

25. DOWNHOLE FLOW OF BOTTOM WATER: IMPLICATIONS FROM TEMPERATURE LOGGING AT HOLE 462A, NAURU BASIN, DEEP SEA DRILLING PROJECT LEG 89¹

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ABSTRACT

Temperature logging at Hole 462A, which has remained undisturbed for 4¼ years after drilling, reveals a very small temperature increase from 1.3°C at the seafloor to 3.9°C at 400 m sub-bottom depth, followed by a steep increase to 24°C at 500 m. This temperature gradient strongly indicates downhole flow of bottom water into the sediments between 400 and 500 m below the seafloor at the time of Leg 89. The downhole flow of bottom water is probably caused by the underpressure in the 70-Ma sediments of the Nauru Basin; this is in contrast to other DSDP holes with similar downhole flow phenomena, such as 395A and 504B, where the bottom water permeates into the underpressured young basaltic basements by hydrothermal circulation. By assuming a constant flow rate of bottom water and a linear temperature gradient of 0.045°C/m for undisturbed sediments, the volumetric downhole flow rate is calculated to be about 1700 L/hr (or 6m/hr. linear rate). For 4¼ years, at least 6×10^7 kg of seawater has been drawn down through the drilled hole into the sediments. The heat-flow value of 48 mW/m² for undisturbed sediments at Site 462 is concordant with the intraplate volcanism about 100 Ma in the Pacific Plate.

INTRODUCTION

The plate age predicted for the position of Site 462 in the Nauru Basin is about 150 Ma, that is, on the older boundary of magnetic anomaly M-26. At Site 462, a sediment layer about 560 m thick is underlain by basaltic sills and flows associated with the intraplate volcanism that occurred about 100 Ma (Larson and Schlanger, 1981). Because extensive intraplate volcanism took place in the mid-Pacific region, including the Nauru Basin, some deviations from a simple cooling-plate model are expected for heat-flow values, subsidence, and sedimentation history of the possibly "Jurassic" deep oceanic basins (e.g., Schlanger, et al., 1981).

During DSDP Leg 61 in 1978, downhole temperatures in Hole 462 were measured using the Tokyo T-probe in sediments ahead of the bit during the drilling (Yokota et al., 1980) and the Gearhart-Owen continuous T-logs (GO-HRT) after the drilling (Larson, Schlanger, et al., 1981). For sediments down to about 250 m sub-bottom in Hole 462, two continuous T-logs after the drilling indicate extrapolated equilibrium temperatures about 2 to 5°C lower than those recorded in good data from the Tokyo T-probe. Because of this discrepancy between the two measurements, the heat-flow value at the Nauru Basin has not been determined (Boyce, 1981). From extrapolated equilibrium temperature gradients, which showed no increase or even decrease in basaltic sills at about 600 to 700 m sub-bottom (Fig. 1), Boyce (1981) suggested that convection of water into basaltic layers might cause such anomalous temperatures if the data were representative of *in situ* conditions.

Downhole flow of bottom water through artificial holes is suggested to occur at several DSDP holes including

Hole 454A in the Mariana Trough (Uyeda and Horai, 1982), Holes 335, 396B, and 395A on the Mid-Atlantic Ridge (Hyndman et al., 1977; Erickson and Hyndman, 1978; Becker et al., 1984), and Hole 504B on the Costa Rica Rift (Becker, Langseth, and Von Herzen, 1983; Becker, Langseth, Von Herzen, and Anderson, 1983; Becker et al., in press), though flow rates were obtained only for Holes 395A and 504B. All these holes are located near a seafloor spreading axis, where hydrothermal circulation is expected in the young basaltic basements.

By using results of the Leg 89 temperature logging, a rate of bottom-water downflow is estimated for Hole 462A by assuming a constant flow rate and a linear undisturbed thermal gradient as measured on Leg 61.

