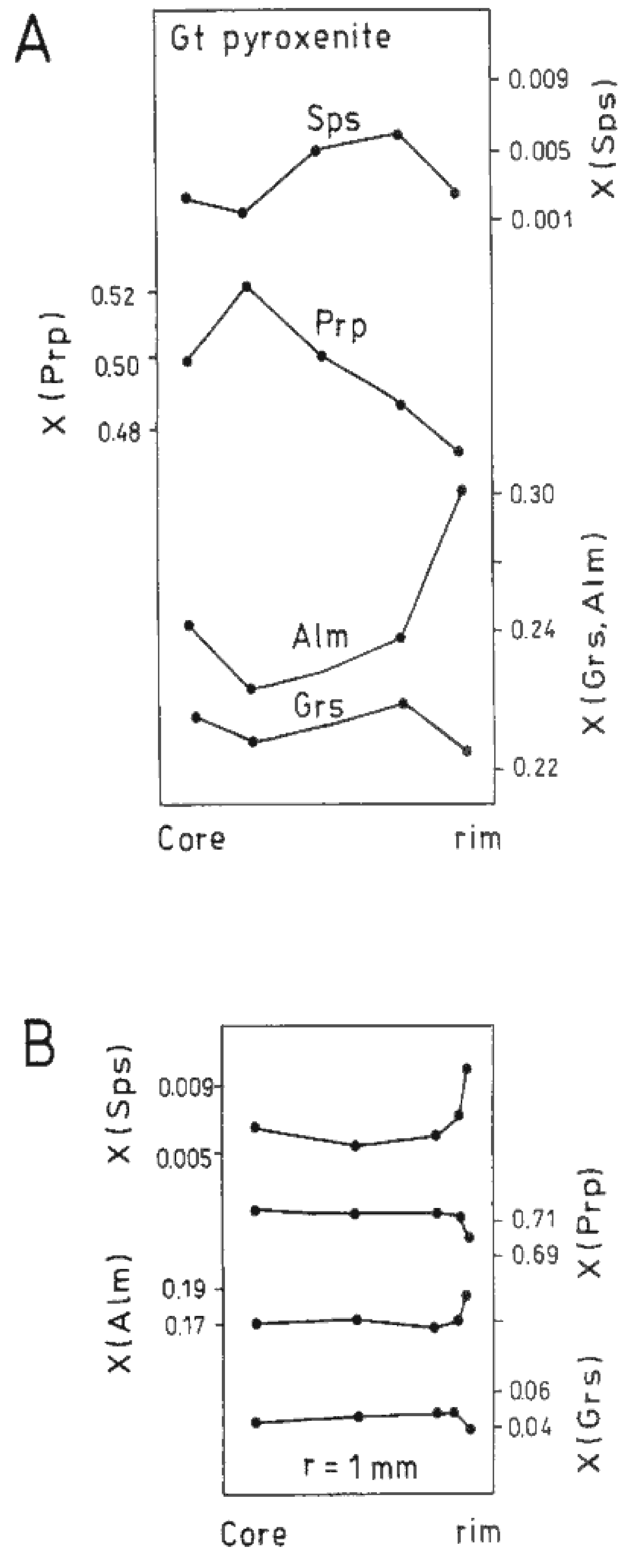

Fig. 6.3 Zonation of garnet - A garnet pyroxenite, B garnet lherzolite. Borehole T7.

Formation of amphibole ± talc at the expense of orthopyroxene at presence of olivine according to the reaction

orthopyroxene + H_2O = *amphibole* + *olivine* (17)

followed by the reaction

orthopyroxene + H_2O = *talc* + *olivine* (18)

is not so widespread.

Reactions (15) to (18) result in development of the assemblage amphibole-chlorite (stage V-a)

and

amphibole-talc-chlorite (stage V-b)

Abundant serpentine was produced by olivine breakdown reaction

olivine + H_2O = *serpentine* + *ilmenite (magnetite)* (19)

so that the late stage VI is represented by the assemblage amphibole-chlorite-serpentine.

The use of petrogenetic grid established by Jenkins (1981) allows to trace the evolution from the garnet to spinel lherzolite stability field, corresponding to high temperature decompression. Significant cooling is indicated by transition from spinel lherzolite through chlorite lherzolite, chlorite-talc-amphibole and chlorite-amphibole-antigorite peridotite fields. This corresponds to development from eclogite to granulite and amphibolite-facies conditions.

c) Garnet pyroxenite

The primary assemblage garnet+clinopyroxene+rutile+quartz is well preserved. Pargasitic hornblende can be stable up to very high temperatures, and is considered as a primary phase (see also Fiala & Paděra 1984). No symplectites develop at the expense of clinopyroxene. However, this does not rule out the possibility of the high-temperature retrogression (studied in eclogites - Boland & van Roehrmund 1983, Joanny et al. 1991), as pyroxenes are low-Jd ones.

7. Geochemistry of granulite facies rocks

The rock set (set I) analysed for major and trace elements comprises samples from all the areas A, B and C. The major element contents were determined by the wet chemical analysis, trace element abundances including rare earths by XRF, AAS, SPA and ICP (for REE) methods. Analyses were performed in the laboratories of the Czech Geological Survey, Prague (see Appendix III, V).

The concentrations of Th, U and K (gamma-spectrometric method in the radiometric laboratory of the Geophysical Institute, Czechoslovak Academy of Sciences) together with some other elements (XRF method) were determined for another set of samples (Set II, courtesy Dr. Fiala, Dr. Vaňková; Appendix IV).

7.1 MAJOR AND TRACE ELEMENT DISTRIBUTION

Two main groups of granulites can be distinguished, based on the major element distribution, which are comparable to the groups A (acid) and B (intermediate to basic) of Fiala et al. (1987) defined for Moldanubian granulites. These authors have put lower limits of 69% SiO_2 and 2.5% K_2O for the group A granulites (K_2O-enriched) against the group B ones (impoverished in K_2O).

The majority of the samples belong to the group A (acid granulites). B_1 granulites - pyroxene-bearing - are represented by a few samples from T38 borehole (set II); subacid pyroxene-free types of the group B_2 come from areas A and C - they correspond to the so-called metapelitic assemblages described above (see Tab. 5.1).

As other major elements than Si and K concerns, a trend of progressive enrichment in Al, Na, Ca, Fe, Mg and Mn can be followed from A to B_2 and B_1 granulites. Concerning the trace elements, preferential concentration of K,Rb and Y in acid granulites, Sr, Cr and Ni in subacid rocks, and strong enrichment of pyroxene-bearing granulites in Cr, Ni and V is characteristic. Just behaviour of Zr and U is not consistent with usual trends of given elements to concentrate in acid or basic compositions, as it is enriched and depleted, respectively, in subacid compositions. This corresponds to conclusions of Fiala et al. (1987).

