Terra Antarctica
1995, **2**(1), 1-6

TERRA ANTARTICA
AN ANTARCTIC EARTH SCIENCE JOURNAL

The Kerguelen Archipelago: A Hypothetic Continental Mafic Protolith

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Received 6 March 1995; *accepted in revised form* 7 June 1995

Abstract - Among the ultrabasic and basic xenoliths which have been entrained by alkaline lavas of the Kerguelen islands, several types can be distinguished. One type represents basaltic segregates reequilibrated in the granulite facies, i.e. in the P-T conditions of the oceanic lower crust and of the upper mantle. These are the focus of this study. The results of our petrologic investigations are in agreement with the existence of a crust thickened by underplating processes as evidenced by the seismic studies. Similarities with the Birrimian terranes are outlined. They indicate that the Kerguelen islands and the northern end of the Kerguelen plateau may be a present-day example of the early stage of continental nucleation, i.e. a mafic continental protolith

INTRODUCTION

The Kerguelen archipelago, located in the northern part of the Kerguelen oceanic plateau, is a surface manifestation of the so-called Kerguelen plume. It is the only oceanic example where magmatic activity occurred over a time-span of 40 m.y. or more (Weis et al, 1987; Storey et al, 1988; Gautier et al, 1990; Giret, 1993; Weis et al, 1993). The abundance of erupted magmas and the plate reconstructions suggest that the Kerguelen plume was above or close to the Southeast Indian Ridge in its early stages, a setting comparable to Iceland today, and later it evolved to an intraplate setting comparable to that of Hawaii (Gautier et al., 1990; Giret, 1993; Charvis et al., 1993). Such a geodynamic evolution is evidenced by a magma sequence giving early (40 Ma) tholeiitic-transitional basalts and late (26 Ma to present) alkaline basaltic series,with respective isotopic ratios of +3 and-6 for ε_{Nd}, 0.7048 and 0.706 for $^{87}Sr/^{86}Sr$ (Weis et al., 1993). Moreover the Kerguelen volcanic and plutonic rocks carry strong Dupal anomaly signatures, with characteristic isotopic ratios, high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ at a fixed $^{206}Pb/^{204}Pb$ in comparison to oceanic island basalts from the North Atlantic and Pacific Oceans (Weis, 1992 ; Weis et al., 1993).

Recently, ultrabasic and basic xenoliths have been discovered in several locations in the Kerguelen archipelago. The inclusions were entrained by the alkaline magmas and they occur in various volcanic outcrops (pipes, dykes and lava-flows) from the Southeastern provinces (Jeanne d'Arc, Ronarc'h and Prince de Galles peninsulae - Gregoire et al., 1992; Gregoire, 1994). They represent a wide spectrum of rock types, stimulating the discussion about the nature and heterogeneities of the upper mantle and lower crust in the southeastern part of the Indian ocean (Recq et al., 1990; Alibert, 1991).

Regarding their textures, the xenoliths have been classified into 3 types, each of them subdivided into 2 or more subgroups according to their mineralogical compositions (Gregoire, 1994).

The first type represents ultrabasic mantle xenoliths (type I) with metamorphic textures. Two mineralogical divisions are distinguished: the spinel-bearing harzburgite group and the spinel-bearing dunite group. Several harzburgites display poikilitic Mg-augite crystals surrounding orthopyroxene, olivine and spinel and make up the poikilitic Cpx- bearing harzburgites. They are distinguishable from the harzburgites *sensu stricto* in which the clinopyroxene is common mantle-type diopside (Gregoire, 1994). No true mantle lherzolites (modal pyroxene >5 % - Streckeisen, 1976) are recognized.

The second type consists of metamorphosed ultrabasic and basic xenoliths with relict magmatic textures (type II). It is subdivided into three mineralogical subgroups. The first, i.e. two-pyroxene-and-spinel series, is the most abundant group since it represents 40 to 45 % of the total collected xenoliths. It consists of ultrabasic rocks such as wehrlites, clinopyroxene-rich lherzolites, websterites ± olivine, and of basic rocks such as metagabbros and metagabbronorites. Some intermediates between ultrabasic and basic rocks also exist (olivine + plagioclase-bearing websterites). The second subgroup, i.e. the clinopyroxene + ilmenite + spinel series, is represented by clinopyroxenites, garnet-bearing clinopyroxenites and by metagabbros. The third subgroup is made of ilmenite-bearing metagabbros.

