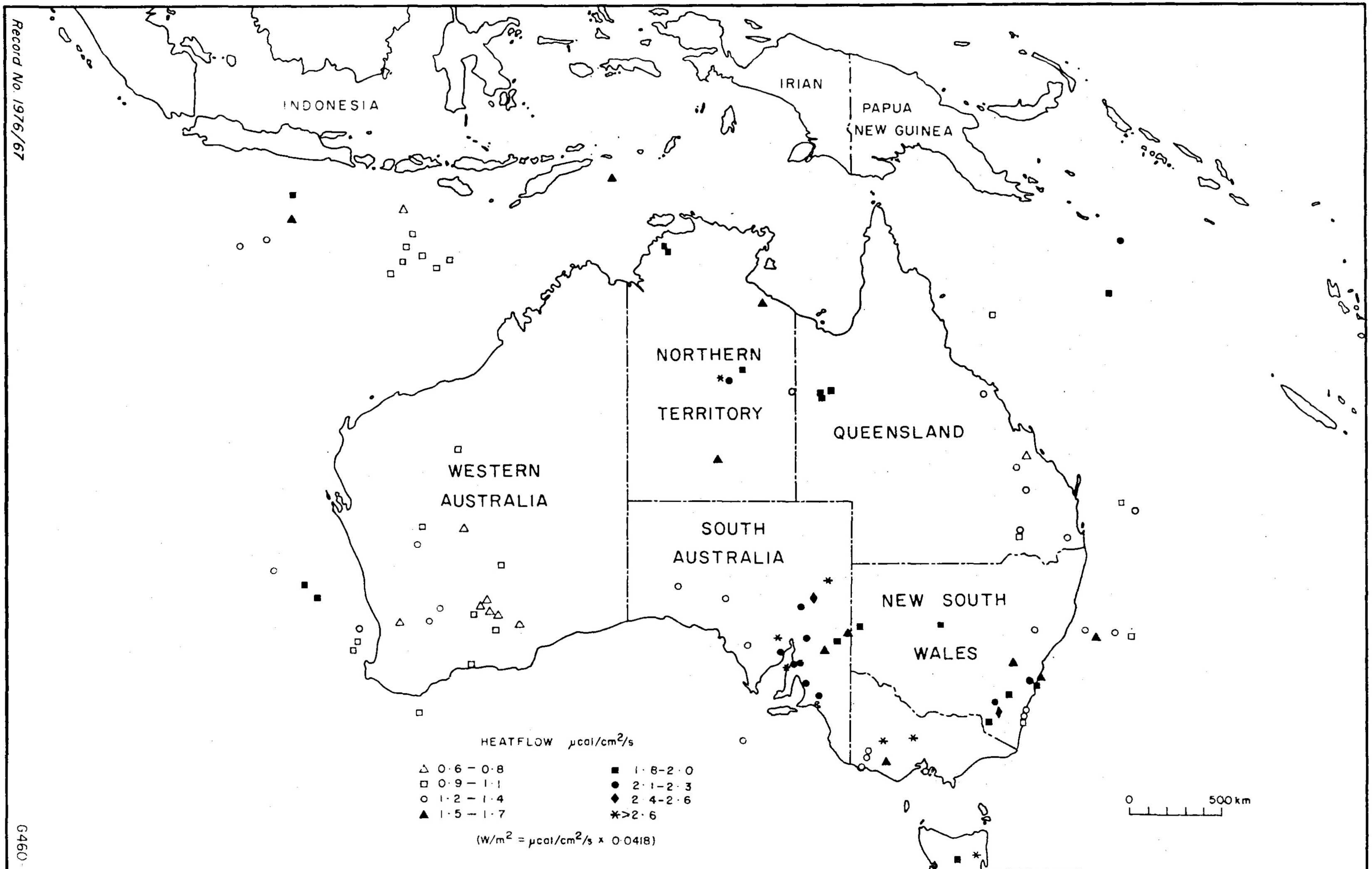

Fig 4 Heat flow values in and around Australia, redrawn from Lee & Uyeda (1965) and Sass et al (1976)

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consequently in ocean regions there are many more data than in continental regions. Much of the international marine work, however, has been directed towards solving problems associated with the seafloor spreading hypothesis and relatively few data are available on the Australian margins (Fig. 4). A co-operative BMR/Lamont-Doherty survey during 1976 south of the Great Australian Bight (BMR file 75/739) includes provision for heat-flow measurements and data will be available soon. Further surveys are proposed in 1976/77 off NW Australia in the Indian Ocean (Lamont-Doherty) and in the Timor Sea (Woods Hole Oceanographic Institute).