METHOD AND OPERATION

Borehole temperatures in Hole 462A were logged using the Schlumberger high-resolution temperature logging tool (S-HRT). Hole 462A was offset about 460 m north-northwest of Hole 462, where temperatures were measured during Leg 61. The reentry cone and 75-m-long bottom assembly used in Hole 462A were left undisturbed after the drilling had stopped on 25 July 1978. Lowering of the S-HRT began at 0300 hr. on 7 November 1982 and ended at 0700 hr.; this was the first operation after the drill string had reentered. The logging tool, lowered at slow winch speed (about 0.3 m/s), met with slight obstructions at 470 and 515 m sub-bottom and blocked at 521 m, probably as a result of a slight blockage of slumped sediments or a discontinuous change of hole diameter, because no difficulty was encountered in the course of cleaning out the hole down below 500 m by using the drill string.

The S-HRT was calibrated several times using a standard mercury thermometer at 0.8 and 25.5°C before and after the logging. Because of the short time-constant of the S-HRT probe (< 30 s; Becker, Langseth, Von Herzen, and Anderson, 1983), the delay in the response of this probe can be ignored at slow winch speeds.

RESULTS AND INTERPRETATION

Temperatures obtained by the S-HRT show a very small increase from 1.3°C at the seafloor to 3.9°C at 395 m sub-bottom, and the temperature gradient increases gradually with depth. Below 400 m, temperatures rise rapidly

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to about 24°C at 500 m, as shown in Figure 1 (solid curve).

For the depth interval with steep temperature gradient, the actual temperature record indicates some fluctuation, with an amplitude of as much as about 1°C (figure 21 of the Site 462 report, this volume). Although a 1-m long sinker bar ahead of the S-HRT probe would generate local mixing of water (Becker et al., in press), this fluctuation of temperature must be due to the up-and-down motion of the logging tool, because the fluctuation varies coherently with the simultaneously recorded tension of the cable. If the fluctuation corresponds to the heave-related motion of the probe relative to the hole wall, the time constant of S-HRT is sufficiently short that no correction for the delay of this probe seems justified.

The temperature distribution in this hole is very similar to that in DSDP holes where downflow rates of seawater have been estimated, such as Holes 504B (Becker, Langseth, and Von Herzen, 1983; Becker, Langseth, Von Herzen, and Anderson, 1983; Becker et al., in press) and 395A (Becker et al., 1984). Because the extrapolation (Boyce, 1981) of equilibrium temperatures from the two GO-HRT logs assumes no movement of water in the hole, the discrepancy between the bottom-hole temperatures and extrapolated equilibrium temperatures suggests water movement in the hole after drilling stopped. Both observations strongly indicate that the downflow of seawater has continued for the 4¼ years since Hole 462A

was drilled. A simple extension of the temperature gradient obtained by the Tokyo T-probe seems consistent with the S-HRT record at 500 m (Fig. 1). A nearly constant temperature gradient of 0.045°C/m in the upper 220 m, obtained from good data of the bottom-hole temperature measurements, can be taken to represent the undisturbed sediment temperatures at this site. Using 1.07 W/m°C for the thermal conductivity of the sediments (Larson, Schlanger, et al., 1981), the undisturbed heat flow becomes about 48 mW/m² for Site 462.

Assuming a linear temperature gradient, G , for undisturbed sediments and a constant linear flow rate in the hole, U , the temperature, T , as a function of depth, z , can be expressed as (Becker, Langseth, and Von Herzen, 1983)

$$T(z) = T_s + G \cdot z - G \cdot [1 - \exp(-A \cdot z)]/A \quad (1)$$

and

$$A = 8 K I(x)/(\pi^2 a^2 C U) \quad (2)$$

where T_s is the temperature at the seafloor, K is the thermal conductivity of the sediments, a is the radius of the hole, and C is the heat capacity of seawater per unit volume. Jaeger (1965) has tabulated the values of an integral involving Bessel functions, $I(x)$, in which x is kt/a^2 (k is the thermal diffusivity of the sediments and t is the elapsed time after the commencement of flow).

