The Canadian Mineralogist
Vol. 34, pp. 1332-1336 (1996)

METASOMATISM AT A GRANITIC PEGMATITE – DUNITE CONTACT IN GALICIA: THE FRANQUEIRA OCCURRENCE OF CHRYSOBERYL (ALEXANDRITE), EMERALD, AND PHENAKITE: REPLY

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We appreciate the comments regarding our paper on beryllium-bearing gems at Franqueira. All the suggestions to improve or change our proposed genetic model are welcome, and we thank Franz *et al.* for their comments and interest. Our main objection to their discussion is based on their assumption that the pegmatite-bearing country rocks have been thrust onto the granites, and both the granites and pegmatites have been metamorphosed and thus should be called metagranites and metapegmatites. In our opinion, this is not at all the case; the interpretations presented by Franz *et al.* thus are not in accordance with our basic observations. Nevertheless, as some doubts are raised owing to possibly incomplete information in our geological introduction, we would like to clarify this aspect.

In our paper (Martin-Izard *et al.* 1995), the host rocks of the pegmatite bodies are clearly described as forming a roof pendant of dunitic and gabbroic rocks of the schistose domain. They consist of metadunite and metagabbro, and were not thrust onto the granites. On the contrary, they were intruded by the granites. These remains of the mafic and ultramafic rocks are the host rock of the pegmatite dikes. The emplacement of the granites occurred at the end of the third tectonic phase. Before intrusion, *i.e.*, during the second tectonic phase, the Lalin–Forcarey Unit, as well as the Ordenes Complex, including dunitic and other ultramafic rocks, were overthrust onto the other groups of the schist domain. Perhaps we didn't stress in our paper that regional Barrovian metamorphism occurred during the second tectonic event, before the emplacement of peraluminous granite, which took place at the end of the third tectonic event. Therefore, the contact between granites and pegmatites with dunites and gabbros is intrusive and not tectonic, and the granites and pegmatites were not affected by metamorphism. They were affected only by a mild tectonic deformation, which occurred during the later stages of the third tectonic phase and produced the curved plagioclase twins, wavy extinction in quartz, and kinked flakes of mica. The lepidoblastic texture is due to the nature of the rock, composed mainly of mica, and to the fact that mica flakes grew more or less parallel to the pegmatite contact; that texture did not arise by tectonic deformation.

An update of the metamorphic and tectonic evolution of the region was given by Martínez-Catalán *et al.* (1995). In order to simplify the regional metamorphic evolution, these authors did not take into account the synkinematic deformation of the peraluminous granites because these were emplaced after the development of regional metamorphism, during the third tectonic phase.

In this way, at Franqueira (Martin-Izard *et al.* 1995), the relationship between pegmatites and granites is not hypothetical. There is no structural discontinuity between the two rock types, and no thrust exists between them. We believe that we made it clear in the paper that 1) the mafic and ultramafic rocks belong to the schistose domain, 2) they were thrust during the second tectonic phase, and 3) at Franqueira,

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the dunitic rock is a roof pendant of the schistose domain cut across by the system of pegmatite veins. Thus no multistage tectonic event can be proposed. The pegmatites were not metamorphosed, and their deformation is strictly local.

Other objections raised by Franz *et al.* concern the geochemical data; we do not agree with their proposed evaluation. The high Na/K value is typical of highly differentiated granitic liquids. Many investigators (London 1987, 1992, Lentz & Fowler 1992, Černý 1993) have explained the pattern expected during the internal evolution of pegmatites: with increasing fractionation, these are expected to generate Na-rich fluid as the melt shifts from the ternary Ab–Or–Qtz minimum with buildup in B, P and Li content. We have found tourmaline and apatite in the Franqueira pegmatites, and have also documented, from a geochemical point of view, high contents of Li (247 ppm in pegmatite, 568 ppm in phlogopitite, and 173 ppm in tremolitite; Table 1 of Martin-Izard *et al.* 1995). We can also attribute the low K content of the pegmatite to the dispersion of this and other elements (P, Be, B, Li) into the dunitic rock to produce phlogopite; only a small proportion of K remains in the pegmatite. As far as the high Ca content is concerned, we have enough Ca at Franqueira to form apatite as a primary mineral phase, with its implications (London & Burt 1982, London 1987); also formed are Be minerals, some tourmaline and phlogopite, which must be rich in Li to explain the high Li content of phlogopitite. In this way, it is not possible to compare the bulk composition of the pegmatites with that of other pegmatites, because at Franqueira their composition changed owing to metasomatic phenomena.

