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THERMAL STRUCTURE OF THE CRUST DURING GRANULITE METAMORPHISM: PETROLOGICAL SPECULATIONS AND GEODYNAMIC IMPLICATIONS

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Abstract: It is shown on a basis of generalization of lateral and vertical distribution of *P-T* parameters in granulite-gneiss belts of various ages that the thermal gradient within the lower crust during granulite metamorphism is rather low, *ca.* 5-10°C/km. Two extreme types of granulitic crustal sections are recognized. First type (GM1) corresponds to normal and especially to thinned (25-40 km) crust. High and ultra-high temperatures (up to 1050°C) are characteristic for the deepest granulites of this type. Second type (GM2) corresponds to thickened (50-55 km) crust. It is characterized by moderately high temperatures in the lower crust (from 700-800°C at crust-mantle boundary). GM1 is generally connected with settings related to the hot mantle upwelling to crust-mantle boundary accompanied by heat and penetrating fluid fluxes and crustal extension or crustal thinning. Maximal heating is characteristic for the most thinned crust, *i.e.*, for riftogenic environment including extension zones in back areas of active continental margins and in the crust of epi-continental sedimentary basins. Metamorphism of GM2 type is related to compression conditions and collision crustal stacking.

key words: granulite metamorphism, thermal structure, crust, thermobarometry

1. Introduction

The appearances of granulite metamorphism are widely distributed in the Early Precambrian from at least 3.65-3.6 Ga (Nutman *et al.*, 1993), they are known in more limited areas in the geological record as late as the Mesozoic (Fiordland complex, southwest New Zealand (Bradshaw, 1989)) and Cenozoic (Hidaka belt, northern Japan (Osanai *et al.*, 1991)). This indicates that high-grade metamorphism is a fundamental process in the evolution of deep continental crust. The extended granulite-gneiss terranes (linear belts and subequant areas) form the most characteristic type of granulitic complexes. The distinct features of these complexes are high-grade metamorphism, restriction of peak metamorphic parameters to the *P-T* realm of granulite and high-temperature amphibolite facies and low water activity; associated rocks formed under lower conditions are usually correlated with later tectonic and metamorphic events. Recent studies of both young and ancient granulite-gneiss terranes do not permit to get enough indisputable interpretation of geodynamic settings of high-grade metamorphism because of the deep nature of the processes and impossibility of any kind of direct observations. There is also controversy in understanding of tectonic processes and geodynamic settings responsible for exhumation of granulitic rocks, although at least some of solutions of this problem are based on uniformitorian analogies. Most of recent tectonic correlations of high-grade metamorphic processes are based on variations of pressure-temperature (*P-T*) regimes and pressure-temperature-time (*P-T-t*) paths (see reviews of Harley (1992), Percival (1994), Rudnick and Fountain (1995)). There is an almost universal agreement among researchers that pressure in granulite-gneiss complexes depends on a depth of metamorphism, *i.e.*, it may be defined in most cases as lithostatic pressure. Nevertheless, in spite of real significant thickness of such complexes, the *P-T* data on local parts of granulite-gneiss terranes are usually considered as representative of metamorphic regimes for these complexes in a whole. Only in recent years the evidences of regular distribution of *P-T* parameters in some granulite-gneiss belts were obtained in a result of careful sampling of their vertical and lateral cross-sections (petrological mapping). By admitting thrust-nappe ensembles of granulite-gneiss belts as lower crustal fragments tectonically displaced to upper crustal levels, we may consider these data as characteristics of *P-T* (depth-*T*) distribution in the lower crust when it was under high-grade metamorphic conditions.

Numerous thermal influences affected granulite-gneiss belts after peak metamorphism which is evident in thermobarometric studies (Fonarev *et al.*, 1993, 1998; Mints *et al.*, 1996a, b). These regional events (metamorphic stages) are divided by significant time intervals and occur under various geodynamic conditions. There are the significant divergences in opinion of researchers on the character of temperature changes during the intervals between metamorphic stages. For understanding of geodynamic nature of granulite-gneiss complexes, establishing the setting of peak metamorphic stage is of highest priority as this stage defines the character of granulite-gneiss complexes. These data permit study of the thermal structure of the crust in areas of initial granulite metamorphism and thus give us a key for interpreting the geodynamic settings of metamorphism.

Published results of petrological mapping of granulite-gneiss complexes are still rare. Below we will discuss three representative examples: (1) Lapland granulite belt in Northeastern Baltic Shield; (2) Nilgiri block in Southern India and (3) Highland complex in Sri Lanka.

It is necessary to specially note that a target of our study included only granulite-gneiss belts proper. Metamorphic complexes of UHP type including complexes originating during major crustal overthickening are not discussed in this paper. We also will not consider problems of exhumation of granulites, corresponding *P-T-t* paths and geodynamic settings.

2. Thermobarometry

Petrological mapping of granulite-gneiss belts makes the problem of coordinating *P* and *T* estimates, obtained using different types of geothermometers and geobarometers, especially acute in the most interesting and most difficult cases namely (1) when the studied rocks have a broadly varied chemical composition and (2) in case of great thickness of the exhumed crust fragment resulted in significant variations in *P-T* from top to bottom. Tc solve the above problem we used the consistent system of geothermometers and geobarometers developed in the Institute of Experimental Mineralogy (Fonarev *et al.*, 1991, 1994). The thermometer subsystem includes the published earlier experimentally based versions of the two-pyroxene (Fonarev and Graphchikov, 1991), garnet-orthopyroxene (Perchuk and Lavrent'eva, 1990), garnet-clinopyroxene (Powell, 1985) and garnet-biotite (averaged from Perchuk and Lavrent'eva, 1983; Holdaway and Lee, 1977) geothermometers. The barometer subsystem includes garnet-orthopyroxene-plagioclase-quartz (Graphchikov and Fonarev, 1990) and garnet-clinopyroxene-plagioclase-quartz geobarometers (Fonarev *et al.*, 1994). A version of garnet-Al_2SiO_5-plagioclase-quartz geobarometer of Koziol and Newton (1989) was also used for metapelites.

Additional testing of both subsystems from data on more than 700 independent experiments reported in 56 recent publications (1989–1997) has confirmed the reliability of thermometers and barometers used here (Konilov *et al.*, 1997a). Experimental conditions and statistics describing deviations of calculated temperatures and pressures from those parameters in experiments are given in Table 1. As seen in the table, the correlation of temperatures and pressures estimated using above mentioned geothermometers and geobarometers, with experimental T and P is rather good over a wide range of temperatures and pressures. The only exception is the garnet-biotite geothermometer. To identify the reason of this exception, a critical analysis of both the experimental data used at testing and the existing variants of the garnet-biotite geothermometer is required. Comparison of our version of the garnet-biotite thermometer, obtained after selection from more than 20 published versions (Fonarev *et al.*, 1991), with recently published experimental data is

Table 1. Comparison of measured and calculated temperatures using different geothermometers and geobarometers.

