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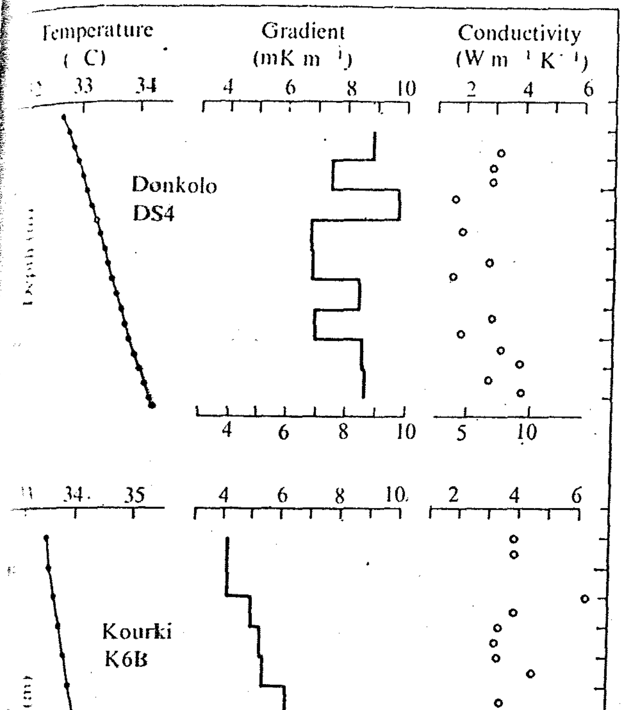
…low heat flow values of 18 ± 2 mW m^{-2} (0.42 ± 0.04 …ric cm^{-2} s^{-1}) and 22 ± 2 mW m^{-2} (0.51 ± 0.05 µcalorie …) have been determined for two sites 85 km apart … West African Precambrian shield in the Niger Re… (Table 1).

…mperature surveys were carried out with a thermistor … in March 1972 in three boreholes, 245 m, 406 m, and …m deep, respectively, in western Niger. The thermal conductivities of solid rock disks, saturated with water before measurement, were subsequently determined on a conventional divided bar apparatus.



…g. 1 Temperatures, gradients and conductivities for the …ed portions of the boreholes. In the graphs for K15 …lid curve represents a survey made nine days after …had stopped at 315 m, and the dashed line represents …mum temperatures predicted from two additional …s made soon after the hole was deepened to 360 m. …ne-day curve and the predicted equilibrium curve …t the measured equilibrium profile for K6B which was only 200 m away.

Figure 1 shows temperature profiles with depth, temperature gradients calculated for 20-m intervals, and thermal conductivities for the analysed portion of three holes. Two sets of temperature data are shown for site K15. Heat flows were calculated using both K15 gradients; the mean is recorded in Table 1 and agrees very well with the heat flow determined from the nearby site, K6B.

The increasing gradient with depth in K6B (Fig. 1) is puzzling in view of the apparently uniform conductivity of the samples from that hole, and suggests the possibility of recent climatic warming. The consensus of climatological opinion[1], however, is that the region was, if anything, cooling rather than warming during recent times. Furthermore, the Donkolo site does not confirm the speculation of a recent regional warming.

The results of radioactive heat production measurements on aggregate samples of core chips are given in Table 1. The mean of 1.2 µW m^{-3} for the basement rock at the Kourki site is taken to be representative of the region.

The two sites of the heat flow determinations are both located in Precambrian terrain on the eastern edge of the exposed West African craton. Six K–Ar ages of rock within 100 km of the heat flow sites[2] range from 2,487–1,206 Myr. The heat flow values reported here substantiate the general observation of low heat flow in Precambrian shields, a result anticipated by Beck and Mustonen[3] from temperature measurements in boreholes in Ghana. These west Niger heat flow values are, however, considerably less than the mean heat flows of any of the other shields. The Southern Africa craton provides a useful comparison; there, fifteen measurements range from 36 to 59 mW m^{-2} with an average of 49 mW m^{-2}. The worldwide average of all shields is near 40 mW m^{-2}.

When heat flow data are coupled with information about the distribution of radioactive heat sources, reasonable estimates of temperatures at depth can be made. For a continental shield, Sclater and Francheteau[4] outline a heat production model based on the petrological concepts of Ringwood[5] and compatible with observed heat flow and surface heat production data. A surface heat flow in the Sclater–Francheteau model of 40 mW m^{-2} is comprised of 28 mW m^{-2} arising from radioactive heat sources in the outer 400 km of the Earth and 12 mW m^{-2} originating at greater depth.

It is clear that the Niger heat flow could be satisfied entirely by the flux originating above 400 km in the Sclater–Francheteau model, or with appropriate fractions of both the shallow and deeper flux. We reject the former option because it possibly implies a nearly isothermal lower mantle, a condition we think unlikely. Therefore, we have calculated temperature models that include some flux from below 400 km, consistent with two constraints: first, the measured surface heat flow, 20 mW m^{-2}; and second a near surface radioactive heat source distribution that diminishes exponentially downward from the measured surface value of 1.2 µW m^{-3}. The logarithmic decrement of the near surface heat source function and the temperature dependence of the thermal conductivity remain variable parameters of the models.