The abundance of Ca that forms apatite and tremolite raises a problem. Nevertheless, we note that associated with the dunite, there is a Ca-rich gabbro (over 12 wt% CaO: Table 1, Martin-Izard *et al.* 1995). Also, the dunite is Ca-rich (over 3 wt% CaO: same Table). Perhaps during regional metamorphism, Ca from gabbro "contaminated" the dunite, such that the host rock gained enough Ca to form tremolite. The pegmatite has no Ca, and the phlogopitite has none either.

The fluid phase that emanates from the pegmatite-forming system can be expected to interact with gabbroic rocks in the roof pendant. According to the compositional characteristics of such a fluid, it is likely that calcic plagioclase will be out of equilibrium with it. We could expect progressive conversion of the original plagioclase to pure albite, with which the fluid phase *would* be in equilibrium. A second reason to expect albitization is that below 400°C, according to the phase diagram for the system Ab–An, pure albite is expected (Smith 1982), the Ca being released into the fluid and reprecipitated locally in the form of calcic metamorphic minerals, here tremolite.

Franz *et al.* stated that we provide only a few data on the major and trace elements concerned. We believe that in the paper, there are sufficient data about geochemistry and major- and trace-element behavior during metasomatism. We analyzed the rocks for even more elements than did Curtis & Brown (1971), even though their paper is on metasomatism due to regional metamorphism. We also analyzed minerals for major and trace elements, and found that the various types of phlogopite and tremolite show well the evolution and behavior of Cr, Ni, Fe and Si in the various parts of the metasomatic zone.

An important objection to our paper is about the thermal energy to form the metasomatic zone. The thickness of individual dykes of pegmatite is up to 40 cm, but the reader should not forget that they form an anastomosing network exposed for several meters; Be, B and P minerals occur only in the zone close to the pegmatite, and most of the Al and K can also be found in the phlogopitite zone (Martin-Izard *et al.* 1995). The dunite body is a roof pendant in the granite; as such, we do not anticipate any problems with thermal energy and fluid volume. The presence of P, B, Li increases the solubility of H_2O in silicate melt, decreases the melt's viscosity, and also facilitates its migration, as found in the Tanco pegmatite (London 1987), where B is fixed as metasomatic tourmaline in the host rock. On the other hand, Franz *et al.* seem to have underplayed the role of the host rock in the metasomatic reactions. Dunite may be very reactive in the presence of a hydrous silicate melt owing to its completely different chemical composition and its lack of water. The reader should note that Figure 13 is schematic, whereas Figure 2 (Martin-Izard *et al.* 1995) is real. Nevertheless, the formation of the broad zone of tremolitite could be problematic, but not impossible with our proposed model.

As far as the other Be minerals in our paragenesis are concerned, please see Figure 12 (Martin-Izard *et al.* 1995) and the review by Barton (1986); in our proposed conditions of formation, it is impossible to find euclase, bertrandite and bromellite. Fluorine is in apatite, and neither topaz nor fluorite was detected. According to our model, Be was efficiently transported a few decimeters from the original source in a system that is not a greisen according to definitions offered by Bates & Jackson (1987) and Taylor (1979).

As far as fluid inclusions are concerned, we wish to make three points. Firstly, literally, we say in our paper that "temperatures of total homogenization range from 318 to 369°C in the liquid state, and from 354 to 373°C in the vapor state". According to this statement and Table 3 of our paper, we indicate that approximately half of the inclusions homogenize in the vapor state, and the other half in the liquid state, representing coexisting immiscible fluids. We never said, as you interpreted, that most of the type-1 inclusions homogenize in an aqueous liquid, and only a few in the carbonic vapor. On the other hand, why should two immiscible fluids homogenize in two contrasting ways? Two fluids can be immiscible, and both can homogenize in the same way (Roeder 1984). Type-1 fluid inclusions are CH_4-rich, and type-2, CO_2-rich, and the ambient pressure probably is above 1 kbar.