System	N_1	N_2	P, kbar	T, °C	Av.	s.d.	R
Opx-Cpx	24	98	0.001-60	875-1650	−45	104	0.824
Grt-Opx	21	75	5-110	850-1950	5	135	0.878
Grt-Cpx	25	219	10-140	850-2035	−39	91	0.904
Grt-Cpx[1]	1	125	15-29	800-1200	−66	133	0.630
Opx-Cpx, Grt-Opx and Grt-Cpx	8	32	10-60	900-1650	−35[2]	95[2]	0.908[2]
Grt-Bt	12	106	2-34	550-1225	122	90	0.626
GOPQ	6	26	5-17	850-1000	−0.07	1.28	0.896
GCPQ	4	20	10-20	850-1000	−0.39	0.84	0.969
GOPO and GCPQ	2	4	10-15	900-1000	−0.30[3]	1.08[3]	

Note: N_1-number of publications; N_2-number of experiments; Av.-average values of T_{exp}-T_{calc} (ΔT) or P_{exp}-P_{calc} (ΔP); s.d.-standard deviation of ΔT or ΔP; R-correlation coefficient of T_{exp} (P_{exp}) and T_{calc} (P_{cale}); [1]Data of Aranovich and Pattison (1995) only; [2]Given T_{ealc} is the average of temperatures calculated from three thermometers; [3]Given ΔP is the difference between the two geobarometers. Abbreviations: Bt-biotie; Cpx-clinopyroxene; Grt-garnet; Opx-orthopyroxene; GCPQ-garnet-clinopyroxene-plagioclase(Pl)-quartz(Qtz) geobarometer; GOPQ-garnet-orthopyroxene-plageoclase-quatrz geobarometer.

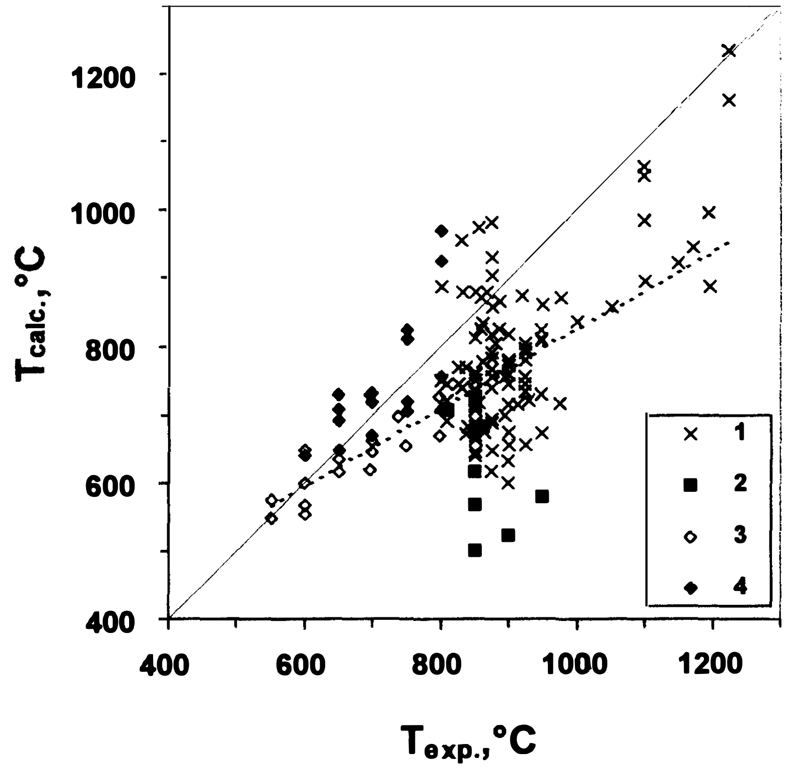


Fig. 1. Comparison of garnet-biotite thermometry utilizing experimental data. Data from: 1—11 undivided publications and unpublished data of J.-M. Montel and D. Vielzeuf (personal communication, 1997), 2—Patiño Douce and Beard (1996) experiments in which X_{Fe}^{Grt} > 0.98, 3—Ferry and Spear (1978), 4—Gessmann et al. (1997). The solid lines delineate a 1 : 1 correspondence between calculated and experimental temperature. The trend-line (dashed) was obtained using of data of Ferry and Spear (1978) only.

shown in Fig. 1, together with data from recent studies, including temperatures calculated using the analytical data of Ferry and Spear (1978). It is clearly seen that new experiments carried out by Gessmann with co-authors (Gessmann *et al.*, 1997) using Ferry and Spear's (1978) design provided results that correspond better to the calibrations of Perchuk and Lavrent'eva (1983) and Holdaway and Lee (1977) than to those of Ferry and Spear (1978). At temperatures near 600°C the divergence between results from various series of experiments is minimal. Thus estimates for low-grade metamorphic stages are generally reliable.

Deviations of obtained T and P values for the two-pyroxene geothermometer and garnet-pyroxene thermobarometers may be quite steadily explained by compositional heterogeneity of products of experiments and metastable crystallization of phases. The run products in 32 experiments consist of an assemblage containing garnet, clinopyroxene and orthopyroxene. It was concluded on the basis of data from those experiments that temperatures calculated on orthopyroxene-clinopyroxene, garnet-orthopyroxene and garnet-clinopyroxene geothermometers selected for our system are in good agreement with each other (Konilov *et al.*, 1997a).

As seen in Fig. 2, estimations made with garnet-orthopyroxene-plagioclase-quartz and