K/Rb

K/Rb ratios in granulites (Fig. 7.1) are comparable to common magmatic and sedimentary rocks (Shaw 1968, Taylor & McLennan 1985). Certain tendency for an increase of K/Rb ratio with decreasing K show only subacid and intermediate to basic granulites. K/Rb ratios of rocks of the B_1 group, where K is below 1 wt %, are not extremely high (vs. Rudnick & Presper 1985).

By their relatively high Rb contents, granulites correspond rather to rock characteristic of upper continental crust than LILE-depleted lower crust (characteristics e.g. in Wedepohl 1991). This contrasts with the assumption of some authors that K/Rb increases with increasing metamorphism (Sighinolfi 1969, Lambert & Heier 1967, Rudnick et al. 1985). The position of the subacid and basic samples above the main trend line (~ 230), however, implies that a certain Rb depletion has occurred.

Th/U

From the analyses available it can be inferred that the average Th/U ratio of B_2 rocks is higher than that of the group A. Basic pyroxene-bearing compositions are characterized by the lowest ratios. The scattered Th/U plots (Fig. 7.2) reflect the large scatter of Th and U values.

Th and U abundances are very low (Append. V), much lower than in magmatic acid rocks (see Fig. 5.3 for comparison with orthogneiss from Boč). Th/U ratios of 3.5-4 are characteristic of most igneous rocks (Rogers & Adams 1978), values close to 4 are typical of sedimentary rocks (McLennan & Taylor 1980). Th/U ratios above 4 are consistent with U depletion relative to Th (Rudnick et al. 1985). In contrast with the observation of these authors, Th/U of studied samples exceeds 10 even for low (ppm) U contents.

K/Th and K/U ratios of studied granulites are in average above the values for the upper crust (K/Th~ 10^3-10^4, K/U defined as 10^4 for granites by Heier & Rogers 1963 in Rudnick & Presper 1990). This is consistent with Th and U depletion of studied granulites relative to the upper crust.

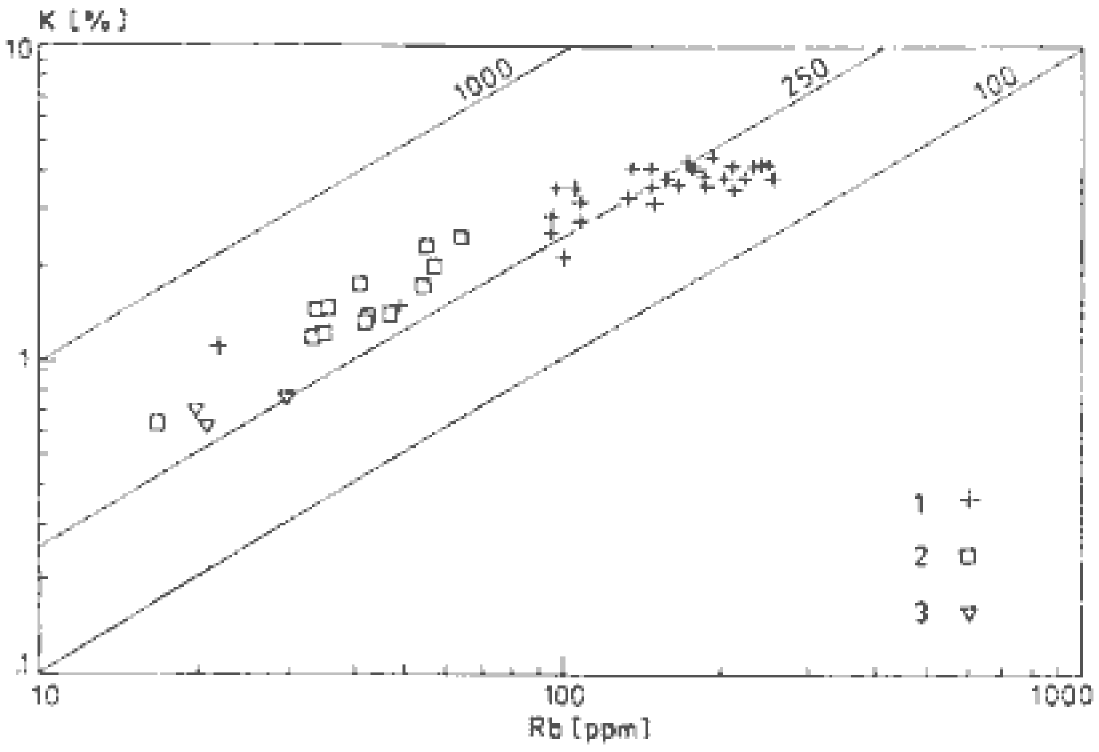

Fig. 7.1 K/Rb plot. 1 - acid granulites, 2 - subacid, 3 - pyroxene-bearing granulites.

Rb/Sr

Rb/Sr ratios (Fig. 7.3) cluster above the value 1, reaching up to 10, for acid granulites; subacid granulites ratios are below 1 (gen. 0.6). These values are typical of upper continental crust (Tarney & Windley 1977).

Summary

The distribution of the major and trace elements of the north Bohemian granulites is comparable to that of Moldanubian granulites, that were studied by Fiala et al. (1987). Pyroxene-bearing samples studied in this work have relatively lower SiO_2, K_2O and P_2O_5 contents and higher FeO_{tot}, MgO, CaO and Na_2O contents compared to B_1 granulites from Moldanubicum. All the rocks are corundum-normative; there were encountered no rocks of the Lišov type (c.f. Vrána 1992).

Acid granulites of the north Bohemia display U ± Th depletion, but neither Rb nor K depletion. They are characterized by content of more than 1wt% of K, and by low to moderate K/Rb and high K/U ratios. Intermediate to basic granulites (B_1 and B_2) with K < 1 wt% (or slightly above in the Set II) display some Rb depletion; they have higher K/Rb and high K/U ratios. These two groups correspond to the systematics of Rudnick & Presper (1990) of Rb-undepleted (i.e. group A in this work) and Rb-depleted (group B) granulites.

7.2 REE DISTRIBUTION

Several samples of granulites belonging to groups A and B2 were analysed for REE (see Append. V; Fig. 7.4). Basic assumption of immobility of REE during high-grade metamorphism (e.g. Green et al. 1972), weathering and alteration (Humphris 1984) is accepted as the first approximation, to be able to put constraints on the nature of granulite precursor and processes during its formation and evolution.

