BOREHOLE TEMPERATURE MEASURING EQUIPMENT AND THE GEOTHERMAL FLUX IN TASMANIA

By G. Newstead* and A. Beck†

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Summary

An instrument, using a thermistor and an A.C. bridge circuit, is described by which temperature measurements in boreholes can be made to 0·01 °C. Results of temperature measurements in Tasmania are given and a value of 2 cal cm^{-2} sec^{-1} is obtained for the heat flux (uncorrected for recent glaciation).

I. Introduction

The object of this paper is, firstly, to describe equipment for measuring the temperature in boreholes, which was developed by one of us (G.N.) as part of a programme of research on remote-reading bridges, and, secondly, to give results for geothermal gradients and heat flux obtained by its use.

The measuring element of the instrument is a thermistor connected by a polythene cable to an A.C. bridge situated at the top of the hole. Thermistors offer obvious advantages for temperature measurement since, because of their high temperature coefficients of resistance (of the order of 4 per cent.), the accuracy with which it is necessary to measure the resistance for a given accuracy of temperature measurement is much less than with other types of resistance thermometry. They have been used previously (Deeter 1948; Misener, Thompson, and Uffen 1951; Standard Telephones and Cables Ltd. 1952) in D.C. bridge circuits; the novel feature of the present equipment is the use of an A.C. bridge. This was chosen mainly because of the ease of obtaining amplification. From the figures given in the paper it will be seen that to detect a temperature change of 0·01 °C requires the measurement of a current of 10^{-9} A which is about two orders of magnitude less than can be measured with available portable galvanometers. Electronic equipment has the advantages of being more portable, more robust, and more easily obtained than a special D.C. galvanometer. The use of D.C. amplifiers is not desirable either under field conditions or for the small voltages in question. Finally, the use of alternating current has other advantages, such as avoiding errors due to thermal and contact e.m.f.'s. It is found that, under typical field conditions, the absolute accuracy of the equipment is of the order of 0·01 °C or better.

The whole of the measuring apparatus is mounted in a suitcase and can be carried in the field. It may be run from either a car battery or dry batteries.

* University of Tasmania.

† Australian National University.

While it was designed primarily for temperature measurements in boreholes, it is hoped to use it also for geothermal prospecting and for temperature measurements in mines and tunnels.

No measurements of the geothermal flux have yet been made in Australia, and it was felt that Tasmania would be a particularly interesting field for them since it has been recently glaciated and has some boreholes through fairly homogeneous strata. It was hoped that, with the above accuracy in the temperature measurements, it might be possible to make a contribution towards the dating of the glaciation. In the event, however, many of the holes proved to be incomplete, unsuitable, or blocked, so that for the present it is only possible to give a few values for the heat flux.

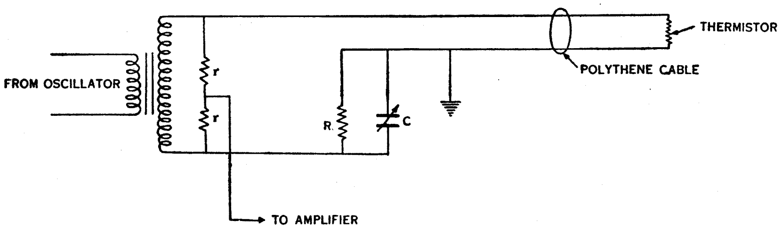

Fig. 1.—Schematic diagram of bridge.

