Table 2 Mean Densities (g cm^{-3}) and Albedos of Planets[19]

Object	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Density	5.46	5.23	5.52	3.36	3.93	1.33	0.69	1.56	1.54	~4
Albedo	0.06	0.76	0.36	0.07	0.16	0.73	0.76	0.93	0.62	~0.14

ions in minerals. For example, there seems to be a significant absorption at ~4300 Å (23,300 cm^{-1}) in the Pluto spectrum, which could mark the lowest field-independent transition[5,6] $^6A_1 \rightarrow {}^4A_1{}^4E(G)$ in octahedral Fe^{3+}. The energy separation of the 4300 Å and 3780 Å Pluto bands (~3,300 cm^{-1}) compares favourably with the separations of the $^4A_1{}^4E(G)$ and $^4E(D)$ levels in Fe^{3+} ions in terrestrial silicates[6]. The Pluto spectrum also shows definite absorption at 4900 Å (20,500 cm^{-1}) and possible absorption at 4020 Å (24,900 cm^{-1}), which could mark the transitions[9] $^6A_1 \rightarrow {}^4T_1(G)$ or $^4T_2(G)$ and $^4A_1E(G)$ in tetrahedral Fe^{3+}. Band wavelengths are compared with those of the same transitions in Fe^{3+} in terrestrial crystals in Table 1.

Both Fe^{2+} and Fe^{3+} ions exhibit a number of spin-forbidden bands in the visible region, and unless spectra of good resolution are available, it is often difficult assigning the bands[12]. Bands of Fe^{3+} in silicates, however, are usually more intense[13,14] than the visible-region bands of Fe^{2+}. There would seem to be sufficient correlations of energies and half-widths of bands in spectra of Pluto and terrestrial crystals to justify the suggestion that the surface of Pluto, at least, is iron-rich.

Although the physical properties of Pluto are not known accurately, the most probable values[15-18] of albedo (~0.14) and mean density (~4 g cm^{-3}) support a model of an Fe-rich planet with only a very tenuous atmosphere. The albedo and density of Pluto are similar (Table 2) to those of Mars, which probably has an Fe-rich surface of oxide and silicate[8]. The Moon (albedo 0.07 and mean density 3.36 g cm^{-3}) has a primarily basalt surface[20]. Allowing for inaccuracies in the determination of the mass of Pluto, the albedo and density are significantly different from those of the giant planets.

The presence of Fe on Pluto is inconsistent with the fractionation of refractory metals and their oxides as proposed by Hoyle[1] and Hoyle and Wickramasinghe[2]. If Pluto accreted in its present part of the solar system it would appear likely that all planets possess Fe-rich centres. On the other hand, it is possible that Pluto formed in an inner part of the solar system.

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Approximate Geothermal Gradients in the North Sea Basin

APPROXIMATE geothermal gradients were determined from bottom hole temperatures for eighty wells in the North Sea Basin, which comprise about 30% of all post-1963 North Sea Basin wildcats. The wells are distributed as follows: onshore Netherlands, fifteen; offshore Netherlands, five; onshore Germany, one; offshore Germany, ten; offshore Denmark, one; offshore Norway, nine; offshore United Kingdom, thirty-nine. The data are displayed on the depth-temperature graph, Fig. 1, and the geothermal gradient contour map, Fig. 2. Before the determination of the geothermal gradients, an assumed surface temperature of 10° C was subtracted from the measured borehole temperature, and drilled depths were converted to depths below the sea bottom or land surface.

Temperatures, taken at hole bottom during electric log runs, were recorded 3–48 h after circulation of the drilling fluid was stopped. According to Lachenbruch and Brewer[1], Jaeger[2] and Beck[3], temperatures recorded in rotary-drilled holes soon after drilling operations have been completed are not equivalent to those of the undisturbed rock, because of the heat generated by the mechanical action of the bit on the rock face and the circulation and redistribution of heat by the mud system. I shall show in a later article, however, that geothermal gradients determined in this manner are likely to be in error by less than 10%.

