Introduction

Granitoids are commonly found in the mantle section of supra-subduction ophiolites, including the Oman ophiolite (Allemann and Peters, 1972; Boudier et al., 1988; Briqueu et al., 1991; Peters and Kamber, 1994; Cox et al., 1999). These granitoids, especially the potassic types, when occurring in deep levels of ophiolites, are almost systematically attributed to an "exotic" meta-sedimentary source and to igneous processes related to subduction and/or obduction rather than to accretion. This scenario certainly accounts for the genesis of part of ophiolitic granitoids such as the Al-rich granitoids forming the Khawr Fakkan massif at the northermmost end of Oman ophiolite, which according to petrological and isotopic data seem to derive from the underlying metamorphic sole (Briqueu et al., 1991; Cox et al., 1999).

The main objective in the present paper is to determine if a metasedimentary source satisfactorily accounts for the formation of all potassic granitoids observed in the Oman Ophiolite. A second question addressed in this paper concerns the petrological and geophysical conditions leading to the genesis of granitoids in the sub-oceanic mantle.
Granitoids have essentially dunitic, more mantle section of the ophiolite. All these potassic granitoids are restricted to the metre-thick dykes. From small lense-shaped pods to swarms (2003). They range in volume and shape documented (Lippard et al., 1996; Benoit et al., 1999; Python and Ceuleneer, 2003), we have sampled numerous occurrences of granitoids in the different massifs of the Oman range, from Wadi Tayin in the Southeast to Wadi Hatta in the Northwest (Fig. 1). The synthetic map presented in figure 1 is based on this comprehensive survey and on the observation of hundreds of thin sections.

Based on this petrographic study and on electron microprobe data, we have selected 33 samples representative of the various kinds of mantle and crustal granitoids for a bulk rock geochemical study (major elements, trace elements, and Nd-Sr isotopes on a selection of 16 samples). We compare our data to the ones collected by Cox et al. (1999) on granitoids from the Khawr Fakkan massif and show that melting of the metasedimentary metamorphic sole alone cannot account for the diversity of field relations and geochemical compositions of granitoids exposed in the Oman mantle. We bring new pieces of evidence supporting the hypothesis that part of them derive from a mantle source affected by a deep and very high-temperature hydrothermal alteration according to experimental data and theoretical models (McCollom and Shock, 1998; Koepke et al., 2004).

Petrography and field relations

According to the classification of Streckeisen (1976) the granitoids included in the present study range in composition from tonalites-trondhjemites (plagiogranites) to granodiorites and granites (potassic granitoids). Granites s. str., appear to be restricted to the northern part of the ophiolite, but occurrences of granodiorites are ubiquitous although their abundance decreases southward. In some areas, granitoids from different families can be associated within a single intrusion (Fig. 1).

Granitoids belonging to the potassic family are not of frequent occurrence in the Oman Ophiolite, apart from the Khawr Fakkan area, where they are exceptionally abundant (Alleman and Peters, 1972; Cox et al., 1999), only a dozen of occurrences have been documented (Lippard et al., 1986; Beurrier, 1987; Python and Ceuleneer, 2003). They range in volume and shape from small lense-shaped pods to swarms of metre-thick dykes.

A main result of our survey is that potassic granitoids are restricted to the mantle section of the ophiolite. All these granitoids have essentially dunitic, more rarely pyroxenitic or wehrlitic wall rocks (Fig. 1). Contact relationships between the potassic granitoids and their host are never clear cut. Dykes always show reactional features at the contacts, and the modal composition of their host peridotite is affected on distances of at least several decimetres away from the intrusion. The most common case is the development of dunitic wall rocks resulting from the preferential depletion in orthopyroxene of the host harzburgite. These relations are even more diffuse in the case of pods which may be surrounded by well developed dunitic walls «impregnated» with interstitial pargasitic amphiboles.

Mantle granitoids, whatever their lithological nature, are, as a rule, spatially associated to major fault zones. These fault zones present evidence for high temperature ductile deformation (mylonites). This is the case of the Muqbariah shear zone (MZ), in the Maqsad area, that is hundred metres thick and can be followed along tens of kilometres along strike (Beurrier, 1987; Amri et al., 1996). There, and in other occurrences where the deformation is less developed, emplacement of the granitoids appear to be contemporaneous with the deformation event. Most of them are foliated and transposed into parallelism with the shear zones, but some individual dykes or lenses have escaped to deformation.

In contrast, plagiogranites occurring at the upper crustal are ubiquitous all along the Oman range, they form plugs of a few tens to hundred metres in size, and are localized at the transition between the isotropic gabbros and the sheeted dyke complex (Amri et al., 1996).
Major and trace compositions

Major elements were analysed by XRF in (CRPG) Nancy. Trace elements data were obtained in Toulouse, by ICP-MS after fusion with lithium borates. The results of major, trace element and Sr-Nd analyses are available to the request.

