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EVOLUTION OF MONOCYCLIC ZONAL-METAMORPHIC COMPLEXES: PROGRADE AND RETROGRADE STAGES, CORRELATIONS WITH GRANITE FORMATION

(Figs. 9)

Abstract: The reconstruction of P-T trends of the prograde stage in different zonal metamorphic aureoles with the help of geothermobarometers shows that, as a rule, they are subisobaric. This points to the fact that metamorphism is caused by fluid-thermal anomalies, and in the conditions of depth stabilization the trends of metamorphism do not coincide with the geothermal gradients lines. The retrograde trends are more diversified: they may be both subisobaric and with correlated fall of temperature and pressure (uplift of geoblocks).

In the course of the studies of the zonality of garnet grains from different subfacies it has been deduced that the prograde zonality (increase of X_{Mg}, decrease of X_{Mn} and X_{Ca}) is characteristic only of garnets from garnet, staurolite-chloritoid, staurolite-chlorite and staurolite-andalusite (kyanite)-biotite subfacies, whereas in all higher-temperature subfacies where in anatexis of injections of granites always take place, the zoning of garnets is retrograde. The general trend of a retrograde processes is metasomatic and it points to the replacement of the alkaline process by the acidic one, as soon as the temperature decreases, which is characteristic of postmagmatic phenomena in granitoids.

The space development of retrograde processes is characteristic of only areas saturated with pegmatites, migmatites of for external contacts of synmetamorphic granites. This proves that the reason for retrograde recrystallization at the descending branch of each metamorphic cycle is circulation of postmagmatic solutions separating from solidifying synmetamorphic granites.

Резюме: Реконструкция P-T трендов прогрессивного этапа в различных зональных метаморфических ореолах с помощью геотермобарометров показывает, что они как правило субизобарические. Это доказывает, что метаморфизм вызывается флюидно-тепловыми аномалиями в условиях глубинной стабилизации, а тренды метаморфизма не совпадают с линиями геотермических градиентов. Ретроградные тренды более разнообразны: они бывают как субизобарические, так и с сопряженным падением температуры и давления (всплывание геоблоков).

При изучении зональности зерен гранатов из разных субфаций установлено, что прогрессивная зональность (рост X_{Mg}, снижение X_{Mn} и X_{Ca}) характерна лишь для гранатов из гранатовой, ставролит-хлоритоидной, ставролит-хлоритовой и ставролит-андалузит(кианит)-биотитовой субфаций, тогда как во всех более высокотемпературных субфациях, где всегда имеет место анатексис или инъекции гранитов, зональность гранатов ретроградная. Общая тенденция ретроградных процессов — метасоматическая, и указывает на смену щелочного процесса кислотным по мере падения температуры, как это характерно для постмагматических явлений в гранитоидах. Площадное развитие ретроградных процессов характерно лишь для участков насыщения пегматитами, мигматитами или для экзоконтактов синметаморфических гранитов. Это доказывает, что причиной ретроградной перекристаллизации на нисходящей ветви каждого метаморфического цикла является циркуляция постмагматических растворов, отделяющихся от застывающих синметаморфических гранитов.

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This paper is concerned with prograde and retrograde evolution of zonal-metamorphic complexes of monocyclic type synchronous with granitoids. What is meant is their internal evolution — from the rise to the fall of geoisotherms. Superposition of metamorphic cycles of a younger age, that is polymetamorphism, is not discussed here.

