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Reprinted form Nature, Vol. 367, January 27, 1994

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OCEANIC plateaus are large accumulations of volcanic and plutonic rocks on the ocean floor, whose detailed nature and origin are only poorly understood. Their immense volumes, frequent occurrence since the Cretaceous period[1] and conspicuous presence in all major ocean basins point to their significance in understanding the Earth's thermal and chemical evolution. We report here the discovery of mafic granulite xenoliths from Kerguelen island, at the northern end of the Kerguelen plateau—one of the two largest oceanic plateaus. Granulites are normally found only in continental settings, where the crust is thick enough to experience the high temperatures and pressures required for granulite–facies minerals

to form. We speculate that the Kerguelen xenoliths represent basaltic magmas underplated during the evolution of the plateau, and more generally that such mafic granulites are an important constituent of the lower parts of oceanic plateaus, which are inaccessible by drilling.

The Kerguelen plateau, in the southern Indian Ocean, extends more than 2,000 km from 46° to 64° S, with a maximum width of 700 km (Fig. 1), and is the second largest oceanic plateau (2.5×10^7 km^3), after the Ontong Java plateau (>5.0×10^7 km^3 (ref. 2)). Its development is believed to have begun with the break-up of Gondwanaland 100–120 Myr ago[3–7] and its evolution has been studied based on information derived from age dating, petrological and geochemical characteristics of volcanic rocks from the Bunbury basalts in Australia, Rajmahal Traps in India, Ninetyeast ridge, Broken ridge, Naturaliste plateau, as well as the Kerguelen islands, as these volcanoes are considered to be surface manifestations of the proposed Kerguelen plume at various stages[4,8,10]. The structure and constitution of the plateau appear to be significantly different between the northern (46°–54° S) and southern (54°–64° S) parts. Based on information gained from seismic stratigraphy, Seasat altimetry and other geophysical observations, both parts are believed to have the characteristics of an oceanic crust; however the southern part is considered possibly to contain rifted, thinned continental crust, and to have experienced a complex history of subsidence, sedimentation and block faulting[11,12]. Indeed, free-fall grab sampling in the Raggatt basin (56–60° S) recovered granitic and metasedimentary rocks of continental affinity[12] (although these could have been transported by icebergs), and the isotope systematics of rocks from Leg 119 Site 738 (in the extreme south of the plateau) suggest continental lithospheric contamination[13]. Drilling and dredging in the central part of the plateau (DSDP Leg 120, Sites 747, 749 and 750, 54°–59° S) produced transitional mid-ocean-ridge basalts (T-MORB) beneath Cretaceous sediments[14].

The northern part of the plateau, which has Kerguelen island at its northern end, is believed to have formed while contiguous or near to Broken ridge 45 Myr ago, when the Kerguelen plume coincided with Southeast Indian ridge[15] (a geodynamic setting similar to Iceland today[16]) and evolved more recently to an intraplate setting akin to that of Hawaii[17–19]. The geochemical characteristics of rocks exposed on Kerguelen reflect this geodynamic evolution, as older (~40 Myr) tholeiitic-transitional basalts display $\varepsilon_{Nd} = +3$ and $^{87}Sr/^{86}Sr = 0.7048$, whereas younger (~26 Myr to present) alkaline basalts show $\varepsilon_{Nd} = -6$ and $^{87}Sr/^{86}Sr > 0.706$ (refs 9, 20).

Xenoliths in volcanic rocks provide unique information about the chemistry and mineralogy of basement rocks beneath volcanoes that cannot be sampled easily, and those from Kerguelen may be used to infer the basement structure and architecture of at least the northern part of the plateau. Numerous basic and ultrabasic xenoliths are found in pipes and dikes of highly alkaline rocks cutting across older plateau lavas[21]. Such occurrences in the Jeanne d'Arc peninsula (Fig. 1) contain basic granulites with granoblastic textures and mineral assemblages typical of the granulite facies: clinopyroxene + orthopyroxene + plagioclase + spinel ± garnet. Some garnet-free samples were described as spinel gabbros[22]. Granulite xenoliths have never before been reported from oceanic islands. Garnet-bearing mafic xenoliths do occur (for example, Salt Lake Crater, Hawaii[23]), but are considered to be high-pressure cumulates from alkaline magmas[24]. Plagioclase-bearing xenoliths are typically igneous-textured gabbroic cumulates without orthopyroxene[25].