In terms of major elements, our potassic granitoids (mantle granites and granodiorites) differ significantly from the Khawr Fakkan granitoids described by Cox et al. (1999). They are richer in silica and, for a given K₂O or Fe₂O₃+MgO content, are poorer in Al₂O₃ (Fig. 2). Another important fact is that Rb and K₂O content in our granites show a well correlation to Ba content which is not present in the Khawr Fakkan granitoids (Fig. 3). These alkalic elements were likely introduced in the mantle section, from which our granitoids derive, together with Ba-containing hydrothermal fluids.

An interesting observation is that the variations in the trace element composition of our samples are not only a function of the lithology but they depend also critically on the nature of their wall rock. This is mainly clear for REE concentrations normalized to chondrite values that present clearly different patterns in granitoids from mantle or from crustal outcrops (Fig. 4).

Crustal plagiogranites, originated from fractional crystallisation of MORB type magmas, have higher REE\textsubscript{N} contents, and they show perfectly flat HREE\textsubscript{N} patterns, while their LREE\textsubscript{N} patterns decrease slightly towards La\textsubscript{N}, except in some more evolved samples. In contrast, the HREE\textsubscript{N} concentrations in mantle granitoids are globally lower than for crustal lithologies and they present a strong enrichment in LREE\textsubscript{N}, originating REE\textsubscript{N} patterns typical of hydrothermally altered depleted mantle sources.

Sr and Nd isotopic composition

We performed Nd and Sr isotopic ratio measurements on a TRITON T1 mass spectrometer (Brest) in static mode. In order to compare the isotopic signatures with the ones from actual MORBs from the Indian Ocean (Engel and Fischer, 1975), we have used the eNd notation, calculated at 100My. ²⁷Sr/⁸⁷Sr was also corrected from 100My ²⁷Rb decay (Fig. 5). Age of about 95-100My is considered as the age of the genesis of the Oman Ophiolite (Tilton et al., 1981).

Figure 5 shows: large isotopic variability within all the samples, some of our granitoid samples have upper- mantle like Nd and Sr isotopic composition, while other have been shifted to higher radiogenic Sr values. This element was most probably introduced in the mantle by hydrothermal fluids. For most of these granitoids we propose a simple two-component mixing model to explain their isotopic signature: depleted mantle source and hydrothermal fluids contribution. Finally, the isotopic signature of the granitoids with lower eNd and higher ²⁷Sr/²⁶Sr, might also be explained by a complementary input to the mantle source of previously subducted terrigenous sediments.

Discussion

The potassic granitoids described in this paper occur as small pods and dykes scattered in the mantle section of the Oman Ophiolite, frequently associated to ductile shear zones parallel to the azimuth of the former spreading center. A depleted mantle source is supported for them by several geochemical characteristics including: a) their lower Al₂O₃ content, and better correlation of K and Rb with Ba content, relative to granitoids derived from a metasedimentary source; b) a typical REE\textsubscript{N} pattern with marked depletion in HREE, with respect to crustal plagiogranites, and enrichment in LREE\textsubscript{N} indicative of a hydrothermally transformed mantle source, and c) their Nd-Sr isotopic signatures plotting in part along the mantle array, despite a probable increase of ²⁷Sr/²⁶Sr ratio due to incorporation of radiogenic Sr to the mantle source by hydrothermal fluids.
The source of silica for these granitoids is to be looked for in the incongruent melting of ortho-pyroxene induced by alkaline-rich aqueous fluids, as suggested by the systematic occurrence of dunitic wall rocks around these granitoids. The great scatter in the K$_2$O/SiO$_2$ ratio that characterizes our suite of hydrothermal granitoids (lithologies ranging from potassic granites s. str. to tonalites) reflects variations in the proportion of fluids and of silicic partial melts dependent on local conditions specific for the genesis of each individual pod.

Conclusions

All granitoids cropping out in the Oman Ophiolite mantle section, including the K-poor, plagiogranitic, end-members, contrast markedly in terms of trace element and isotopic compositions with the more classic crustal plagiogranites, which derive from MORB magmas (Figs. 4 and 5), pointing to different conditions of genesis and melt sources between them.

The formation of Al-poor granitoids in the shallow mantle can be viewed as the deepest and hottest (T$^\circ$ likely in the range of 800°C-900°C) expression of hydrothermal alteration of the oceanic lithosphere, making possible a subsequent, localized partial melting of the mantle source. The absence of potassic granitoids at crustal level may reflect the low probability for the rare silicic melts formed in the mantle of reaching the crust. Mantle ophiolitic granitoids should not be considered systematically as deriving from an «exotic» metasedimentary source, instead, in our opinion, some of them must represent a new «hydrothermal» type to be included among the various kinds of granitoids generated during oceanic accretion.

References