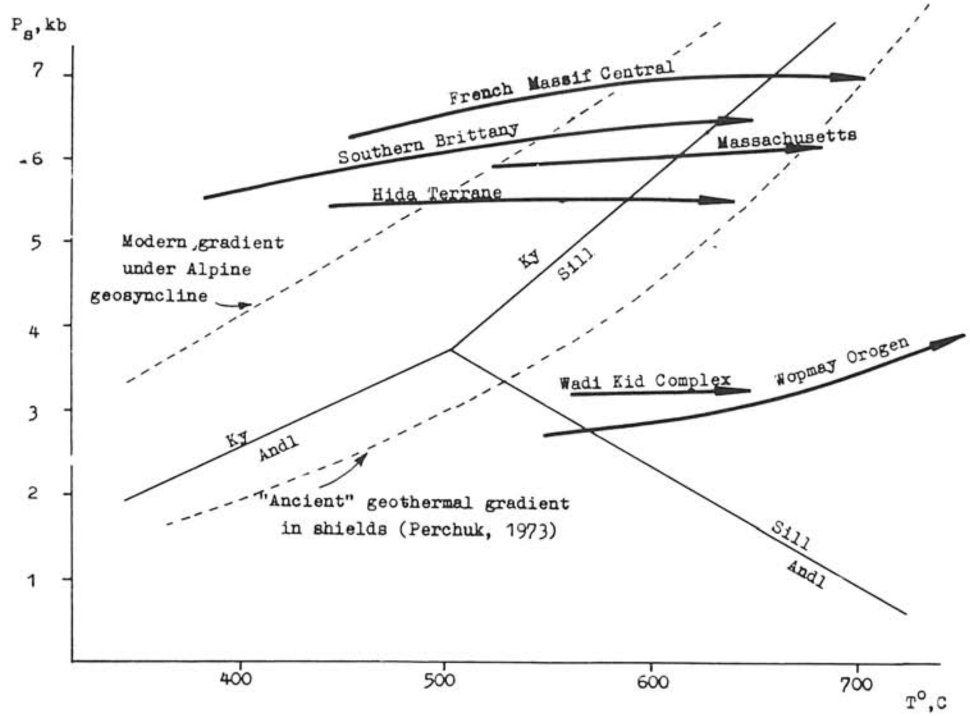

Fig. 1. P-T trends of the prograde metamorphism are deduced using several variants of biotite-garnet geothermometers, garnet-plagioclase-Al_2SiO_5-quartz geobarometers and petrogenetic grid: French Central Massif (Delor et al., 1984); Southern Brittany (Triboulet, 1983); Massachussetts (Tracy et al., 1976); Hida Terrane (Hiroi, 1983); Wadi Kid Complex (Reymer et al., 1984); Wopmay Orogen (St-Onge, 1984).
Lines of the geothermal gradients — from Перчук (1973); aluminium silicate triple point from Holdaway (1971).

It is possible to reconstruct a complete P-T - trend of each cycle at the stages of the rise and the subsequent fall of the temperature on the basis of the application of geothermobarometers and petrogenetic grids when investigating zonality of minerals. Geobarometric investigations of associations of the prograde stage inside individual aureoles frequently point to the fact that this stage trend is of either slightly declined or subisobaric character which is more often (Fig. 1). These trends are borrowed from the following works: Tracy et al., (1976); Hiroi (1983); Triboulet (1983); Delor et al., (1984); St-Onge (1984); Reymer et al., (1984) in the latter work the definition of P-T parameters of the garnet zone was not accepted, since it was based on a single sample). All of these trends, except for one, are from the publications of 1983—84 and their reconstruction is based on the latest barometers. As in shown, all the trends are almost horizontal. The pressure constancy inside the ensialic aureoles is also corroborated by the general analysis of paragenesises. Here are two ex-

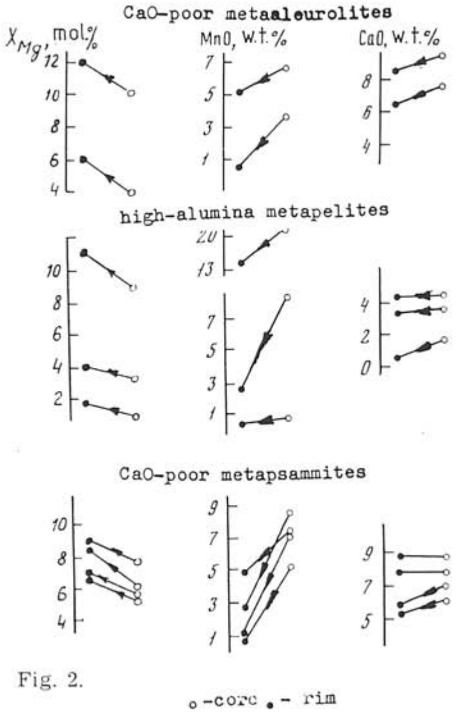

Fig. 2.

