doi: 10.1111/j.1365-3121.2008.00839.x

Could Iceland be a modern analogue for the Earth's early continental crust?

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ABSTRACT

For the last two decades, Iceland and other oceanic plateaux have been considered as potential analogues for the formation of the early Earth's continental crust. This study examines the compositions of silicic rocks from modern oceanic plateaux, revealing their differences to Archaean continental rock types (trondhjemite–tonalite–granodiorite or TTG) and thereby emphasising the contrasted mechanisms and/or sources for their respective origins. In most oceanic plateaux, felsic magmas are thought to be formed by fractional crystallization of basalts. In Iceland, the interaction between mantle plume and the Mid-Atlantic ridge results in an abnormally high geothermal gradient and melting of the hydrated metabasaltic crust. However, despite the current 'Archaean-like' high geothermal gradients, melting takes place at a shallow depth and is unable to reproduce the TTG trace element signature. Consequently, oceanic plateaux are not suitable environments for the genesis of the Archaean continental crust. However, their subduction could account for the episodic crustal growth which has occurred throughout the Earth's history.

Terra Nova, 20, 463–468, 2008

Introduction

Most juvenile continental crust is generated in subduction environments where felsic magmas are either differentiated melts from the partial melting of a fluid-metasomatized peridotite, or direct melts from the subducted slab. However, a small proportion of juvenile felsic magma is also generated in oceanic plateaux either by melting of the thick, hydrated basaltic crust or by fractional crystallization of basaltic magma (e.g. Martin and Sigmarsson, 2007a). For decades, several authors have proposed that, on the early Earth, plate tectonics was dominated by plume dynamics (Smithies *et al.*, 2005; Bédard, 2006; among others) and that the primitive continental crust could have formed in an Iceland-like geodynamic environment (Marsh *et al.*, 1991; Sigmarsson *et al.*, 1991; Jónasson, 1994).

The purpose of this paper is to compare the geochemical signatures of felsic rocks generated in oceanic plateaux with the Archaean crust and to discuss the possible role of oceanic plateaux in early continental crust genesis.

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Oceanic plateaux

Today, plume activity results in the genesis of Large Igneous Provinces (traps or oceanic plateaux); which mainly consist of basalts, with rare silicic rocks. Three oceanic plateaux, Iceland, Hawaii and Kerguelen, contain small amounts of silicic lavas. In Iceland, their volume reaches 5–10% of the erupted lavas, which is inferred as resulting from the interaction between the mantle plume and the mid-Atlantic ridge (e.g. Marsh *et al.*, 1991; and Discussion below).

Figure 1 shows that, in Hawaii, silicic magmas are only slightly silica-saturated, in Kerguelen they display a large range of composition extending from silica oversaturated to undersaturated, whereas in Iceland they are oversaturated with more than 10% of normative quartz, with a composition ranging from tholeiitic to alkaline.

Table 1 shows that the felsic magmas from oceanic plateaux are characterized by SiO_2 contents > 60%, moderately high $Fe_2O_3 + MgO + MnO + TiO_2$ contents (4.4–5.5%), and very low Mg number (Mg# ~0.2). They are alkali-rich ($8\% < Na_2O + K_2O < 12\%$) with relatively high K_2O/Na_2O (0.6–0.9). The Iceland felsic lavas differ slightly from other plateaux in having higher SiO_2 and Mg#, and slightly lower alkali content. REE contents are high ($La_N > 250$ and $Yb_N > 20$), and their patterns are moderately fractionated ($6 < (La/Yb)_N < 15$) with slight negative Eu anomalies (Fig. 2a). In an N-MORB normalized multi-element diagram (Fig. 2b), all display high contents for most trace elements, with very strong negative anomalies for Ba, Sr and Ti. Transition element contents are generally low (Ni < 8.2 p.p.m., Cr < 10 p.p.m., V < 18 p.p.m.).