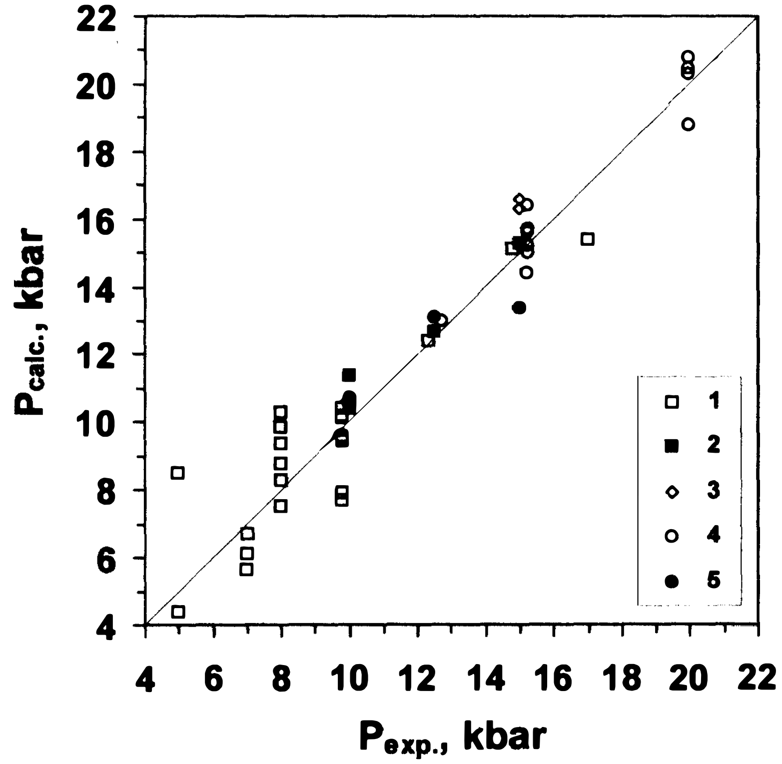


Fig. 2. Comparison of garnet-pyroxene (Grt-Opx-Pl-Qtz and Grt-Cpx-Pl-Qtz) barometry utilizing experimental data from 8 publications and unpublished experimental data of J.-M. Montel *and D.* Vielzeuf *(personal communication, 1997). Grt-Opx-Pl-Qtz geobarometer: in assemblages Grt + Opx + Pl + Qtz (1), Grt + Opx + Cpx + Pl + Qtz (3) or Grt + Opx + Pl + Qtz ? (5); Grt-Cpx-Pl-Qtz geobarometer: in assemblages Grt + Cpx + Pl + Qtz (2) or Grt + Opx + Cpx + Pl + Qtz (4). The solid lines delineate a 1 : 1 correspondence between calculated and experimental pressure.*

garnet-clinopyroxene-plagioclase-quartz geobarometers are in good agreement with the pressures in corresponding experiments. Four experiments yielded a garnet-orthopyroxene-clinopyroxene-plagioclase-quartz association as a run product. The pressures calculated on two geobarometers from these experiments have an average divergence 0.3 kbar only.

As a source of analytical data for the Lapland granulite belt and in limited part for Nilgiri block our own data were used. In the Nilgiri case most of the data were utilized from available publications (Janardhan *et al.*, 1982; Raith *et al.*, 1983, 1990; Srikantappa *et al.*, 1992; Srikantappa, 1996; Touret and Hansteen, 1988). For petrological characteristics of Highland complex thermobarometric estimates published by Schenk *et al.* (1991) and Schumacher and Faulhaber (1994) were used.

3. Results of Petrological Mapping

Lapland granulite belt (*LGB*) (the western fragment of extensive Lapland-Kolvitsa belt) in the northeastern Baltic Shield is a well-known high-grade unit. It was interpreted as thrust-nappe ensemble on a basis.of structural and seismic data (*e.g.*, Gaal *et al.*, 1989;

MINTS *et al.*, 1996b). LGB is dominated by metapelitic gneisses except in its eastern branch where metapelitic gneisses alternate with mafic rocks. The irregularly metamorphosed gabbro-anorthosite bodies are localized in the base of the thrust ensemble. This ensemble is underlying by a tectonic melange zone that includes dunite-harzburgite boudinated bodies inferred as the detached fragments of mantle (MINTS, 1993).

Estimation of *P-T* conditions in successive units of the lower section of the LGB thrust-nappe ensemble was accomplished by V.I. FONAREV and A.N. KONILOV (Institute of Experimental Mineralogy), using above mentioned system of consistent mineral thermometers and barometers. About 100 samples were studied and 15-20 mineral grains were analyzed in each sample.

The metamorphic evolution of the LGB is characterized by the following succession of events (Fig. 3) (MINTS *et al.*, 1996a, b). (1) The earliest fixed metamorphic stage M1 (860-920°C, 11.3-12.6 kbar) corresponds to a lower crust environment in riftogenic setting. (2) The second metamorphic event M2 is characterized by the lower metamorphic conditions: 780-810°C, 10.3-11.9 kbar. (3) For the most intensive metamorphism M3 there were estimated temperatures 675-720°C, pressures 9.3-7.6 kbar. (4) The conditions of the final high-grade metamorphic stage M4 were: 565-605°C, 5.3 kbar. Rapid transport of the heated tectonic slices during the M3 and M4 stages resulted in the origin of inverted metamorphic zoning in the autochthonous rocks reasoned by the heat flux from above to downwards and subsidence under the weight of overthrusted ensemble. The corresponding parameters of progressive metamorphism of the Korva tundra gneisses and blastomylonites in melange zone were 590-695°C and 8.5 kbar. As it is seen from Fig. 3,

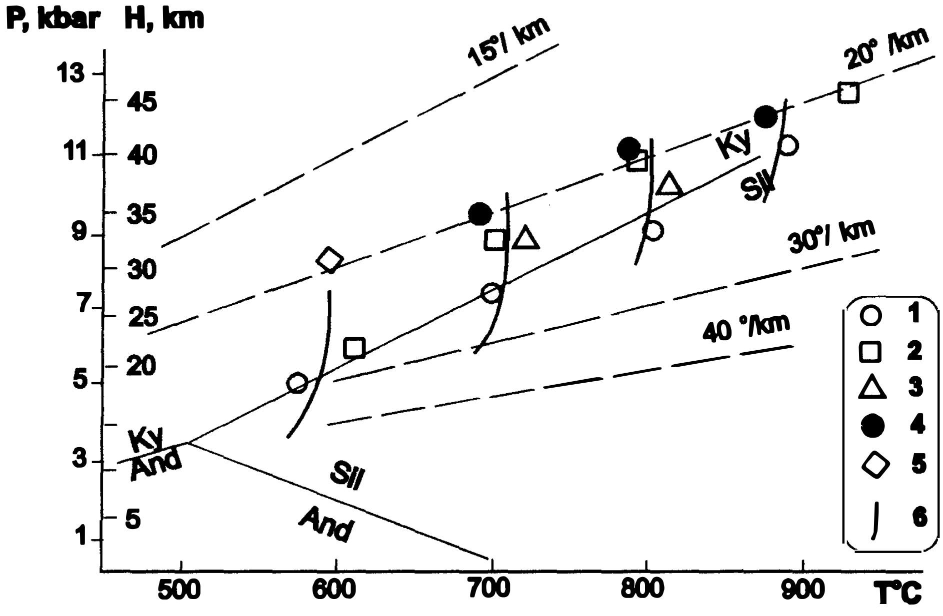


Fig. 3. Lapland granulite belt: P-T conditions and thermal gradients for successive metamorphic events. 1-5—averaged data for felsic and mafic granulites Yavryoki River (1) and Salnye Tundra Mount (2), metaanorthosites (3), garnet amphibolites (metagabbro) (4), kyanite-bearing gneisses of subnappe zone (5); 6—thermal gradient lines. The position of the stability fields of the aluminum silicates from (HOLDAWAY, 1971).

averaged *P-T* characteristics of successive units in the lower section of the LGB thrust-nappe ensemble demonstrate a very insignificant decrease of metamorphic temperatures from lower to upper units. Corresponding values of thermal gradient within sampled part of LGB are: M2 – 5°C/km, M3 – 9°C/km (Fig. 3); thermal gradient values for M1 and M4 events could not be satisfactory estimated due to scarcity of data.