3. OBJECTIVES OF GEOTHERMAL STUDIES IN AUSTRALIA

A principal function of BMR is to obtain and publish regional geophysical and geological data to highlight prospective areas and so stimulate development in the private sector. One reason for the apparent lack of interest in Australian geothermal resources is that regional data are not readily available; consequently there is no general realization that warm and hot water reservoirs do exist, or if so to what extent. Clearly there is a need for increased BMR activity in this area to correct the present deficiency.

As an initial step in assessing geothermal resources in Australia all natural thermal areas should be indexed. Possible economic targets can then be established and detailed surveys initiated to establish their extent. Warm springs are obvious energy prospects; many are known in Australia (particularly on the outflow margins of the artesian basins) and some could provide thermal energy sufficient for local heating and minor industrial purposes. For large-scale electricity schemes, however, it is probable that drilling would be required to supplement the flow rates of most springs. In some regions, moreover, (e.g. along the eastern coast and in Tasmania) any cost advantage would be minimized by existing capital investments in coal and hydro-electric plant which are run below capacity. Each of these factors should be considered in BMR feasibility studies.

For general investigations of heat flow and crustal structure, a measuring program on an opportunity basis is probably the most realistic to ensure rapid regional coverage. For measurements of heat flow on land it is necessary to obtain temperatures to depths over 100 m and consequently temperatures are most commonly measured in deep boreholes (occasionally measurements in tunnels and mines are suitable). BMR has a continuing program of stratigraphic drilling and it is estimated that at least six holes each year would be of sufficient depth to give unambiguous heat-flow data. Casing would be required for most holes to ensure access for periods of up to one year after drilling (temperatures measured at times less than a year may be subject to transient cooling or heating from the fluid circulated during drilling). Measurements solely in stratigraphic and exploration boreholes, however, may produce biased heat-flow distribution patterns, and therefore complete regional coverage would require special purpose holes in granitic and other hard-rock areas; in view of drilling costs such holes may not be feasible in the immediate future.

Marine programs in heat flow must also be considered in conjunction with other investigations. Meaningful data can be obtained with probe type instruments, but only in water depths greater than 1 km. Probes take up to 5 minutes to reach thermal equilibrium, and the ship must be stationary during this period. Present BMR deep-water investigations do not require a ship to stop on station and consequently a marine heat-flow program in the short term may be costly and disruptive. With future BMR marine programs of stratigraphic drilling and deep ocean floor sampling it is probable that heat-flow measurements can be incorporated with little extra cost.

Although geothermal electric schemes depend at present wholly on the suitability of natural steaming grounds there are proposals to establish artificial aquifers in hot dry rock (Smith et al., 1973; Burnham & Stewart, 1973). The problems encountered are mainly technological and concern methods of inducing fractures to allow full fluid circulation and heat extraction. BMR work in this field could be restricted to trial drilling in granitic bodies in order to determine representative temperatures and permeabilities from grain boundary fractures.

It is proposed that the initial aims of BMR in heat-flow studies should be as follows:

(i) To collate all available thermal data in order to emphasize economic prospects and determine regional heat-flow patterns.

(ii) To undertake regional measurements of heat flow in deep holes (drilled for other purposes) as they become available.

and

(iii) To initiate detailed surveys in areas of high heat flow which may contain concentrated sources of energy.

