Precambrian granulites of the Aldan shield, eastern Siberia, USSR

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Abstract. Precambrian granulites of the Aldan shield in southern Yakutia, USSR, form a massif of 200,000 km² bounded by younger fold-belts to the south, west and east. The massif consists of several blocks that reflect a primary heterogeneity of composition and differences in structural and thermodynamic evolution of different parts of the area. According to structural and petrological data the massif can be divided into two megablocks: eastern Aldan and western Aldan. They are separated by a narrow meridional fold-belt. Structural evolution of this central zone was determined by the geodynamics of the megablocks and was completed in the late Archaean. Towards the south, this central zone is 'transformed' into the relatively small Sutam block adjoining the Stanovoy fold-belt that bounds the Aldan shield on the south. The Sutam block is separated from the other structural units of the Aldan shield by a system of north trending grabens filled by post-Archaean sediments.

The Aldan shield is composed of Archaean high-grade granulites, while the Stanovoy foldbelt, to the south, consists of highly foliated Proterozoic rocks metamorphosed under relatively lower-grade conditions. However, relics of the granulites are mapped within the fold-belt. They contain high-grade assemblages (e.g. Opx +Sil + Qz, Sap + Qz, Opx + Gr + Sil, etc.). One of the relics, the Tokskii block, which is only slightly touched by diaphthoresis, is located in the southeastern part of the Stanovoy fold-belt. Metamorphic conditions of the Tokskii block are compared with those of the Sutam block and a similar evolution of the units is revealed.

Mineral assemblages and mineral compositions do not vary within each unit, but they change in a north-south direction. The Opx + Sil + Qz assemblage has been found only in Sutam and Tok, but not in eastern Aldan and western Aldan. The Sap + Qz assemblage has been found in the Tokskii block but has not yet been found in the Sutam block. The pyrope content in garnets, from metapelites of both blocks, is significantly higher than that from the Aldan (eastern and western blocks) rocks to the north. The most important assemblages from different units of the Aldan shield have been studied using the electron microprobe in order to unravel the metamorphic evolution of the granulites and thus to deduce the thermodynamic regime of this evolution. A geodynamic model for the Aldan shield is discussed in terms of Archaean island arc development.

Key-words: Aldan shield; Archaean; geobarometry; geothermometry; granulites; metamorphic reactions; retrograde stage

Abbreviations used in the text and figures

| Ab | = albite |
|------|-----------------|
| Act | = actinolite |
| Alm | = almandine |
| Am | = amphibole |
| An | = anorthite |
| And | = andalusite |
| Andr | = andradite |
| Bi | = biotite |
| Cal | = calcite |
| Cd | = corundum |
| Chl | = chlorite |
| Cor | = cordierite |
| Срх | = clinopyroxene |
| Dol | = dolomite |
| En | = enstatite |
| Fs | = ferrosilite |
| Fsp | = feldspar |
| G | = graphite |
| Gr | = garnet |
| Gros | = grossular |
| 11 | = ilmenite |
| Ку | = k yanite |
| Mt | = magnetite |

Mu = muscovite

| 01 | = olivine |
|-----------|--|
| Орх | = orthopyroxene |
| Or | = orthoclase |
| Os | = osumilite |
| Pl_{25} | = plagioclase (with An-content) |
| Pyr | = pyrope |
| Qz | = quartz |
| Ru | = rutile |
| Sap | = sapphirine |
| Sc | = scapolite |
| Sil | = sillimanite |
| Sp | = spinel |
| Sph | = sphene |
| Spes | = spessartine |
| Wol | = wollastonite |
| Zo | = zoisite |
| С. | - Content of component i (wt %) |
| N_1 | -Mole percentage of component 'i' in mineral |
| 1 | —Temperature. °C |
| P | Pressure, kbar |