Two temperature models for Niger, along with a typical 40 mW m^{-2} shield geotherm and a melting point curve, are shown in Fig. 2. One model, which we have called an 'upper limit' model, represents the likely upper limit for the temperature distribution beneath western Niger, consistent with the listed constraints. It is characterised by a logarithmic decrement of the heat source of (5 km)$^{-1}$ and a uniform thermal conductivity of 2.5 W m^{-1} K^{-1}. We prefer the second model which uses a logarithmic decrement of (8 km)$^{-1}$ and a modest increase of thermal conductivity

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Table 1 Heat flow and heat production data

Site	Latitude	Longitude	Borehole	Depth interval (m)	Heat production ($\mu W\ m^{-3}$)	Heat flow ($mW\ m^{-2}$)
Donkolo	14° 53′N	0° 55′E	DS4	60–245		18 (0.42)
			DS3	140–250	1.8 (4.3)*	
Kourki	14° 25′N	0° 20′E	K6B	180–406		22 (0.52)
			K15	160–358		21 (0.51)
			K6B	60–190	1.3 (3.2)	
			K6B	210–410	1.2 (2.8)	
			K15	50–190	1.1 (2.6)	
			K15	200–360	0.96 (2.3)	
			K16	50–100	1.2 (2.9)	

* Numbers in brackets refer to heat production in 10^{-13} calorie $cm^{-3}\ s^{-1}$ and heat flow in μcalorie $cm^{-2}\ s^{-1}$.

with temperature, following Schatz and Simmons[6]. Neither of the Niger models reaches the temperatures of the average shield geotherm. Furthemore, unless the entire section of the upper mantle below the West African shield is severely depleted in heat producing isotopes, the heat flow originating below a depth of 400 km must be only 7 mW m^{-2}, about half the corresponding value for the average shield. We therefore must conclude that the Precambrian crust and underlying upper mantle of western Niger probably comprise one of the coldest regions in the outer 400 km of the Earth.

The mechanical consequences of this 'cold spot' are worth brief consideration. The plate tectonic model of Earth dynamics envisions a rigid, mechanically strong lithosphere overlying a weak and deformable asthenosphere. The base of the lithosphere has no rigorous definition; it is commonly equated to the top of the upper mantle seismic low velocity zone. This zone usually begins at depths of 50–150 km, depending on the tectonic setting. We suggest another working definition for the boundary between the lithosphere and the asthenosphere: that depth at which the viscosity of the Earth has diminished from its high surface value to 10^{20} kg $m^{-1}s^{-1}$ (10^{21} poise). Such a viscosity for the asthenosphere is suggested by postglacial rebound, and also

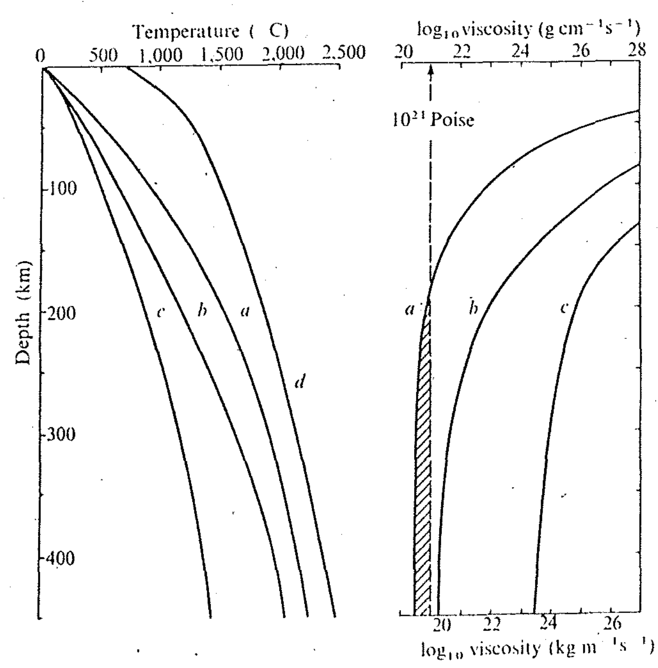

Fig. 2 The variation of temperature and viscosity with depth for three heat flow–heat production models: *a*, Average shield; *b*, Niger upper limit; *c*, the preferred Niger model, *d*, melting point.

by the velocities of lithospheric plate motion over asthenosphere.

We have calculated the viscosity as a function of temperature, and thus of depth, for the temperature models shown in Fig. 2. We have followed the development of Weertman[7], which relates the viscosity to temperature dependent creep and dislocation glide. The calculations assume a stress of 10^4 N m^{-2} (0.1 bar) and the melting curve shown in Fig. 2. The calculated viscosity profiles also shown in Fig. 2. The model for the average shield temperature implies a lithospheric thickness of some 175 km for a typical shield, a value quite consistent with seismically determined values reported for various shields. The models for West Africa suggest that the lithosphere extends to depths well below 400 km; whether an asthenosphere is developed at greater depths is somewhat uncertain. Our conclusion is that the lithosphere is very thick, and the asthenosphere is very thin or absent beneath West Africa.

The logical consequence of a thick lithosphere and poorly developed or absent asthenosphere would be that motion of the lithosphere would be impeded. In the extreme, the plate would be rendered immobile. Burke and Wilson[8] have indeed suggested that such has been the case for the African plate since the early Miocene.

Has the African plate run aground?

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[1] Van Zinderen Bakker, E. M., *Palaeoecol. Afr. surround. Antarct.*, 7 (1972).
[2] Brunnschweiler, R. O., *Geology*, 22, 1 (1974).
[3] Beck, A. E., and Mustonen, E., *Nature phys. Sci.*, 23 (1972).
[4] Sclater, J. G., and Francheteau, J., *Geophys. J. R. astr. Soc.*, 20, 509 (1970).
[5] Ringwood, A. E., in *The Earth's Crust and Upper Mantle* (edit. by Hart, P. J.); (Am. geophys. Union Geophys. Monogr., 13, Washington, DC, 1969).
[6] Schatz, J. F., and Simmons, G., *J. geophys. Res.*, 77, (1972).
[7] Weertman, J., *Rev. Geophys. Space Phys.*, 8, 1 (1970).
[8] Burke, K., and Wilson, J. T., *Nature*, 239, 5372 (1972).