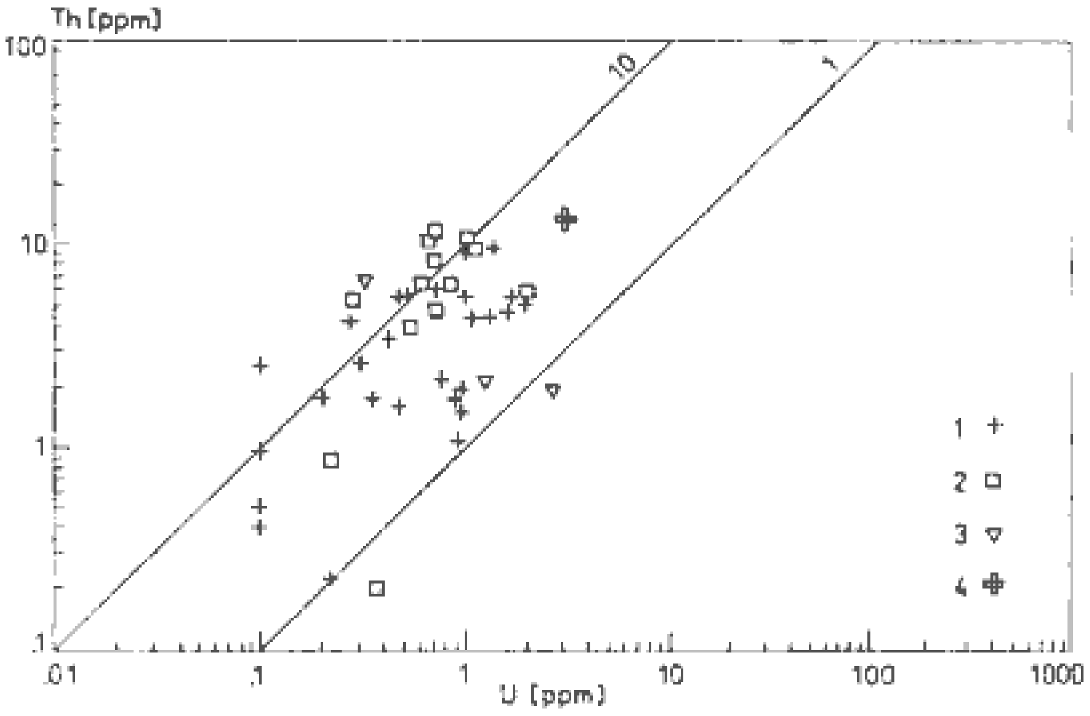

Fig. 7.2 Th/U plot. 1 - acid granulites, 2 - subacid granulites, 3 - pyroxene-bearing granulites, 4 - orthogneiss from Boč.

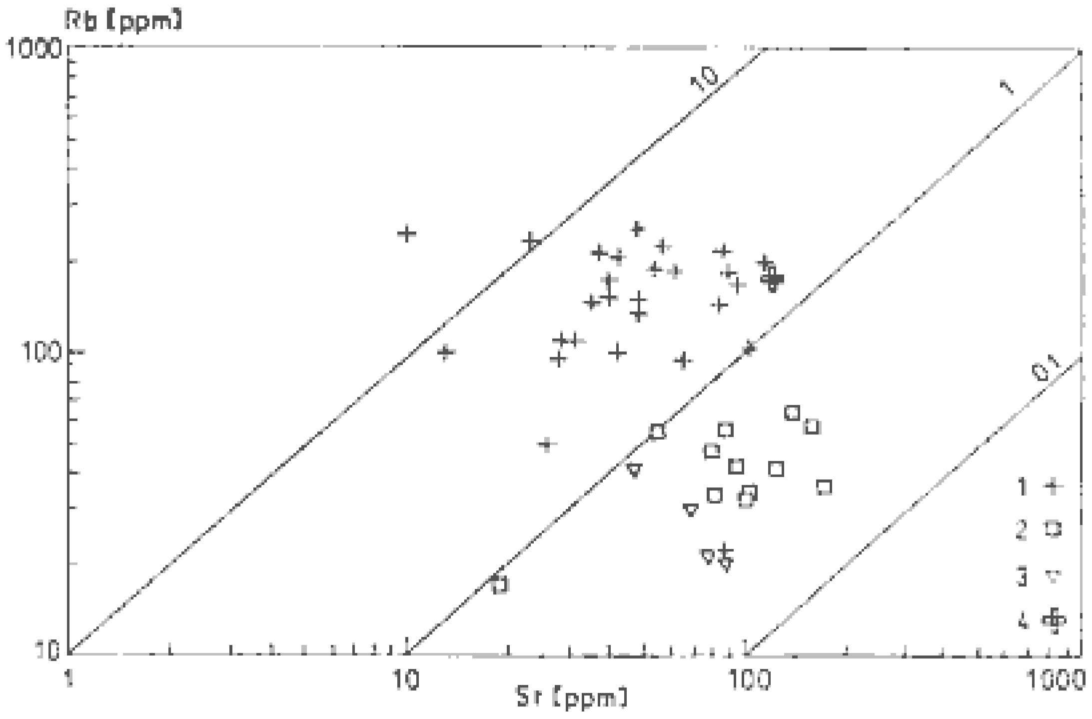

Fig. 7.3 Rb/Sr plot. 1 - acid granulites, 2 - subacid granulites, 3 - pyroxene-bearing granulites, 4 - orthogneiss from Boč.

Granulites are characterized by fractionated REE patterns with slight LREE enrichment. $(La/Yb)_N$ corresponds to 1.96-7.25 (Append. VII), for the majority of the samples is above 3. Such low values are typical rather of post-Archean granulites (Rudnick & Presper 1990). Subacid rocks display higher (xenolith X1c) or similar (Stráž nad Ohří samples) fractionation than the acid ones. Xenolith X1a has LREE abundances often below the detection limit. At the same time, it is depleted in Rb and Zr, and enriched in Al, compared to other acid granulites.

Subacid granulites contain a week negative anomaly, except for samples from Stráž without any anomaly. More pronounced negative Eu anomaly is characteristic of acid granulites. The anomaly decreases (becomes less distinct) with increase in modal plagioclase. There is a positive correlation between the Eu/Eu* and An in plagioclase in acid granulites (more pronounced negative Eu anomaly in samples with more acid plagioclase). Within the groups (especially group A), total REE decrease with increasing acidity of the rocks. The dependencies given above are in agreement with the trends observed in magmatic (granitic) sequences, and are considered as indications of a progressive removal of Pl from the magma (Cullers & Graf 1984). This is consistent with a fractional crystallization model of differentiation of a magmatic source, where increasingly silica rich granitic rocks containing more Na-rich plagioclase and more pronounced negative Eu anomaly are produced (ibid.). The only inconsistence is a lack of positive correlation between La/Yb ratio and silica contents of granulites.