In some of the granulite xenoliths with the Mg# (=100 Mg/(Mg + Fe)) >73 and with high Al_2O_3 and CaO, sapphirine ($[(Mg, Fe)_{8-x}(Al, Fe)_x]^{VI}[Al_x Si_{6-x}]^{IV}O_{20}$, where $4 \leqslant x \leqslant 5$ was

TABLE 1 Compositions of sapphirine and host xenoliths

	Sapphirine			Whole rock	
	MG91116	MG9199A		MG91116	MG9199A
SiO_2	13.36	14.19	SiO_2	44.54	47.38
TiO_2	0.11	0.11	TiO_2	0.03	0.04
Al_2O_3	64.08	61.85	Al_2O_3	27.59	30.74
Cr_2O_3	0.54	1.06	FeO(t)	2.49	1.21
FeO	2.6	5.34	MgO	10.24	3.41
MgO	18.95	18.55	MnO	0.05	0.03
NiO	0.29	0.09	CaO	13.91	17.12
MnO		0.02	Ma_2O	1.08	1.19
CaO	0.05	0.04	K_2O		0.04
Na_2O	0.04		P_2O_5	0.02	0.01
K_2O	0.04				
	Cation content*			CIPW norms	
Si	0.779	0.828	C	0.57	
Ti	0.005	0.005	Or		0.17
Al	4.401	4.252	Ab	9.15	10.00
Cr	0.025	0.049	An	68.88	77.90
Fe^{2+}	0.127	0.261	DiFe		0.70
Fe^{3+}			DiMg	4.30	
Mg	1.646	1.613	HyFe	0.01	0.80
Ni	0.013	0.004	HyMg	0.08	4.00
Mn		0.001	Fa	2.9	0.40
Ca	0.003	0.003	Fo	17.83	1.50
Na	0.004		Mt	0.47	0.20
K	0.003		Ilm	0.06	0.03
			Ap	0.05	

Sapphirine analysed by electron microprobe, whole rock analysed by X-ray fluorescence, results in wt%. CIPW norms represent an idealized mineralogical composition (wt%) calculated from chemical analysis of the rock. C, corundum; Or, orthoclase; Ab, albite; An, anorthite; DiFe, Fe-diopside; DiMg, Mg-diopside; HyFe, Fe-hypersthene; HyMg, Mg-hypersthene; Fa, fayalite; Fo, forsterite; Mt, magnetite; Ilm, ilmenite; Ap, apatite. Other significant minerals for P–T estimates are the clinopyroxene 2 with Mg# (see text) from 87 to 92, orthopyroxene with Mg# from 84 to 92, spinel with Cr# = Cr/(Cr + Al) from 0.02 to 0.03, garnet with Mg# = 83 and the plagioclase from An_{83} to An_{87}. MG 91-116 is a garnet + sapphirine-bearing granulite, MG 91-99A is a sapphirine-bearing garnet-free granulite.

* Per formula unit (10 oxygens).

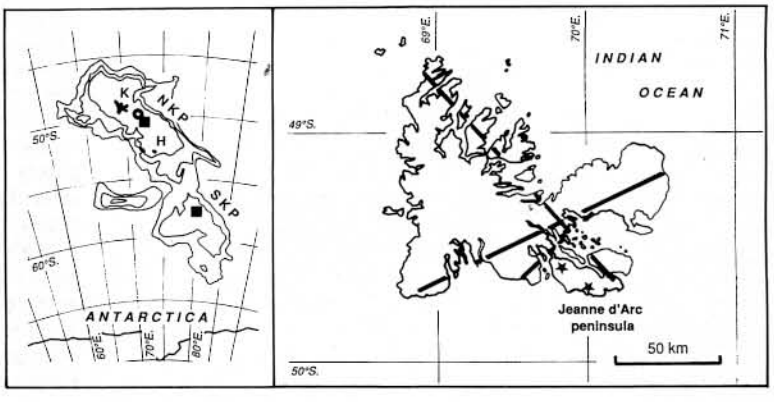

FIG. 1 The Kerguelen plateau (left) and the Kerguelen island (right). Symbols on the left-hand map have the following meanings; K, Kerguelen islands; H, Heard and MacDonald islands; NKP, northern Kerguelen plateau; SKP, southern Kerguelen plateau; solid black squares, seismic refraction profiles on the Kerguelen plateau, with the diagonals of the squares corresponding to the profiles[40]; white star in solid black circle, dredged Cretaceous cherts[41]. Symbols on the right-hand map have the following meanings; bold lines, seismic refraction profiles[34]; black stars, location of the xenoliths referred to in this paper.