4. PROGRAM PROPOSALS

An immediate field program can be based on existing BMR drilling projects. From the economic viewpoint two drilling areas are of particular interest in geothermal studies: the Georgetown region of Queensland and the Naracoorte-Penola section of the South Australian coast. The first of these contains hydrothermally altered granite and is close to the Tallaroo and Innot hot springs. Four holes are programmed by BMR to depths of 100 m during the 1976 field season, and if at least one hole is extended to 150 m it will be possible to obtain heat-flow data to gauge the economic potential of the hot spring reservoirs. In South Australia a drilling traverse between Penola and Naracoorte has been completed (BMR file 1975/991); again the maximum depth of penetration was 100 m. Heat-flow measurements in these holes would be useful in the planning stage of schemes to extract the energy in the artesian waters of the neighbouring Murray and Otway basins (such as the central heating scheme proposed for the Portland Hospital, BMR file 1974/582).

For the more general aim of gathering regional data, several of the drilling sites presently programmed by BMR for other purposes may be suitable for heat-flow measurements. The most useful of these would be the holes planned for the Alligator River and Pandanus Creek in N.T. and also the Hay River bore in the Georgina Basin. In the A.C.T. there is a continuing program of stratigraphic drilling and several holes deeper than 100 m are expected to become available for heat-flow studies in 1976/77; such local holes may also be valuable for long-term testing of techniques and instruments, and consequently casing is desirable for at least one A.C.T. site.

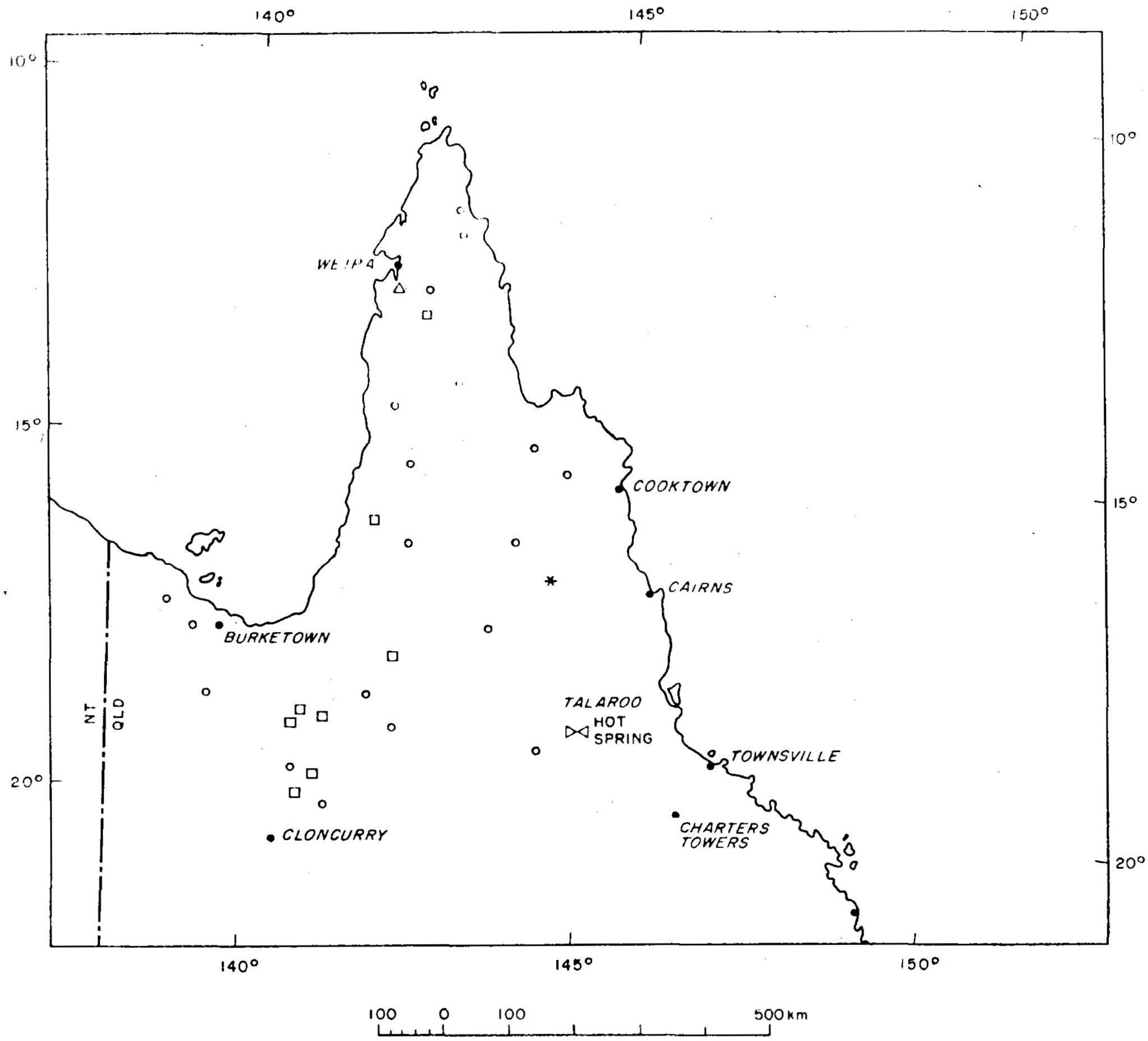
Although heat-flow studies are most conveniently based on current BMR drilling programs there are many older bores drilled by other institutions (including private companies) throughout Australia; as most of these are in artesian basins and are a major source of water for stock use, they are probably unsuitable for heat flow measurements since the temperature gradients will be perturbed by the water flow. Other holes, however, have been drilled for mineral exploration or for stratigraphic mapping and are now abandoned. In some cases abandoned holes have been capped and access should still be possible. In other cases holes may be sealed with a surface plug (or simply left to collapse) and some drilling would then be required before temperature gradients could be measured. A summary of borehole locations in northern Queensland has been made by Smart et al., (1976); those which may be suitable for heat-flow studies are shown in Figure 5 and illustrate some potential for rapid regional surveys of heat flow (summaries of boreholes are not at present available for other parts of Australia and considerable time would be required to compile an index).