 X_i — Mole fraction of component i

INTRODUCTION

The Aldan shield is located within the region drained by the Aldan river (Fig. 1) and occupies about 200,000 km². The history of its study is associated with the names of many famous Russian geologists, such as V. N. Zverev, D. S. Korzhinskii, Yu. K. Dzevanovskii, N. G. Sudovikov and A. A. Kadenskii. They determined the general stratigraphic sequence of the Aldan massif and its folded border, and created the first schemes of mineral facies for the rocks. Marakushev & Kudryavtsev (1965) suggested that the Opx + Sil + Qz assemblage, discovered by Kadenskii (1960), in the Sutam block is a highpressure equivalent of Cor + Gr. According to this, Marakushev (1965) introduced a new terminology: the Sutam mineral facies of depth (Opx + Sil + Oz) and the more shallow Aldan facies (Cor + Gr). Later Kitsul (1971), Duk, Balaganskii & Zedgenizov (1975), Kitsul, Bogomolovs, Duk & Zedgenizov (1978), Kitzul & Zedgenizov (1979), Balaganskii (1979), Perchuk,



Fig. 1. Map of southern Yakutia, showing the investigated metamorphic complexes as hachured areas, which are, from North to South, Aldan Shield, Sutam Block, and Tokskii Block.

Kitsul, Podlesskii, Gerasimov, Aranovich & Fed'kin (1981) considered peculiarities of metamorphic zoning, revealed the major stages of metamorphic and structural evolution of the region and obtained the first geochronological data.

The purpose of the present paper is to review the information available on the structural geology and estimate the physical and geodynamic conditions of metamorphism on the basis of new analytical, petrological and experimental data.

The present paper is based on extensive sampling from three areas (Fig. 1) undertaken during expeditions in 1979 and 1981 to the Aldan shield, organized by the Institute of Experimental Mineralogy of the USSR Academy of Sciences and the Institute of Geology of the Yakutian Office of the Siberian Branch of the USSR Academy of Sciences.

OUTLINE OF METAMORPHIC GEOLOGY

The Aldan shield consists of the Aldan massif bounded on the west, south and east by fold-belts. The massif is composed of Precambrian granulites and granitoids. Available radiometric age data range from 1800 to 3400 m.y. The youngest age, 1800–1900 m.y., for apatite from the granulites, has been determined by the 206 Pb/ 207 Pb method (Tugarinov, Bibikova, Gracheva, Lyalikov & Smirnov, 1977). This age could be related to diaphthoresis connnected with granitization.

According to structural and petrological data, the Aldan massif can be divided into several tectonic units—the eastern Aldan zone (eastern Aldan), the western Aldan zone (western Aldan), the central folded zone and the southern Sutam block (Sutam) (Fig. 2). The units differ in lineament morphology, peculiarities of disjunctive



Fig. 2. Simplified geological map of the Precambrian granulitic complex of the Aldan shield. Approximate foliation and lineation trends in the granulites are marked (1-5): the Central zone (1), the Eastern zone (3), the Western zone (2), the Sutam block (5) and the Stanovoy fold-belt (4). 6 = unconformity between sediments and underlying Precambrian granulites. 7a = tectonic boundaries of the granulite blocks and megablocks. 7b = the Stanovoy fault dividing the Aldan shield from the Stanovoy fold-belt.

tectonics and development of the magmatic and metamorphic processes. The central folded zone, separating eastern Aldan from western Aldan (Fig. 2), was formed during the second folding cycle (F_2). The folding structures of the first cycle (F_1) were almost obliterated by subsequent prograde metamorphic processes (Glebovitskii, Duk & Kitsul, 1982).

Each megablock can be further divided into several tectonic units (blocks) with specific petrological and structural features of metamorphic evolution. To understand the degree of this heterogeneity, we have sampled all the blocks exposed in localities along the Aldan river, the Uchur river and the Timpton river (Fig. 1). As the river valleys cut across the main linear elements, we succeeded in collecting samples of granulites from different parts of the eastern Aldan and the western Aldan zones. In the southern part of the Aldan shield (the Sutam block) the samples have been collected from outcrops in the Sutam river (Fig. 3).