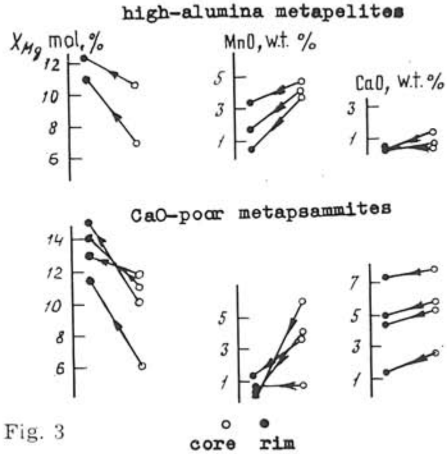

Fig. 3

Fig. 2. Prograde zoning in garnets from the garnet zone of the sillimanite-kyanite aureole of the Highlands (Кориковский — Федоровский, 1980).

Fig. 3. Prograde zoning in garnets from the staurolite-chloritoid zone of the sillimanite-kyanite aureole of the Patom (Кориковский — Федоровский, 1980).

amples. Thus, in the most deep-seated talc-kyanite and eclogite complexes ($P_s > 7$ kbar) signs of the same high pressure are found in the low-temperature zones as well, for example, stability of the peculiar paragenesis chloritoid + talc (Кориковский и др., 1983). On the other hand, a low-dense mineral cordierite is never encountered in the ordinary kyanite-sillimanite aureoles ($P_s = 4$—6 kbar) in the biotite and garnet zones, which fact could bear witness to the absence of signs that the low-temperature zones of the aureoles are less deep-seated. Meanwhile cordierite is stable in the biotite and garnet zones of many andalusite-sillimanite aureoles ($P_s = 1$—3 kbar).

A wide range of criteria shows that it is characteristic of the ensialic metamorphic aureoles their formation is not in the course of burial, but at the stage of depth stabilization. The prograde P-T trends of zonal aureoles, especially beginning from Proterozoic, do not coincide with the geothermal gradients lines (Перчук, 1973) but intersect them. This is their main distinction from the P-T trends of Archean granulites schields, whose trends coincide with the geothermal gradients.

Obviously the main reason for prograde zonal metamorphism in deep sections is thermal anomalies caused by the rise of fluid-heat flows, and granites are their effect, but not their cause. A specific fluid regime of the granite formation, being persisted inside each complex, proves the depth character of these flows. It is precisely for this reason, the granites composition, especially that in big bodies, does not depend at all on the composition of country rocks. For example, leucocratic two-mica and biotite granites which are the most typical of the regionally-zonal aureoles are equally often encountered both in eugeosynclinal belts where metabasites markedly prevail, and in miogeosynclinal basins with terrigenous rocks among which metabasites are fully absent.

A series of retrograde reactions occurs after the peak of metamorphism and granite formation. Two cardinal questions arise in this connection: are they caused simply by temperature decrease, and from where do the solutions originate? One of the answers to these questions follows from the investigation of the zonality of metamorphic garnets. The low-temperature subfacies worth to be considered first. For example, in the garnet-zone of the kyanite-sillimanite aureole of the Patom Highlands (Кориковский — Федоровский, 1980) garnets possess only prograde zoning (Fig. 2): the increase of Mg/Mg + Fe ratio from the core to the edges, with Mn and Ca content parallely decreasing. This is typical of the garnet zone in any aureoles. In the next staurolite-chloritoid zone of the Patom aureole the garnet zoning is also only prograde (Fig. 3) and this is a characteristic of this subfacies, no matter where.