In most North Sea wells several further temperature readings are available from intermediate log runs. A plot of these temperatures versus depths indicates in almost every case a decrease in geothermal gradient with depth. This decrease can also be observed by plotting the bottom hole geothermal gradient versus depth for all wells. The geothermal gradient in wells drilled in the deeper sub-basins of the North Sea basin (for example, the Tertiary basin centre near the Norwegian–

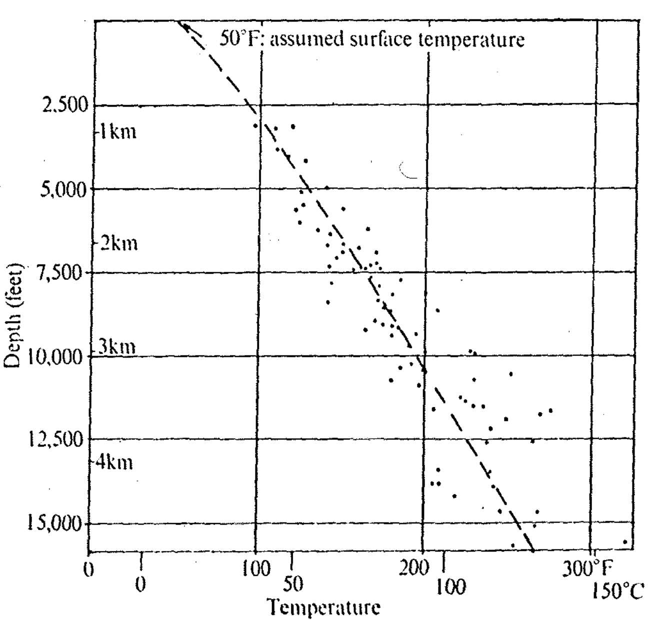

Fig. 1 Depth-temperature relation for eighty wells in the North Sea Basin.

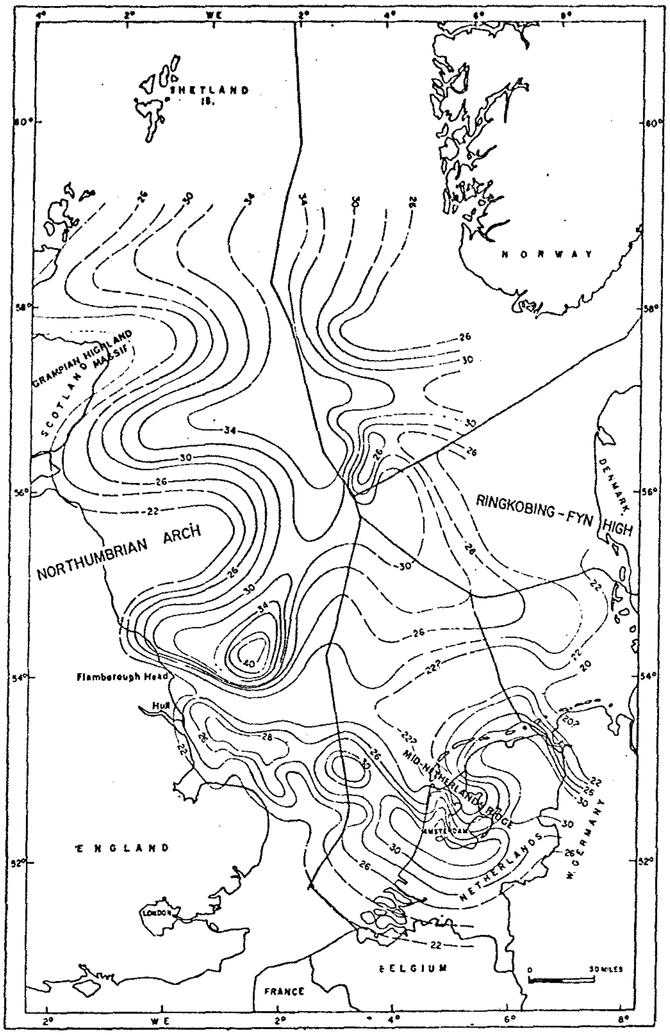

Fig. 2 Approximation of the geothermal gradient in the North Sea Basin based upon bottom hole temperatures recorded on mechanical well logs contours at 2° C/km interval.