The Sedimentary Basins Group in BMR is now analysing temperature data from the Canning Basin in order to predict levels of maturation in petroleum prospects. The available data, however, were obtained by private companies in adverse and varying conditions while drilling was in progress; these data should be verifield by measuring thermal gradients in abandoned holes which have now returned to thermal equilibrium. If in addition thermal resistivity logs are obtained (from core samples held in BMR) then it will be possible to make detailed computations of heat flow in each sub-basin to extend regional data in the south of Western Australia. Twelve sites suitable for heat-flow studies have been located between Derby and Halls Creek; the condition of other bores in the area is unknown and these should be reconnoitred for future surveys.

Because temperatures in newly drilled holes need one year to reach equilibrium, initial BMR heat-flow programs must be concerned with indexing of known thermal areas and with measurements in existing abandoned bores as discussed above. However, it is also important to prepare holes from current drilling for future measurements of heat flow; site visits will be essential in some instances to ensure that adequate casing is inserted when needed and also to allow observations of equilibration rates (relaxation times).

A suitable program for the 1976/77 financial year may be as follows:

PROJECT	SITE	PERIOD
Logging abandoned bores	Nth QLD	4 weeks, April 1977
Observations of relaxation	ACT	intermittent, all year
Logging of bores, Nth Canning Basin	WA	3 weeks, Sept. Nov. 1976
Conductivity measurements	Canberra	intermittent, all year
Cataloging of abandoned boreholes	Canberra	intermittent, all year
Computing	Canberra	continuous
Analysis of available temperatures in Great Artesian Basin	Canberra	5 weeks, June-July 1976
Site inspection, casing and temperature measurements	Georgetown S.A. (Penola) Pandanus Ck.	1 week, Nov. 1976 1 week, opportunity 1 week, Mar. 1977



LEGEND

- o Stratigraphic/plugged and abandoned
- □ Abandoned water-bore
- * Hydrographical observation hole
- △ Capped water-bore

Fig.5 Borehole locations in north Queensland potentially suitable for heat flow measurements

(Data extracted from Smart et al, 1976)

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Evaluation of exploration techniques

A further activity compatible with the functions of BMR is to examine and develop techniques and instruments suitable for resource evaluation. In the case of geothermal exploration all techniques are in their infancy and most are oriented towards defining the extent of thermal anomalies which are already obvious from surface expressions such as geysers. Search techniques have been based primarily on measurements of electrical resistivity (by a variety of methods) with support in later stages from geochemical analysis of trace elements in surface water. However, in some instances, gravity, magnetic, and seismic data have also proved suitable and it is not possible at present to recommend any one method for general use. Testing programs in BMR should now be designed to determine which of the available techniques are most suited to Australian conditions.