Geochronological investigations gave evidence of a long-term tectono-metamorphic history of the Lapland granulite belt. U-Pb isochron determinations from magmatic zircons and whole-rock Sm-Nd data display 2.47–2.43 Ga intrusive age of gabbro-anorthosite bodies. Their emplacement was immediately followed by the earliest high-grade metamorphism fixed by U-Pb 2.42–2.41 Ga age of granulitic zircons in metamorphosed parts of intrusive bodies (M1 event) (MITROFANOV *et al.*, 1993, 1995; FRISCH *et al.*, 1995; KAULINA, 1996). Temporal coincidence of magmatic and high-grade events is supported by 2.52 Ga U-Pb age of magmatic zircons from enderbite-gneisses in the Kolvitsa belt (eastern branch of LGB) (KAULINA, 1996). In disagreement with above data, all obtained age estimates characterizing origin of protoliths of metasedimentary and metaigneous granulitic rocks are not older than 2.28–2.2 Ga (BIBIKOVA *et al.*, 1993; J.S. DALY, personal communication). The following succession of high-grade events was recently characterized in detail by U-Pb isochron data on metamorphic zircon generations from metaigneous and metapelitic rocks: M2 at 2.18 and 2.06 Ga (KAULINA, 1996); intensive high-grade recrystallization (M3) dated in zircon grains at 1.95–1.90 Ga (BERNARD-GRIFFITS *et al.*, 1984; BIBIKOVA *et al.*, 1993 and others); and metamorphic processes (M4) were generally completed by 1.88 Ga (MITROFANOV *et al.*, 1995).

The Nilgiri granulite block is situated in northern part of the South India granulite area close to its boundary with Archean granite-gneisses of Dharwar craton. Detailed description of the Nilgiri granulites has been given by SRIKANTAPPA *et al.* (1992) and SRIKANTAPPA (1996). Granulites are dominated by garnet-bearing enderbite-gneisses, mafic orthopyroxene-plagioclase rocks (mostly metagabbros and metaanorthosites), garnet-pyroxene-plagioclase rocks together with metadolerites and metaultramafites and with relatively rare metasediments (banded iron quartzites, kyanite- and garnet-bearing quartzites, garnetiferous gneisses). A petrology of Nilgiri granulites was carefully studied by many researchers (JANARDHAN *et al.*, 1982; RAITH *et al.*, 1983, 1990; TOURET and HANSTEEN, 1988; SRIKANTAPPA *et al.*, 1992; SRIKANTAPPA, 1996). Distribution of *P-T* parameters was characterized on the basis of 84 areally distributed samples. According to C. SRIKANTAPPA with co-authors the garnet-pyroxene assemblages were stable during two early high-grade metamorphic events (stages). They related both "cores of minerals" and "matrix grains" to the first event, whereas the second event was unequivocally characterized by coronitic structures. The available data revealed a regular decrease in metamorphic parameters during the first metamorphic event from 750°C and 9–10 kbar at the northern boundary of Nilgiri block southward to 730°C and 7 kbar. To be sure that this spatial variation of *P-T* estimates and values of inferred thermal gradient are independent of the thermobarometers used we have recalculated *P-T* estimates using published analytical data and the consistent system of thermometers and barometers. Garnet-pyroxene assemblages were considered only and *P-T* values from mutual solutions of the garnet-orthopyroxene (clinopyroxene) geothermometers with garnet-orthopyroxene (clinopyroxene)-plagioclase-quartz geobarometers were used. According to obtained results, granulite samples collected from shear zones that bounded the Nilgiri block, are characterized by specific *P-T* relationships and most probably do not belong to the Nilgiri complex proper, therefore they were excluded from further consideration. The results of the processing of the analytical data from various publications are in concordance. The good agreement between estimated pressure and temperature values obtained from Opx- and Cpx-bearing rocks (KONILOV *et al.*, 1997b) allowed us to combine *P-T* values in rocks containing either ortho- or clinopyroxene and to obtain the generalized picture of temperature dependence on depth during the two stages of high-grade metamorphism (Fig. 4).

The pattern of areal distribution of obtained first stage pressure values in general coincides with the pattern that was initially reported by M. RAITH and C. SRIKANTAPPA with co-authors. The only difference is that recalculated pressure interval is extended toward lower values. However, there are some deviations from the overall regular decrease in pressure from ~9.5 kbar (at 770°C) in the northern part to ~4.0 kbar (at 650°C) in the south. The nature of these deviations is unclear. The explanations might be found in analytical or geobarometry errors or local tectonic displacements. Besides, supposed first stage estimates could belong to two distinct metamorphic events. A specificity of areal distribution of *P-T* values for second event cannot be in steadily estimated due to scarcity of analytical data. The inferred value of 《internal》 t hermal gradient is ~6°C/km for first event and ~4°C/km for second one (Fig. 4, see 9 in Fig. 5). Inferred variations of pressure values permit us to consider Nilgiri block as a slab of lower crust originally *ca.* 20 km thick. The temperatures corresponding to one depth are in a narrow range inside the sampled area of around 1500 km^2. This suggests that the mantle heat source responsible for high-grade metamorphism was directly below the original Nilgiri crustal block and/or was comparable in size with that block.

According to geochronological data presented in above mentioned papers, Rb-Sr and Sm-Nd determinations constrain the age of protoliths to around 2.5 Ga. U-Pb isochron data for granulitic zircons yield the same 2.51–2.49 Ga age for earliest high-grade metamorphic event. Second event was dated by 2.4–2.3 Ga (Sm-Nd on garnet grains). Final uplift and cooling were dated at *ca.* 1.2 Ga by Rb-Sr isotopes in biotite (SRIKANTAPPA, 1996).

