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METAMORPHIC EVOLUTION OF SHIELDS AND FOLD-BELTS

(Figs. 9, Tab. 1)

Abstract: The geological position of metamorphic facies in the system marginal sea — island arc — Benioff zone is considered and P-T model of their evolution is developed. From studing evolution of the regional metamorphism three main problems arise: 1) tectonic control; 2) thermodynamic regime of the evolution; 3) the sequence of the metamorphic events with time. Solving all these problems enables to understand the main regularities of metamorphic processes. Both paragenetic analyses and thermometry and barometry allow to describe the metamorphic evolution in terms of temperature (T) and pressure (P). In Precambrian shields the prograde metamorphic stage is "erased" by diaphthoresis and as a result the prograde diffusion zoning in the coexisting minerals can not be preserved. Meanwhile, the prograde mineral reactions in the rocks can be found (substitution of biotite by hypersthene, garnet — by cordierite etc., Korikovsky, 1979; Perchuk et al., 1984). However, the retrograde chemical zoning is typical for participants of these reactions. Evolution of the P-T parameters of metamorphism can be described by the microprobe analysis of zoned coexisting minerals with the following application of geothermometers and geobarometers studied experimentally. In the fold metamorphic belts framing the shields mentioned above P-T parameters increase up to the granulitic conditions very rarely. The multiplied diaphthoresis is not typical for these formations and zoning in the coexisting minerals can reflect prograde as well as retrograde stages of metamorphic evolution. Some examples of such formations are given. The regional metamorphism of shields and fold belts is shown to occur at the conjugate PT-change. The time duration is not to be the main factor of metamorhpic evolution because it is determined by the following: 1) the degree of rock dislocation; 2) amount and composition of fluids and 3) intensity of the heat flow.

Резюме: Рассмотрена геологическая позиция метаморфических фаций в системе окраинное море-островная дуга-зона Беньоффа и развита P-T модель их эволюции. Три основных проблемы возникают при изучении эволюции регионального метаморфизма: 1) тектонический контроль; 2) термодинамический режим на всех стадиях эволюции; и 3) последовательность метаморфических событий и их продолжительность во времени. Совместное решение всех этих проблем позволит познать главнейшие закономерности формирования метаморфических формаций. Парагенетический анализ в совокупности с методами термометрии и барометрии позволяют записать в терминах температуры (T) и давления (P) метаморфическую эволюцию. В породах докембрийских щитов поргрессивный этап метаморфизма затушевывается при диафторезе и не проявляется в диффузионной зональности сосуществующих минералов. Вместе с тем, можно встретить минеральные парагенезисы прогрессивного типа (замещение биотита гиперстеном, граната — кордиеритом и т. п.). Но в минералах из этих ассоциаций также возникает зональность регрессивного типа. Запись эволюции PT-параметров метаморфизма можно осуществить на

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Symbols: Am — amphibole, And — andalusite, Bi — biotite; Chl — chlorite, Cor — cordierite,; Cpx — clinopyroxene; Chd — chlorithoid; Gr — garnet; Ky — kyanite, Mu — muscovite, Opx — orthopyroxene; Pl — plagioclase; Sil — sillimanite; St — staurolite; Qz — quartz; P — pressure; T — temperature, °C.

основе микрозондового анализа зональных сосуществующих минералов и соответствующих геотермометров и геобарометров, выведенных теоретически и экспериментально. В складчатых областях, нередко представляющих собой более молодые обрамления щитов, PT-параметры метаморфизма очень редко возрастают до условий гранулитовой фации. Редко здесь можно встретить многократное наложение диафтореза и потому зональность сосуществующих минералов может отражать как прогрессивный, так и регрессивный этапы метаморфизма. Такие примеры приводятся для нескольких формаций. Показано, что региональный метаморфизм щитов и складчатых областей осуществляется при сопряженном изменении PT-параметров. Время не является главным фактором эволюции метаморфизма, срок которого определяется степенью дислоцированности пород, присутствием флюидной фазы и интенсивностью теплового потока.

Numerous investigations on distribution of the heat flows in the island arcs and marginal basins as well as calculations of the isothermic surfaces up to 1100—1200 °C (to a depth of 100 km) enable to expand significantly our knowledge about geotectonic and thermodynamic regimes of metamorphism developed in the shields and fold belts.