As mentioned earlier one of the major obstacles to routine heat-flow programs has been the need to measure temperatures in boreholes which have reached thermal equilibrium. Commonly, equilibrium is not possible in periods less than one year and this fact requires that boreholes be cased to prevent collapse. It is theoretically possible, however, that steady-state temperatures and thermal parameters can be calculated from observations of the cooling rate at successive depths while drilling is in progress. If these transient methods prove accurate, substantial savings in time and capital can be expected in routine heat-flow programs. Adequate testing of the transient techniques will require direct comparisons with data obtained by conventional methods in which equilibration times up to one year are required after drilling has ceased. Full appraisal must consequently extend over several years.

Rock testing/laboratory facilities

The processes which lead to mineralization (and even the types of rock which can exist within the Earth) ultimately depend upon the distribution with depth of temperature and pressure. Some attempt should consequently be made in BMR heat-flow programs to determine these parameters for the crust and mantle in Australia. Pressures can be reasonably well determined by combining seismic observations with velocity/density data but temperatures must be extrapolated from surface gradients under the constraint that the observed heat flow is not exceeded. For these extrapolations it is necessary to know both the variation with depth of thermal conductivity and also the distribution of radioactive heat sources. The first problem can be tackled entirely through laboratory tests using standard materials in high-pressure/high-temperature apparatus (possibly in co-operation with University groups) but measurements of radioactivity are meaningful only if specimens are adequately sampled in very deep boreholes or along surface exposures of granitic sequences.

The equipment and personnel required to implement a modest heat-flow program are discussed in Appendices 1 and 2. The instruments for field use are simple and inexpensive but high precision can be obtained only with periodic calibrations of the temperature sensor. Further laboratory facilities will be required for routine measurements of thermal conductivity. Rock cutting facilities must be available together with space to store the samples. More extensive laboratory facilities will be required for any program which includes provision for investigation of the thermal parameters under extreme conditions of heat or pressure.

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APPENDIX 1. EQUIPMENT AND COSTS

For determinations of heat flow the basic requirements are (1) precise thermometry to establish thermal gradients, and (2) apparatus for measuring thermal conductivity in core samples.

For (1) the choice of instrument depends upon whether measurements are to be made at sea or on land. For land-sited boreholes the simplest and most commonly used method employs a thermistor probe attached to a long cable. Resistance changes measured on a sensitive bridge at the surface then reflect temperatures at successive probe depths. A digital multimeter in some circumstances would be a desirable alternative to the resistance bridge (e.g. when continuous monitoring is required). For gradient measurements at sea, however, the sensing probe must contain several thermistors at set spacing; long cables are not practicable in this situation and consequently the relative temperatures are frequently recorded on strip chart recorders which are housed on the body of the probe. In either case (sea or land) accurate field measurements depend upon periodic laboratory calibrations of the thermistor sensor (which may be subject to drift) - a platinum resistance thermometer and bridge is required for this purpose. Costing details are given in Table 1.

For (2) the most common and reliable techniques are based on variations of the divided bar apparatus; here steady temperature gradients are established across assemblies containing a standard material and a core for which conductivity values are required (Fig. 6). Cylindrical samples for measurement must first be cored from bulk material and the ends polished smooth and made parallel. Prior to mounting in the divided bar apparatus each sample is degassed in a vacuum system so that the pores can be filled with water.

The sample preparation required with the divided bar apparatus precludes measurements in muds or in poorly consolidated cores. For this type of material a needle probe technique is widely adopted. A constant current source and a chart recorder are the principal requirements together with a hypodermic needle which is used as a housing for a heat source (consisting of a loop of resistance wire) and a thermistor temperature sensor.