The third group consists of cumulates which are hornblendites, biotitites, biotite-bearing clinopyroxenites and common oceanic crustal gabbros, peridotites and pyroxenites (type III).

Some composite xenoliths have also been observed. They are associations of type I/type II, type I/type III and type II/series 1 and 2.

This paper focuses exclusively on the two-pyroxene-and-spinel-bearing xenoliths of type II which contain plagioclase and which are basaltic segregates reequilibrated in conditions of the oceanic upper mantle and lower crust. We use petrological information provided by these xenoliths to explore the basaltic segregation processes and its role in the thickening of the oceanic crust (14-20 km), as deduced from geophysical data (Recq et al., 1990). The discussion focuses on the genetic relationships between some specific segments of the oceanic crust, as expressed in the Kerguelen archipelago, and the birth of continental crust. Several models for this have already been published. There are those who propose the continental crust formed by plate convergence systems as in active margins operating during Archean times (Taylor, 1967; Weaver & Tarney, 1984; Patchett & Arndt, 1986). Others prefer vertical processes involving burial followed by mobilisation of basic rocks, without any significant role of plate tectonics (Taylor & McLennan, 1985). Others at least outline the underplating processes beneath continental rift zones (Lambert, 1981; Kroner, 1984) or the development of large igneous provinces giving the oceanic plateaus (Cox, 1980; Arndt & Goldstein, 1989; Abouchami et al., 1990; Boher et al., 1992). An attractive example of the last proposal is given by the Birrimian Terranes in West Africa, at 2.1 Ga (Boher et al., 1992), which are believed to be composed of abyssal flood tholeiites erupted at large distances from the continents to which they were incorporated while subduction or collision was active.

PETROGRAPHY

The plagioclase-bearing two pyroxenes + spinel xenoliths have a well developed granoblastic texture and mineral assemblages such as olivine + clinopyroxene1 + orthopyroxene1 + spinel1 + plagioclase ± clinopyroxene2 ± orthopyroxene2 ± spinel2 (websterites) or as clinopyroxene1 + orthopyroxene + plagioclase + spinel ± clinopyroxene2 ± garnet ± sapphirine. Orthopyroxenes, clinopyroxenes and spinels produced by re-equilibration as well as garnet and sapphirine occur in coronitic or symplectitic reaction zones. Althought metamorphic textures dominate, there are relict magmatic microstructures evident. For example, there may be a regular succession of centimetric layers of leucogabbro and pyroxenite which represent primary magmatic layering and some relict ortho- and mesocumulate textures.

MINERALOGY

Ferromagnesian minerals have a relatively high mg* ratio ($mg^*=100xMg/Mg+Fe_{total}$) with mineral contents such as: Ol : 79.4-81.8, Cpx : 79.2-94, Opx : 74.1-93.3, Spl : 59.5-88.9, Grt : 66.4-88.1 (abbreviations according to Kretz, 1983). The mg* ratio is higher in the sapphirine + garnet rock types. Olivine is Mg-rich ($fo_{79.20-81.60}$) and occurs also in the websterites. The clinopyroxene is a green Al-diopside (Al_2O_3 : 5.60-11 wt%) with minor amounts of titanium, sodium and chromium. Coronitic and symplectitic clinopyroxene have similar compositions to the anhedral grains. The orthopyroxene ($en_{69.50-92}$) is pale green Al-enstatite (Al_2O_3 : 3.80-8.80 wt%). The plagioclase, of anhedral shape, is usually a bytownite or a labradorite ($an_{87.35-59}$). The garnet + sapphirine metagabbros have plagioclase showing an inverted zoning with cores of $an_{83.60-84.30}$ and rims of $an_{77.80-80.10}$. The garnet is pinkish. It is a pyrope with substantial grossular and almandine components. The garnet has higher MgO in sapphirine-bearing rocks than sapphirine-free xenoliths (respectively $prp_{67.20-77.30}$ $alm_{9.70-13.80}$ $grs_{8.65-18.80}$ and $prp_{53.60-64.05}$ $alm_{20.50-27.15}$ $grs_{12.60-20.70}$). It was formed by reaction of pyroxenes, plagioclase and spinel. The spinel contains more than 90 % of spinel and hercynite end-members. In the olivine + plagioclase-bearing websterites, two types of spinel occur. One is a pale brown Al-spinel (Al_2O_3: 58-62 wt%; with 3-6 wt% Cr_2O_3 contents) with inclusions of the pyroxenes and olivines. The second is a pale green interstitial spinel that is Cr-free but Al-richer (Al_2O_3: 64-67 wt%). In the sapphirine + garnet metagabbros, the Cr-content of the spinel varies widely from the pyroxene-rich layers with cr* ratio ≈ 4 (cr* = 100xCr/Cr+Al) and to the plagioclase layers with cr* ≈ 0.75. Moreover the spinel is systematically Mg-richer in these metagabbros (mg* = 82-87) than in the other plagioclase-bearing two pyroxenes and spinel xenoliths (mg*: 54.30-78.20). Sapphirine occurrence is related to spinel alteration. In