But the picture changes drastically in the higher-temperature subfacies. In the similar Massachussetts aureole (Tracy et al., 1976) the prograde zoning remains only in the medium parts of the garnet grains (Fig. 4) in the staurolite-kyanite zone, and occasionally in the staurolite-sillimanite zone; the retrograde zoning (decrease of X_{Mg}, increase of Mn and Ca content) being superposed on it at the edges of the grains. Relics of the prograde zoning obliterate completely in all subsequent subfacies, and the retrograde zoning is formed along the entire grains profile. The application of a biotite-garnet thermometer with the use of the compositions of biotite inclusins into garnets gives conformal picture of a temperature changes in the course of crystallization of each individual grain of garnet (the right column in Fig. 4).

Absolutely similar data have been obtained for zonal-metamorphic complexes. The diagram (Fig. 5) shows a summarised P-T trend of the prograde and retrograde branches of the idealized zonal aureole and the garnet zonality in it. The following picture has always been the same: the garnet, the staurolite-chloritoid and the staurolite-chlorite subfacies are characterized only by the prograde zoning in garnets, the staurolite-kyanite (andalusite) and the staurolite-sillimanite subfacies are characterizied by prograde zoning in the medium part and by the retrograde zoning at the edges, the higher-temperature subfacies are characterized only by the retrograde zoning.

The reason for this rather unusual situation will become clear if one takes into consideration the fact that starting precisely from the staurolite-kyanite (andalusite) subfacies for the first time a big quantity of pegmatites and quartz-feldsphatic injections and granitization phenomena increasing with rising temperature appear.

Therefore, it will be more natural to connect the retrograde garnets changes with the space circulation of the postmagmatic solutions; and vice versa, these