Additional geochronological study was carried out by K. SUZUKI using chemical Th-U-total Pb method (SUZUKI and ADACHI, 1991) in our sample of charnockite from the Doddabetta quarry in central part of the Nilgiri block. This age determination was carried out in the same thin-section, in which we studied the compositions of minerals and temperature and pressure of silicate equilibrium. The distribution of age estimations in two studied zircon grains (75 points) is regular. In the central zones of both grains some estimations lay in intervals 3.09–2.86 and 2.70–2.56 Ga, whereas the most representative group of points (48 of 75) yields an isochron age of 2.45±0.02 Ga (error given to the age is of 2σ). Besides,there are some points close to perimeter of studied grains where values range from 2.37 to 1.88 Ga. The geological meaning of the older dates is unclear. These estimates might fix the time of initial magmatic processes. The younger ages are obviously related to two successive metamorphic events that were divided by a time interval exceeding 100 Ma.

As in many other similar cases it is very difficult to interpret the *P-T* evolution of granulites for the time interval between distinct metamorphic events. Our observations in

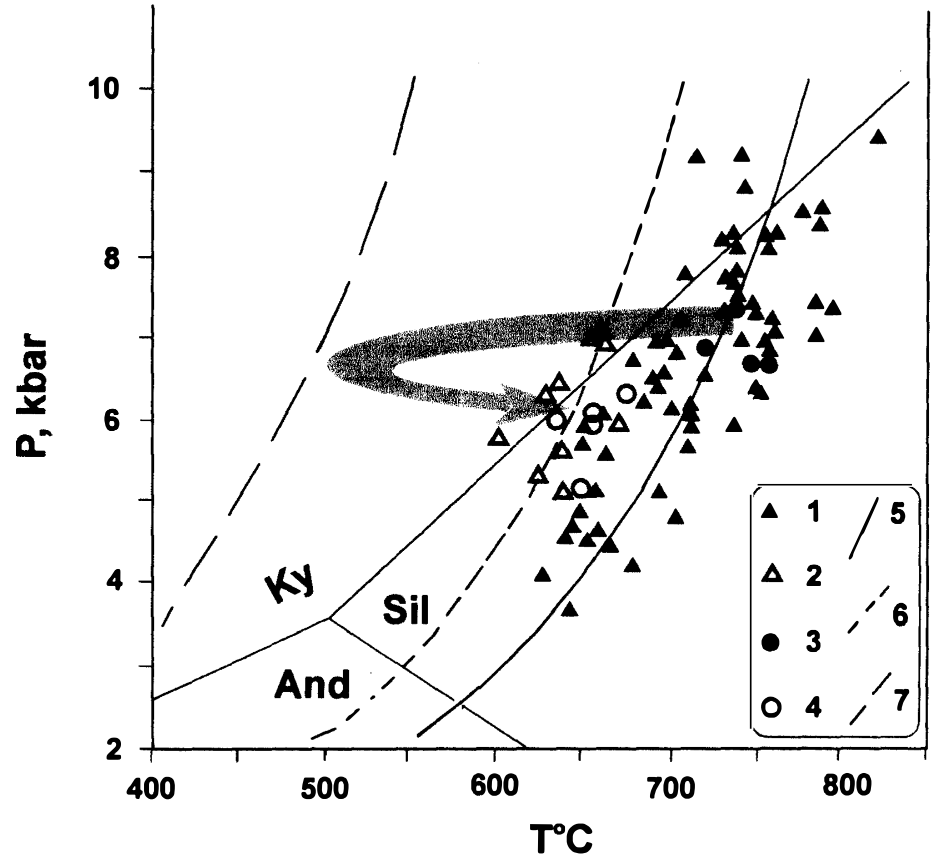
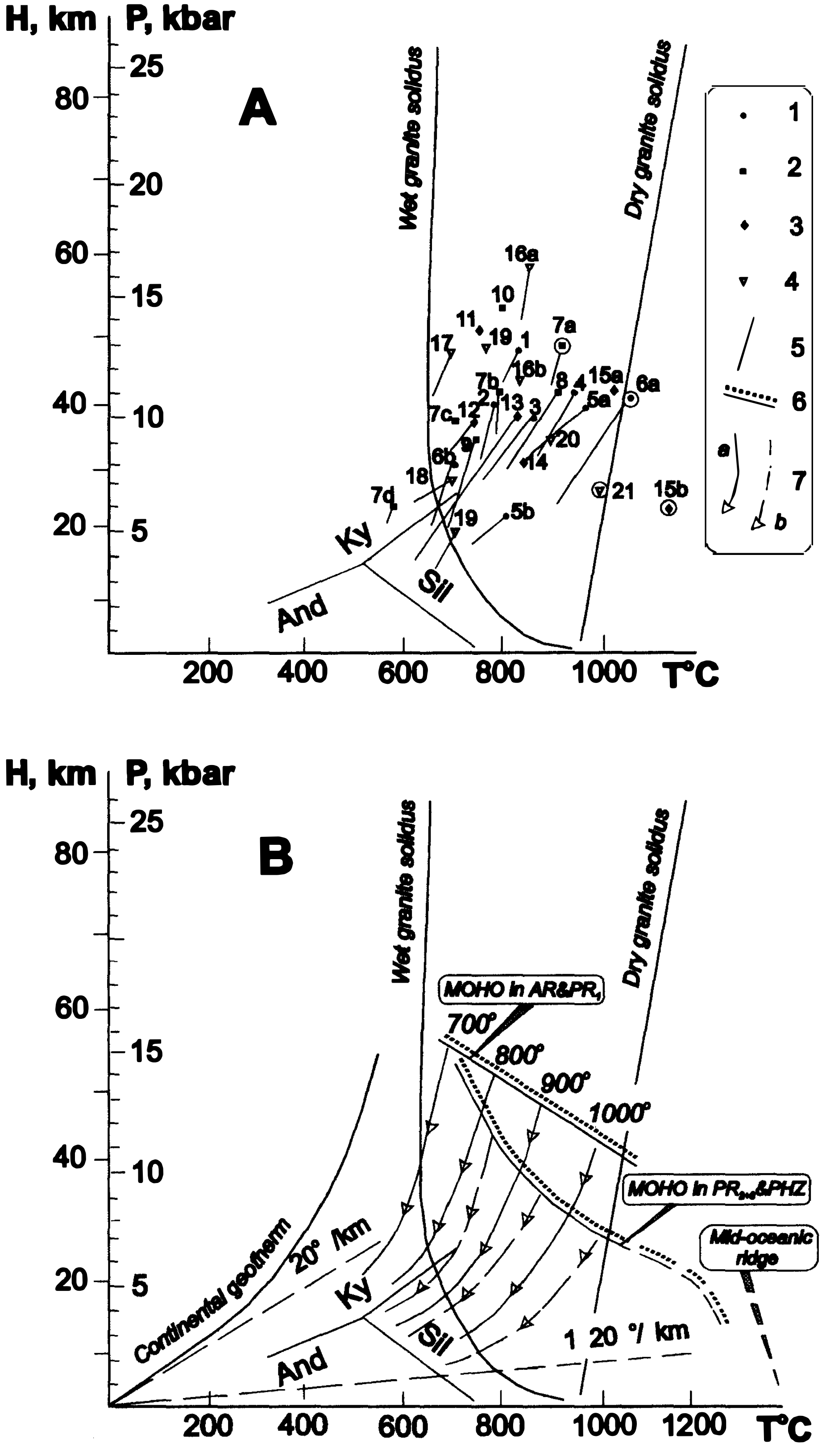