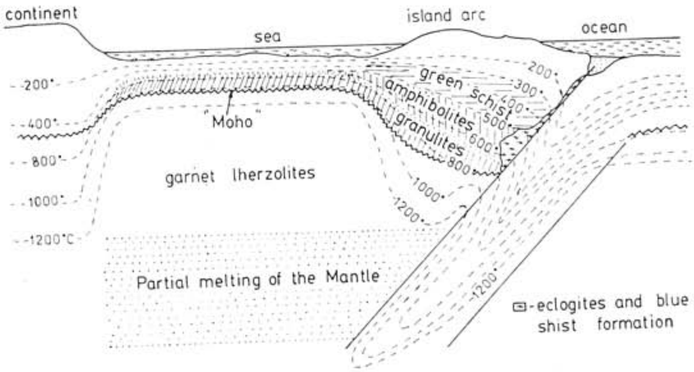

Fig. 1. Cross-section beneath marginal sea depression and island arc. Distribution of isotherms in the Earth's crust and in the mantle according to the heat flow data are shown in respect to the position of the major metamorphic facies.

Fig. 1 presents a schematic geophysical section through the continental margin, the sea, the island ars and the Benioff zone. The isotherms plotted show a typical distribution of temperature beneath these kinds of sections. The approximate positions of the main metamorphic facies (granulitic, amphibolitic, greenschist as well as glaucophane schist) are also shown in the section in accordance with our geological experience. Most granulites are noticed to be formed under tectonic and thermodynamic regimes in the lower crust beneath the deep-sea basin. In the basement of the island arcs granulites may form high grade parts of the zoned metamorphic complexes, for example, the Ladozhskaya Formation of the Baltic shield.

Table 1

Internally consistent system of mineralogical thermometers and barometers used

Thermometers and barometers	References
Thermometers	
St + Gr, Chl + Gr, Chd + Gr, Am + Gr Cpx + Gr, Am + Cpx, Am + Pl, Am + Opx	Перчук (1966, 1976, 1970) Perchuk (1968, 1969)
Bi + Gr, Cor + Gr	Перчук (1967 a, 1970) Perchuk (1971); Perchuk-Lavrent'eva (1983)
Barometers	
P-T grid for pehnite-pumpellyite facies	Perchuk—Aranovich (1980)
Cor + Gr + Sil + Qz	Перчук (1973); Perchuk (1977); Aranovich—Podlesskii (1983)
Pl + Gr + Sil + Qz	Аранович—Подлесский (1980)
Cpx + Gr	Perchuk (1968); Перчук (1970)
Bi + Gr + Sil + Qz + Mu ± St	Перчук (1973, 1983) Perchuk (1977)
Opx + Gr + Sil + Qz Opx + Gr + Cor + Qz	Perchuk et al. (1984)

Fig. 1 also shows that P-T conditions of metamorphism are determined chiefly by the position of the chosen volcanogenic or sedimentary complex in respect to the relatively cold Benioff zone and the belt of the intensive magmatic processes in the inner part of the island arc.

According to the heat flow distribution three main geostructural units can be distinguished:

1) The marginal deep-sea basin with moderate grade of metamorphic conditions above the Moho boundary.

2) Middle parts of the island arcs with sharp temperature changes across isotherms and zoned metamorphic complexes developed. For example, the Archean Ladozhskaya Formation (And-Sil type), the White Sea Formation (Ky-Sil type) as well as numerous zoned metamorphic complexes in the Phanerozoic fold belts.

3) Metamorphism along the Benioff zone. According to the scheme in Fig. 1 the metamorphic zoning is mainly formed due to changes in depth and slightly — due to temperature increasing. Miyashiro considers this kind of metamorphic processes as "high pressure metamorphism" with development of