To estimate the degree of REE depletion, granulite REE abundances were normalized by those of the NASC (North American Shale Composite), representative of the upper continental crust (Haskin et al. 1966). From Fig. 7.5 it is evident, that acid granulites are generally undepleted, except from slight Eu and/or LREE depletion in a few samples. Several subacid granulites are relatively LREE-depleted, but not Eu-depleted.

The REE distribution patterns of the north Bohemian granulites are comparable with felsic calc-alkaline granulite from the Blanský les Massif in the south Bohemian Moldanubicum (Jakeš in Kodym et al. 1978), just the total REE contents are somewhat higher in the former ones. Perpotassic granulite from South Bohemia is more differenciated ($(La/Yb)_N = 22.9$). In view of a significant enrichment of HREE in garnet of the felsic granulite (Jakeš in Kodym et al. 1978), this indicates the importance of garnet fractionation in the development of perpotassic granulites (Vrána 1989). West Moravian granulites (Fiala et al. 1987) contain more pronounced negative Eu anomaly.

7.3 INTERPRETATION

Acid granulites (group A) of the north Bohemia are slightly depleted in U and Th, but their K and Rb contents are similar to the average upper continental crust (Taylor & McLennan 1985). This, together with high SiO_2 contents, relative enrichment in Sr and Zr, and insignificant average Cr and Ni enrichment (see also Wedepohl 1981 in Wedepohl 1991), is not consistent with a residual origin. B_1 and B_2 granulites, displaying Rb depletion, have higher Cr and Ni contents than the upper crustal values. However, their K/Rb ratios and depletion in Sr and Zr are also not characteristic of restites. Therefore, formation of granulites studied by anatexis and removal of partial melts into upper parts of the crust (e.g. Lambert & Heier 1968, Sighinolfi 1971, Fyfe 1973) is ruled out. Operation of a an alternative mechanism - a simple dehydration, that results generally in undepleted LILE character, or just a selective migration of some elements (e.g.Gray 1977) - appears more acceptable.

Depletion in Th and U can be attributed to a selective removal by a fluid phase; this is consistent with Tarney & Windley (1977) or Newton et al. (1980b), who assumed that fluid fluxing (escaping of volatile-rich phase; esp. CO_2-rich fluids) without partial melting could be responsible for some LILE depletion. Non-depleted Rb contents confirms the suggestion of Tarney & Windley (1977) that Rb depletion does not reflect granulite metamorphism, but depends mainly on availibility of fluids for Rb removal. Higher U than Th depletion corresponds to preferential removal of more mobile U (Taylor & McLennan 1985).

Similarly to the main and trace element characteristics, neither the REE distribution patterns are consistent with the depleted character of granulites. Lower crustal rocks representing residuum after the melt extraction should have positive Eu anomaly, to balance the upper crustal Eu depletion (Jakeš & Taylor 1974, Taylor & McLennan 1985). Granites formed by dry syngranulitic

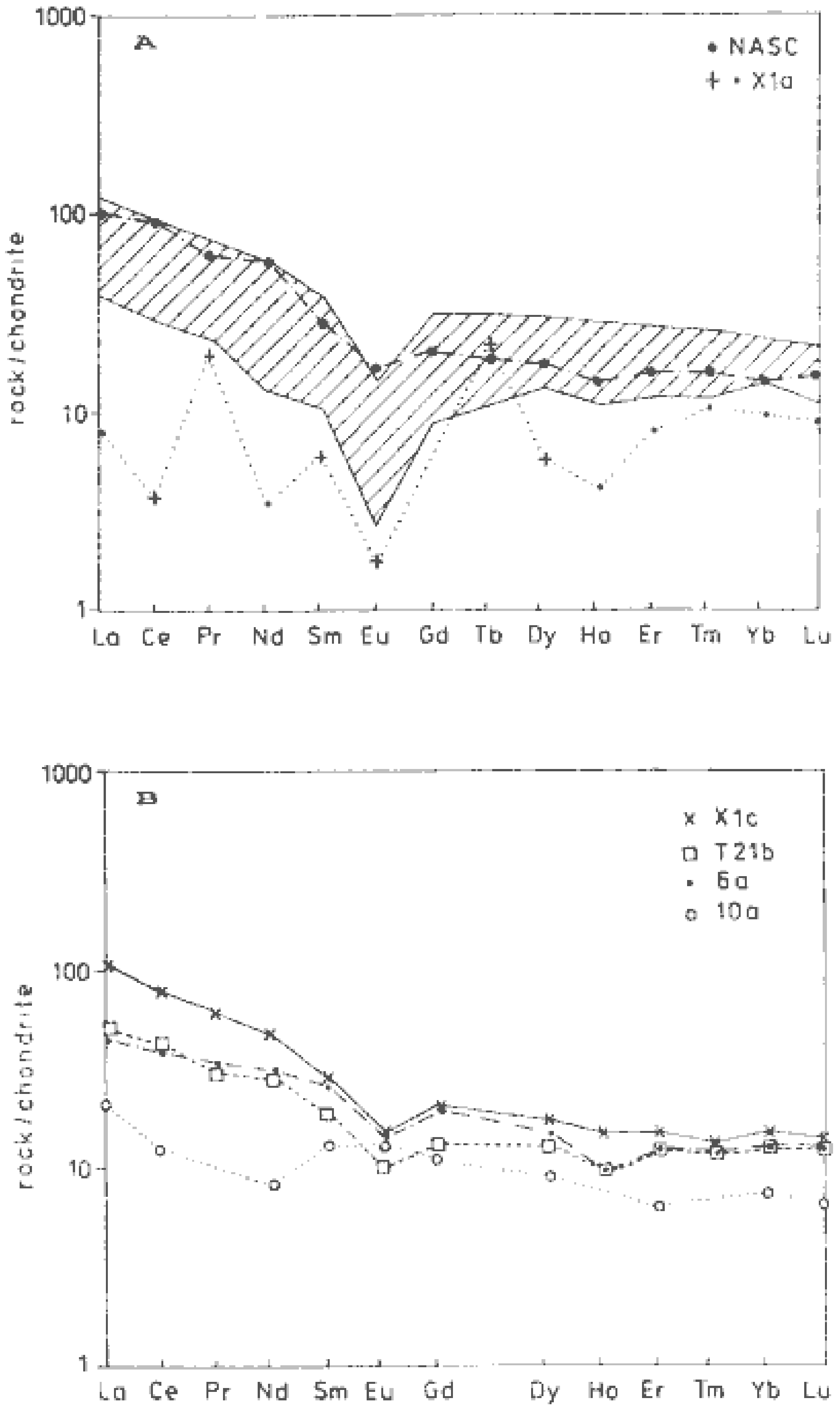

Fig. 7.4 Chondrite - normalized REE distribution patterns of granulites (Values for chondrites according to Henderson 1984). A -acid granulites, B - subacid granulites. X1a - anomalous xenolith sample, X1c, T21b - xenoliths; 6a, 10a - Stráž nad Ohří quarry; + - detection limits.

anatexis are characterized by positive Eu anomaly, too (Pride & Muecke 1980). Negative Eu anomaly observed in studied granulites is typical of average upper continental crust. Almost all post-Archaean sediments and late Proterozoic and Paleozoic granites contain negative Eu anomaly (Taylor & McLennan 1985, Cullers & Graf 1984). Negative Eu anomaly is to a major part inherited from the source rocks (Wedepohl 1991).