The needle probe instrumentation can be modified to allow the use of transient measuring techniques in hard rocks (Cull, 1974). While less accurate than the divided bar the transient techniques do not require such detailed sample preparation and consequently conductivity in deep bores can be logged in detail using a statistical approach. Transient techniques have also proved suitable for measuring thermal conductivity of materials in bulk and consequently they may find application for borehole logging in situ.

EQUIPMENT COSTS

Assuming that initial BMR interest will centre on land based surveys it will be essential in many situations to allow for casing costs. Since temperature measurements often cannot be made for up to a year after drilling, free and continuing access can only be guaranteed by inserting pipe for the full length of each hole. Casing cannot be economically retrieved and consequently will constitute most of the recurring costs. If holes other than those drilled by BMR are used then casing costs must include charges for transport and also for running-in time (less than one day in most instances). In some stratigraphic holes the rock strength is such that no casing is required.

For measurements of thermal conductivity, laboratory equipment must include some form of divided bar apparatus which is shown schematically in Figure 6. In construction of such apparatus most of the cost (Table 1) is incurred by the need for a hydraulic press and two temperature baths. There is also some workshop time involved in machining the heat transfer discs and assembling them in the press.

Before samples can be run on the divided bar equipment considerable sample preparation is necessary. Coring and cutting facilities already exist in BMR and it is necessary only to supplement these with coring bits of suitable diameter and to purchase a face lapping machine (which can be used to advantage in other rock testing programs).

Secondary to the divided bar apparatus is a requirement for needle probe instrumentation to allow measurements in mud. The electronic components are readily available but probe construction requires some experience. Assembly of a resistance/voltage converter and DC amplifier will require BMR workshop time.