TABLE 2 Summary of the geothermometric data from field samples

Assemblage	Method	No. of samples	No. of mineral pairs	T(°C) average	T(°C) range
cpx–opx–pl–sp–gt	Wells, opx/cpx[28]	2	5	920	900–970
cpx–opx–pl–sp–gt	Ellis & Green, cpx/gt[29]	2	5	970	910–1000
cpx–opx–pl–sp–gt	Harley, opx/gt[30]	2	5	930	890–980
cpx–opx–pl–sp–gt–sa	Wells, opx/cpx[28]	2	7	985	950–1000
cpx–opx–pl–sp–gt–sa	Ellis & Green, cpx/gt[29]	2	6	970	950–990
cpx–opx–pl–sp–gt–sa	Harley, opx/gt[30]	2	5	965	920–1010
cpx–opx–pl–sp	Wells, opx/cpx[28]	6	12	920	880–970
cpx–opx–pl–sp–sa	Wells, opx/cpx[28]	3	7	925	860–960
				P(GPa) average	P(GPa) range
cpx–opx–pl–sp–gt	Harley, opx/gt[31]	2	5	1.2	0.85–1.50
cpx–opx–pl–sp–gt	Harley & Green, opx/gt[32]	2	5	1.1	0.75–1.45
cpx–opx–pl–sp–gt–sa	Harley, opx/gt[31]	2	6	1.3	1.00–1.60
cpx–opx–pl–sp–gt–sa	Harley & Green, opx/gt[32]	2	6	1.1	0.80–1.45

Abbreviations used: cpx, clinopyroxene; opx, orthopyroxene; pl, plagioclase; sp, spinel; gt, garnet; sa, sapphirine.

found in symplectitic intergrowth with garnet, clinopyroxene and rarely plagioclase: it was also found in coronitic reaction zones with clinopyroxene, spinel, ±garnet. Sapphirine generally occurs in granulite-facies metamorphic rocks in continental crust, and this seems to be the first report of its occurrence in an oceanic environment. In a typical coronitic occurrence in sample MG91-116 (Table 1), for instance, sapphirine occurs surrounding spinel, and is in turn surrounded by garnet. This occurrence has a striking petrographic resemblance to a kimberlite-borne granulite xenolith from Stockdale, Kansas[26].

The major-element composition of the sapphirine-bearing granulite (Table 1) implies protoliths rich in calcic plagioclase and high-Mg minerals. MG91-116 is a normative troctolite with calcic plagioclase and high-Mg olivine, whereas MG91-99A can be compositionally termed an anorthositic gabbro. Rare earth element (REE) abundance patterns of clinopyroxene, garnet, sapphirine and plagioclase in MG91-116 (determined by an ion microprobe at Woods Hole Oceanographic Institution using techniques described previously[27]) are characterized by uniformly low overall abundance levels (clinopyroxene has 0.7–1 times chondrite for La to Sm, 2 times chondrite for Eu, and lower concentrations for heavy REE with 0.2 times chondrite for Yb; garnet has 0.25–2 times chondrite for La to Sm, 5 times chondrite for Eu, and 0.6 times chondrite for Yb), and positive Eu anomalies in all mineral phases. All our data are consistent with a troctolitic protolith. Detailed accounts of mineral and whole-rock geochemistry will be published elsewhere.

Pressure–temperature conditions estimated using various thermobarometric methods[28–32] range from 0.6 GPa, 900 °C to 1.6 GPa, 1,000 °C (Table 2), corresponding to depths of ~20–45 km (Fig. 2). The stability of sapphirine considered in the $CaO–MgO–Al_2O_3–SiO_2$ (CMAS) system involves a quartz-absent invariant assemblage of clinopyroxene + orthopyroxene + spinel + plagioclase + sapphirine + garnet around 1.0 GPa, 900 °C (ref. 33), which is in general agreement with the above estimated conditions. However, the textural relationships observed are not sufficient to precisely constrain P–T paths of the granulites. It may be suggested, nevertheless, that a significant increase in depth must have been experienced by MG91-116, if the protolith was indeed calcic plagioclase + forsteritic olivine as indicated by the bulk composition. On the other hand, there are numerous pyroxene granulites with well developed spinel-two-pyroxene symplectites, which could be produced simply by isobaric cooling of an olivine-plagioclase assemblage at relatively low pressures.