Mapping and sampling of the area have shown that the Sutam block consists of two tectonic



Fig. 3. Simplified geological map of the Sutam block in the southern part of the Aldan shield. (1) Proterozoic and Jurassic unmetamorphosed rocks. Archaean granulites (2-6): (2) biotite-garnet gneisses, (3) pyroxene and garnet-pyroxene granulites, amphibole-garnet rocks, (4) quartzites, (5) enderbites, (6) an undivided metamorphic unit consisting of hypersthene and aluminous gneisses, basic granulites, quartzites, calc-silicate rocks and calciphyres, (7) granulites of the contacting blocks, (8) the Stanovoy fold-belt. Granites: (9) Archaean, (10) Proterozoic, (11) Mesozoic, (12) tectonic boundaries (a) between the main blocks and (b) within the Sutam block deduced from mineral assemblages, (13) stratigraphic boundaries, (14) the sample localities.

units (the southern and northern parts) composed of granulites with clearly defined mineral assemblages. The eastern Aldan and western Aldan units are composed of metapelites, garnet-biotite gneisses and biotite crystalline schists interlayered with calc-silicate rocks and calciphyres. They are intruded by younger granites. The highest-grade granulites are exposed in the southern part of the central folded zone as it passes gradually into the Sutam block. They are represented by hypersthene-sillimanite gneisses, pyroxene-garnet crystalline schists and garnetsillimanite-cordierite rocks.

The fold-belts, yielding a Proterozoic age, are composed of crystalline schists and gneisses which were remetamorphosed from the Archaean granulites during diaphthoresis (Bibikova, Shuldiner, Gracheva, Panchenko & Makarov, 1984). Finds of the relict high-pressure assemblages Opx + Sil + Qz, Opx + Gr + Sil and Sap + Qz + Gr(Karsakov, 1978) among foliated rocks of the epidote-amphibolite facies are petrological evidence in support for geochronologic data. The rocks containing the high-pressure assemblages belong to the relict tectonic block, known as the Syvakano-Tokskii block, located between the Syvakan and the Tok rivers (Figs 1 and 4). In the present paper this unit is called the Tokskii block. The oldest age, of 3.4 b.y. has recently been determined for zircons from granulites of southern Aldan (U-Pb method). Zircons from plagiogneisses from western Aldan, have yielded and age of 3.3 b.y. (²⁰⁶Pb/²⁰⁷Pb method). Similar rocks from the tectonic blocks, located in the western



Fig. 4. Simplified geological map of the Tokskii block. (1) Cainozoic sediments, (2) Mesozoic volcanic and sedimentary rocks, (3) Mesozoic granitoids, (4) early Proterozoic metamorphic rocks, (5) Archaean metamorphic rocks of the Stanovoy complex, (6) Archaean and Proterozoic granitoids, (7–9) Archaean metamorphic rocks of the Chogar complex: (7) lower series, (8) middle series and (9) upper series, (10) metabasites and metaultrabasites, (11) charnokites and enderbites, (12) leucocratic granites, (13) blastomylonites and diaphthorite rocks developed upon Archaean granulites, (14) geological boundaries, (15) faults, (16) the sample localities.

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part of the Stanovoy belt (Fig. 2), have yielded a zircon ${}^{206}\text{Pb}/{}^{207}\text{Pb}$ age of $2585 \pm 20 \text{ m.y.}$ (Bibikova *et al.*, 1984). This age corresponds to the youngest stage of the metamorphic evolution of the Aldan massif rocks. Granulites of the Tokskii block are probably of the same age.

MINERALOGY

Mineral assemblages of the major varieties of the Aldan shield metamorphic rocks are listed in Table 1. Minerals analysed by microprobe are marked. In this section we consider only those minerals that provide information on the thermodynamic conditions of formation and evolution of the Aldan granulites. Table 2 provides representative mineral analyses. Full analytical data are available from L. L. Perchuk on request.

Garnet

Garnets represent different stages of the metamorphic evolution of the Aldan massif. Their composition varies within relatively wide limits depending on the bulk rock composition and the physical conditions of formation. By and large, the garnets are solid solutions of the almandinepyrope series and grossular-andradite series (Fig. 5).