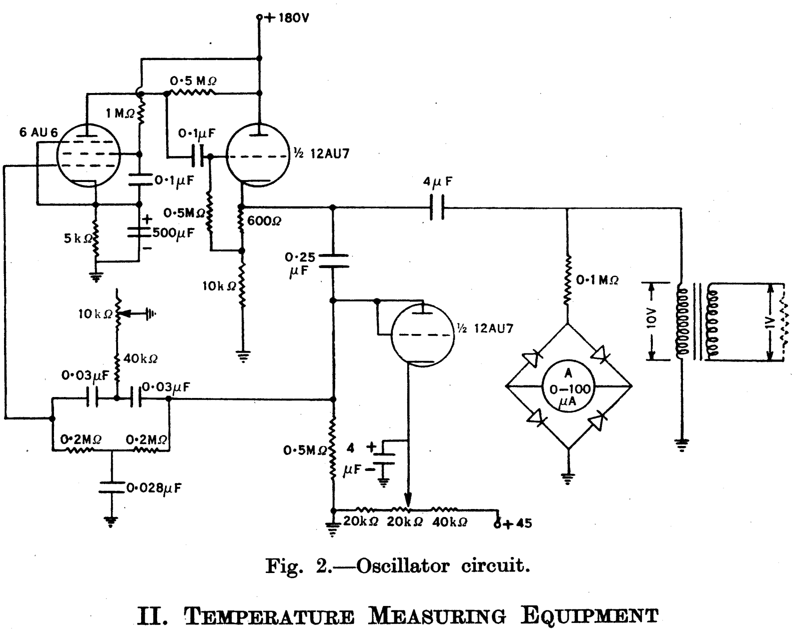

Fig. 2.—Oscillator circuit.

II. Temperature Measuring Equipment

A schematic circuit diagram is shown in Figure 1. The resistance R is a five dial Muirhead box, type A25U, the arms r are two 100 Ω " Minalpha " resistances, and the variable condenser C is built up from good quality mica dielectric condensers with air dielectric trimmers. The thermistor is an S.T.C. type A. Several values of resistance were used, but type A1522/100, which has a nominal resistance of 10^5 Ω at 20 °C, was found best to cover the range of temperature in the boreholes. The cable was a Telcon type PT11 with about 1500 ft always in circuit.

The requirements for the oscillator are constancy of output and reasonable frequency stability and waveform. The frequency of 40 c/s was chosen in order to make the capacity currents in the cable small compared with the currents in the thermistor. A bridged T feedback oscillator with diode output stabilization as described by Lynch and Robertson (1946) and shown in Figure 2, was used. The oscillator develops 0·8 V across the bridge and a built-in voltmeter enables this voltage to be monitored. Controls are provided to set the output voltage and to vary the frequency by a small amount so as to centre it in the amplifier pass band.

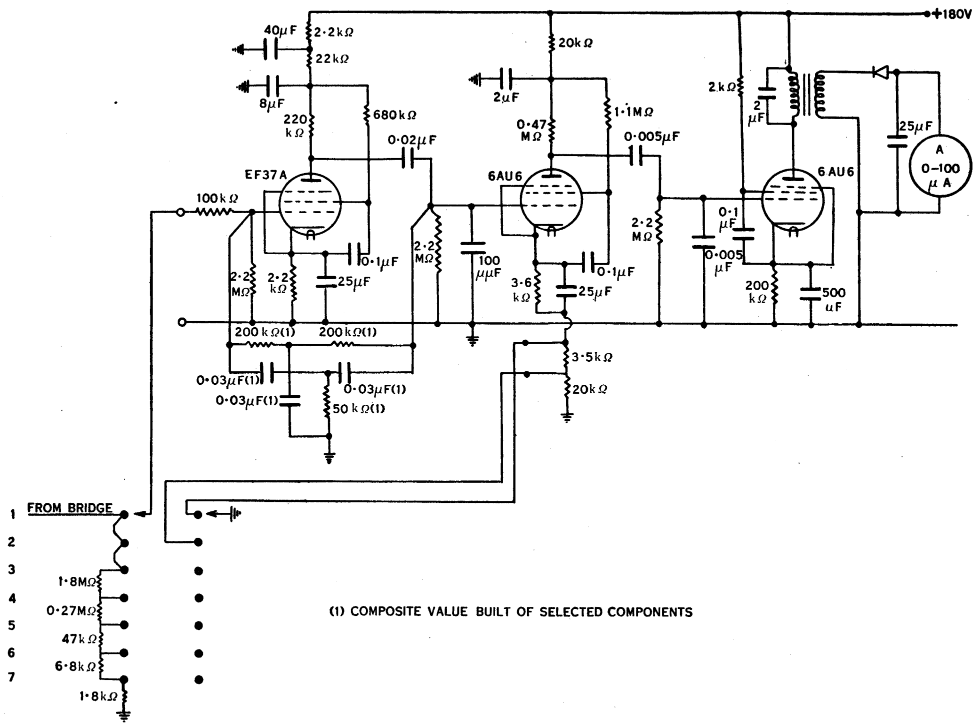

Fig. 3.—Amplifier circuit.