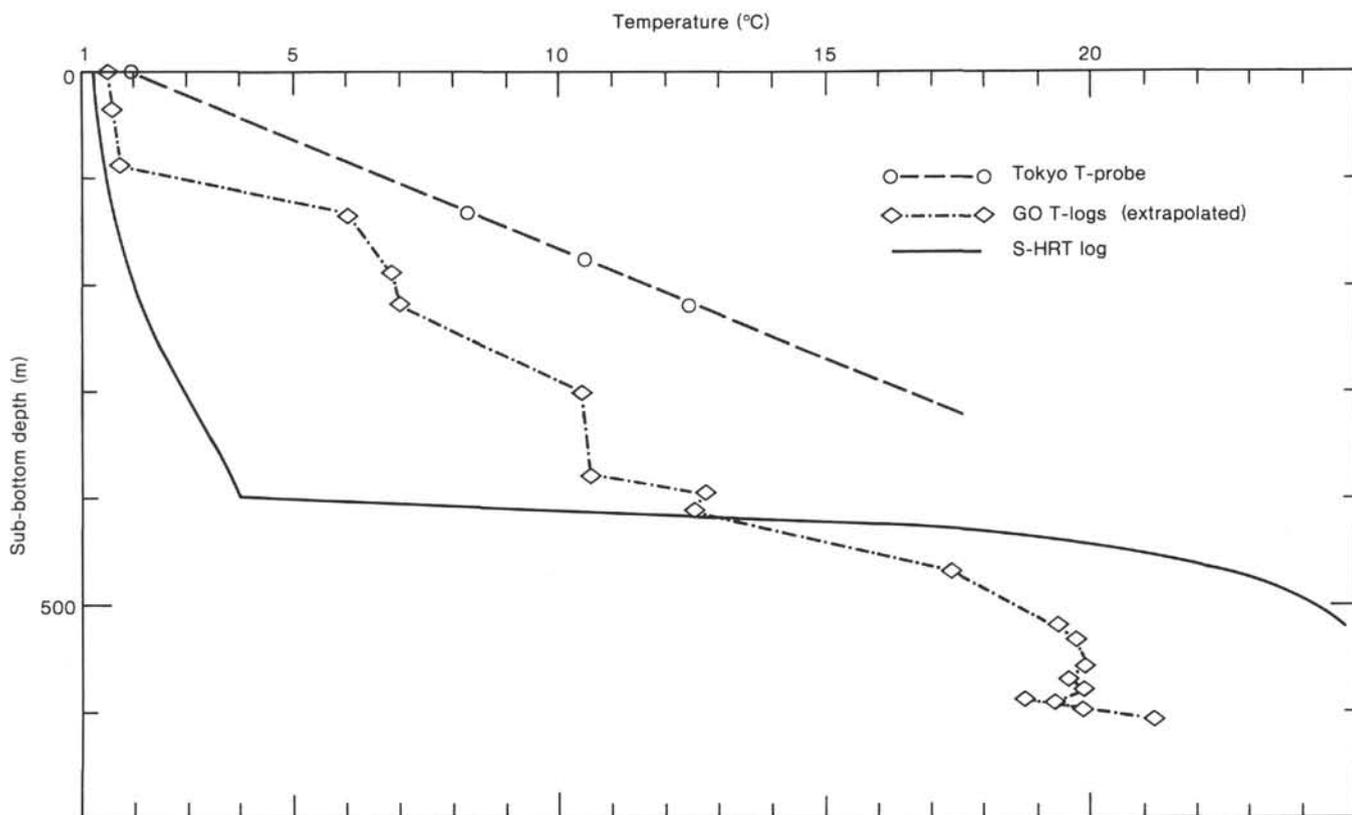


Figure 1. Borehole temperatures measured in the upper part of Hole 462 (broken line) using the Tokyo T-probe during drilling of sediments (Leg 61) and in Hole 462A (solid curve) using the S-HRT (Leg 89). Dotted curve indicates equilibrium temperatures extrapolated from the two GO-HRT logs taken after Hole 462 was drilled (Leg 61). Leg 61 data are from Boyce (1981).

By fitting the obtained temperatures down to 395 m sub-bottom depth with calculated ones, where constants used are $C = 1 \text{ cal/cm}^3$, $k = 0.005 \text{ cm}^2/\text{s}$, $G = 0.045^\circ\text{C}/\text{m}$, $a = 30 \text{ cm}$ and $t = 1550 \text{ days}$, the downflow rate, U , is obtained as 6 m/hr . (1.7 mm/s), which translates to a volumetric rate of 1700 L/hr . (Fig. 2). Because the variation of the value of $I(x)$ in Equation (2) becomes small for the long time elapsed after drilling, the ambiguity of the hole diameter does not largely affect the result for the volumetric downflow rate ($\approx a^2 U$). For example, a reduction of a by half (say, from 40 to 20 cm) results only in about a 40% decrease.