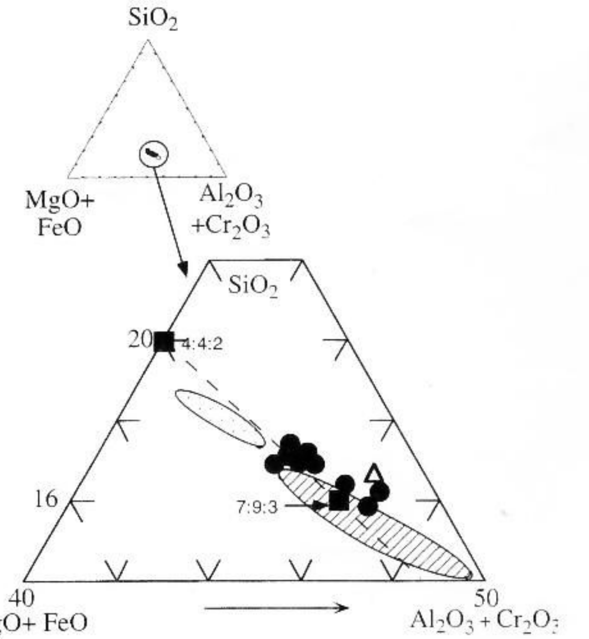

Fig.1 - Compositions of Kerguelen sapphirine in the triangular diagram SiO_2-MgO+FeO-Al_2O_3+Cr_2O_3. Black circles : sapphirine ± garnet-bearing metagabbros of Kerguelen (type IIa xenoliths). Black squares: compositions of theoritical sapphirine endmembers. Open triangle: basic granulites of Delegate (New South Wales, Australia, Griffin and O'Reilly, 1986). Shadowed area : basic granulites of Finero (Italian Alps, Sills et al., 1983). Oblic lined area: basic granulite xenoliths of Stockdale (Kansas, USA, Meyer and Brookins, 1976).

the SiO_2-MgO + FeO-Al_2O_3 + Cr_2O_3 diagram (Fig. 1), the sapphirine plots close to the substitution line Mg + Si —> Al + Al. Significant Cr_2O_3 (0.5-1.2 wt%) and NiO (0.2-0.35 wt%) are present in the sapphirine.

WHOLE ROCK CHEMISTRY

Whole rock chemistry (see Tab. 1) outlines some characteristics of the various rocks. The xenoliths of the two pyroxenes and spinel series, containing plagioclase, have high Al_2O_3 and CaO contents and are relatively Si-poor (SiO_2: 41.30-48.90 wt%). The mg* ratios range from 82 to 91 and are highest in the sapphirine + garnet-bearing rocks. The low contents of TiO_2 (< 0.38 wt %), K_2O (< 0.56 wt %), P_2O_5 (< 0.03 wt %) and of incompatible trace elements (Zr, Nb, Rb, Y) are consistent with a cumulate origin of these rocks as indicated by their petrographic features. The same conclusion is reached from their REE spectra (Fig. 2) which show low REE contents and are flat but with positive Eu anomalies, probably due to plagioclase accumulation. On the other hand, the REE abundances and patterns similar to those of the "in situ" gabbroic dykes of MORB affinities which cut the orogenic lherzolite massif of Lanzo (Italian Alps - Bodinier, 1989), and similar to those of gabbros and anorthosites which have been dredged in the central part of the Indian ridge (Hedge et al., 1979 - Fig. 2), suggest tholeiitic-transitional affinities.

The sapphirine + garnet-bearing inclusions are the Al-richest rocks of the Kerguelen archipelago. Moreover, their Al content exceeds those of other sapphirine-bearing meta-igneous rocks such as those found at Stockdale in Kansas, USA (Meyer & Brookins, 1976) and at Delegate in New South Wales, Australia (Griffin & O'Reilly, 1986) or as in the Finero intrusions in the Italian Alps (Sills et al., 1983; Christy, 1989), although their other chemical characteristics (CaO, mg*) are comparable.