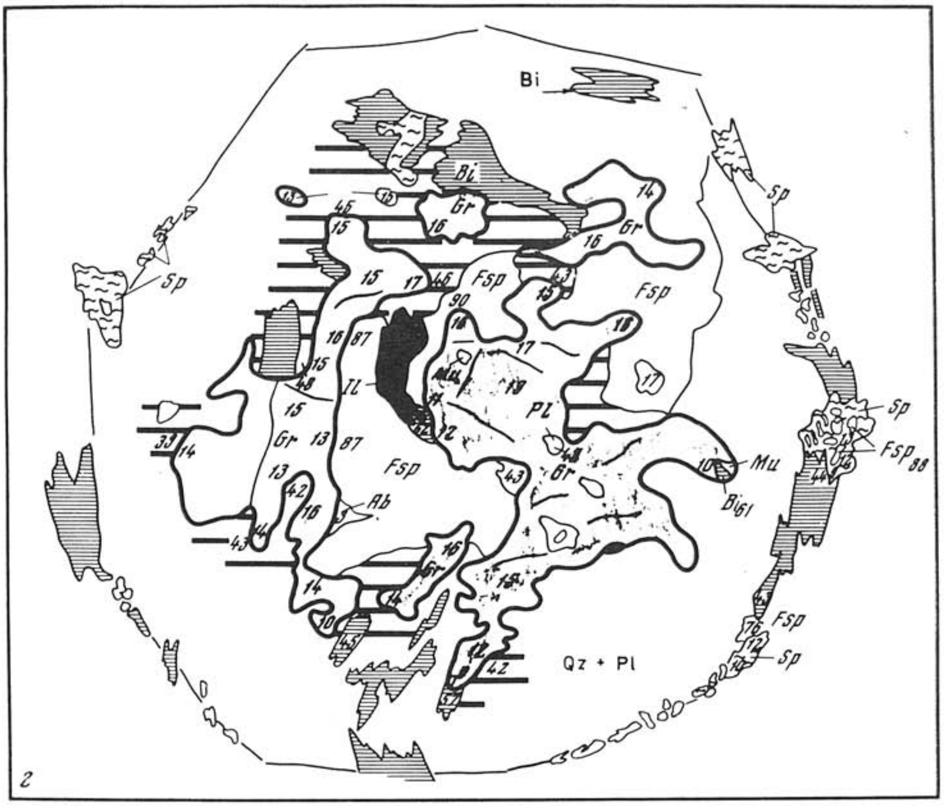

Fig. 2. The relict garnet grain with noticeable chemical zoning from gneiss of the Precambrian Hanka complex. Substitution of the grain by a plagiogranitic material can be seen.

zoning from zeolitic and prehnite-pumpellyitic rocks through greenschists, blueschists to the amphibolitic zone (E r n s t, 1971). Tectonic regime of metamorphism in these zones judging from the well-known Sambagawa (Japan), Maskytovskii (the S. Urals), Franciscan (California) etc. complexes is very complicated. For example, a tectonic contact between the blueschist zone and garnet amphibolites is typical of the formations.

There is no sharp boundary between the metamorphic complexes of the above main geostructural units (see Fig. 1). But detailed investigation of the, metamorphic evolution of the rocks of each unit enables to diagnose and reconstruct with assurance the thermodynamic and geostructural situation.

Mineralogical thermometry and barometry are of prime importance together with detailed microprobe analysis of minerals coexisting in a chosen metamorphic rock (Tab. 1). In Fig. 2 (a sample from the Hanka crystalline massif, Far East) together with substitution of the garnet grain by a plagiogranitic material one may also see a marked zoning in the relict garnet grain pointing to the fact that granitization has developed with decreasing both T and P, i. e. at the retrograde metamorphic stage.

Let us consider gradually thermodynamic regimes of metamorphism in the mentioned geostructural units during their evolution, i. e. the main thermodynamic parameters:

Metamorphism of the Precambrian shields and mid massifs without clearly defined zoning was likely to occur in the sufficiently dislocating marginal parts of the continents with the highly developed large depressions and thick strata of volcanogenic-sedimentary rocks. It was almost impossible to find evidence of the prograde metamorphic events in granulites of the shields, but zoning in minerals maintains some tracks of the retrograde stage. For instance, the Mg/Fe ratio decreases to the rim of the Gr grains, but in coexisting minerals this ratio increases (exchange equilibria). Otherwise, especially in the polymineralic equilibria the Mg/Fe ratio of each coexisting mineral might decrease simultaneously with increase of the distribution coefficient.

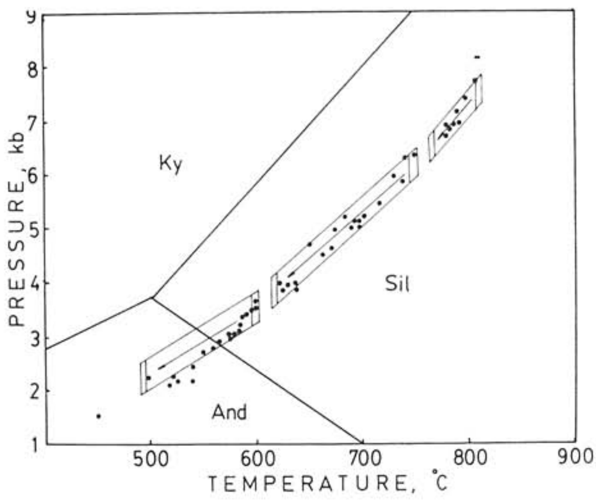

Fig. 3. P-T trend of the retrograde metomorphic stage in the Precambrian Hanka complex, Far East (П е р ч у к и др., 1983).

