On jotunites and their origin

By Jean-Clair Duchesne
Department of Geology, University of Liège

The 1.8 Ga magmatism in the Ukrainian shield includes an episode of jotunitic magmatism at the origin of anorthosite massifs, mafic intrusions and dykes. What is the state-of-the art about jotunites? This short comment intends to answer this question.

According to Streckeisen (1974, 1976), charnockitic rocks constitute a genetic suite characterized by the presence of hypersthene (or fayalite + quartz) and perthitic feldspars in many of its rocks. In this suite jotunite is synonymous to hypersthene monzodiorite or monzonorite. In this definition, the relative proportion of hypersthene is not mentioned but it is implicit that hypersthene is the only pyroxene or at least the dominant one. The presence of ferrous olivine (instead of pure fayalite) + clinopyroxene is common in typical members of the charnockitic suite, as e.g. in the Bjerkreim-Sokndal layered intrusion (South Norway), in mangerite (Duchesne and Wilmart, 1997; Wilson et al., 1996) or in olivine bearing gabbronorite transitional between norite and mangerite (Wilson et al., 1996). Another characteristic of jotunite in the AMCG (anorthosite-mangerite-charnockite-(rapakivi)granite) suite is the high Fe, Ti and P contents (Dymek and Owens, 2001; Owens and Dymek, 1992; Owens et al., 1993; Robins et al., 1997; Vander Auwera et al., 1998). With mg# below 0.5, FeOt >12-13 wt% and andesine plagioclase (An<50), they could also be called ferrodiorite or ferromonzodiorite when K-feldspar/(plagioclase+Kfeldspar) ratio is above 10%. This nomenclature is currently used by North American researchers and has the advantage to point to a possible link with ferrobasalts in other contexts than the AMCG suite, as for instance with the Crater of the Moon series of volcanic rocks (Duchesne, 1990; Emslie, 1978)

Emslie initiated the discussion of the origin of ferrodiorite (Emslie, 1978, 1980). In his model on the formation of anorthosites he postulated a mantle-derived basaltic parental liquid that started differentiation in a deep-seated magma chamber. This magma crystallizes plagioclase (that floats and accumulates at the roof of the intrusion) and olivine and mafic minerals (that sank on the floor). Subtraction of these minerals leaves behind a residual melt of ferrodioritic composition. The floated plagioclase forms a mush that diapirically rises through the crust to mid-crustal level to give rise to anorthosite massifs. The ferrodioritic residual melt is entrained by the uprising plagioclase mush. This view was challenged by the occurrence, in Rogaland (South Norway), at the margin of an anorthosite body of a jotunite (formerly called monzonorite) grading through a porphyritic facies to the anorthosite (Demaiffe et al., 1973; Demaiffe and Hertogen, 1981; Duchesne et al., 1974). The lack of a negative Eu anomaly in the jotunite precluded a previous crystallization of plagioclase (Duchesne et al., 1974) and, thus, a residual origin. Consequently the jotunite was considered as parental to the anorthosite (Duchesne and Demaiffe, 1978). Later it was shown experimentally that the jotunite can not result from fractionation of a basaltic melt (of mantle origin) at the pressure of formation of the anorthosite (*c.* 13 kbar) but is produced by melting of a (mela)gabbroic source (of crustal origin) (Longhi et al., 1999). It should be stressed, however, that in both models jotunite/ferrodiorite have a common status, they coexist in equilibrium with andesine anorthosite (Vander Auwera et al., 1998).

In several anorthosite provinces, jotunites/ferrodiorites are associated with a series of charnockitic rocks such as mangerites and charnockites, e.g. in the Laramie anorthosite complex (Mitchell et al., 1996), in the Grenville Province (Dymek and Owens, 2001; Owens and Dymek, 1992; Owens et al., 1993), and in the Rogaland anorthosite province (Duchesne et al., 1989; Wilmart et al., 1989) where liquid lines of descent produced by fractionation of jotunite/ferrodiorite were defined. The Rogaland LLD is based on a series of rocks occurring in dykes and at the margin of mafic intrusions (Bolle et al., 2003; Duchesne et al., 1989). The Tellnes dyke is a major component of the trend and it associates Fe-Ti-P-rich jotunites continuously grading into mangerites, quartz mangerite and charnockites (Wilmart et al., 1989). The original liquid character of the major rock types is supported by their chilled microtextures (with apatite needles and granular Fe-Ti oxides dispersed in all minerals). Jotunites at the margins of the Hidra and Bjerkreim-Sokndal intrusions revealed compositions less rich in P_2O_5 and consequently named "primitive" jotunite to distinguish them from "evolved" jotunites richer in P_2O_5.