Several authors proposed that felsic rocks in oceanic plateaux are generated by high degrees of fractional crystallization of basaltic magmas (Marsh *et al.*, 1991; Cousens *et al.*, 2003; Gagnevin *et al.*, 2003; Martin and Sigmarsson, 2005; Shamberger and Hammer, 2006; Martin and Sigmarsson, 2007a). This mechanism accounts for high incompatible element contents and low contents of compatible elements in the residual liquid. The strong depletions of Ba, Sr and Eu are consistent with large-scale feldspar fractionation. Relative to Hawaii and Kerguelen, the Iceland felsic magmas have slightly higher transition element contents and Mg#,

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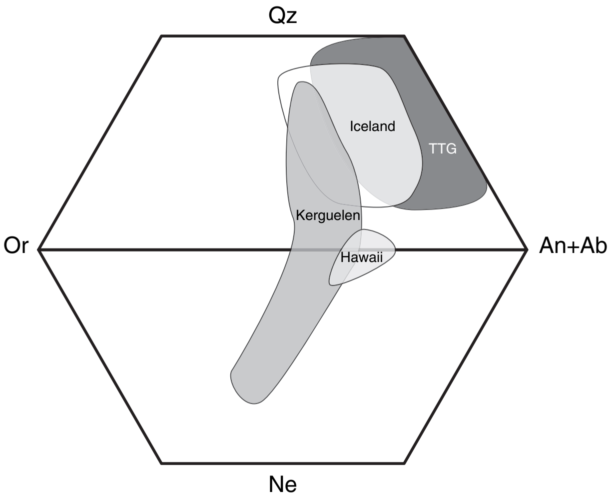

Fig. 1 CIPW normative quartz – orthoclase – (anorthite + albite) – nepheline [Qz – Or – (An + Ab) – Ne] diagram, showing the composition of Archaean TTG and felsic rocks from Iceland, Hawaii and Kerguelen.

but lower alkali contents and Th/U, indicating that tholeiitic basalt is the most suitable source for the latter. Consequently, it has been proposed that, in Iceland, depending on their location relative to the ridge-axis and the centre of the plume, felsic magmas could be generated either by fractional crystallization or by partial melting of hydrated basalts (Martin and Sigmarsson, 2007a, and references therein). The larger amounts of silicic rocks in Iceland point to there being a greater efficiency of partial melting in order to generate the felsic magmas.

Archaean TTG

Archaean trondhjemite–tonalite–granodiorites (TTG) have normative quartz and plagioclase compositions (Fig. 1). They are characterized by SiO_2 contents > 60% with moderately high $Fe_2O_3 + MgO + MnO + TiO_2$ contents (4.9%). Their Mg# is high for silicic magmas (0.43) and their alkali content is moderate ($Na_2O + K_2O = 6.6\%$), with low K_2O/Na_2O (0.4; Table 1). The TTG are rich in LREE ($La_N \sim 100$) but HREE-poor ($Yb_N \sim 3.2$), which results in a strongly fractionated REE-pattern [$(La/Yb)_N \sim 30$] with no Eu anomaly (Fig. 2a). In an N-MORB normalized multi-element diagram (Fig. 2b), TTG display a fairly regular pattern except for a strong negative anomaly of Nb–Ta and a smaller one for Ti. Transition element contents are relatively high (Ni ~19 p.p.m., Cr ~38 p.p.m., V ~48 p.p.m.) for magmas with SiO_2 close to 68%.

Most researchers consider that TTG were generated by melting of hydrated basalt, but they disagree about the exact site of this melting. The two possibilities are: (1) partial melting of basalt which underplated thickened crust (Rudnick, 1995; Albarède, 1998; Bédard, 2006) and (2) a subducted hot oceanic slab that melted rather than dehydrating (Martin, 1986; Rollinson, 1997; Foley *et al.*, 2002; Martin and Moyen, 2002; Condie, 2005; Martin *et al.*, 2005). However, Kamber *et al.* (2003) and Kleinhanns *et al.* (2003) propose that TTG are generated by extensive fractional crystallization of water-rich basalt in a subduction environment.

Both TTG and felsic magmas in oceanic plateaux are thus assumed to derive from basalt either by fractional crystallization or by partial melting. We examine the contrasting mechanisms below.