Over the last few years we have studied (П е р ч у к и др., 1983; Perchuk et al., 1984) metamorphism of the Hanka massif, the Aldan shield and Ladoga Formation. Using several thousands of microprobe analyses and the phase correspondence principle we have proved that prograde metamorphic reactions do not proceed in the granulites. But retrograde metamorphic reactions are definitely seen and allow to reconstruct the evolution of metamorphism in terms of the P-T parameters.

Fig. 3 shows a trend of the P and T decrease of the retrograde metamorphic stage in the Precambrian Hanka massif (Far East). It agress well with Berdnikov and Karsakov's data (Бердников—Карсаков, 1983) on cryometry and homogenization of the gas-liquid inclusions in minerals of the same rocks. No metamorphic zoning in the Hanka Formation was found at the Japan Sea shelf and the continental margin (К о н о в а л о в, 1984). As in seen from Fig. 3 evolution of metamorphism of the Hanka Formation rocks accomplishes in the andalusite stability field, while sillimanite is the most popular among metapelites. But we managed to discover andalusite in these rocks metamorphosed at the retrograde stage, thus proving mineralogically that the trend of Fig. 4 is quite correct.

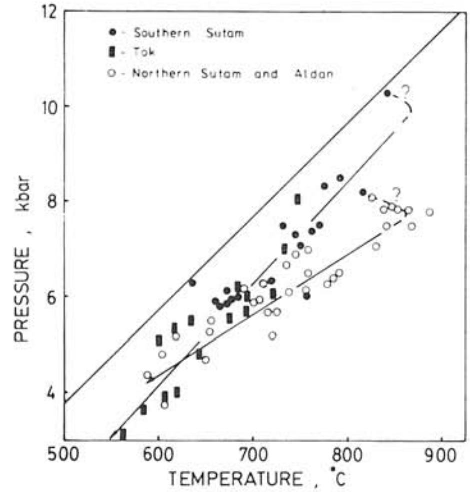

Fig. 4. P-T trend of the retrograde metamorphic stage in the Precambrian Aldan shield, Eastern Siberia (P e r c h u k et al., 1984).

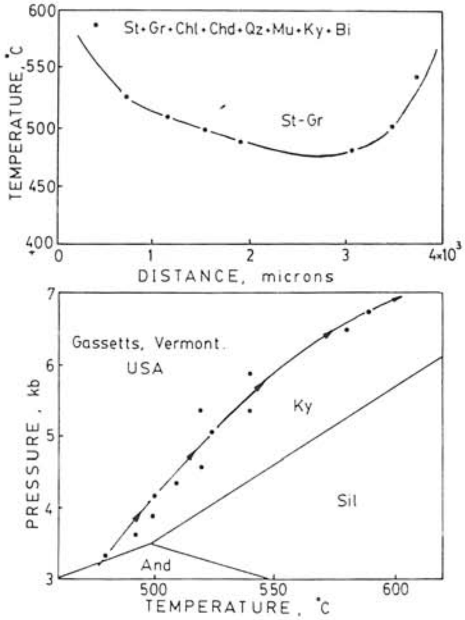

Fig. 5. Temperature profile across zoned garnet grain from kyanite-staurolite schist of the Early Paleozoic Vermont metamorphic Formation (USA) and P-T trend of prograde stage of metamorphism (according to analytical data by T h o m p s o n et al., 1977); the profile and trend were deduced with a help of mineralogical thermometers and barometers mentioned in Tab. 1.

The Archean Aldan shield (Eastern Siberia) exposed over two hundred thousand square kilometers consists exclusively of the granulites. To a rough approximation, it was divided by A. A. M a r a k u s h e v (М а р а к у ш е в, 1965) into two depth units: northern (Aldan facies) and southern (Sutam facies). The high pressure Sutam unit adjoins the Aldan unit along the large fault. The most high grade Opx+Sil+Qz rocks formed at $T \approx 820$ °C and $P = 11$ kbar may be found there. In comparison with the Aldan granulites the exposure area of the Sutam unit is very small and unlikely to account for one tenth of the Aldan unit. South-eastwards, within the boundaries of the Stanovoy fold belt relics of the Archean basement as a part of the Sutam unit are also exposed (the Tokskii block). Hypersthene-sillimanite granulites are well developed there, but they were intensively altered during the Proterozoic folding cycle (Stanovoy metamorphism).