Slight LREE depletion of the subacid (metapelitic) samples compared to the upper crustal values might result from a certain amount of partial melting, as LREE tend to be preferentially partitioned into the melt phase (Haskin 1984). However, the REE distribution patterns of A and B_2 groups are not complementary, as would be so in the case of mobilizate and restite.

Another mechanism leading to selective depletion of some elements - e.g. incompatible elements such as Rb or U (cf. Heier 1973) - might be the release of a fluid phase during metamorphism. However, presence of CO_2, F, Cl, Na and/or other phases and elements capable to form complexes with REE is essential for REE transport in a fluid phase (Mineyev 1963). Even in case that such phase was available, this mechanism would lead to a selective loss of HREE (Humphris 1984), and therefore cannot account for the LREE depletion observed.

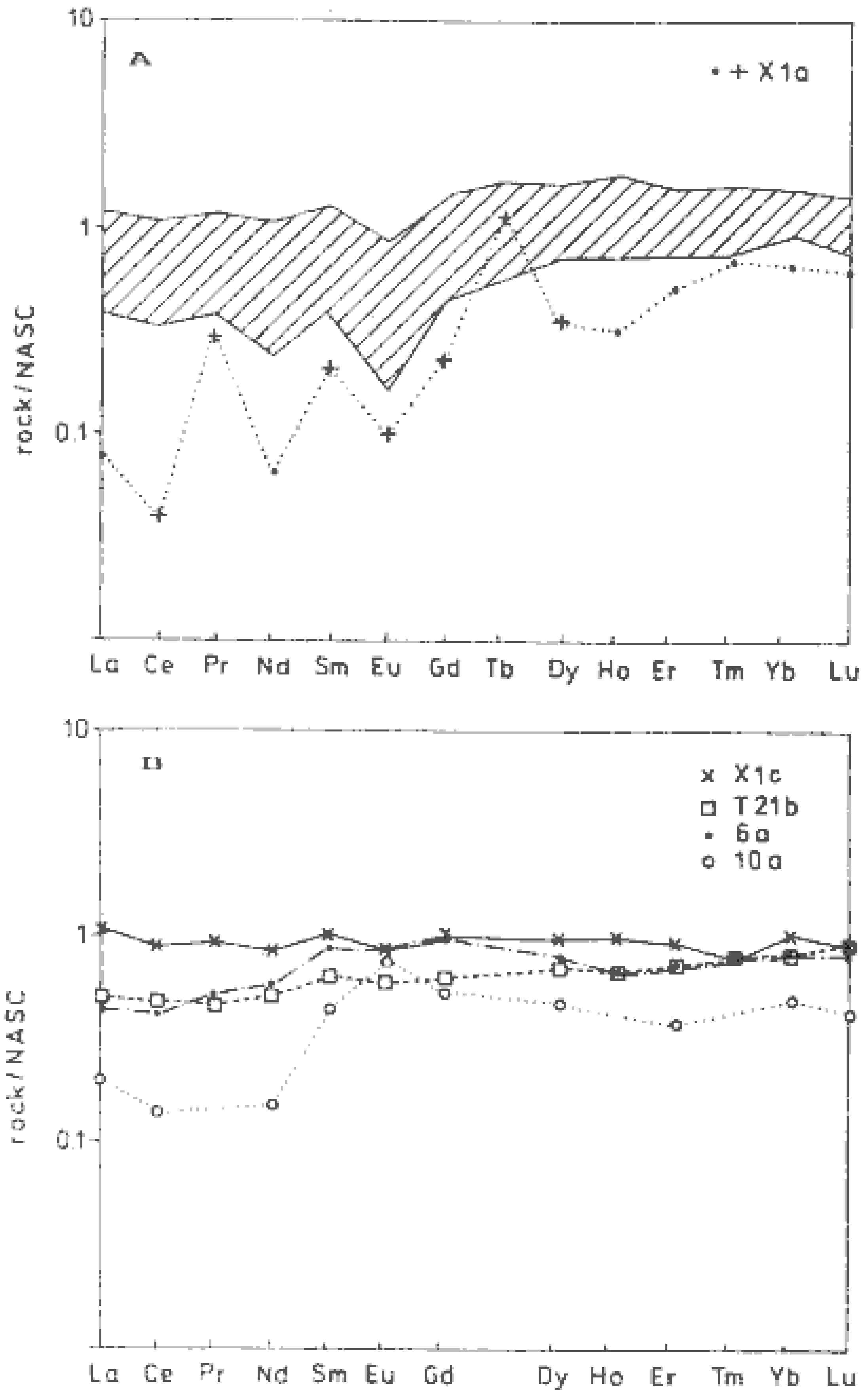

Fig. 7.5 REE distribution patterns of granulites, normalized by NASC (values by Haskin 1966). Samples as 7.4.

It is therefore assumed, that depletion could be either inherited from the source, or caused by removal of enriched late-stage melts to higher crustal levels. Destabilization of LREE-concentrating minerals such as zircon by later processes (Humphris 1984) seems improbable in case of the studied samples.

Lower crustal partial melting with ascent of granitic magma, leaving behind granulitic residues, has been widely discussed recently (e.g. Clemens 1990). As documented by experiments (see Rudnick & Presper 1990 for discussion), the residua from granites may have characteristics of undepleted granulites (La/Yb around 4, upper-crustal LILE abundances), provided that the separation of the melt and the residue is incomplete. This leads again to the conclusion that a process other than partial melting may be recquired to cause LILE depletion in granulites (Rudnick & Presper 1990).

It is concluded that the distribution of the major and trace elements including REE is not consistent with the residual origin of the north Bohemian granulites. This is in agreement with the conclusions of Rudnick & Presper (1990) that granulites are not restites, and that crystal fractionation may be the main process responsible for imparting the negative Eu anomaly on the upper crust. Addition of elements during retrogression does not appear to account for the non-depleted nature of the rocks (cf. Matějovská & Vaňková 1980, Pin & Vielzeuf 1983).