The circuit diagram of the amplifier is shown in Figure 3. The first stage incorporates a bridged T feedback circuit (Valley and Wallman 1948) to make it very selective : the resonant frequency is 40 c/s and the pass band is only a few cycles centred about this. An EF37A pentode is used to cut down microphonic effects. The design of the last two stages is quite conventional. The first two steps of the attenuator reduce the gain of the second stage by introducing cathode degeneration, and the next steps attenuate the input ; the reduction of gain is approximately seven times per step. Bridge balance is indicated as a minimum on the 0–100 μA meter which receives the rectified output of the third stage. On full sensitivity, 2·5 μV input gives full-scale deflexion ; this sensitivity is more than required and allows for deterioration of the amplifiers as the batteries run down and the valves age. The input impedence at 40 c/s is $10^5\ \Omega$ and the amplifier noise produces a standing current of 5 μA. The power consumption of the whole equipment is $0\cdot6$ A at 12 V and 15 mA at 180 V.

The 1500 ft of cable, which covers the depths of the boreholes investigated, is wound on a reel; because of the danger of overstressing the cable if the measuring head sticks, the head is supported by a thin wire rope wound on a separate reel and run over a measuring wheel connected with a counter which reads depth directly. The cable and wire rope were clipped together every 100 ft. As an additional check on measured depths the wire rope was marked at 50-ft intervals.

Details of the temperature measuring head are shown in Figure 4. The essential problem in the design of the head is the provision of a water-tight seal on the cable which will not strain its dielectric. This has been effected by modifying a method of Munroe and Penny (1952). A polythene plug P is

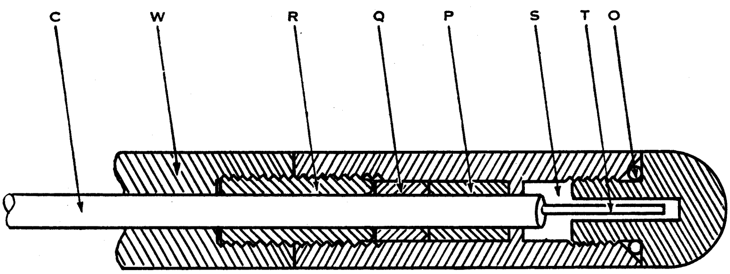

Fig. 4.—Temperature measuring head.

compressed by a ring Q which is forced in by a screw R until the polythene flows, making a seal with the cable C; the necessary setting of the screw R was found by preliminary experiments. These seals are easily made and have been tested in the laboratory to over 1000 lb/in.^{2}. This seal provides a watertight compartment S in which the thermistor T is situated. To facilitate assembly, which is frequently done in the field, the end of the compartment is removable and is sealed by a rubber O-ring at O; a cover, not shown in the figure, protects the thermistor from damage when removing the end. A brass weight W brings the total weight of the head up to about 12 lb. The diameter of the head is 1 in.

Enclosing the thermistor in this way implies that it requires several minutes to attain the temperature of its surroundings. This time lag has not proved to be a disadvantage, since in some earlier experiments with a thermistor in contact with the water it was found that fluctuations of temperature (presumably due to the stirring of water when lowering the head) occurred and took some minutes to die down.

III. Theory of the Method

The balance condition of the bridge requires that the capacity C and resistance R be adjusted to be equal to the capacity and resistance in the cable arm. The capacity balance is completed first; it is found that this does not alter appreciably as the cable is unreeled, indicating that the effect of the strains which occur in the cable in practice is negligible.

The thermistor with the cable in circuit was calibrated in the laboratory against a standardized mercury-in-glass thermometer (equipment for platinum thermometry not being available in Tasmania). The method is thus one of substitution and many sources of error are eliminated; its performance, however, is limited by the stability of the thermistor. The makers' data indicate that their products can be relied upon to 0·01 °C and Doucet (1951) gives the limits of a similar type as $\pm 0 \cdot 002$ °C, but there is very little published information available on this point. In view of this we have adopted the practice of quickly checking the calibration at two or three points at each return to the laboratory. In all cases when a complete recalibration has been made, the original values have been reproduced to the required order of accuracy.

The complete calibration was carried out in a bath which was thermostatically controlled to 0·01 °C. Measurements were made at temperature intervals of about 1 °C, interpolation between these points being made by assuming the resistance R_T of the thermistor at temperature T to be of the form

$$R_T = a(T)e^{b(T)/T},$$

where $a(T)$ and $b(T)$ are slowly varying functions of T.