In Fig. 4 the P-T trends for the rocks of the Aldan unit does not deviate to the kyanite field; it is defined for the Sutam and partly emphasized for the Tokskii block.

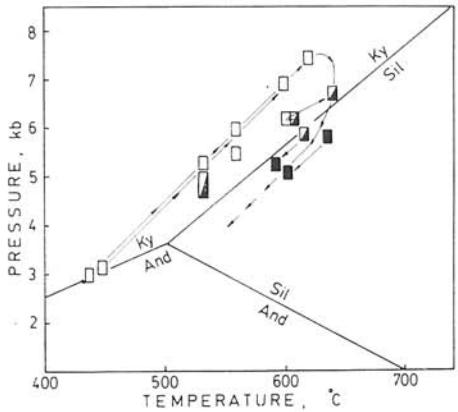

Fig. 6. Prograde and retrograde stages of metamorphism of mica schists from Penfold Greek, British Columbia, Canada (after analytical data of Fletcher — Greenwood, 1979).

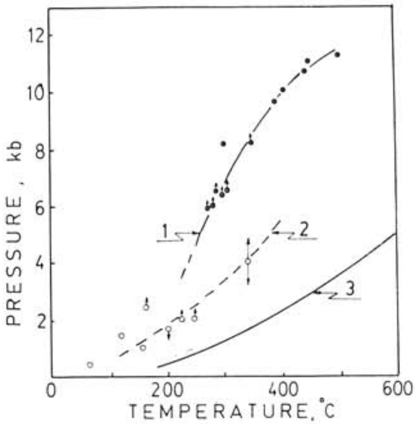

Fig. 7. P-T trend of prograde metamorphism of volcanic-silica sediments in the subduction zones (after Perchuk — Aranovich, 1980).
Explanations: 1 — glaucophane schist provinces; 2 — zeolite and prehnite-pumpellyite rock complexes; 3 — geothermal gradient beneath Precambrian shields and some Paleozoic metamorphic belts.

Comparing P-T regimes with a position of granulites in the geophysical section (see Fig. 1) we may conclude that the Aldan unit has been formed beneath the marginal deep-sea basin, while the Sutam one was metamorphosed beneath the island arc zone. A long life of the tectonic zone is marked by magmatic processes: Mesozoic granodioritic and dacitic magmatism is widespread (Антонов, 1984).

Metamorphic belts of Precambrian to be founded and developed on the volcanogenic-sedimentary basement of the inner parts of the island arcs were described many times in the petrological literature. The Ladozhskaya Formation represented by a complete section (of the 100 km thickness) of metamorphic facies is one of a large group of such zoned belts. Prograde metamorphic reactions hardly proceed in this formation; only garnet associating with staurolite, biotite and andalusite has occasionally a prograde chemical zoning. However, prograde reactions widely occur in the zoned complexes of the amphibolitic metamorphic facies.

In most complexes of a kyanite-sillimanite type there are garnets with a prograde chemical zoning. For instance, lower Paleozoic metapelites of Vermont (USA) (see Fig. 5), the Penfold Greek mica-bearing schists (British Columbia, Canada) (see Fig. 6). Amphibolites widespread in the eugeosyncline metamorphosed zones of the Paleozoic section (in the Western Carpathians) may be also included into the same metamorphic type. Phase relations and chemical compositions of coexisting minerals followed by evaluation of P-T conditions of metamorphism in the area have been recently described in a special paper (Перчук и др., 1984).