The layer of a steep temperature rise (400–500 m sub-bottom) would correspond to an underpressured reservoir where the bottom water penetrated radially. Although

the origin and cause of the underpressure in this layer remain unknown, it is probable that the downhole flow would decrease with time, as evidenced in Hole 504B (Becker, Langseth, Von Herzen, and Anderson, 1983; Becker et al., in press). If a similar mechanism holds in Hole 462A, it is estimated that at least $6 \times 10^7 \text{ kg}$ of seawater has been drawn down through the hole and penetrated into sediments for $4\frac{1}{4}$ years in the Nauru Basin.

DISCUSSION AND IMPLICATIONS

The heat-flow value of $48 \text{ mW}/\text{m}^2$ calculated for Site 462 is slightly higher than that expected from a “root- t ” decrease curve of a normal oceanic basin. It seems concordant, however, that the temperature structure was affected by the intraplate volcanism about 70 to 110 Ma

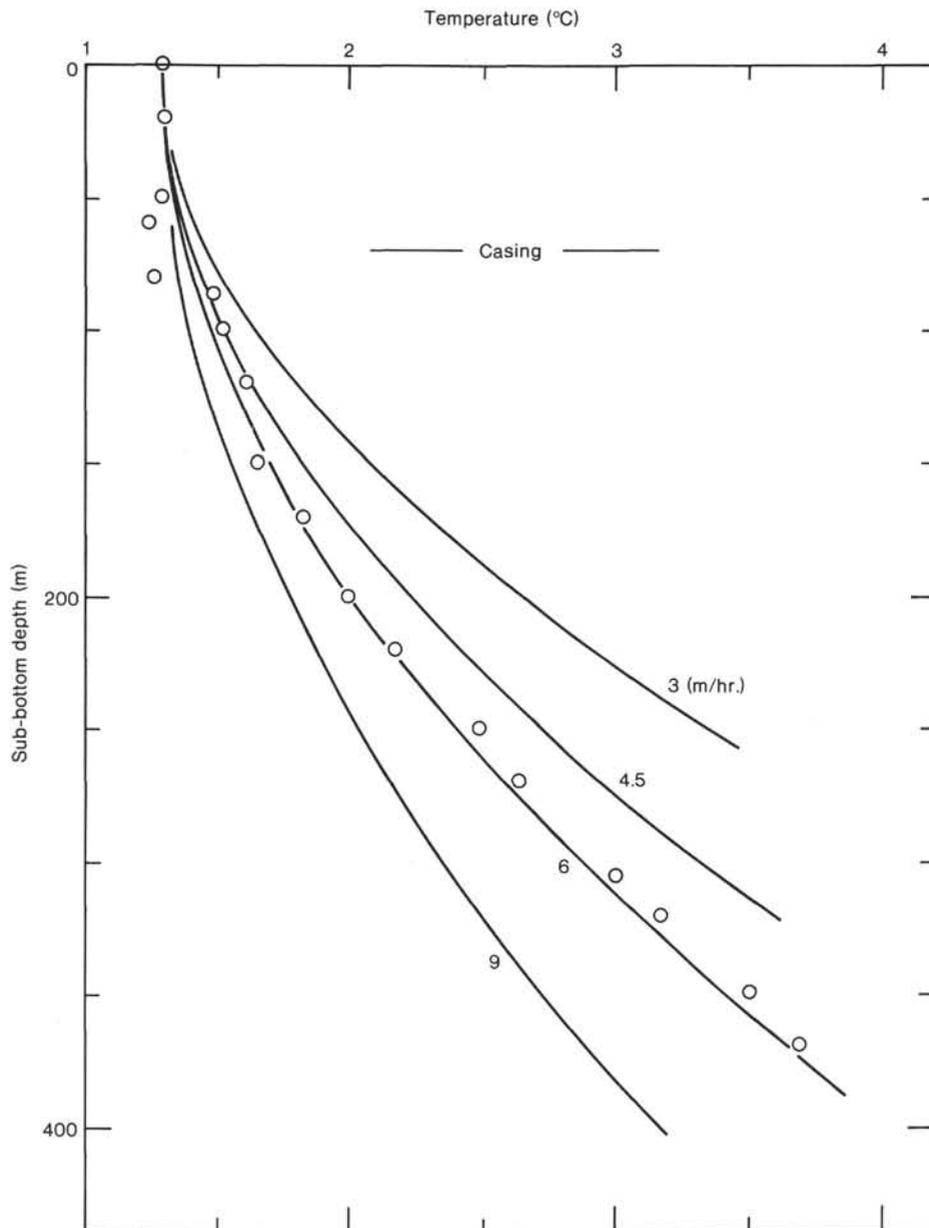


Figure 2. Observed temperatures and theoretical curves at 1550 days, Hole 462A. Flow rate of 6 m/hr. corresponds to volumetric flow rate of 1.7 kL/hr.

(Schlanger et al., 1981), so that the heat-flow value obtained is similar to values for approximately 100-Ma ocean crust in the Pacific (Parsons and Sclater, 1977).

The downhole flow rate obtained is of an order of magnitude similar to those for previously estimated DSDP holes (395A and 504B, as listed in Table 1). In the Nauru Basin, the downhole flow of seawater probably resulted from underpressures in the sediments of age up to about 70 Ma, rather than in young basaltic basements in other DSDP holes with downhole flow phenomena. If the radial flow through the hole wall is controlled by Darcy's Law, the pressure difference between the underpressured reservoir and the hole is high enough between 400 and 520 m sub-bottom. From only the temperature measurements, a small amount of radial flow in the upper part of the layer cannot be resolved, so that the upper boundary of the reservoir may not be fixed at 400 m sub-bottom but may depend on time, as evidenced in Hole 504B (Becker et al., in press). The permeability of sediments generally decreases with depth, and it changes by orders of magnitude. In the underpressured reservoir in this depth range, where the lithology is lower Eocene to middle Maestrichtian chert and limestone or lower Maestrichtian to upper Campanian volcanoclastic sediments (Larson, Schlanger, et al., 1981), the permeability of sediments is likely to be high.