To determine the sensitivity and accuracy of the equipment, the theory of the resistance balance must be examined more closely. The resistance R_T of the thermistor is of the order of $10^5\ \Omega$ at 20 °C and its temperature coefficient α_T is of the order of 0·04. Thus a change in temperature of 0·01 °C causes a change in resistance of 40 Ω and applies a voltage of 50 μV to the amplifiers, which are thus seen to have adequate sensitivity.

The series resistance of the cable is approximately 14 Ω per 1000 ft of lead and return: the constant part of this is eliminated by the method of calibration, and the change in series resistance caused by likely variations in temperature will be less than 2 Ω with 1500 ft of cable in circuit. Thus the series resistance of the cable and the effect of temperature on it may be disregarded.

The effect of the shunt resistance of the cable and its variation with temperature and strain is more difficult to estimate. Taking the capacity of 1500 ft of cable as 0·03 μF, 40 c/s for the frequency, and 3×10^{-4} for the power factor of polythene gives 450 MΩ for the shunt resistance R_s of the cable.

Since

$$\frac{1}{R} = \frac{1}{R_s} + \frac{1}{R_T},$$

the change δR in R due to a change δR_s in R_s is

$$\delta R = \frac{R^2}{R_s^2}\delta R_s,$$

and the change δR due to a 30 per cent. change of shunt resistance for the case in which $R \simeq R_T \simeq 10^5\ \Omega$ and $R_s = 4 \cdot 5 \times 10^8\ \Omega$, is about 7 Ω, which again is negligible compared with the 40 Ω change in R due to a change of 0·01 °C.

Another possible source of error is the heating of the thermistor by the voltage applied to it. The dissipation constant of the thermistor is $0 \cdot 28$ mW/°C and at balance the voltage applied to it is $0 \cdot 4$ V. Taking $10^5\ \Omega$ as the resistance of the thermistor, we get a temperature rise of $0 \cdot 005$ °C due to the applied voltage. That this effect is not causing error can be demonstrated by varying the voltage applied to the bridge and noting that the balance resistance setting is unchanged; if heating of the thermistor were causing false readings the balance resistance would be a rapidly changing function of the applied voltage. Nevertheless, the voltage in the thermistor is maintained at a constant value during the calibration and the measurements.

The above discussion is intended only to indicate the orders of magnitude of the possible sources of error and to show the feasibility of the method in principle. To check it, and to test the behaviour of the cable and the general reliability of the equipment, a series of experiments was made in which the thermistor was replaced by a 200,000 Ω resistance similar to those in the box R, and the cable was immersed in a tank whose temperature could be varied. It was found that a change of 20 °C in the temperature of the cable gave an error equivalent to approximately $0 \cdot 01$ °C.

IV. Temperature Measurements in Boreholes

The results of temperature measurements in five boreholes are recorded in Table 1; in all cases the holes had been drilled for some time and so were in thermal equilibrium. The depths given are corrected for stretch of the cable and, when necessary, for inclination of the hole. These results appear to represent all the useful information of this type at present available in Tasmania—measurements were also made in a number of other holes but results are not recorded here because cores were not available. The holes studied are:

Borehole No. 1.—Hole No. 5001 of the Hydro-electric Commission at the Great Lake; height above sea-level 3378 ft; mean annual* air temperature $5 \cdot 9$ °C. This hole is in a tholeiite (quartz-dolerite) sill with some evidence of multiple intrusion. The hole stopped at 1050 ft and did not penetrate the sill. There is no systematic jointing and no reason to believe that the hole departs from the vertical. Core recovery is complete and, as the core is being studied systematically from the petrological point of view elsewhere, we propose subsequently to make more accurate measurements of its thermal conductivity and its variation with composition. The rock may be described roughly as consisting of plagioclase and pyroxene in approximately equal amounts with a mesostasis of 10–20 per cent. Magnetite and ilmenite are occasionally present in amounts of up to 5 per cent. The grain size ranges from $0 \cdot 5$ to 3 mm.

Three independent sets of measurements, which are in excellent agreement, have been made on this hole at different times, (i) those recorded in Table 1, (ii) some measurements with maximum thermometers, and (iii) another set of

* In all cases the mean annual air temperatures are given merely as an instance of climate, they are not considered sufficiently reliable to use in connexion with the observations. Usually they represent averages over only a few years and are not for the actual site but for one considered to have similar climatic conditions.

readings which are not reproduced since the thermistor was not available for recalibration.