Fig. 4. Nilgiri block: P-T conditions and thermal gradients for two high-grade metamorphic events. 1—cores of minerals (published data), 2—coronitic assemblages and rims of minerals (published data), 3—cores of minerals (this study, Doddabetta), 4—rims of minerals (this study, Doddabetta). Thermal gradients: 5—peak metamorphic stage, 6—coronitic assemblage stage, 7—"normal" continental geotherm. Suggested P-T-t path for studied area (see text) is marked by grayish arrow.

the Doddabetta quarry which are briefly characterized below,allow us to suggest that there was significant cooling of the Nilgiri granulites, possibly to the stable continental geotherm, between the two high-grade events. We could see that edges of the garnet crystals are more calcic in comparison with their centers, that is evidence for replacement of magnesium by calcium at constant iron content. This type of garnet zoning is widespread in South India, including the Nilgiri block (RAITH *et al.*, 1983). We observed signs of this process in various rocks not only in Doddabetta (charnockitic and corundum-garnet-bearing rocks), but also in some other outcrops including moderately rare tourmaline- and kyanite-bearing quartzites from Kodanad in northern part of Nilgiri block; the tourmaline composition is close to dravite $Na_{0.60}Ca_{0.32}Mg_{2.17}Fe_{0.75}Cr_{0.01}Al_{5.96}Ti_{0.08}Si_{5.92}B_3O_{27}(OH)_4$ (assume boron and OH have the stoichiometric values) and the interrelations of cations correspond to a field of high-grade Al-rich metapelites according to HENRY and DUTROW (1996). An increase of calcium content in garnet reflects change in the environment chemistry. In all investigated samples from Doddabetta, without any exceptions, there is ferroan dolomite with practically constant magnesium-iron ratio ($Mg_{0.79-0.84}Fe_{0.16-0.22}Ca_{0.92-0.97}$ in charnockites and $Mg_{0.82-0.84}Fe_{0.17-0.19}Ca_{0.95-0.96}$ in corundum-bearing rock). Dolomite crosses and


A
H, km
P, kbar
80
60
40
20
25
20
15
10
5
200
400
600
800
1000
T°C
Wet granite solidus
Dry granite solidus
16a
10
11
19
1
7a
17
16b
7b
8
4
15a
6a
2
13
3
5a
7c
12
9
20
6b
14
18
7d
21
15b
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H, km
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80
60
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800
1000
1200
T°C
Wet granite solidus
Dry granite solidus
MOHO in AR&PR1
700°
800°
900°
1000°
MOHO in PR2-3&PHZ
Mid-oceanic ridge
Continental geotherm
20° /km
Ky
Sil
And
1 20 °/ km

Fig. 5

replaces garnet or occurs as inclusions situated in microcracks in garnet, corundum and other minerals. The presence of dolomite in Doddabetta was previously reported by TOURET and HANSTEEN (1988), in many other publications a presence of carbonates in the rocks of Nilgiri charnockite suite was pointed out (RAITH *et al.*, 1983; SRIKANTAPPA *et al.*, 1986). According to TOURET and HANSTEEN (1988) the daughter mineral from primary fluid inclusions is Fe-Mg carbonate which does not contain calcium. Thus we suggest that dolomite formed by a moderately low-temperature hydrothermal process between two high-grade metamorphic events (Fig. 4). It subsequently was a source of calcium for crystallization of garnet rims enriched in grossular. We note that the details in the *P-T-t* trajectory shown in Fig. 4 are not yet clear.

The Highland complex, Sri Lanka, is dominated by metapelite and metamafite rocks (mostly garnet-orthopyroxene-plagioclase, garnet-orthopyroxene-clinopyroxene, orthopyroxene-plagioclase schists and cordierite-, garnet-cordierite-biotite- and garnet-sillimanite (andalusite)-biotite-bearing gneisses) with intercalations of quartzites and wollastonite-bearing marbles. Some of granulites were interpreted as metamorphosed igneous rocks of bimodal basalt-rhyolite series that included alkaline rocks and A-type granites which are evidence for a riftogenic environment (SCHENK *et al.*, 1991).

According to results of petrological mapping (600 outcrops were examined, *P-T* parameters were obtained at 115 localities, SCHUMACHER and FAULHABER, 1994), peak *P-T* values decrease gradually southwestward from more than 9 kbar and 900°C in the north-eastern edge of the belt to less than 750°C and 5 kbar. Structurally the Highland complex belongs to thrust nappe ensemble formed by rocks of lower crust approximately 14–15 km

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Fig. 5 (opposite). P-T condition estimates (A) and thermal structure of the crust (B) during granulite metamorphism. 1–4—metamorphic complexes, ages: Archean (1), Paleoproterozoic (2), Neoproterozoic (3), Phanerozoic (4), circled symbols show metamorphosed mafic-ultramafic bodies at the base of granulite-gneiss belts; 5—P-T variations of single metamorphic events; 6—approximate positions of crust-mantle discontinuity, 7—supposed geothermal gradient trends: in Early Precambrian (a), in Neoproterozoic and Phanerozoic (b). MOR-mid ocean ridge.