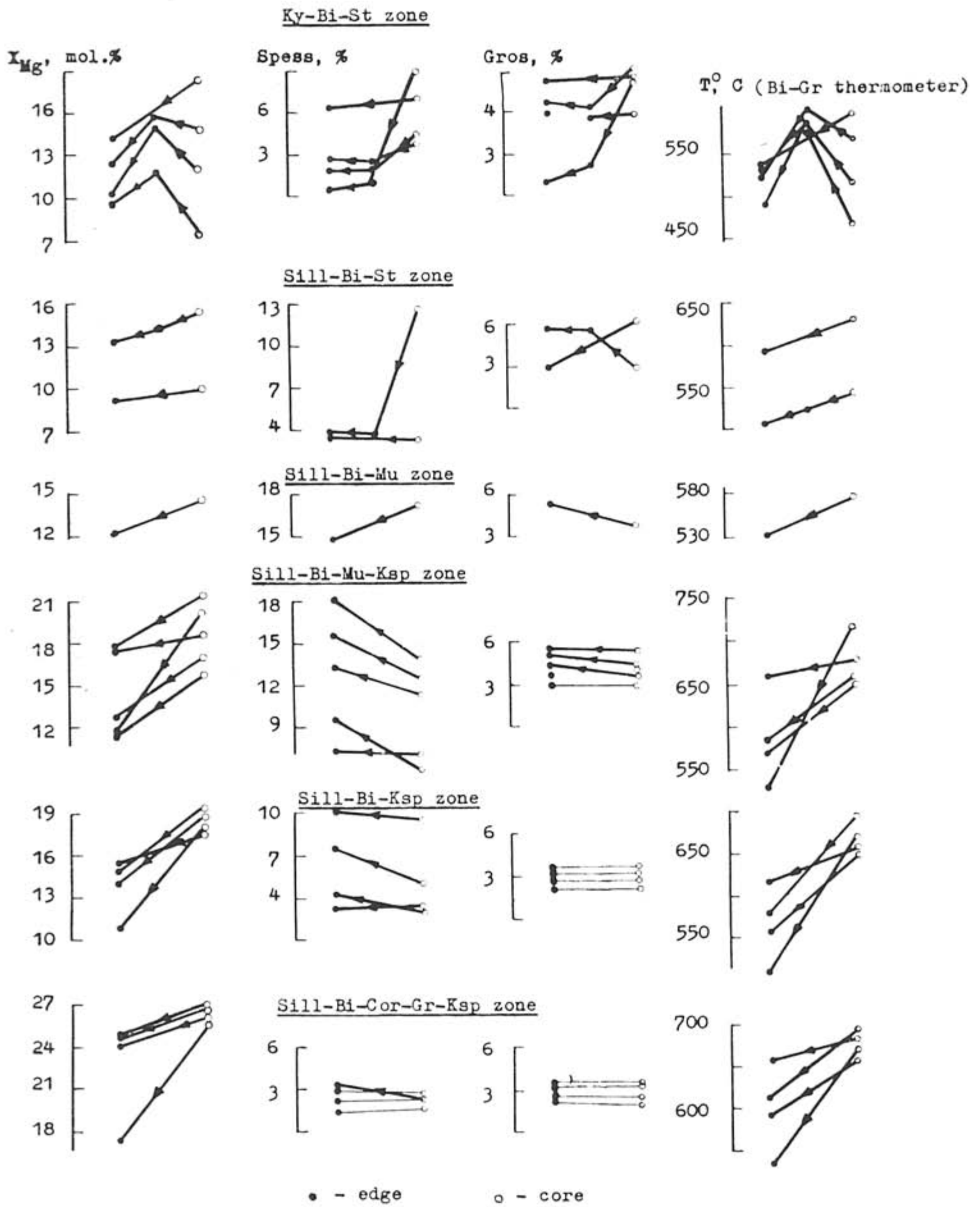

Fig. 4. Zoning in garnets from several metamorphic zones of the sillimanite-kyanite aureole of Massachussetts (Tracy et al., 1976), and temperature of crystallization of the internal and external parts of the garnets grains obtained from a biotite-garnet geothermometer.

changes are absent where there are no granites injections, that is, in the lower-temperature subfacies.

This conclusion has been corroborated unexpectedly during investigation of eclogites and talc-kyanite schists — that is, rocks whose minerals — talc and omphacite are not stable even with slight addition of alkalies, especially of K_2O. In the supracrustal Tasmania complex (Räheim, 1975) in unchanged

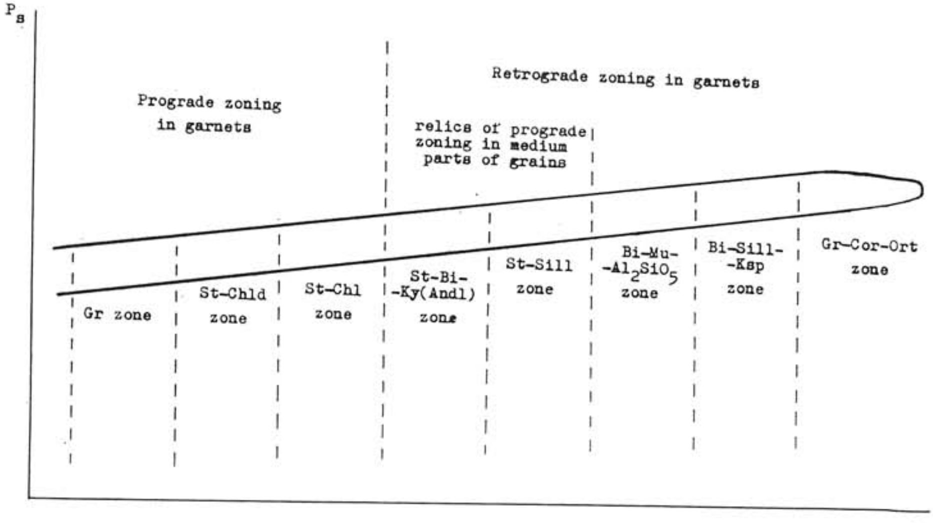

Fig. 5. A distribution of different types of zoning in the garnet grains inside a typical idealized metamorphic aureole.