The existence of granulites beneath Kerguelen offers a new interpretation of the geophysical data. Seismic refraction studies of the northern part of the Kerguelen plateau[34] have established that a 8 to 9-km-thick layer with average compressional wave velocity (V_P) of 5.5 km s^{-1} (identified as oceanic layer 2) is underlain by oceanic seismic layer 3 with $V_P = 6.6$ km s^{-1} extending to depths of 14–17 km. Beneath this apparently more typical, but thickened oceanic crust, a zone with $V_P = 7.2–7.5$ km s^{-1} is recognizable and the crust–mantle boundary cannot be modelled as a single step. The 'low-velocity' region is interpreted as either serpentinized mantle peridotites or underplated magmas. Following the idea proposed for rifted continental margins[35,36], for continental flood basalts[2], and for the Kerguelen plateau, it was argued that the observed $V_P = 7.2$ km s^{-1} could be consistent with underplating of large quantities of picritic melt with ~16 wt% MgO (ref. 34).

Based on the compressional wave velocities measured in minerals in the laboratory (see, for example, Table 2 of ref. 35), plagioclase-bearing mafic rocks such as granulites are consistent

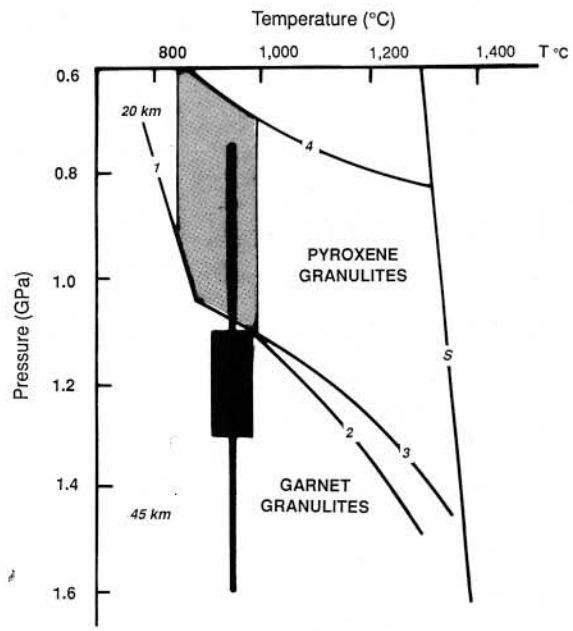

FIG. 2 P–T estimates for sapphirine-bearing granulites from Kerguelen. The dark-shaded area represents the average range of P–T conditions measured on garnet-bearing granulites with deviations given by the bold lines. The light-shaded area (in the pyroxene granulite field of the CMAS system[32]) indicates the range of temperature calculated for Kerguelen garnet-free granulites. Univariant reaction curves as follows: 1, orthopyroxene + plagioclase + spinel → sapphirine + clinopyroxene; 2, orthopyroxene + spinel + plagioclase → sapphirine + garnet; 3, orthopyroxene + spinel + plagioclase → clinopyroxene + garnet; 4, olivine + plagioclase → orthopyroxene + clinopyroxene + spinel. S indicates basalt solidus.

with the observed range of V_P (7.2–7.5 km s^{-1}). For instance, V_P calculated for a garnet granulite consisting of plagioclase (40 wt%), clinopyroxene (30%), orthopyroxene (10%) and garnet (20%) is 7.38 km s^{-1}, and plagioclase (6.166 km s^{-1}) and garnet (8.921 km s^{-1}) have opposing effects on calculated V_P of rocks. Occurrences of mafic granulites as xenoliths are abundant in Kerguelen island. Indeed, in addition to the localities in the southeastern part of the islands, at least four localities were discovered and sampled in recent field seasons in the northeastern province, the Courbet peninsula. They indicate that a significant volume of granulite could exist beneath the islands and the northern Kerguelen plateau. The existence of a 'low-velocity mantle' zone beneath oceanic islands has been recognized beneath Marquesas[37], and the progressive changes in seismic velocities have also been proposed for the Madagascar ridge[38] and the Crozet plateau[39]. Based on our finding, we speculate that mafic granulites can account for the observed seismic characteristics, and thus can be important constituents in those oceanic areas where large-scale magma production is predicted. If granulites represent underplated basaltic magmas and cumulates therefrom, which are otherwise not sampled by subaerial or submarine volcanics, their trace element and isotopic characteristics and geochronology are fundamentally important for understanding of the evolution of oceanic plateaus. □

Received 16 April; accepted 30 November 1993.

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ACKNOWLEDGEMENTS. We thank F. Albarède for his encouragement, and the following institutions for chemical analyses; ENSMSE (France), C.N.R.S. Microprobe of Clermont–Ferrand (France), and W.H.O.I. (Woods Hole, USA). This work was supported by the Polar Research and Technology Institute (IFRTP, Paris), the French CNRS URA No 10, the Belgian FNRS, and the University Jean Monnet-Saint Etienne, France.