Discussion

Comparison of TTG with oceanic plateaux

Na_2O and K_2O

In oceanic plateaux, the total alkalis ($Na_2O + K_2O$) are close to 12%, which is very high when compared with values for TTG (6.6%). This is interpreted in terms of both degree of differentiation and source composition. Martin and Sigmarsson (2007b) showed that in basalt flows, the composition (i.e. K_2O/Na_2O) of felsic melts in segregation veins is mainly controlled by the composition of the parental magma. In mantle plume environments, the basaltic precursors are already alkali-rich, which, combined with high degrees of differentiation, results in alkali-rich derived magmas ($Na_2O + K_2O > 11\%$). The TTG, considered as being generated by ~25% melting of tholeiitic metabasalt (Martin, 1987), would logically produce magmas with lower alkali content. In Iceland, erupted lava suites have tholeiitic to alkaline compositions, leading to felsic magmas having moderate concentrations ($Na_2O + K_2O \sim 8.1\%$), which lie between the typical oceanic plateau and TTG values. This is clearly illustrated in Fig. 1, where Iceland lava compositions plot between the Kerguelen and TTG fields.

HREE

The HREE show a stark contrast between Archaean TTG [e.g. chondrite normalized Yb concentration (Yb_N) ~3.2] and felsic magmas from oceanic plateaux (e.g. $Yb_N > 20$). The low HREE content of Archaean TTG is classically assigned to garnet fractionation, possibly associated with hornblende (e.g. Arth and Hanson, 1972; Jahn *et al.*, 1981; Martin *et al.*, 1983; Condie, 1986; Martin, 1987; Rapp *et al.*, 1991). Furthermore, Nair and Chacko (2005) demonstrate that a substantial (> 20 vol.%) fractionation of garnet is required, which corresponds to depths as great as 50–60 km. Consequently, in oceanic plateaux, the high HREE content of their felsic lavas demonstrates that garnet was not a significant residual or a cumulative phase during their genesis and that, in contrast to TTG, they are generated at a shallower depth ($\ll 50$ km), where garnet is unstable.

Ba, Sr and Eu

The felsic rocks of oceanic plateaux also differ from the Archaean TTG by their relatively low Ba, Sr and Eu concentrations, which points to the

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Table 1 Average major and trace element compositions of primitive continental crust (Archaean TTG) and felsic rocks from oceanic plateaux of Iceland, Hawaii and Kerguelen.

	Archaean TTG		Iceland		Hawaii		Kerguelen	
	Mean	CI (*n*)	Mean	CI (*n*)	Mean	CI (*n*)	Mean	CI (*n*)
SiO_2	68.8	0.2 (1104)	69.2	0.4 (434)	62.6	0.5 (47)	62.8	0.7 (99)
TiO_2	0.38	0.01 (1104)	0.66	0.05 (250)	0.52	0.04 (36)	0.45	0.05 (99)
Al_2O_3	15.5	0.1 (1104)	14.1	0.2 (424)	18.4	0.6 (46)	17.4	0.5 (99)
Fe_2O_3*	3.24	0.09 (1104)	4.11	0.21 (434)	3.85	0.95 (47)	3.39	0.50 (99)
MnO	0.05	0.00 (1130)	0.12	0.01 (424)	0.28	0.02 (36)	0.13	0.01 (99)
MgO	1.25	0.05 (1103)	0.63	0.05 (434)	0.48	0.06 (37)	0.41	0.07 (99)
CaO	3.15	0.07 (1104)	2.04	0.11 (402)	1.32	0.36 (47)	1.23	0.16 (99)
Na_2O	4.67	0.05 (1104)	4.91	0.12 (433)	7.50	0.21 (47)	6.29	0.27 (99)
K_2O	1.92	0.05 (1104)	3.15	0.12 (434)	4.27	0.36 (46)	5.65	0.24 (99)
P_2O_5	0.14	0.01 (1104)	0.08	0.01 (383)	0.15	0.03 (36)	0.13	0.03 (99)
Mg#	0.43	–	0.23	–	0.20	–	0.19	–
Rb	65.0	2.8 (991)	90.1	4.6 (161)	132	4 (24)	132	21 (43)
Ba	713	34 (866)	500	35 (168)	392	52 (23)	261	156 (39)
Th	6.73	0.60 (420)	12.7	0.9 (135)	8.84	0.41 (23)	22.8	6.9 (23)
U	1.46	0.16 (280)	3.57	0.33 (91)	1.94	0.34 (15)	5.29	1.67 (15)
Nb	7.1	0.4 (545)	99.0	9.1 (140)	126	4 (24)	114	18 (43)
Ta	0.78	0.14 (201)	7.63	0.86 (91)	7.76	0.63 (15)	8.50	2.13 (21)
Sr	489	14 (996)	108	11 (179)	29.9	5.5 (23)	60.7	25.6 (43)
Zr	156	8 (858)	650	49 (160)	847	33 (24)	767	130 (43)
Hf	3.95	0.32 (223)	18.8	1.5 (92)	18.8	1.7 (16)	20.6	2.9 (21)
Y	11.5	1.1 (788)	93.6	6.1 (158)	68.7	6.3 (24)	43.3	5.9 (43)
Sc	6.4	0.47 (309)	5.95	1.18 (72)	6.93	0.14 (7)	4.05	1.44 (20)
V	47.9	2.9 (408)	18.8	5.3 (63)	5.75	1.36 (16)	2.54	1.21 (15)
Cr	37.8	3.3 (573)	9.27	2.66 (95)	6.26	1.91 (23)	3.60	0.66 (12)
Ni	18.7	1.6 (531)	7.82	1.46 (101)	8.19	2.80 (21)	7.78	1.58 (19)
La	31.1	1.9 (629)	81.7	7.4 (120)	71.4	6.0 (23)	106	15 (28)
Ce	57.8	3.6 (655)	172	14 (127)	138	10 (30)	204	29 (28)
Nd	22.7	1.5 (537)	78.1	6.1 (108)	62.9	6.2 (22)	75.5	9.2 (28)
Sm	3.49	0.22 (527)	17.1	1.1 (110)	11.5	1.6 (16)	13.6	2.0 (28)
Eu	0.91	0.04 (525)	2.85	0.26 (110)	2.81	0.31 (16)	1.81	0.48 (28)
Gd	2.43	0.13 (517)	15.2	1.1 (66)	9.87	1.29 (15)	12.0	3.8 (7)
Tb	0.33	0.02 (350)	2.73	0.17 (108)	1.62	0.22 (16)	1.45	0.23 (22)
Dy	1.66	0.12 (260)	16.7	1.5 (40)	10.2	1.2 (15)	10.4	4.3 (7)
Er	0.79	0.07 (229)	9.50	0.93 (42)	5.98	0.66 (15)	5.70	2.67 (7)
Yb	0.66	0.04 (507)	8.97	0.56 (98)	5.88	0.59 (16)	4.51	0.69 (28)
Lu	0.13	0.01 (411)	1.35	0.08 (110)	0.95	0.09 (16)	0.64	0.07 (21)