Tab.1 - Representative bulk rocks and normative (CIPW) compositions of type IIa Kerguelen plagioclase bearing xenoliths. MG-91-1: olivine + plagioclase-bearing websterite, MG-91-116: garnet + sapphirine-bearing metagabbro, GM-92-404 : garnet-bearing metagabbro, Arc 343: pyroxenes-bearing metagabbro, MG-91-99A : sapphirine-bearing garnet-free metagabbro. Major elements and CIPW norms are given in wt%, trace elements are given in ppm.

Major elements	MG-91-1	MG-91-116	GM-92-404	Arc 343	MG-91-99A
SiO2	42.81	44.54	45.57	47.15	47.38
Al2O3	11.53	27.59	17.19	21.51	30.74
Fe2O3total	10.79	2.77	7.19	4.03	1.34
MnO	0.16	0.05	0.11	0.07	0.03
MgO	21.79	10.24	15.05	6.68	3.41
CaO	9.72	13.91	11.58	14.99	17.12
Na2O	0.90	1.08	1.14	2.17	1.19
K2O	0.00	-	0.08	0.56	0.04
TiO2	0.16	0.03	0.38	0.29	0.04
P2O5	0.01	0.02	0.02	0.02	0.01
PF	0.76	0.74	0.82	1.10	0.43
Total	98.64	100.97	99.12	98.57	101.74
mg*	79.99	87.98	80.56	76.65	83.44
CIPW norms					
Qz	-	-	-	-	-
C	-	0.50	-	-	-
Or	-	-	0.47	3.30	0.24
Ab	6.48	9.14	9.81	12.05	10.07
An	27.42	68.87	42.28	47.30	78.42
Ne	0.62	-	-	3.42	-
Di	16.53	-	12.79	21.53	5.12
Hy	-	0.09	7.27	-	4.88
Ol	43.58	20.71	25.23	8.18	2.12
Mt	1.84	0.47	1.38	0.69	0.23
Ilm	0.31	0.06	0.72	0.55	0.08
Ap	-	0.05	0.05	0.05	-
Trace elements					
Ni	735	303	450	145	63
Co	105	34	-	32	10
Cr	1386	182	-	316	251
V	75	8	-	69	14
Sc	21	9	-	22	12
Cu	12	4	-	85	3
Zn	60	17	38	20	11
Ga	9	12	13	14	15
Rb	4	3	6	13	5
Sr	84	143	131	230	172
Y	3	3	8	6	2
Zr	18	16	22	31	16
Nb	5	4	5	5	4
Ba	10	12	39	55	20

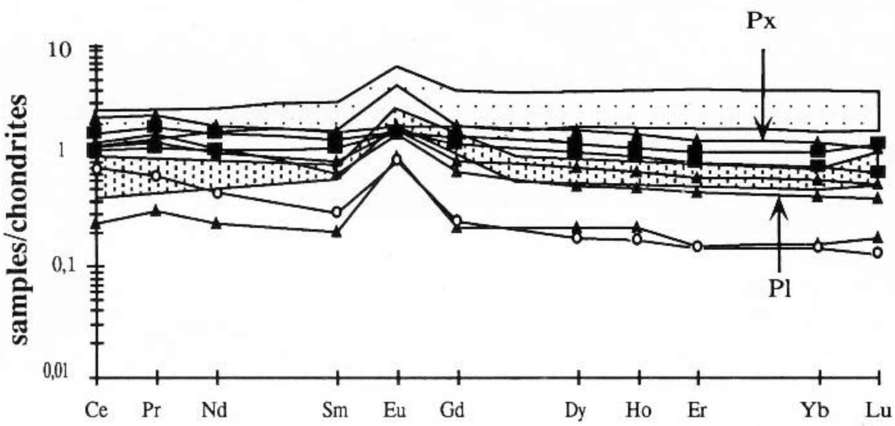

Fig. 2 - Chondrites normalized REE patterns of type IIa xenoliths of Kerguelen (see text). Normalizing factors are from Nakamura (1974), Sun and McDonough (1989) and McDonough and Frey (1989). Open circle: sapphirine + garnet-bearing metagabbros; black triangles: sapphirine-bearing garnet free metagabbros; black squares: olivine + plagioclase-bearing websterites; Px and Pl: respectively pyroxene-rich layer and plagioclases-rich layer in the same sample. Dotted area: gabbro and anorthosite dredged in the central part of the Indian ridge (Hedge et al., 1979). Dashed lined area: *in situ* gabbroic dykes of the orogenic lherzolite massif of Lanzo (Italian Alps, Bodinier, 1989).