Modelling the evolution of the Rogaland LLD from primitive jotunite to charnockite by fractional crystallization was constrained by experimental data (Vander Auwera and Longhi, 1994; Vander Auwera et al., 1998) and mass balanced calculations (Duchesne and Charlier, 2005). It should be emphasized that the LLD, which extends from 47% SiO_2 to 66% SiO_2 encompasses on parts of its trajectory trends defined in other environments: the Tellnes trend is very similar to the Crater of the Moon trend (Leeman et al., 1976), as noted by (Duchesne, 1990), and to ferrodiorites of the Laramie anorthosite complex (Mitchell et al., 1996).

In order to revive the debate on the crustal or mantle origin of ferrodiorite/jotunite, a series of experiments have been conducted on an olivine tholeiite melt (implicitly of mantle origin) to try to show that ferrodiorite could be formed by fractionation and could reproduce the LLD (Whitaker et al., 2003; Whitaker et al., 2007; Whitaker et al., 2008). The experiments were conducted at various pressures and dry conditions (0.4 and 1.8 wt% bulk water at 4.3 kbar, and 0.05 wt% bulk water at 6.8 and 9.3 kbar) (Whitaker et al., 2007).

We compare in major element Harker variation diagrams the residual liquid compositions of experiments with the Rogaland LLD (Fig. 1). Detailed comparison of the residual liquid composition at 4.3 kbar shows a good agreement for MgO, CaO and K_2O, particularly for values above 53 % SiO_2. The Al_2O_3 in the experiments is somewhat higher and the FeOt lower than in the other trends, which according to Whitaker et al. (2007), could be caused by the higher Al and lower Fe concentrations in the starting material relative to the natural samples. The enrichment in Ti at nearly constant SiO_2 content is observed, but that in Fe and P does not match the natural trends. The high FeOt and P_2O_5 contents of the "evolved" jotunites of the Rogaland LLD are not accounted for. Whitaker et al. (2007) also mention such discrepancies in their comparison with the ferrodiorites of the Laramie anorthosite complex. However, observing the experimental liquids evolution at 9.3 kbar that shows a strong enrichment in P_2O_5 as well as in TiO_2 and FeOt, these authors proposed that the Fe-Ti-P-rich ferrodiorites (jotunites) can be generated by high-pressure fractional crystallization (Whitaker et al., 2007). This mechanism appears thus plausible to explain the "evolved" jotunite composition, but it must be stressed that at 9.3 kbar a further evolution of this melt by fractional crystallization will NOT give rise to intermediate and acidic melts, but to undersaturated melts. Longhi et al. (1999) have shown that for pressures higher than 5 kbar in dry conditions a thermal barrier separates liquids evolving towards acidic rocks from those evolving towards undersaturated melts. If some Fe-Ti-P-rich jotunite deriving from fractionation of olivine tholeiite magma may be produced at high pressure at the base of the crust, it is possible that a decrease in pressure due to adiabatic rise through the crust could bring the melt to the favourable conditions for SiO_2 enrichment. An increase in water content by secondary processes would also give the same result, the disappearance of the thermal barrier (Longhi et al., 1999). However, it must be accounted for that the Fe-Ti-P melts have a high density, which will make difficult their ascent through the crust over long distances. Even in a polybaric evolution, the formation process of Fe-Ti-P-rich jotunites form olivine tholeiite thus appears questionable.