Number of compiled values (*n*) and confidence interval at 2σ (CI) are also indicated. Oceanic plateau compositions are compiled from GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/); Archaean TTG values are from Martin and Moyen (2002) and Martin *et al.* (2005).

prominent role played by plagioclase and K-feldspars during their genesis (e.g. Martin and Sigmarsson, 2007a). This supports the inference that, in contrast to Archaean TTG, these rocks were generated at a relatively shallow depth.

Nb and Ta anomalies

Another noticeable difference is the strong Nb–Ta depletion in Archaean TTG, which is not present in felsic rocks from the oceanic plateaux. In TTG, as well as in modern adakites, this anomaly is generally considered as reflecting Fe–Ti-bearing phase fractionation, with the most likely mineral involved being rutile (Foley *et al.*, 2002; Rapp *et al.*, 2003; Xiao *et al.*, 2006). The stability of rutile confirms the need for a pressure of >12 kbars during the formation of TTGs.

Transition elements and Mg#

Fractional crystallization is a powerful process in depleting the residual liquid of highly compatible elements. In most felsic magmas, transition elements and Mg are strongly compatible and their low concentrations in most felsic lavas from oceanic plateaux support their principal genesis by fractional crystallization. However, silicic magmas from Iceland have transition element contents, as well as Mg#, that are not as low as of those from Hawaii and Kerguelen. This is most likely caused by the less alkaline affinities of the magmatic source as well as the dominant role played by partial melting mechanisms in their genesis (Martin and Sigmarsson, 2007a). The Archaean TTG have both Mg# and transition element contents that are significantly higher than the felsic rocks from the oceanic plateaux, supporting the hypothesis that they were generated mainly through partial melting.