Although permeabilities of sediments and basaltic sills and flows at Site 462 were not measured, there remains a possibility that mixtures of chert and limestone or volcanoclastic sediments could have higher permeabilities than younger sediments (Morin and Silva, 1984). A sediment layer about 400 m thick could not hold underpressures for more than about 10^5 yrs. (Becker, Langseth, and Von Herzen, 1983), if the permeability of these sediments is 10^{-14} to 10^{-17} m², (Bryant et al., 1974). This would seem to rule out the possibility that the under-

pressures might be a relict of pressure decrease caused by cellular hydrothermal circulation confined to the lower part of sediments or by subsidence of the cooling plate which had been reheated by mid-plate volcanism. Whatever mechanism causes underpressures in the sediments, it must be active now in the Nauru Basin.

If the 400-m-thick sediments do not contribute to the overpressure, the hydrostatic pressure of a cold water column ($\sim 4^\circ\text{C}$) in the hole would cause the excess pressure relative to the hot undisturbed sediments ($\sim 25^\circ\text{C}$). The excess pressure at 500 m sub-bottom becomes less than 0.1 bar, because the average density difference becomes about 0.002 g/cm³ for the same salinity, provided that the pore pressure of undisturbed sediments is hydrostatic. The required permeability of sediments in the underpressured reservoir becomes about 0.1 darcy (10^{-13} m²) for the downhole flow rate of 6 m/hr., a 100-m-thick reservoir, and 4¼ yrs., provided that the radial flow of water obeys the pressure-diffusion equation (Becker, Langseth, and Von Herzen, 1983). The fact that Hole 462A has remained open for 4¼ years without casing below the bottom-hole assembly suggests that there is no apparent deformation of sediments, and may support the assumption that the pore pressure in the 400-m-thick sediments does not exceed hydrostatic pressure. It may be that the permeability of sediments gradually decreases with depth down to 400 m sub-bottom and then increases abruptly to generate a dominant radial flow through the hole wall. At about 500 m sub-bottom, the excess pressure tends to diminish as a result of both decreased permeability and reduced temperature difference.