1–6—Archean: 1—Limpopo, Zimbabwe (TSUNOGAE et al., 1992), 2—Kapuskasing, Superior, Canada (MÄDER et al., 1994), 3—Narryer, Yilgarn, West Australia (MUHLING, 1990), 4—Lewis, northwest Scotland (CARTWRIGHT, 1992), 5—Minto, Superior, Canada: peak (5a) and second (5b) metamorphic stages (BÉGIN and PATTISON, 1994), 6—Napier, Enderby Land, Antarctica: Early (6a) and Late (6b) Archean metamorphism (HARLEY and HENSEN, 1990);

7–10—Paleoproterozoic: 7—Lapland, northeastern Baltic Shield, metamorphic stages: M1 (7a), M2 (7b), M3 (7c), M4 (7d) (MINTS et al., 1996a, b), 8—Sutam, Stanovic, Aldan Shield (KITSUL, 1986; LEVCHENKOV et al., 1987), 9—Nilgiri, Southern India (this study), 10—Grenville, Canada (HOFFMAN, 1989);

11–15—Neoproterozoic: 11—Telohat, Algeria (BARBEY et al., 1989), 12—Sveconorwegian belt, southwestern Baltic Shield (LINDH et al., 1990), 13—Highland Complex, Sri Lanka (SCHUMACHER and FAULHABER, 1994), 14—Rauer, East Antarctica (TAIT and HARLEY, 1988), 15—Musgrave, Central Australia: granulites (15a), Giles layered igneous complex (15b) (BALLHAUS and BERRY, 1991);

16–21—Phanerozoic: 16—Moldanubian granulites: Bohemian massif (16a) (KOTKOVÁ 1995), Austria (16b) (RICHTER and PETRAKAKIS, 1995), 17—Fiordland, New Zealand (BRADSHAW, 1989), 18—Omenica, British Columbia (SEVIGNY et al., 1990), 19—Saint Bartelemy, Pyrenees (DE SAINT BLANQUAT et al., 1990), 20—Ivrea, Alps (FRANZ et al., 1995), 21—Tinaquillo peridotite, Venezuela (SEYLER and MATTISON, 1989).

thick that was upthrusted northeastward. Correspondingly, metamorphic conditions in lower part of a nappe may have resulted from a high-T/high-P conditions of *ca.* 27°C/km, whereas rocks of higher crustal level included in the upper part of a nappe, resulted from moderate-T/moderate-P conditions that reached *ca.* 40°C/km (see 13 in Fig. 5). The thermal gradient within the granulite facies complex proper was only about 10°C/km. Above mentioned estimates and distribution of P-T values shown at Fig. 5 have been obtained by R. Schumacher with colleagues using geothermometer and geobarometer of Bhattacharya *et al.* (1991). Schumacher and Faulhaber (1994) compared these estimates with another set of P-T data obtained using other thermometers and barometers. Essentially, the 《internal》 thermal gradient values are practically the same in both sets of estimates.

Geochronological and petrological data bear witness to a complicated tectonic evolution and polymetamorphic history of the Highland granulites. Data characterizing protolith ages are as follows: protoliths of orthogneisses were formed 2.2–3.0 Ga ago (model Sm-Nd age, Milisenda *et al.*, 1988); ion microprobe dating of terrigenous zircons from metapelites yields *ca.* 2.0 Ga (Kröner *et al.*, 1987). Ages of granulitic type zircons are around 0.61–0.55 Ga (U-Pb estimates on concordia intersections). However,dating of granulitic zircon grains from high-temperature pyroxene-bearing metabasite layer and from pigeonite-bearing charnockite yield 2.3 and *ca.* 1.85 Ga, respectively (Hölzl *et al.*, 1994). Schenk *et al.* (1991) have suggested that age of earliest metamorphism may be reasonably correlated with charnockite origin 1.85 Ga ago. V. Schenk with co-authors estimated the metamorphic conditions for that event from P-T values obtained from cores of minerals. It seems probable that earliest high-grade event could be partially simultaneous with late stages of sedimentation. In such a case, ages of 0.61–0.55 Ga (Pan-African event) most probably fix the time of younger intensive high-grade metamorphism when most mineral parageneses was formed, including coronitic overgrowths of the early high-grade metamorphic minerals. P-T conditions of second (the Pan-African ?) event in comparison with peak parameters were estimated as being approximately 150°C and 1 kbar lower (Schenk *et al.*, 1991). Uplift and cooling ages are fixed by Rb-Sr data that scatter around 0.46 Ga (Hölzl *et al.*, 1991). This stage includes more significant pressure decrease and further cooling.

R. Schumacher with colleagues have noticed this type of distribution of P-T parameters, the absence of a simple explanation of the fact, and the lack of a definite geodynamic interpretation.

4. Discussion

4.1. *A distribution of P-T conditions in vertical cross-sections of granulite belts (Preliminary generalization)*

As it was shown above, the inferred P-T cross-sections of some well-studied granulite-gneiss belts demonstrate limited temperature variations out significant pressure variations. Detailed data of such kind are rare yet, although reports of similar P-T cross-section of some other granulite-gneiss belts have been published recently. Besides, in a number of cases vertical distribution of P-T parameters may be estimated,although with less certainty than in the examples discussed above, using data on sampled localities from various levels of many granulite-gneiss belts. Figure 5 shows the *P-T* distributions that characterize metamorphic conditions (mostly for peak event) in a number of granulite-gneiss belts of various ages and from various areas worldwide.

Assuming the granulite-gneiss belts are sections of former lower crust, the integrated *P-T* data shown in Fig. 5 are to be considered as characteristic of *P-T* parameters in the crust during high-grade metamorphism, from crust-mantle discontinuity up to a depth of 15–20 km. The rocks in the basal part of granulite-gneiss belts, especially those accompanied by synmetamorphic or premetamorphic mafic-ultramafic bodies, can be interpreted as slabs of the lowest crustal rocks that were originally close to the crust-mantle discontinuity.

In Fig. 5 the suggested position of the crust-mantle discontinuity is shown in *P-T* realm (separately for the Early Precambrian and for the Neoproterozoic and Phanerozoic time). There is a clear dependence of the temperature at crust-mantle discontinuity on the crustal thickness. Respectively two extreme types of crustal sections can be observed in the integrated scheme in Fig. 5. First type corresponds to normal and especially to thinned (25–40 km) crust. High and ultra-high temperatures (up to 1050°C) were estimated in the deepest granulites of this type. Temperatures for upper parts of such crustal sections (at 10–15 km depth) are around 750–800°C. The second type corresponds to thickened (50–55 km) crust. It is characterized by moderately high temperatures in the lower crust, *i.e.*, from 700–800°C at crust-mantle boundary and moderate temperatures of 650–700°C in the middle crust. These two extreme types of granulite metamorphism can be called as GM1 and GM2, respectively.

A surprising result of our calculations is that geothermal gradient within the lower crust during granulite metamorphism is rather low, *ca.* 5–10°C/km. Extended upward, this gradient results in high temperatures and rather high *T*/*P* values in corresponding sections of upper crust. The thermal gradient in upper crust in such cases varies from 25°C/km for GM2 and up to 100–120°C/km for the distinctive GM1 case. Our proposed model for the thermal structure of the lower crust during granulite metamorphism differs significantly from conventional models. It is characterized by greater curvature of thermal gradient lines and their steep inclination in the lower crust. Such differences in thermal gradients in lower and upper crust during high-grade metamorphism permit us to discuss some deductions regarding two subjects: petrological speculations and their geodynamic implications.