CONDITIONS OF REEQUILIBRATION

The reequilibrated mineralogical assemblages lie within the P-T conditions of the granulite facies (Wilkinson, 1975; Kay & Kay, 1981; Griffin & O'Reilly, 1987; Rudnick & Taylor, 1987). This thermodynamic constraint added to the occurrence of sapphirine had never been reported before in an oceanic environment (Gregoire et al., 1994). Moreover, the textures and the paragenesis are in agreement with a major cooling event (± a small pressure increase - Gregoire, 1994).

This dynamic evolution is evidenced by the exsolution in the pyroxenes and by the coronitic and symplectitic minerals (Opx2, Cpx2, Spl2, Spr and Grt), which may be related to reaction such as :

(1) Ol + Pl —> Opx2 + Cpx2 + Spl2 in the olivine and plagioclase-bearing websterites

(2) Opx + Pl + Spl —> Spr + Cpx2 in the sapphirine-bearing garnet-free metagabbros

(3) Opx + Pl + Spl —> Spr + Grt in the garnet ± sapphirine-bearing rocks

(4) Opx + Spl + Pl —> Cpx2 + Grt in the garnet ± sapphirine-bearing rocks

The subsolidus evolution of olivine- and plagioclase-bearing websterites crosses the boundary (reaction 1) between the "low pressure granulite stability field" and the "pyroxenes granulite stability field" (De Waard, 1965; Griffin & O'Reilly, 1987 - Fig. 3). Experimental studies of this reaction constrain the thermodynamic conditions to between 0.5 to 0.8 GPa at 900 to 1000 °C (Irving, 1974; Gasparik, 1984 ; Wood & Holloway, 1986). This corresponds to a depth range of 15 to 25 Km. Reactions 2, 3 and 4 represent re-equilibration in the pyroxene granulite stability field for the garnet-free metagabbros and in the garnet granulite stability field for the garnet-bearing metagabbros (De Waard, 1965; Griffin & O'Reilly, 1987 - Fig. 3). Reaction (4) occurs in the $CaO-MgO-Al_2O_3-SiO_2$ system (CMAS) at 1.1 GPa and 900 °C (Gasparik, 1984). The presence of iron and sodium, as in our samples, shifts the conditions of the