However, the forced radial flow of bottom water into the aquifer, resulting from the excess pressure of the cold water column, may not cause a significant downflow of seawater into the sediments, unless the permeability of this layer is about 0.1 darcy, which is nearly the same order of magnitude as the permeability of the basaltic basement (Zoback and Anderson, 1983). To check the applicability of this mechanism, estimates of the permeability of the sediments and the pore-pressure distribution are obviously desired for *in situ* downhole measurements.

Although the downhole flow phenomenon is not a direct consequence of hydrothermal activity, DSDP holes previously suggested to have downhole flow of bottom water are generally in regions where hydrothermal circulation is expected in the basaltic basements (Anderson and Zoback, 1982; Zoback and Anderson, 1983; Langseth et al., 1984). In general, the underpressured region is expected to be far larger than the overpressured region, where the upwelling of pore fluid through artificial holes could occur, as suggested by Duennebieer and Blackinton (1980). From Site 462, the nearest seamount is Ujao Atoll, in the Marshall seamounts, about 200 km to the northeast, and Kusae Island is about 350 km to the southwest. It is unlikely that hydrothermal circulation similar to that expected in the small (several kilometers wide) sediment pond at Site 395 near the Mid-Atlantic Ridge (Langseth et al., 1984) is active now in the Nauru Basin.

There remains a possibility that hydrothermal activity may be continuing in the Nauru Basin (1) if condi-

Table 1. Characteristics of DSDP Holes for which the downflow rates have been estimated.

	395A ^a	504B ^b	462A ^c
Latitude	22°45.35'N	01°13.62'S	07°14.50'N
Longitude	46°04.90'W	80°43.82'W	165°01.90'E
Seafloor depth (m)	4483	3460	5177
Sub-bottom depth (m)	Leg 45: 610	Leg 69: 489	Leg 61: 1069
	Leg 78B: 610	Leg 70: 835 Leg 83: 1287.5 Leg 92: 1350	Leg 89: 1209
Sediment thickness (m)	90	274.5	560
Casing depth (m)	100	300	75 ^d
Bottom depth of downhole flow (m)	>100 (250-500) ^e	320-400	400-500
Reservoir (age, Ma)	Basalts (7.3)	Basalts (6.2)	Sediments (70-80)
Seafloor age (Ma)	7.3	6.2	>110
Downflow rate (kL/hr.)	Leg 78B: >1 (5) ^f	Leg 70: 6 (1/7) ^f Leg 83: 1.7 (2) ^f Leg 92: 0.17 (3.5) ^f	Leg 89: 1.7 (4.25) ^f
Undisturbed heat flow (mW/m ²)	49	200	48
	37 ^g		
Temp. gradient (°C/km)	85 28 ^g	114-200	45

^a Becker et al. (1984).

^b Becker, Langseth, and Von Herzen (1983); Becker, Langseth, Von Herzen and Anderson (1983); Becker et al. (in press).

^c This work.

^d Depth of bottom hole assembly; no casing was employed.

^e Estimated high permeability rock layer.

^f Lapsed time after drilling (in years).

^g Estimated from nearby usual heat-flow measurements.

tions there are similar to those of the exceptionally anomalous high heat flow observed in the 80-Ma crust in the northwest Atlantic (Embley et al., 1983), or (2) if sources of basin-filled sills and flows are still active or contributing to the pore-water circulation but the probable mechanism is undeniably the excess pressure caused by the cold water column of the artificially drilled hole. A more detailed heat-flow survey of old ocean basins such as the Nauru Basin should be made.

Although the cause of underpressure in the sediments beneath Hole 462A remains unknown, the downhole flow of bottom water seems a common phenomenon in the DSDP holes that have been left open for a long time. Further investigations of physical properties are obviously needed in deep holes in old oceanic basins, as well as in those near the diverging plate boundary.

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APPENDIX

Note Added by Co-Chief Scientists, October 15, 1985

Recently we learned that an El Niño event late in 1982 affected sea level in the western equatorial Pacific (K. Wyrtki, personal communication, 1985). See Site 462 report (this volume) for comments about total depth of Hole 462A at the end of Leg 61 (1068 m) compared to apparent depth when reentered during Leg 89 (1071 m). The discrepancy may have resulted from inaccurate pipe measurements or sea level rise or both. If sea level had risen at Site 462 between 1978 and 1982, the added pressure should be considered as a possible factor in the flow of seawater into the bore hole.