DIVIDED-BAR IDEALIZED SECTION

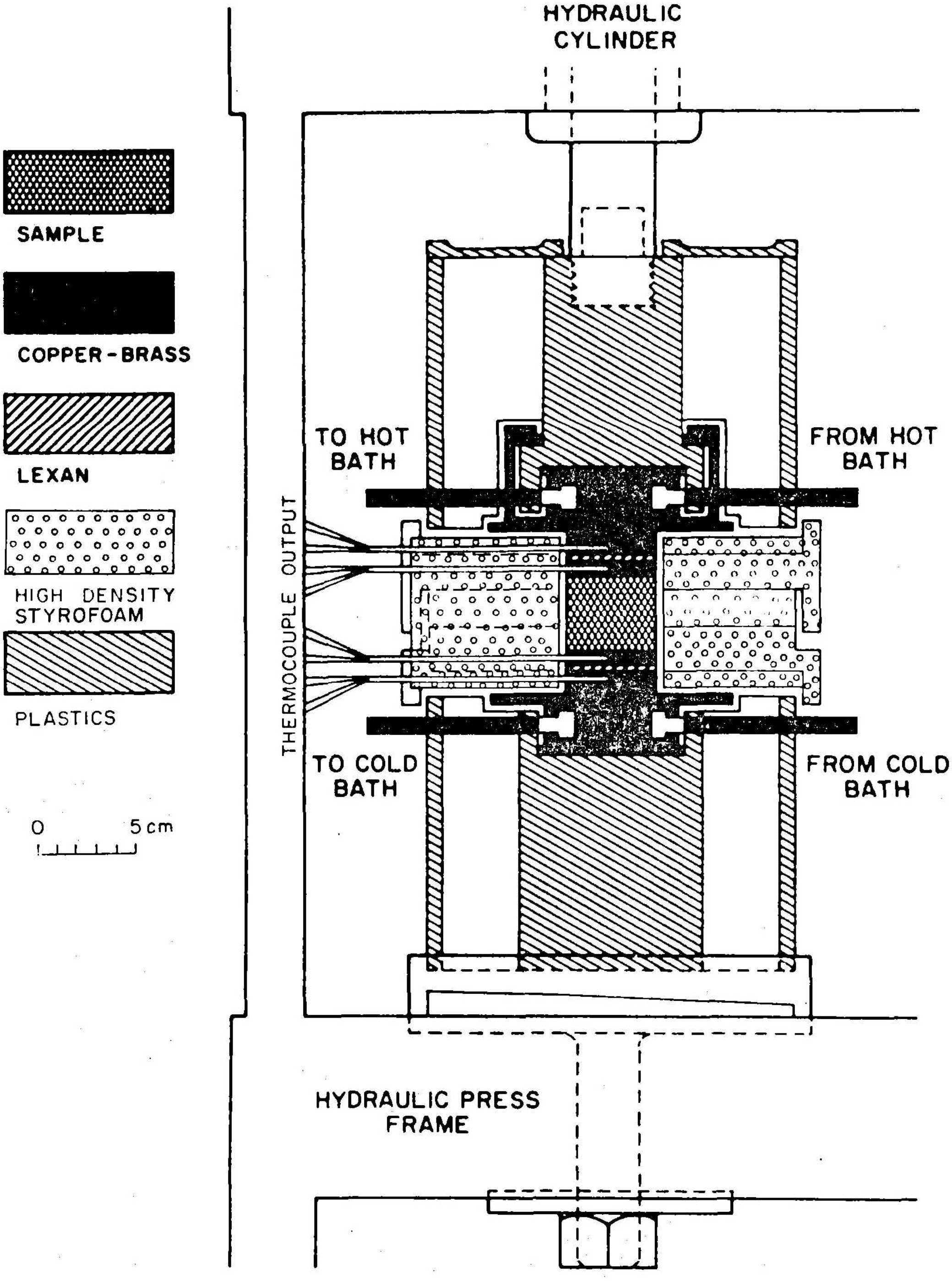

Fig 6 Schematic diagram of divided bar apparatus for thermal conductivity measurements.

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APPENDIX 2. STAFF REQUIRED

The program outlined in sections 3 and 4 of this Record could be implemented reasonably effectively by two officers: a geophysicist and a technical officer (science).

The duties of the technical officer would include responsibility for conductivity measurements, including sample preparation. Normally not more than five samples can be prepared and run on the divided bar apparatus in each working day. Comprehensive logging of holes may require that conductivity values be obtained at 1-metre intervals; if the level of field activity is such that 1000 m of borehole is available each year with full coring (e.g. 5 holes each of 200 m), then 200 man-days will be required each year for conductivity measurements alone. In many holes the sampling interval can be greater than 1 m, and measurement effort will be reduced accordingly. Other duties will include equipment testing and thermistor calibration.

Data analysis and compilation together with survey planning must be the responsibility of a geophysicist and should to some extent be integrated with other regional structural surveys. Computer modelling of reservoir systems and heat-flow anomalies should constitute part of the analysis of data. Design and development of techniques and instruments can proceed concurrently with other work and in co-operation with the technical officer.

In general, field measurements in boreholes can be conducted by a single officer, but in difficult terrain, assistance by a field hand may be necessary.

To maintain continuity in BMR heat-flow programs it is desirable that a second geophysicist be attached to the group to gain expertise in the field. Together with some data analysis, specific projects can be formulated on peripheral problems including thermal modelling of local crustal features, investigation of thermal effects in seismic profiling, and study of the role of thermal gradients in oil and gas migration.

TABLE 1
ESTIMATED EQUIPMENT COSTS

THERMOMETRY	
300 m of 3 core cable (with strain member)	$ 1,000
Cable reel	150
Depth counter	20
Precision resistance bridge	400
4½ digit multimeter	600
Platinum resistance thermometer and temperature bridge (Leeds & Northrup)	800
DIVIDED BAR CONDUCTIVITY APPARATUS	
Thermostatically controlled water baths and circulating pumps (2 off)	$ 650
Hydraulic press	400
Monitor with chart output	400
Digital voltmeter	500
Consumables	850
SAMPLE PREPARATION	
Diamond coring bit	$ 80
End face lapping equipment	1,500
NEEDLE PROBE	
Constant-current power supply	$ 500
Resistance/voltage transducer	80
DC amplifier	60
Chart recorder	500
Probe assembly	100
RECURRING COSTS	
Casing of boreholes ($2 per metre) initially not more than 1000 m per year	$ 2,000
Travel and allowances, computing, repair and maintenance and miscellaneous operating costs	5,000