United Kingdom median line, the Permian basin on the German and Dutch shelf and the Southwest Netherlands basin) decreases at an average rate of 0.69° C/km for the depth interval 7,000–16,000 feet. In the remainder of the North Sea the average rate of decrease is 1.13° C/km for the depth interval 4,000–12,000 feet. As a result of this decrease of gradient with depth, the geothermal gradient map (Fig. 2) is based on data which are not strictly comparable because of the varying total depths (3,200 to more than 15,000 feet).

The cause of the decrease in geothermal gradient with depth may be the increase in thermal conductivity with depth. An increase in this parameter for most rock types would accompany an increase in density. Such an increase in thermal conductivity would result in heating of the more thermally opaque overlying rocks.

The distribution of geothermal gradient highs and lows in the North Sea Basin is governed by the major structural elements; usually, low geothermal gradients occur over positive structural elements, and high geothermal gradients occur in deep post-Permian basins. The broad area with high geothermal gradients in the northern part of the North Sea coincides with the centre of the Tertiary sub-basin. This thermally positive trend probably results from the blanketing effect of thick Tertiary claystones and shales. A smaller (more areally restricted) positive thermal anomaly, with gradients locally exceeding 40° C/km, occurs east of Flamborough Head in the United Kingdom sector. The anomaly, which is indicated by three wells, does not coincide with any known structural or stratigraphic anomaly.

A negative thermal anomaly with an east–west trend extends from offshore Germany to south of Flamborough Head. This anomaly coincides approximately with the centre of the Permian evaporite sub-basin. Geothermal gradients derived from temperatures measured in the Permian and Carboniferous below the massive Permian salt beds are much lower than those derived from temperatures measured at the top of the salt beds. This suggests that the salt is an effective heat transfer agent, rapidly conducting the heat arriving near its base to the overlying rocks.

South of the negative thermal anomaly, a positive anomaly curves around the southern edge of the Permian salt basin from the North-East Netherlands to near Hull on the east coast of England. The anomaly coincides with the Southwest Netherlands basin over part of its length; thick Mesozoic rocks underlie the anomaly throughout its length.

This positive thermal anomaly is deeply embayed by a negative anomaly extending from the Permian sub-basin along the Mid-Netherlands Ridge. The low geothermal gradients measured in pre-Permian formations on the ridge are probably the result of shallow Carboniferous rocks with high thermal conductivities. Similar negative thermal anomalies occur over Hercynian or Caledonian highs extending into the North Sea Basin. These include the Northumbrian Arch, Ringkobing-Fyn High, and the Grampian Highland massif. Positive thermal anomalies extend into grabens or basins such as the Midland Valley Graben and the Moray Firth embayment between the positive structural elements.

To put the North Sea data into regional perspective, the average geothermal gradient and heat flow in Alpine basins[4–6] and Great Britain[7] are compared with these parameters in the North Sea Basin (Table 1). An average thermal conductivity of 0.004 to 0.005 calories cm^{-1} s^{-1} $°C^{-1}$ is assumed for North Sea rocks.

Table 1 Average Geothermal Gradients and Estimated Heat Flow Values in Alpine Basins, Great Britain, and the North Sea Basin

	Temperature gradient °C/km	Average heat flow 10^{-6} calories cm^{-2} s^{-1}
Bavarian Molasse Basin	28	1.35
Carpatho-Ukraine Flysch Basin	29±	1.05
Transcarpathian Inner Deep	65±	2.6
Vienna Basin	25–35	1.2
Little Hungarian Basin	45–50	2.0
Great Britain	32.3	1.31
North Sea Basin	29.7	1.19–1.48

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