eclogites garnet always possesses prograde zoning (Fig. 6), in slightly amphibolized eclogites it acquires retrograde zoning but only in the narrow edge zone, and in amphibolites with omphacite relics it possesses retrograde zoning almost along the entire grain. Zoning is always prograde (often with an enormous difference of garnet magnesiality from the core of the grain to its edge) in talc-kyanite schists alternating with eclogites, and in metapelites, whereas it is retrograde in albitized schists.

Thus the retrograde changing even extreemly magnesial high-temperature garnets absolutely has no connection with a normal temperature decrease — all these rocks have undergone the retrograde stage. But it is connected only with the areas of circulation of alkaline solutions, contributing to simultaneous albitization and amphibolization.

If one considers the chemism of retrograde reactions on the whole, it will become apparent that their main distinction from prograde ones lies in their metasomatic character, with an alkaline process being followed by an acidic one with falling temperature. This is an unambigous indication of the real source of the solutions.

For example, high-temperature retrograde reactions in metapelites are replacement of garnet, cordierite and staurolite by secondary biotite and feldspathization of rocks (Fig. 7). The arrows on the diagram — appearance of biotite-K--feldspar paragenesis — show that the reactions are accompanied with an increase of K and Na content in the rocks; that is, they are of an alkaline character.

The subsequent medium-temperature retrograde processes have a diametrically opposite tendency. In metapelites it is most often replacement of feldspars, biotite and garnet by muscovite (Fig. 8), formation of secondary alumina

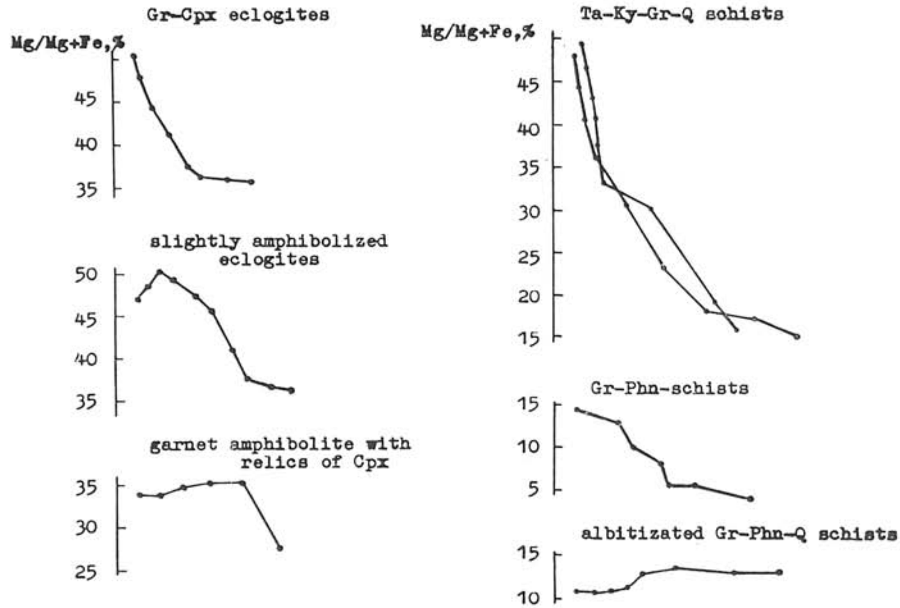

Fig. 6. Zoning in the garnets from unaltered and amphibolized eclogites, talc-kyanite schists, unalterated and albitizated garnet schists from Tasmania (R ä h e i m, 1975).