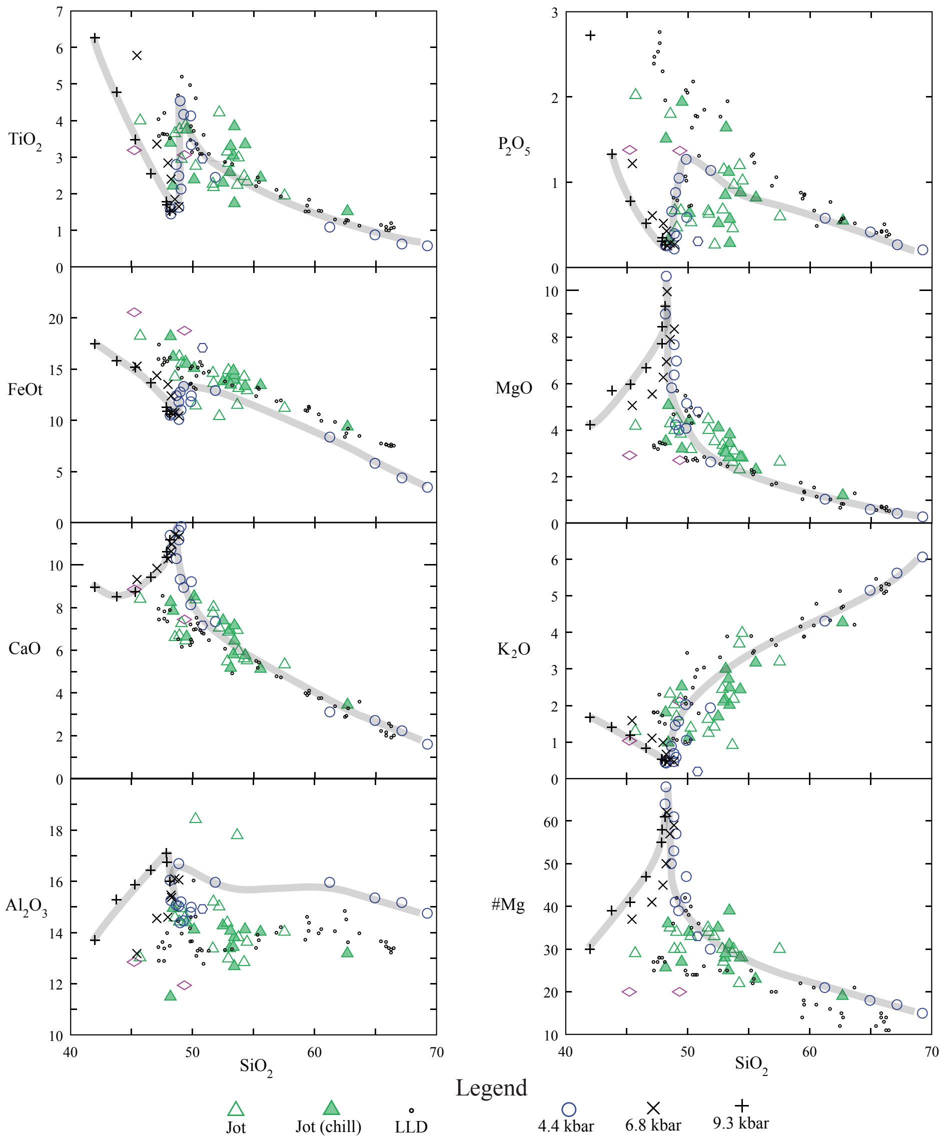

Figure 1: Harker variation diagrams comparing the experimental data on olivine tholeiite (Whitaker et al., 2003; Whitaker et al., 2007) with the Rogaland LLD and the KPC jotunite and ferromonzodiorite. The evolution trends of the residual liquids at 4.4 and 9.3 kbar are underlined (after (Duchesne et al., 2017)

Another mechanism to generate jotunite has been proposed by Longhi et al. (1999). In the olivine-plagioclase-quartz system (projected from clinopyroxene), experiments at 13.5 kbar in dry conditions have shown that the Tjørn composition (a typical primitive jotunite) is located on the thermal barrier defined above and characterized by a tie line between plagioclase and high-alumina orthopyroxene. Jotunite, thus, cannot derive from any mantle derived basaltic melts. The only possible mechanism to generate such melts is through melting of a plagioclase + pyroxenes assemblage at *c.* 13 kbar, that is at the base of a thickened crust or in a crustal tongue (Duchesne et al., 1999). In Rogaland, the evolution from primitive jotunite to evolved jotunite by fractionation at medium-crust pressure is substantiated in the Bjerkreim-Sokndal layered intrusion that displays the ad hoc series of cumulates (Duchesne and Charlier, 2005; Vander Auwera et al., 1998; Wilson et al., 1996). This evolution can involve some crustal contamination (Bolle et al., 2003) but it is not necessarily the case, as for instance in the Tellnes dyke that is produced by simple fractional crystallization (Wilmart et al., 1989).

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