Data given above correspond to the characteristics of the geotectonic Group I of the European Variscan granulites of Pin & Vielzeuf (1983), as opposed to the Group II, significantly depleted in LILE due to the operation of syngranulitic anatectic processes (granulites of old shields). Low contents of heat-producing elements Th and U are common in European granulites of the Group I, as documented for instance in Moldanubicum (Fiala et al. 1987, Scharbert et al. 1976), or for Saxony (Fiala & Vaňková 1985). Such a depletion was not observed by Tarney & Windley (1977) in Polish granulites, in contrast to data in Pouba et al.(1985) for the Czech part of the same granulite body.

7.4 IMPLICATIONS FOR THE PROTOLITH AND EVOLUTION OF GRANULITIC ROCKS

Geochemical data were plotted in classification diagrams in order to put some constraints on the character of the granulite precursor.

In the diagram of the normative contents Ab-Or-Q (Fig. 7.6), acid granulites densely populate the region that corresponds to the wer granite minimum. The subacid ones are shifted off the granite minimum away from the Or apex. The 'transitional' Kamenec samples plot in between the two groups. Rb, Ba and Sr relative concentrations of the studied rocks fall mainly in the field of normal granites (Fig. 7.7). However, in the group A granulites there is a distinct trend from normal to strongly differentiated granites. Some subacid granulites from the Set II fall into the field of granodiorite. In the classification diagram of Peccerillo & Taylor (1976; Fig. 7.8), granulites A are situated in the field of high-K rhyolites and dacites, while majority of B_2 granulites fall in the field of calc-alkaline dacites, which is consistent with their K_2O contents below 2.5%. With the exception of the T7 borehole samples, their position is contrasting with subacid granulites from Moldanubicum (Fiala et al. 1987). B_1 granulites correspond to andesites. The classification of Jensen (1976; Fig. 7.9) based on less mobile elements (Fe, Ti, Mg and Al) is consistent with the results given above, just some B_2 samples are situated in the field of andesites.

Corresponding position of rocks in diagrams based on both mobile and less mobile elements implies that there were no substantial changes of chemical composition during metamorphism (cf. Jakeš 1969). Similar characteristics were found for Moldanubian granulites Fiala et al. (1987).

In the classification diagram of Weisbrod (1970; Fig. 7.10), group A and B_1 granulites are situated in the field of igneous rocks, showing a discontinuous trend from rhyolites to dacites, andesites, almost to basalts. B_2 rocks appear to be metasedimentary, corresponding mainly to arenites and greywackes.

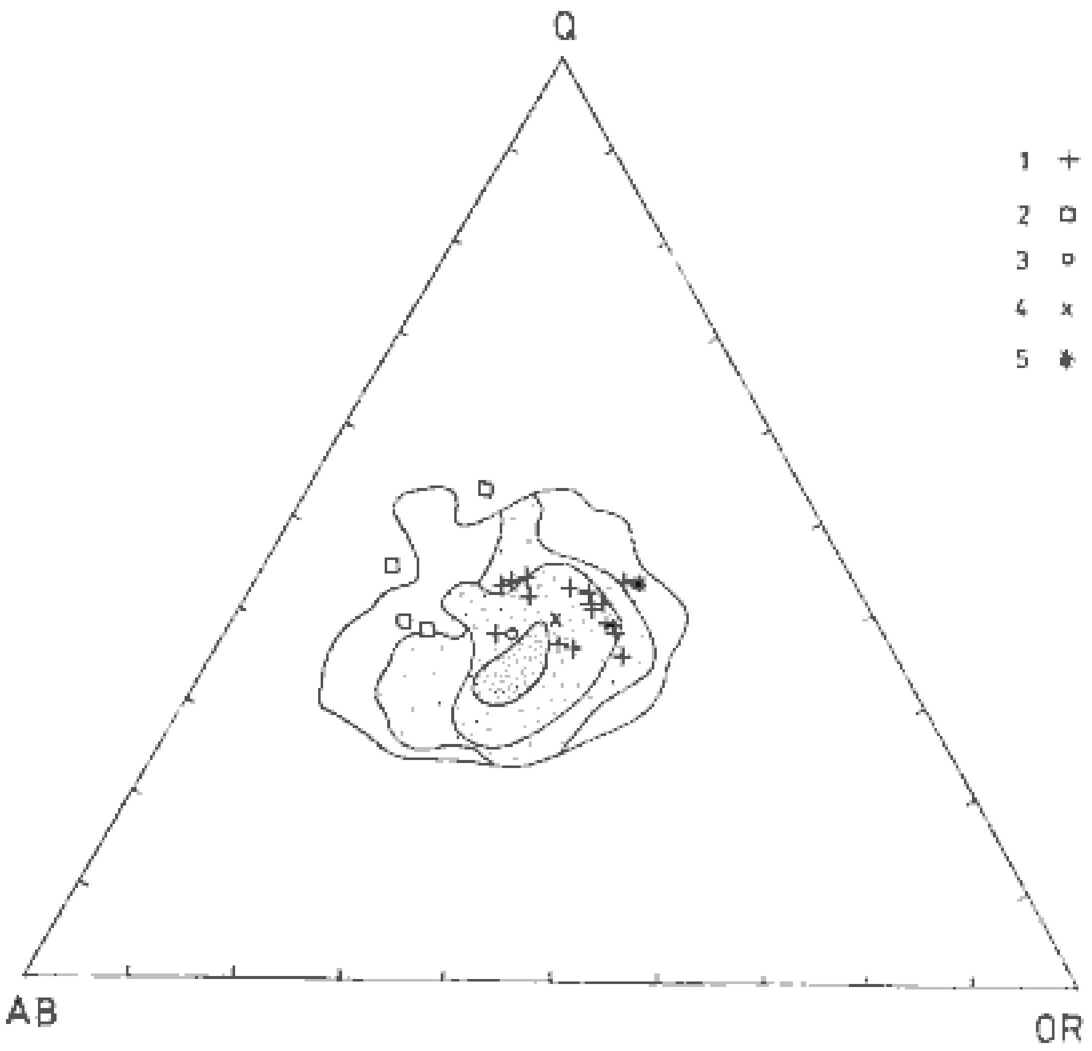

Fig. 7.6 *Normative contents of studied granulites in Ab-Or-Q diagram. The frequency distribution of 1190 granitic rocks (Winkler & von Platen, 1961) is expressed by fields with increasing density of stipples. 1 - acid granulites, 2 - subacid granulites, 3 - 5 -experimental minimum piercing points in the system Ab-Or-An-Q-H_2O (James & Hamilton 1969) for 0, 3, and 5 wt% of An in the system, respectively.*

The data given above are interepreted in the following way:

- Compositional differences (different position in classification diagrams) of group A vs. B imply primary inhomogeneity of the rocks - different source rocks.
- Granulites of the group A (acid) were probably derived from magmatic protolith of granitic/rhyolitic composition. Compared to Proterozoic granites (Taylor & McLennan 1985), they are enriched in Si, Al, Ca, and Sr. Their composition corresponds quite well (with the exception of Si and Na) to orogenic rhyolites (ibid.).
- Group B_1 (pyroxene-bearing granulites) is represented just by intermediate to basic rocks, for which andesites or even basalts are suggested as source rocks. These granulites are enriched in Cr and Ni relative to these volcanic rocks.
- Granulites B_2 (subacid) are rather of metasedimentary origin, with premetamorphic source rocks corresponding to arkoses and/or greywackes. There is a good agreement between their composition and that of post-Archean shales and NASC (Taylor & McLennan 1985). Whole-rock chemistry and REE distribution correspond to a large extent to the greywackes with intermediate quartz contents (ibid.). Nevertheless, there is a lower degree of LREE/HREE enrichment in the studied granulites. The B_2 rocks are depleted in U, Rb and Th relative to amphibolite-facies gneisses.

The inferences for the groups A and B_2 granulites are supported by the REE distribution patterns, discussed in previous chapters. Meta-igneous and meta-sedimentary precursors have also been documented among Moldanubian granulites (Fiala et al. 1987). Presence of pyroxene-bearing samples with variable SiO_2 contents

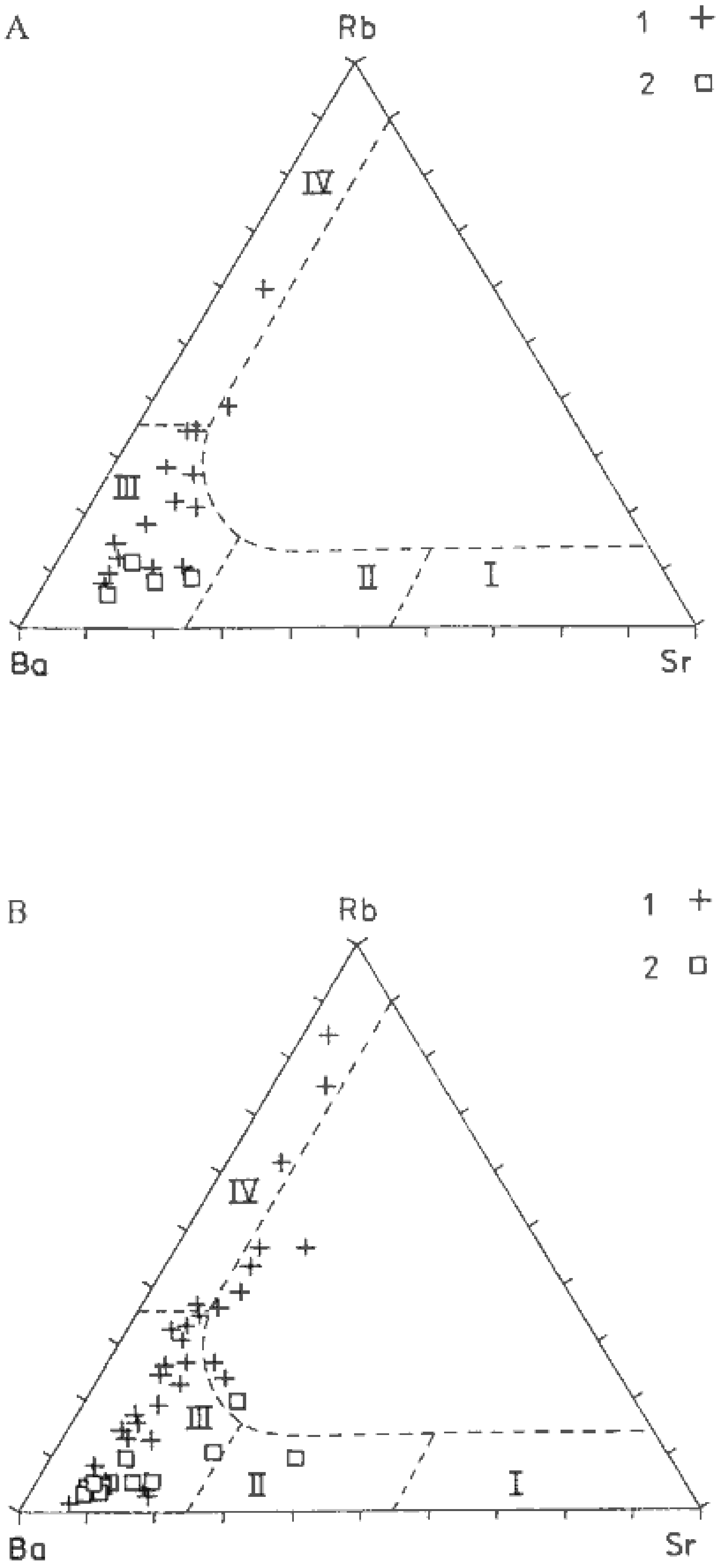

Fig. 7.7 Ba-Rb-Sr diagram; a - set I, B - set II; typical relative concentration fields for I -diorite, II - granodiorite, III - normal granite, IV - strongly differentiated granite (ElBousiely and ElSokkary 1975) ; 1 - acid granulites, 2 - subacid granulites.

enabled these authors to suggest that these granulites represent acid, subacid and intermediate members of normal calc-alkaline rock series.

Additional constraints are needed to specify if the precursors of acid granulites were volcanic or plutonic rocks, as these two cannot be distinguished only on the basis of geochemical and petrochemical criteria (see also Vrána 1992). The idea of a volcanic (rhyolitic) precursor of the Bohemian Massif granulites, widely accepted in older times (see e.g. Zoubek 1948a, Hokr et al. 1974), has been abandoned recently (cf. Fiala et al. 1987). The supracrustal anatectic origin for the acid granulite precursor in terms of non-eutectic partial melting or dry hypersolvus HP melting is often being discussed at present time (Vrána & Jakeš 1982, Vrána 1989, 1992, Mísař et al. 1984, Wendt et al. in prep.).