Grossular-andradite garnets contain insignificant amounts of other components (not exceeding 1-2 wt %). These garnets are typical of silicate marbles of all the units of the Aldan massif, with the grossular content being within the range of 65-100 mol%. Grossular garnet occurs in equilibrium with scapolite, plagioclase, quartz and calcite (Table 1). This implies that the mineral reaction $Gros + CO_2 = An + Cal + Qz$ may have taken place in the rocks. However, no grossular reaction rims were observed between plagioclase, calcite and quartz in the thin sections, whereas there are contacts between the grossular garnets and these minerals. The absence of the reaction relations can be explained by the significant contents of the other components in garnet, and that of albite in plagioclase:

| N ^{Gr} _{Gros} | N ^{Pl} _{An} |
|---------------------------------|---|
| 94.5 | 69 |
| 96.8 | 8.1 |
| 95 | 39.2 |
| 71.5 | |
| | N ^{Gr} _{Gros} 94.5 96.8 95 71.5 |

N^{Gr}_{Gros} – grossular content of a garnet (mole %).

Several generations of the grossular garnet, which is typical of Aldan shield rocks, provide

evidence for recrystallization of the marbles at the retrograde stages of metamorphism. Zoning in garnets was not observed.

In some calc-silicate rocks grossular-andradite garnet occurs together with grossular-almandine one. For instance, in sample Ald-4 we found two garnets:

$$(Ca_{2.91}Mn_{0.03}Fe_{0.06})(Al_{1.87}Fe_{0.13})Si_{3}O_{12}$$

and

$$(Ca_{2.04}Mn_{0.03}Fe_{0.92})Al_{2.01}Si_{2.99}O_{12},$$

but we could not find any morphological differences between them.

A garnet of specific composition,

was found in a calc-silicate rock from the Sutam block (sample Sut-67) in association with carbonates, olivine, clinopyroxene and magnetite.

Garnets of the metapelitic rocks are mainly pyrope-almandine, and almost all of them show zoning. Microprobe investigations have revealed that the almandine content always increases from cores of the garnet grains towards rims. The N_{Mg} values vary over wide ranges, which are almost constant for each unit of the Aldan shield. Figure 6 shows that cores of the western Aldan garnets associated with cordierite, sillimanite and quartz are richer in almandine in comparison with garnets of the Sutam and Tokskii blocks. With reference to the rims and cores, N_{Mg} of the western Aldan garnets ranges from 12 to 32, and that of the eastern Aldan garnets ranges from 15 to 35. Garnets from the Sutam metapelites show the broadest variations of N_{Mg} . In the north-eastern part of the Sutam block, N_{Mg} of the garnet cores reaches 50 while that of the rims is 16-20 (Sample Sut-72). Garnets with a slightly higher pyrope content are abundant in the south-western part of the Sutam block (Fig. 6). Similar garnets were found in metapelites of the Tokskii block.

Garnets from different zones and blocks of the Aldan shield differ not only in composition, but also in morphology of the grains and in the character of reaction relations with other minerals as well as in types of zoning. Metapelites of western Aldan commonly contain elongated garnet grains formed at final stages of diaphthoresis and recrystallization of the Archaean metamorphic rocks. As a rule, these garnets contain no inclusions, have no significant diffusion zoning, and are enriched in the almandine component (N_{Mg} = 16–19). The stage of the formation of such garnet grains corresponds to development of the rim zones of other garnet grains found