Borehole No. 2.—Hole No. 7005 of the Hydro-electric Commission on the Dee tunnel line ; height above sea-level 2412 ft ; mean annual air temperature 8·8 °C ; in tholeiite similar to No. 1. There was a small flow of water from this hole.

Borehole No. 3.—Hole No. 7006 of the Hydro-electric Commission on the Dee tunnel line ; height above sea-level 2350 ft ; mean annual air temperature 8·8 °C ; in tholeiite similar to No. 1.

Borehole No. 4.—Hole No. 48R of the Electrolytic Zinc Company at Rosebery ; height above sea-level 651 ft ; mean annual air temperature 10·6 °C ; cased to 300 ft.

This hole and No. 5, which is close to it, are drilled through a sequence of interbedded rhyolites and rhyolitic tuffs. In some cases phenocrysts of plagioclase, or plagioclase in the crystal tuffs, suggest that the magma approached a dacitic composition. Although devitrified, a few slides indicate perlitic cracking and suggest the former presence of obsidians and vitric tuffs. All the rocks have suffered recrystallization and, in some cases, a fine groundmass consists almost entirely of interlocking grains of quartz. A little sericite may be present in some rocks and a weak schistosity is indicated in some specimens. Veins of quartz and of quartz-calcite are common and in some rocks vughs and veins of chlorite also occur. Certain slides, showing silicification, probably contain as much as 90 per cent. of quartz.

Both these holes have peculiarities which make them unsatisfactory for calculation of heat flux : (i) they are not straight, the depths given in the table are corrected for the known inclination of the hole to the vertical but not for possible wandering in azimuth ; (ii) they are on a relatively steep hillside ; (iii) they are in the neighbourhood of an ore body of galena, blende, and pyrites ; (iv) large underground water movements occur in the area.

Borehole No. 5.—Hole No. 42R of the Electrolytic Zinc Company at Rosebery ; height above sea-level 866 ft ; mean annual air temperature 10·7 °C ; material similar to No. 4. There was a small flow of water from the hole.

V. Conductivity Measurements

The thermal conductivities were measured in a divided bar apparatus similar to that described by Benfield (1939). The brass rods were calibrated against disks of crystalline quartz cut with their plane faces parallel to the optic axis, using the value given by Griffiths and Kaye (1923) for the conductivity of quartz. The cooling water was maintained at $26 \pm 0 \cdot 02$ °C by a thermostat and the mean temperature of the specimens was about 30 °C in all cases. The temperature gradient in each brass rod was measured by three copper-constantan thermocouples used in conjunction with a Leeds and Northrup type K2 potentiometer. Cores from holes 4 and 5 were 1 in. in diameter and were turned and ground down to 21 mm. The cores of holes 1 and 2 differed in diameter from 21 mm by only 1 or 2 per cent. and were used as they stood, a correction being

TABLE 1

TEMPERATURES AND CONDUCTIVITIES IN BOREHOLES

Hole No.	Depth (ft)	Temperature (°C)	Conductivity (cal, c.g.s., °C)
1	56	—	0·0046
	101	8·63	—
	202	10·06	0·0047
	302	11·42	—
	343	—	0·0047
	480	—	0·0046
	513	14·34	—
	603	15·53	—
	612	—	0·0046
	704	16·84	—
	784	—	0·0049
	804	18·13	—
	864	—	0·0048
	906	19·40	—
	947	—	0·0048
	996	20·49	—
	1033	20·91	—
2	20	—	0·0046
	25	9·29	—
	50	9·49	—
	100	9·72	—
	122	—	0·0047
	151	10·17	—
	200	10·96	—
	227	—	0·0048
	252	11·58	—
	314	—	0·0052
	316	12·38	—
3	25	7·72	—
	45	8·42	—
	100	9·09	—
	151	9·78	—
	202	10·46	—
	252	11·13	—
4	51	10·16	—
	54	—	0·0080
	87	—	0·0081
	101	10·44	—
	138	—	0·0097
	150	10·77	—
	201	11·14	—
	250	11·41	—
	300	11·73	—
	350	12·20	—
	359	—	0·0102
	399	12·73	—
	410	—	0·0092
	485	—	0·0077
	497	13·70	—
	548	—	0·0099
	588	14·67	—
	610	—	0·0057
	640	15·22	—
	646	—	0·0043
	687	15·78	—
5	22	—	0·0140
	47	10·60	—
	98	10·97	—
	194	11·20	—
	242	—	0·0111
	295	11·57	—
	393	12·43	—
	445	—	0·0098
	493	13·33	—
	549	—	0·0101
	593	14·31	—
	645	—	0·0093
	691	15·16	—
	736	—	0·0118
	742	—	0·0050
	787	16·04	—
	844	—	0·0058
	851	—	0·0060
	877	16·98	—
	898	17·17	—