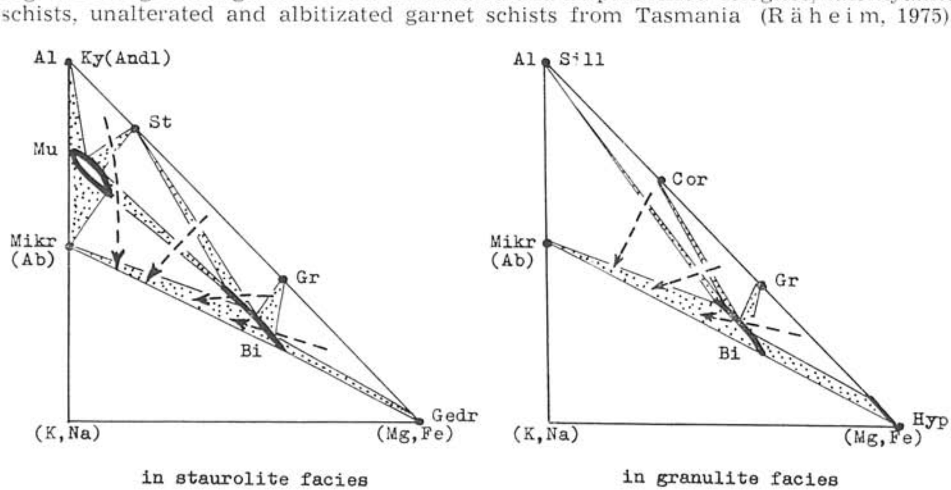

Fig. 7. A metasomatic tendency during the high-temperature retrograde stage in metapelites (an alkaline trend) on the diagram Al-(K, Na)-(Mg, Fe).

silicates, and also silification and tourmalinization. The arrows on the diagram show that these are typical acidic leaching processes accompanied with an increase of Al-quantity in the rocks with the loss of alkalies and bases (Korzhinskiy, 1965). Such bleaching zones are always conformal with numerous veins of redeposition — chlorite-, biotite- and epidote-veins.

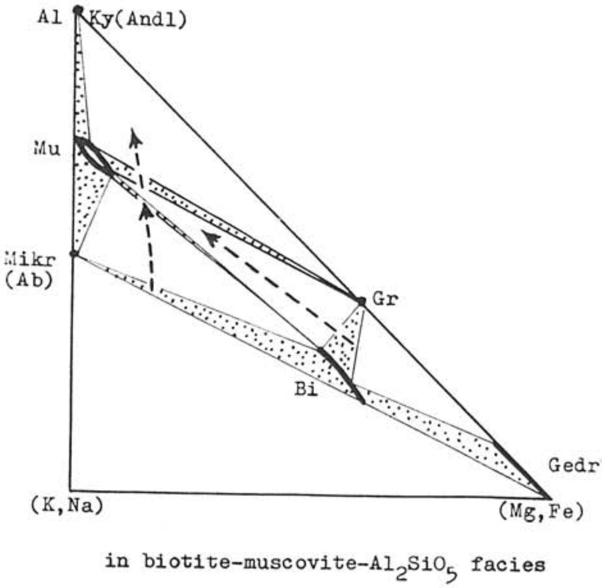

Fig. 8. A metasomatic tendency during the medium-temperature retrograde stage in metapelites (an acidic leaching process) on the diagram Al-(K, Na)-(Mg, Fe).

To everyone who investigated granitoids it is obvious that by their mineralogical manifestation and time retrograde reactions are synchronous with postmagmatic processes occurring in granitoids and quartz-feldspar injections, saturating these terrains. Thus, there are two observations, the first: localization of the retrograde phenomena on the whole and the retrograde changing of garnets exactly in the areas saturated with veined pegmatoid material or in the exocontacts with granites; the second: the inversion of the composition of the solutions from alkaline to acidic with falling temperature — which point to the fact that the reason for retrograde metamorphism is circulation of the postmagmatic solutions associated with granites in their veined or massive manifestation.