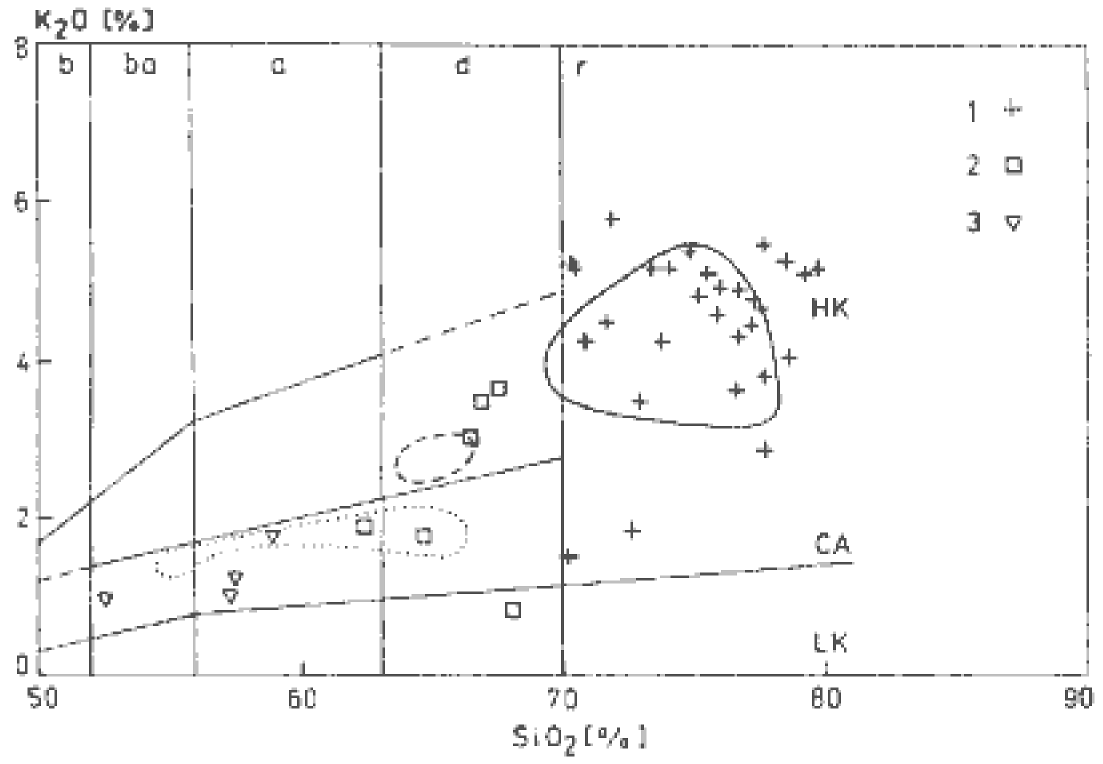

Fig. 7.8 Classification diagram after Pecerillo & Taylor (1976); 1 - acid granulites, 2 - subacid, 3 - pyroxene-bearing granulites. Fields for the three granulite types of Moldanubian (Fiala et al. 1987) also shown. HK - higk K series, CA - normal calc-alcaline series, LK - low K series. r - rhyolite, d - dacite, a - andesite, ba - basaltic andesite, b - basalt.

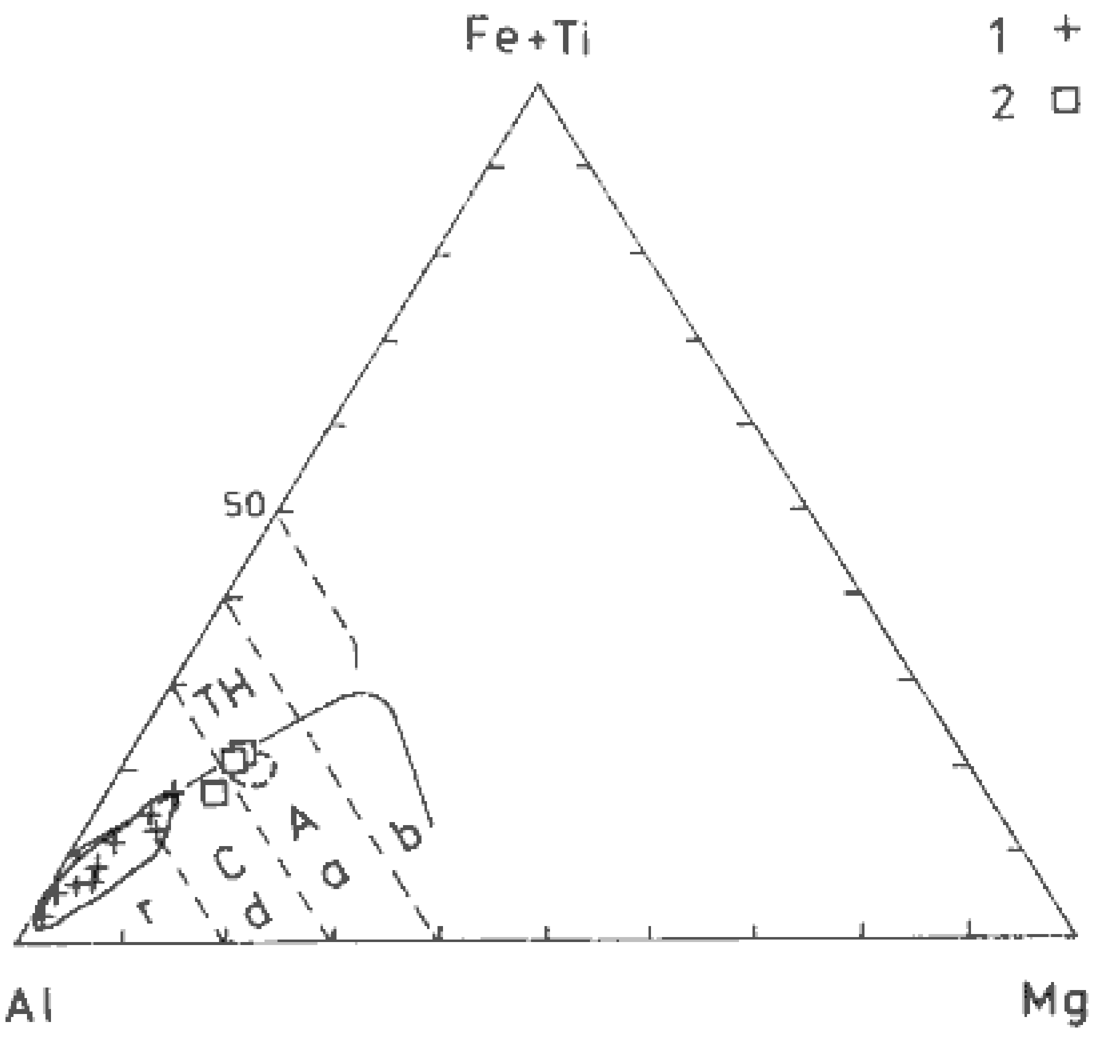

Fig. 7.9 Classification diagram of Jensen (1976); 1- acid, 2- subacid granulites; TH - tholeiitic fieLd, CA - calc-alkalic field. r - rhyolite, d - dacite, a - andesite, b - basalt.