made for the error in diameter. This correction has been studied in detail both theoretically and experimentally and will be described elsewhere. The cores from hole No. 3 were only $\frac{3}{4}$ in. in diameter and so could not be measured in this apparatus. Four sections, 1, 2, 4, and 6 mm in thickness, were cut for each experiment, the 1 mm section being used to make a slide for petrological examination and the others being ground flat to within 0·0005 in. In most cases a film of glycerol was used at the contact surfaces.

Values of the conductivities are given in Table 1, the units being c.g.s., calorie, and °C. It is believed that these are accurate to within 4 per cent. Since we find a variation of this order between samples a few inches apart in the core, there is no point in pushing the accuracy further, though an attempt will be made with an improved apparatus to correlate the variations of conductivity with petrological properties for the case of hole No. 1.

VI. The Heat Flux

In all cases this has been estimated by plotting temperature against thermal resistance from the surface. Results for the individual holes are as follows.

Borehole No. 1.—The value of the heat flux is $2\cdot04\times10^{-6}$ cal cm^{-2} sec^{-1}.

Borehole No. 2.—The anomalous behaviour at the lower depths is presumably caused by the flow of water mentioned. Using only the results for depths greater than 100 ft gives a value of $2\cdot06\times10^{-6}$ for the heat flux.

Borehole No. 3.—In this case, as mentioned above, conductivities were not measured but, since the hole is close to No. 2, a reasonable value of the heat flux may be obtained by using the observed thermal gradient in conjunction with the harmonic mean of the conductivities measured in hole No. 2. This gives a value of $2\cdot07\times10^{-6}$.

Borehole No. 4.—The temperature-depth curves both of this hole and No. 5 suggest that they are "two-layer" holes but in fact the rocks are of the same type throughout, though there are large variations both of composition and thermal conductivity. The heat flux in this case is $2\cdot47\times10^{-6}$.

Borehole No. 5.—The first 300 ft have been disregarded because of the water flow mentioned above. The lower depths give a heat flux of $2\cdot54\times10^{-6}$.

The general conclusion drawn from these results is that the heat flux in Tasmania has the relatively high value of 2×10^{-6} cal cm^{-2} sec^{-1}. This is based on hole No. 1 alone which has been very carefully investigated. It is unfortunate that no other hole which could be regarded as satisfactory from the point of view of thermal measurements was available and, for this reason, we have included the other four holes as corroborative evidence. Nos. 2 and 3 confirm this value satisfactorily and Nos. 4 and 5, being in the neighbourhood of a sulphide ore body, would be expected to give somewhat higher values.

These values do not allow for the influence of the recent ice age on the present heat flux. It is usual to estimate this roughly by assuming that the surface assumed its present mean annual temperature V immediately on the conclusion of the ice age: if t is the time since this conclusion, and k, ρ, and c are the thermal conductivity, density, and specific heat of the surface material, the heat flux at depth will be greater than that at the surface by an amount

$$V(k\rho c/\pi t)^{\frac{1}{2}},$$

which, with the values $V=5\cdot9$ °C for hole No. 1, $\rho c=0\cdot5$, $k=0\cdot0050$, gives an addition of $0\cdot42\times10^{-6}$ to the heat flux if t is given the reasonable value of 5000 years.

VII. Acknowledgments

The authors are greatly indebted to the Hydro-electric Commission of Tasmania and the Electrolytic Zinc Company for putting many facilities at our disposal and for the ready cooperation of members of their staffs. Thanks are also due to Professor S. W. Carey of the University of Tasmania for advice on the selection of boreholes, to Dr. Germaine Joplin of the Australian National University for the petrological descriptions of the specimens, and to Professor J. C. Jaeger of the Australian National University for suggesting the construction and applications of the instrument.

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