4.2. *Petrological speculations*

Approximation of thermal gradients in the crust as straight or slightly curved lines is not suitable for discussing granulite complexes and may lead to erroneous conclusion about significant differences in 《metamorphic regimes》 or 《types of metamorphism》 (high- or low-pressure) in various parts of the same granulite belts. Instead, inferred 《type of metamorphism》 may be only a consequence of a depth of intracrustal decoupling that could have divided originally unbroken granulitic crust. Correspondingly, *P-T-t* paths, caused by tectonic and thermal transformations,must differ significantly depending on the relative position of sampled locality in the studied belt. Hence, regular *P-T* variations in the original granulite crustal sections during single metamorphic event are to be taken into account in *P-T-t* modeling. The real nature of low thermal gradient in lower crust under granulite conditions is unclear yet. One explanation is, that there was high thermal conductivity during granulite metamorphism due to fluid penetration and intensive deformations. It is also possible that increased thermal conductivity due to appearance of partial melts was of special significance. Heat transfer with moving partial melts and penetrating fluids may also play role. In any case it seems evident that the lower crust under granulite conditions could be a very effective heat conductor. Hence, cooling was rapid after cessation of heat flux from the mantle. What influence could high conductivity have had on cessation of mineral reactions and for conservation of created granulitic assemblages ? Could this have resulted in significant cooling between successive high-grade events similar to our suggested scenario for the metamorphic evolution of the Nilgiri block or multiple heating episodes proposed by HAND *et al.* (1994a, b) for the Jetty Peninsula in the northern Prince Charles Mountains, East Antarctica ? We do not know as yet. (There is much to do!).

4.3. Geodynamic implications

The second question concerns the geodynamic interpretations of various types of metamorphic complexes which have been divided in light of above mentioned regularities. Complexes of GM1 type are generally connected with geodynamic settings related to hot mantle upwelling accompanied by heat and penetrating fluid fluxes together with crustal extension or/and crustal thinning. Maximal heating is characteristic for the most thinned crust, *i.e.*, for the riftogenic environment (including extension zones in back areas of active continental margins) and, possibly, for the crust of epi-continental sedimentary basins. It may be supposed that metasedimentary granulites were formed as a result of expansion of high-grade metamorphic aureole to the lower part of sedimentary successions of such basins. This idea may be supported by the features of geological evolution in above characterized regions. It is important to note that earliest peak events in the LGB and in the Nilgiri block occurred 2.5–2.4 Ga ago, *i.e.*, at the time of well-known rifting of the Late Archean supercontinent. Earlier, we had interpreted later high-grade overprints in the LGB rocks (see above) as linked with succeeding extension events in the Paleoproterozoic evolution of Baltic Shield and North America craton (MINTS *et al.*, 1996b; MINTS, 1998). MARKER (1985) first suggested that the protoliths of LGB rocks were originated through sedimentation and volcanism in a basin similar to Phanerozoic back-arc basins. The suggested 1.85 Ga age of the first high-grade event fixed in the Highland complex coincides with the time of anorogenic within-plate magmatism in the Laurentia group continents. As all the continents were probably united 1.85 Ga ago, it seems possible that processes of the same type took place in southern continents too. This supposition is supported by the similarity between the sedimentary and igneous protoliths of Highland complex with the protoliths of the Lapland granulites. A set of premetamorphic protoliths (terrigenous-chemogenic sediments, bimodal igneous series with alkaline rocks) is evidence most probably for downwarping due to extension and/or thinning of the crust. Charnockite emplacement is related to a similar setting as it was not followed by rapid exhumation of lower crustal rocks. Hence, the above noted features of distribution of peak *P-T* parameters in the Highland complex are be related to such type of geodynamic environment.

Alternatively, metamorphism of GM2 type is related to compression conditions and collision crustal stacking. In the *P-T* realm the GM2 complexes are closely linked with ultra-high pressure rocks originating as a result of especially intensive crustal stacking and deep subduction. It is important to note the limited expanse of GM2 in the lower crust and its gradual but rapid transition to middle and low temperature metamorphic rocks. We suppose then that the above features of thermal structure of crust can be considered as an indication of areal distribution of settings of granulite metamorphism and gray gneiss origin.

The available data are evidence that there are no important differences between metamorphic conditions in the Early Precambrian and Phanerozoic settings of high-grade metamorphism. However, data integrated in Fig. 5 show that crustal thinning associated with high-grade conditions was evidently more significant in Neoproterozoic and Phanerozoic in comparison with Early Precambrian. Developing above ideas we may suppose that high-velocity lower crust of passive margins might be formed by GM1 rocks that were originated in riftogenic environment before breaking up of a continent.

One deduction more: due to significant curvature of thermal gradient lines, the high values of the surface heat flow may not be evidence of especially high temperatures at crust-mantle discontinuity.

5. Conclusion

Main conclusions are as follows.

(1) Two extreme types of crustal sections can be observed from integrated scheme of distribution of pressure-temperature estimates in granulitic rocks. First type (GM1) corresponds to normal and especially to thinned (25–40 km) crust. High and ultra-high temperatures (up to 1050°C) are characteristic for the deepest granulites of this type. Second type (GM2) corresponds to thickened (50–55 km) crust. It is characterized by moderately high temperatures in lower crust (700–800°C at crust-mantle boundary) and up to 650–700°C in the middle crust.

(2) Thermal gradient within the lower crust during granulite metamorphism (《internal》 thermal gradient) is rather low, *ca.* 5–10°C/km. This results in high temperatures and rather high T/P values in corresponding sections of upper crust.

(3) GM1 is generally connected with settings related to hot mantle upwelling accompanied by heat and penetrating fluid fluxes and crustal extension or/and crustal thinning. Maximal heating is characteristic for the most thinned crust, *i.e.*, for riftogenic environment (including extension zones in back areas of active continental margins) and in the crust of epi-continental sedimentary basins. Metamorphism of GM2 type is related to compression conditions and collision crustal stacking. In the *P-T* realm the GM2 complexes are closely linked with ultra-high pressure rocks which originated as a result of especially intensive crustal stacking and deep subduction.

(4) A possible explanation of the nature of low thermal gradient within lower crust under granulite conditions is high thermal conductivity during granulite metamorphism due to fluid penetration and intensive deformations. It is also possible that an increase of thermal conductivity due to appearance of partial melts was of special significance. Heat transfer with moving partial melts and penetrating fluids also play a role.

(5) Regular *P-T* variations in the original granulite crustal sections during single metamorphic event are to be taken into account at *P-T-t* modeling.

(6) There are no important differences between metamorphic conditions in the Early Precambrian and Phanerozoic settings of high-grade metamorphism.

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