Secondly, why do we need to form a gas poor in carbonic species and a gas rich in carbonic species? CH_4 and CO_2 differ so much in density that they can separate into two different aqueous fluids, as is the case at Franqueira.

Thirdly, the presence of CO_2 and CH_4 together in the same inclusion is a commonly cited phenomenon. At Franqueira, we do not cite the presence of graphite (Kreulen 1987) because under the microscope, we cannot see it, and we cannot analyze it with a microprobe. The H_2 may diffuse out of the inclusion, but this phenomenon must be generalized and not restricted to a very precise position in the minerals, for example in the core of the emerald that appears later than phenakite. Also, type-1 and type-2 inclusions can be found together in the core of the emerald. Why would diffusion have happened only in a selected number of inclusions? Nevertheless, we can propose two possible alternative explanations: the partial reaction of CH_4 with H_2O to form H_2 and CO_2 at the beginning of emerald crystallization; in this way, we can capture type-1 and type-2 inclusions at the same time. The other explanation involves type-1 inclusions coming from the reaction $3\ CO_2 + 8\ NH_3 = 3\ CH_4 + 4\ N_2 + 6H_2O$ (Kreulen 1987), but we need to test for the presence of N_2. In spite of these possibilities, we contend that the most likely explanation involves immiscibility between two fluids.

The fluid inclusions found in emerald from Habachtal (Nwe & Grundmann 1990) differ from those at Franqueira. On the contrary, the fluid inclusions in phenakite and emerald from Gravelotte (Nwe & Morteani 1993), and in particular, the presence of type-1 and type-2 inclusions, are practically the same as at Franqueira. We admit that we should have known about their work. Nevertheless, Nwe & Morteani suggested an evolution by progressive oxidation of CH_4 (they also do not cite the presence of graphite) that is not possible to apply to Franqueira, because the H_2O–CO_2 inclusions appear only in the core of emerald crystals, together with the H_2O–CH_4 inclusions, and are followed by inclusions, again of H_2O–CH_4. Raman microprobe analysis could help to solve the problem.

According to all the above explanations, the alternative model proposed for Franqueira is not possible. At Franqueira, we have no shear zones, and metamorphism did not affect the pegmatites and the metasomatic zone, as it did at Habachtal (Nwe & Grundmann 1990) and Gravelotte (Nwe & Morteani 1993).

In our proposed model (Martin-Izard *et al.* 1995), we have the same first conditions of mineralization, namely the contact between the two geochemically contrasting rocks. However, Franqueira is not of the schist type of mineralization, as no schist is present. Secondly, "blackwall zones" were not formed during regional metamorphism at Franqueira; metasomatic zones were formed during the emplacement of the granites, and *do not* exhibit a deformation-induced foliation. At Franqueira, the pegmatites cut across a roof pendant, and the thermal energy of the granites could be sufficient to form, at the beginning of the process, orthoamphibole (some of it remains inside the emerald crystals and between tremolitite and dunite: Martin-Izard *et al.* 1995) at approximately 550°C (Tracy & Frost 1991), and later, tremolite, phlogopite, phenakite and chrysoberyl, and, with the increase in the activity of H_4SiO_4, the partial transformation of the two last minerals, over a wide range of temperatures (380–600°C: Barton 1986), into emerald. At Gravelotte (Nwe & Morteani 1993), there is no chrysoberyl; during the metasomatic phenomenon, the phenakite and the core of the beryl crystals are formed, and only during the multistage metasomatism does the emerald resume growth.

In summary, no multistage regional metamorphism occurred at Franqueira; phenakite, alexandrite, emerald, apatite, tourmaline and phlogopite formed during a metasomatic stage involving reaction between pegmatites and a roof pendant of dunite. Nevertheless, it is clear that several questions remain open.

Acknowledgements

This work was financed by the CYCIT, project GEO91/1077, and University of Oviedo project df91/21527. We thank Robert F. Martin for his suggestions, which improved the clarity of this reply.

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Received September 4, 1996, revised manuscript received October 14, 1996.