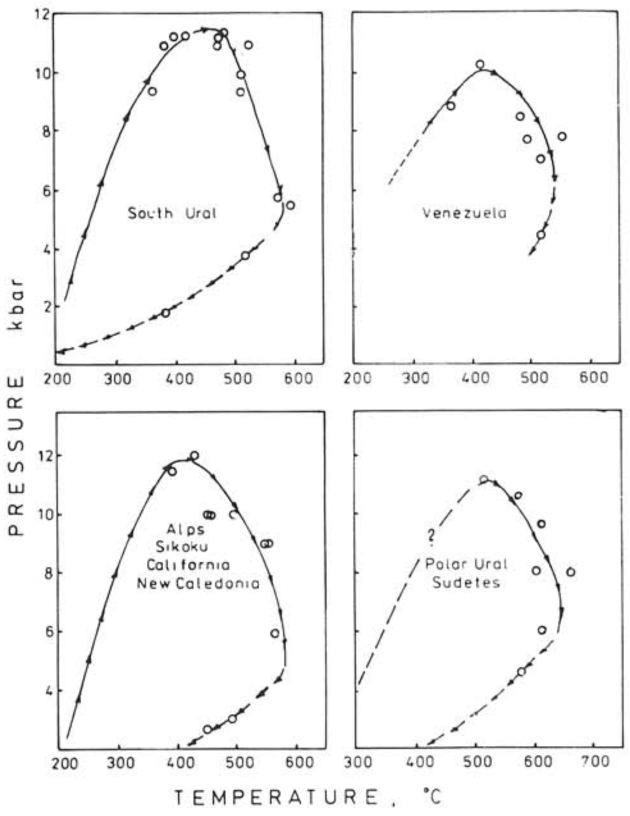

Fig. 8. P-T evolution of metamorphic rocks in some blue-schist belts (after Perchuk, 1977, p. 336).

Four metamorphic complexes differing in regime of metamorphism have been distinguished: the Small Fatra, the High and Low Tatras, the Small Carpathians. The latter was formed at the lowest pressure. The prograde metamorphic stage is sharply changed by the retrograde one. The other complexes are much deeper and have a clearly seen prograde stage of metamorphism.

Thus, in contrast to the shields and mid massife the fold belts are characterized by a highly developed zoned metamorphism and markedly defined retrograde and prograde metamorphic stages.

The complexes metamorphosed along the upper roof of the Benioff zone are very close in thermodynamic regimes to the above cited ones (see Fig. 1). They are represented by zoned assemblages of glaucophane schists with iron-rich eclogites and garnet amphibolites. Low temperatures of metamorphism cause a very small dT/dP gradient. As was mentioned above Miyashiro placed strong emphasis in the development of the low grade metamorphic processes beneath the external island arcs on this type of metamorphism.

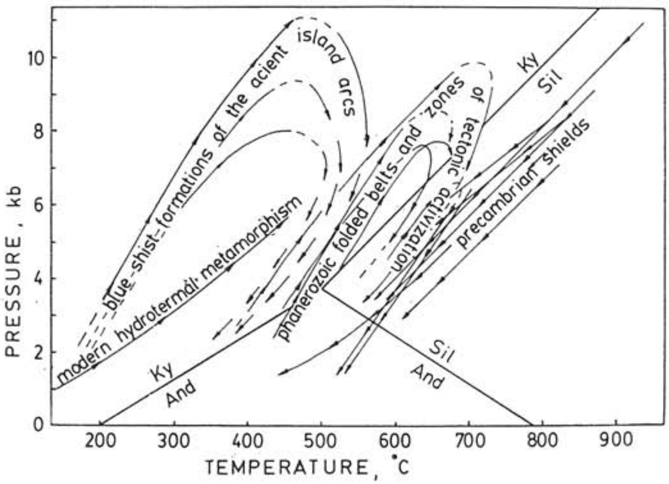

Fig. 9. Summarized trajectories of the P-T conditions of metamorphism of shields and fold-belts.

We have calibrated the metamorphic zoning along the Benioff zone in terms of P and T (Fig. 1). The results are shown in Figs. 7 and 8. The former reflects our previous calibration (Перчук, 1973) concerning, basically, the right side of the loop as the latter shows recent (Perchuk—Aranovich, 1980) calibration of the prograde part of the loop.

In most glaucophane schist provinces tectonic blocks of the Gr amphibolites and eclogites occur within the outer boundary of the blueschists. Drop in pressure (while temperature slightly increases) is typical of these parts of zoning.

In summary, we may conclude that all the three geostructural units, namely:

1) shields, i. e. ancient deep-sea depressions;

2) the moderate grade metamorphic belts, i. e. ancient inner sides of the island arcs, and

3) the low grade metamorphic belts belonging to the ancient outer sides of the island arcs, i. e. developing along the Benioff zones, differ not only in tectonic evolution, but also in thermodynamic regimes of metamorphism.

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The author is responsible for language correctness and content.