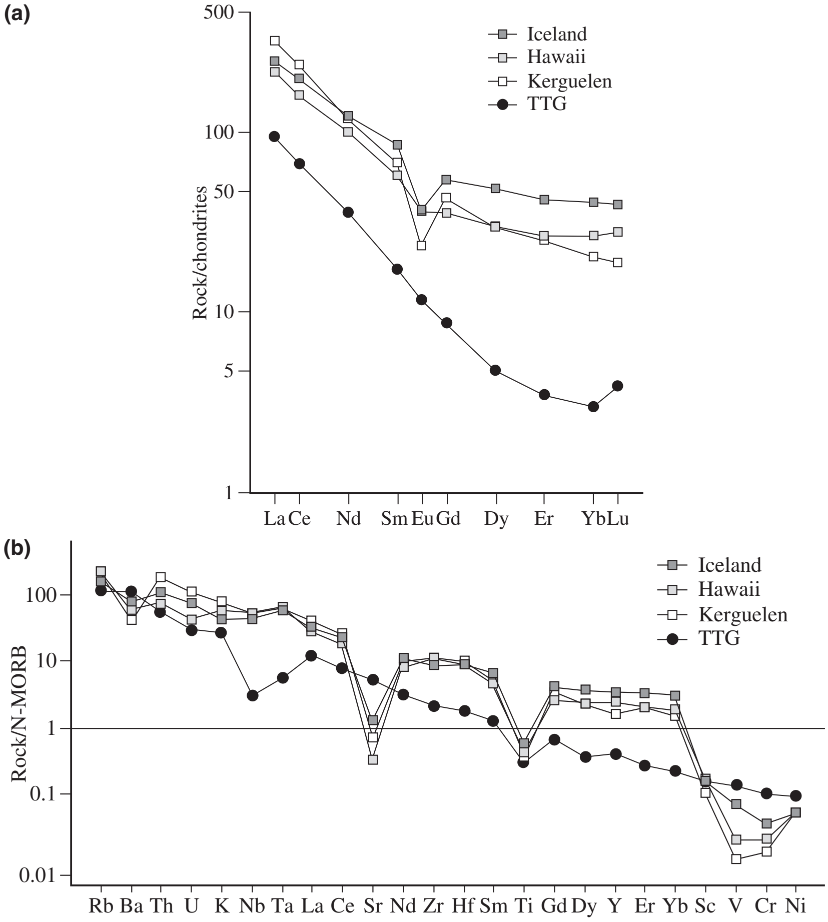

Fig. 2 (a) Chondrite-normalized (Nakamura, 1974) Rare Earth Element patterns and (b) N-MORB-normalized (Sun and McDonough, 1989) multi-element diagrams comparing the average Archaean continental crust composition (TTG) with those of oceanic plateaux of Iceland, Hawaii and Kerguelen.

Role played by oceanic plateaux in continental crust genesis

Clearly Archaean TTG and felsic magmas generated today at oceanic plateaux have significantly different compositions, which indicate different petrogenetic mechanisms and/or sources. The Archaean TTG were generated at great depth (in the garnet stability field; > 50 km), whilst felsic magmas from oceanic plateaux are generated at shallower depth (≪ 50 km; in the feldspar stability field). Furthermore, the Archaean TTG have transition element contents and Mg# higher than observed from experimental melting of basaltic material, which is explained in terms of interaction of percolating TTG melts through mantle peridotite (e.g. Maury *et al.*, 1996; Rapp *et al.*, 1999; Smithies, 2000; Martin and Moyen, 2002). These interactions reinforce the inference that the TTG magma source is located at great depth, under a mantle wedge thick enough to allow significant interactions to take place. The low concentration of transition elements and low Mg# in felsic magmas from oceanic plateaux preclude interaction with mantle peridotite, but are consistent with shallow petrogenetic processes.

Modern oceanic plateau environments, although able to produce small amounts of felsic magmas are thus unable to give rise to magmas of Archaean TTG composition. The best evidence in favour of the Archaean subduction model is that today, where Archaean-like geothermal regimes are recreated in subduction environments, TTG-like magmas (adakites) are generated (Martin, 1986; Drummond and Defant, 1990; Sigmarsson *et al.*, 1998; Martin, 1999). In contrast, even when exceptionally high geothermal conditions, similar to Archaean ones, are achieved in oceanic plateaux such as around Iceland, no TTG or adakitic-like magma is generated. Consequently, present felsic magmatism in oceanic plateaux cannot be considered as a modern analogue of Archaean continental crust genesis.