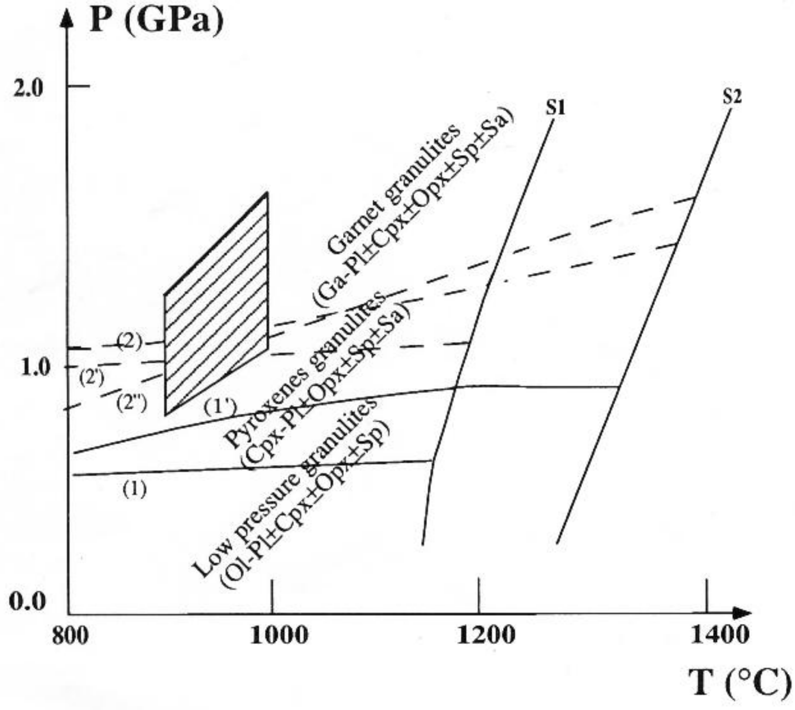

Fig. 3 - P-T conditions for the mineral assemblages of type IIa plagioclase-bearing xenoliths of the Kerguelen archipelago. Cpx: clinopyroxene, Ga: garnet, Ol: olivine, Opx: orthopyroxene, Pl: plagioclase, Sa: sapphirine, Sp: spinel. Bold lines: reaction Ol + Pl —> Opx + Cpx + Sp (1) after Irving (1974) and (1') after Kushiro & Yoder (1966), Gasparik (1984), Wood and Holloway (1984). Broken lines: reaction Opx + Cpx + Pl + Sp —> Ga (2) after Gasparik (1984), (2') after Irving (1974) and (2") after Kushiro & Yoder (1966). The dashed area represents the calculated P-T conditions for garnet ± sapphirine metagabbro xenoliths of Kerguelen archipelago. S1: solidus after Irving, 1974 (basic granulite R 398). S2: solidus after Gasparik, 1984 (CMAS).

reactions which are calculated in this system. However, the opposite influence of these two elements permits a good estimation of the subsolidus evolution of the Kerguelen two-pyroxene-spinel xenoliths containing plagioclase. Several geothermometers and geobarometers have been tested to assess the conditions of the subsolidus evolution (Wells, 1977; Ellis & Green, 1979; Harley & Green, 1982; Harley, 1984a and b). These procedures give temperatures around 850-1000 °C for garnet-free facies and 900-1000°C at 0.75-1.60 GPa for the garnet-bearing facies (Fig. 3), i.e. approximatively 22 to 50 km in depth. Such results are very similar to those which have been obtained for Delegate and Stockdale xenoliths as well as for Finero granulites (Meyer & Brookins, 1976; Griffin & O'Reilly, 1986; Sills et al., 1983; Christy, 1989).

DISCUSSION

The seismic profiles of the Kerguelen Archipelago have established the existence of a thick oceanic crust with a progressive Moho at 14 to 20 km in depth (Recq et al., 1990). The calculated or experimental P-T estimations imply an origin varying between those of the oceanic mantle (garnet-bearing metagabbros) and those of the oceanic lower crust (olivine + plagioclase-bearing websterites) including the crust-mantle boundary (garnet-free metagabbros). Thus, the Kerguelen two-pyroxene-spinel, type II xenoliths represent upper mantle and lower crustal segregates of mantle-derived tholeiitic-transitional basaltic magmas. The isotopic data confirm these tholeiitic-transitional affinities (Mattielli et al., 1995). The occurence of these deeply metamorphosed basaltic segregates provides evidence for significant magmatic underplating processes beneath the Kerguelen archipelago, as recently proposed by seismic studies (Recq et al., 1990). Such a thickening and growth of the oceanic crust may be generated indeed by the intrusions of tholeiitic-transitional basalts at different levels of the lithosphere and may be responsible for the granulitic metamorphism as evidenced above.

Basaltic flows on the Island are intruded by many plutonic complexes in which all the basic, intermediate and acid rocks have mantle isotopic signatures (Giret, 1983 and 1993). The volume of those plutonic bodies, 15% of the archipelago, as well as the volume of the rocks which have been metamorphosed in the granulite facies in the crust-mantle boundary suggest a density decrease of the Kerguelen archipelago lithosphere regarding its oceanic environment. Therefore we propose that the Kerguelen archipelago represents an oceanic lithospheric bud whose low density creates isostatic buoyancy and prevents sinking or subduction. The thermobarometric conditions which are calculated from the granulitic assemblages of Kerguelen basic inclusions are similar to those which have been proposed for some lower continental crust involved in thinning processes (Wass & Hollis, 1983; Arculus & Ruff, 1988; Johnson, 1989). That leads to comparison of the thickened Kerguelen oceanic lithosphere with thinned continental lithosphere, and consequently to a model in which the oceanic Kerguelen islands and surrounding plateau represent a continental nucleation process and may be a present-day example of the first stage of the model proposed by Boher et al. (1992) for the Birrimian terranes: a mafic continental protolith.

ACKNOWLEDGEMENTS

We thank the following institutions for chemical analyses : ENSME (France), C.N.R.S Microprobe of Clermont-Ferrand (France) and M.R.A.C. I.C.P.M.S. of Tervueren (Belgium). This work was supported by the Polar Research and Technology Institute (IFRTP, Brest, France), the French CNRS URA N°10, the Belgian FNRS and the University Jean Monnet, France. Constructive comments and suggestions by S.Y. O'Reilly have greatly improved the manuscript.

Editorial handling: C.A. Ricci

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