It is no coincidence that exactly at the retrograde but not at the prograde stage a big supply of volatiles characteristic of the fluid phase of granites is observed — a supply of B (tourmalinization), F (fluorite muscovites, topaz and fluorite appearance), sulphates, Cl and CO_2 (scapolitization and carbonatization of amphibolites).

In distinction from the prograde stage, P-T trends of the retrograde stage (Fig. 9) are much more varied — from almost isobaric trends in Massachussetts

(T r a c y et al., 1976) and French Massif Central (D e l o r et al., 1981) till trends with a separate (Southern Calabria — S c h e n k, 1984) or correlated (Coast Mountains — H o l l i s t e r, 1982) temperature and pressure decrease. The second and the third types of trends are characteristic of tectonic regimes with fast inversion, manifesting itself in the form of enormous faults and

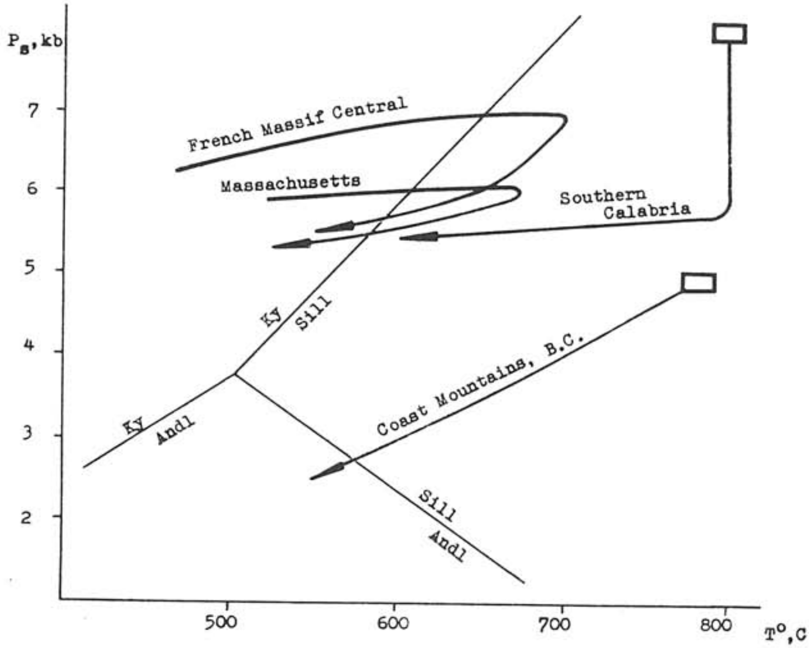

Fig. 9. Three typical variants of the retrograde metamorphic trends: A — subisobaric, French Massif Central (D e l o r et al., 1984), and Massachussetts (T r a c y et al., 1976); B — with a separate temperature and pressure decrease, Southern Calabria (S c h e n k, 1984); C — with a correlated temperature and pressure decrease, Coast Mountains (H o l l i s t e r, 1982).

rise of granite domes. But such trends like the one deduced by H o l l i s t e r in Coast Mountains (Fig. 9) are much more occasional since in the majority of metamorphic complexes uplift takes place later — on the orogenic stage of molass-forming. As a rule, the orogenic stage is always postmetamorphic.

The unity of postmetamorphic granites is always connected with the orogenic stage — these are "hot" granites, surrounded by hypabyssal hornfelses, which superimpose on the metamorphic rocks of the previous stage.

An uplift and an erosion usually occur only upon complete accomplishment of even the lowest-temperature retrograde processes of the regional stage. Do we have any evidence of that? Yes, we have. It is known, that a low-temperature alteration is usually associated with diaphthoritic sutures, where substational greenschists reworking and blastomilonitization are displayed. Formation of such sutures is a normal way of accomplishment of life of each metamorphic cycle. It is worth mentioning that pebbles of such greenschist diaphthorites can always be found in clastic molasses of the orogenic stage. Consequently, the retrograde phase, as a rule, is fully over during the pre--orogenic stage, before the uplift and the erosion of geoblocks.

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