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PETROGENESIS OF RARE-ELEMENT GRANITIC PEGMATITES - EVIDENCE AVAILABLE AND MISSING LINKS

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Granitic pegmatites of the rare-element class typically occur in terrains of the low-pressure amphibolite facies of metamorphism, within the Abukuma metamorphic facies series, emplaced at 4 - 2 kbar and consolidated at ~750 - 650 to ~500 - 400° C. Bulk compositions correspond to the thermal minima and eutectics in the $Ab+Or+Qtz+H_2O$ system for the geochemically primitive types, and in the $Ab+Ecr+Qtz+H_2O$ system for the Li-rich varieties. Modifications of the bulk composition of tourmaline-, phosphate- and lepidolite (±topaz)-rich pegmatites correspond to those experimentally established for the minima in B-, P- and F-bearing systems. Crystallization of even the most complex rare-element pegmatites from highly hydrous magmas is also verified by experiments simulating the typical internal structure and mineral assemblages of zoned bodies: LONDON's work demonstrated crystallization of pegmatites from homogeneous melts, H_2O-undersaturated till the very last stages of consolidation, in contrast to the classic hypothesis best formulated by JAHNS & BURNHAM, which claims the coexistence of silicate melt + exsolved fluid phase through most, if not all of the solidification.

The most prominent questions to be answered about the internal evolution of rare-element pegmatites are those of aplitic units and of mechanisms of fractionation. Early aplitic units typical of layered pegmatites, but also encountered in zoned and quasi-homogeneous bodies, are so far an enigma. Extreme fractionation gradients spanning very short distances across thin pegmatite veins require research into speciation of rare elements in pegmatite melts and of factors controlling their precipitation.

Despite these gaps in our knowledge, the magmatic nature of the parent medium, from which the rare-element pegmatites solidify in an essentially closed system, is well established and generally accepted, in contrast to diverse aqueous hypotheses that are only of historical interest today. However, the derivation of pegmatite-generating melts is still disputed. The controversy is focused on magmatic vs. metamorphic derivation of pegmatite-generating melts.

Numerous field- and laboratory-based lines of evidence were established in a multitude of rare-element pegmatite populations that link the pegmatites with late stages of consolidation of specialized fertile (leuco)granites: (1) rare-element pegmatites form facial pods within parent plutons, or transect margins of plutons into their metamorphic envelopes; (2) pegmatitic rocks constitute cupolas of the fertile granites, or (3) zoned aureoles surrounding the plutons, with the pegmatites progressively differentiated from the interior through the marginal into the extreme exterior dikes; (4) late-crystallizing pegmatite pods trapped within parent granites are locally exact duplicates of exterior pegmatites in the metamorphic roofs of these granites; (5) continuous textural, mineralogical and geochemical evolution links the parent granites and their pegmatite progeny, the geochemical trends being analogous to those known from highly fractionated rhyolite suites; (6) the abovementioned P-T conditions of consolidation and the bulk compositions fit the tail-end of fractionation expectable in highly evolved granitic intrusions.

The main problem to be solved is the nature of granitic magmas that generate the rare-element pegmatites on one hand, and mineralized granites or greisen- and vein-type deposits on the other. The answer probably is in different degrees of saturation in volatile agents, and in their qualitatively and quantitatively different representation.

Metamorphic models claiming direct anatectic origin of rare-element pegmatite melts are based on the absence of outcropping granitic parents, or speculations unsupported by physical evidence. The hypotheses range from low-percentage melting of lithologies pre-enriched in the "pegmatitic" rare elements to hydrothermal influx of these elements into barren pegmatite-generating magmas.

All these hypotheses are burdened by numerous problems: (1) Lithologies that may serve as protoliths extraordinarily enriched in rare elements (such as evaporites) are scarce in high-grade metamorphic terrains, particularly in the Archean; they do not cover the full spectrum of elements represented in complex pegmatites, and they would be prone to devolatization and dispersion early in prograde metamorphism. (2) Extremely low-percentage melting would be required to generate anatectic magmas even remotely similar to complex pegmatites (and only if partition coefficients that work at above ~20 % melting could be realistically extrapolated to 0.5 - 1 % melting). (3) Concentration of rare elements encountered in complex pegmatites would require substantial removal of these elements from very large volumes of available source rocks, such as metapelites. (4) Segregation of low-percentage melts (~3 %) from enormous volumes of protoliths into restricted spaces occupied by complex pegmatites would be physically difficult, and probably impossible. (5) Were such a segregation feasible, the melts seeping through metamorphic lithologies would react with them and lose most of their content of rare elements in the process. (6) Systematics of radiogenic isotopes are sharply discordant between pegmatites and their host rocks, including deep-seated analogs of the latter. (7) Cases of "aborted segregation" of highly fractionated pegmatite melts in *statu nascendi* within metamorphic protoliths have not been observed.

The critical factor in any potential metamorphic model is the behavior of biotite - by far the most significant carrier of HFS elements and rare alkalis in metamorphic lithologies. Melting scenarios involving the bulk of biotite but conserving (at least most of) plagioclase + quartz do not seem petrochemically feasible; melting of biotite takes place in high-% anatexis which prevents substantial accumulation of lithophile rare elements. A recent experiment by ICENHOWER & LONDON generated low-% melt enriched in rare elements by recrystallization of biotite, but in a H_2O-oversaturated environment which does not seem to be geologically realistic in prograde metamorphism. Thus the concept of direct metamorphic derivation of rare-element pegmatites is so far not supported by any feasible mechanism.

THE AGE OF THE ÖTZTAL-MIGMATITES - STILL A MATTER OF DEBATE

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The Ötztal basement exhibits several migmatite bodies, formed in situ from biotite-plagioclase-gneisses and biotite-schists (Winnebach near Längenfeld/Ötztal; Verpeil near Feichten/Kaunertal; Nauderer Gaisloch E of Reschenpaß). So far, geochronological studies have only revealed minimum ages for the migmatisation. The genetic relation between migmatites and the intrusion of surrounding magmatites is not yet proved. Rb/Sr-mineral-dating shows "Caledonian" to "Alpine" model ages depending on the post-anatectic metamorphic overprint.

The minimum age for the anatexis in the Winnebach-migmatite is defined by a muscovite age of 461 ± 8 Ma. The migmatites of the Reschenpaß area are cross-cut by pegmatites for which an age of 472 ± 26 Ma is reported (Rb/Sr whole rock data, SCHWEIGL, 1993).

All before mentioned migmatites are in direct contact or in the nearest vicinity of metagranitoids. Thus, the heat source for the migmatisation of the paragneisses could be suspected in these magmatites. The age of migmatisation would then correlate with the intrusion ages of these rocks. The intrusion age of the Alpeiner granite E and W of the Winnebach-migmatite is still not known. The metagranitoids surrounding the Feichten-migmatite (Kaunertal) are believed to have intruded around 481 ± 7 Ma (Pb/Pb zircon evaporation age, HOINKES et al., 1994), although some of the zircons yield older ages of ~ 530 Ma (pers. comm. U. KLÖTZLI). The not well defined intrusion age of the Klopair-tonalite (Nauderer Gaisloch, Reschenpaß) is around 520 Ma (SCHWEIGL, 1993). None of these intrusion ages is without debate and/or backed up with other geochronological methods. Additionally, no direct field evidence is found proving the direct connection between magmatites and migmatites.

Rb/Sr-whole-rock-measurements from the Winnebach-migmatite show that the in situ migmatisation has not lead to a complete homogenisation of the Sr-isotopes.