The ability to melt basalt at a reasonably low temperature is controlled by the availability of water or by the degree of crustal alteration (hydration). Indeed, basalts that are emplaced in a rift system will suffer widespread hydrothermal alteration, whereas underplated basalts tend to remain dry, as recorded in deep enclaves from Kerguelen, which have re-equilibrated under granulite facies conditions (Grégoire *et al.*, 1998). In Iceland, the partially hydrated lava pile progressively subsides because of loading and drifts away from the ridge-axis (Pálmason, 1986). However, this subsidence is unlikely to have enabled the lower crust to become hydrated. Also, if the crustal thickness in Iceland is as much as 40 km (e.g. Kaban *et al.*, 2002), garnet and rutile should be stable, but the relatively high HREE signature of the Icelandic silicic magmas preclude an origin through partial crustal melting leaving a garnet-rich residue. Even where collision between an oceanic plateau and a subduction zone could induce hydration and melting of the lower part of the plateau, as proposed for the genesis of silicic magmas in the Caribbean plateau, (White *et al.*, 1999; Vogel *et al.*, 2004), the HREE concentration are not as depleted as those of the TTG, showing that residual garnet did not play a significant role.

Although Archaean continental crust is unlikely to be generated in an oceanic plateau environment, plume tectonics during Hadean times (Smithies *et al.*, 2005) could have led to melting of a thick oceanic plateau, thus producing the early 'proto-continental crust'. This proposition cannot be evaluated because of the lack of a comprehensive rock record from these earliest times. However, the 4.4–4.0 Ga zircon crystals extracted from Jack Hills meta-quartzites

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(Wilde *et al.*, 2001) are considered typical of those found in granitoids (Cavosie *et al.*, 2004). Their REE patterns (Type-1 zircon of Cavosie *et al.*, 2006) indicate that they most likely crystallized from a host silicic magma, which had strongly fractionated REE patterns (e.g. Harrison *et al.*, 2008 and references therein).

Does this mean that oceanic plateaux never played a significant role in continental crust genesis? Today, in some rare environments, oceanic plateaux are subducted. For instance, the Carnegie ridge that is generated by the Galapagos hot spot activity has been subducted beneath the South American plate in Ecuador for the last 5 Ma (Sallarés and Charvis, 2003). There, the volcanic activity is more marked than in other parts of the Andes, the arc is larger and adakites are generated (Bourdon *et al.*, 2003; Samaniego *et al.*, 2005; Hidalgo *et al.*, 2007). This indicates that an increase in magmatic activity can result from the subduction of basaltic oceanic plateau.

Throughout the whole Earth's history, crustal growth has been preceded by super-events (i.e. 3.8, 2.7, 1.8, 1.1 and 0.5 Ga), each typically lasting 250–350 Ma (McCulloch and Bennet, 1993; Condie, 1998; Hawkesworth and Kemp, 2006). Several authors consider that mantle plume activity could be responsible for the periodicity of the Earth's crustal production (Stein and Hofmann, 1994; Albarède, 1998). Albarède (1998) proposed that plume activity resulted in the emplacement of large oceanic plateaux, which, upon subduction, may melt and generate continental crust. As the subduction of oceanic plateaux corresponds to a significant volume increase of warm basalt subducted, the volume of juvenile continental crust formed through partial melting of such basalts also significantly increases. Periodic subduction of large oceanic plateaux may thus have contributed to the episodic crustal growth.

Conclusion

Iceland, with its abnormally high geothermal regime, is the modern oceanic plateau that best fits the Early Earth conditions. However, the abundant felsic magmas of Iceland are unlike Archaean TTG. Consequently, Iceland cannot be regarded as a modern analogue for the Archaean crust. This is because of low pressure conditions for partial melting of metabasalts in Iceland. Felsic magmatism at oceanic plateaux must therefore be considered as subordinate during continental crust formation in comparison with the magmas produced at subduction zones. However, when subducted, the oceanic plateaux could be responsible for the episodic crustal growth, which has occurred throughout the Earth's history.

Acknowledgements

We are deeply grateful to J-Y. Cottin for fruitful discussions, and to R. Rapp, H. Rollinson, B-M Jahn and A. Kemp for very constructive comments on the manuscript and their thorough reviews. We appreciate the efficient English corrections by Fran Van Wyk de Vries. This work was funded by the French-Icelandic 'Jules Verne' cooperation program and the Icelandic Science Foundation.

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Received 5 November 2007; revised version accepted 6 August 2008