| l'able 2 | . Selecte | d comp | osition | I III | ierais u | sed for | Inermo | metry | and bar | ometry pecimen | number | | | | | | | | | | | | |
|---|---|--|--|---|---|---|---|--|--|--|---|--|--|--|--|--|--|--|---|---|--|-----------|---|
| | | | | Sut-2/1 | | | | | | Sut-2/2 | | | | Sut-6 | | | | Sut- | 10 | | | | |
| Mineral | " ë | Opx1 | Cor | Opx1 | Cor ₁ | Gr, | Opx 3 | 5 | Opx1 | Cor | Opx 2 | Cor ₂ | υ | Opx | Cor | ō | Opx1 | Ŀ, | Opx ₂ | ŗ. | Opx, | | |
| SiO ₁ SiO ₂ TiO ₁ A1,O ₃ A1,O ₃ MgO MnO MnO K ₂ O K ₂ O K ₂ O K ₂ O | 40.07 40.07 22.72 24.46 12.29 0.32 0.32 0.87 | 51.85 5.73 5.73 5.73 5.73 5.73 22.83 0.06 0.06 0.05 9.25 | *49.76 33.76 3.57 10.87 10.87 | 51.10 | 49.34 33.42 3.54 11.31 1 | 40.12 22.71 24.95 11.22 0.32 0.87 0.87 0.87 | 51.98 5.60 5.60 0.06 0.06 0.05 0.05 0.01 | 39.60 0.05 25.17 12.5.17 12.90 0.37 0.37 0.37 0.37 0.05 | 51.06 0.11 5.57 5.57 5.57 19.89 0.11 0.11 0.06 0.06 0.04 | 49.19 49.13 34.12 3.50 11.14 0.04 0.04 0.04 0.02 8.06 | 50.44 5.37 5.37 19.55 23.50 23.50 0.02 0.04 0.02 99.16 | 49.07 0.02 33.53 3.51 11.41 11.41 0.02 0.02 0.03 0.03 0.03 | 39.82 22.42 24.47 12.70 0.45 0.03 0.01 0.01 | 50.03 0.08 19.00 23.29 0.13 0.03 79.61 | 48.13 32.21 3.25 11.08 0.02 0.01 0.03 94.73 | 40.15 | 50.79 6.75 6.75 16.83 24.62 0.12 0.12 0.12 | 39.42 39.42 22.78 12.88 0.53 0.53 1.47 1.47 99.91 | 51.80 5.22 15.10 26.95 0.11 | 39.45 39.45 22.98 24.28 11.66 0.55 0.04 0.04 | 49.95 0.03 7.35 7.35 0.03 0.12 0.07 98.99 | | |
| | | | ; | | | | | | | | Spe | cimen nu. | nber | | | | | | | | | | |
| | | Sut-28 | | | Sut-28 | | | | | | Sut-61 | | | | | Sut-7 | 12 | | | Ch | ıg-2 | | |
| Mineral | Gr | Opx1 | Gr, | Opx ₂ | Gr, | Ы | ษั | Opx1 | Opx2 | ີຍໍ | PI2 | Gr | Opx3 | ġ, | Opx. | ū | Cor | Gr | Opx1 | Opx1 | Opx3 | Gr, | Opx4 |
| $\begin{array}{c} \text{SiO}_1 \\ \text{TiO}_2 \\ \text{TiO}_2 \\ \text{Al}_2 O_3 \\ \text{MgO} \\ \text{MgO} \\ \text{MnO} \\ \text{MnO} \\ \text{MnO} \\ \text{CaO} \\ \text{Ma}_2 O \\ \text{Ka}_2 O \\ \text{Ka}_2 O \end{array}$ | 39.58 22.56 22.31 14.48 0.52 0.29 | 49.16 | 39.54 | 49.45 7.25 18.11 24.11 24.11 1 1 0.11 99.03 | 39.48 39.48 22.55 22.35 22.35 14.57 0.33 0.28 0.28 0.28 99.53 | 65.71 65.71 21.51 - - 9.94 9.94 | 41.26 23.34 17.27 17.32 17.35 0.39 0.39 99.61 | 5 50.37 1 7.79 1 3.98 5 26.89 1 99.03 | 50.78 7.46 13.91 27.02 27.02 | 40.86 22.07 18.59 17.17 0.19 0.37 - | 64.90 21.57 1.67 1.07 10.19 99.73 | 40.42 40.42 22.94 20.32 14.94 14.94 0.46 99.08 | 52.71 7.46 15.39 15.39 24.27 | 40.34 40.34 22.94 15.81 0.27 99.69 | 51.50 7.84 7.84 12.90 27.14 | 39.57 39.57 20.01 30.19 6.76 0.22 0.78 0.78 0.78 0.02 | 49.65 33.65 7.00 7.60 0.02 0.10 98.03 | 40.61 | 50.65 0.14 7.75 14.89 25.63 0.33 25.63 0.33 99.40 | 51.46 7.08 14.97 25.94 25.94 0.09 99.53 | 51.21 0.12 7.56 14.98 25.77 0.14 | 40.99 | 50.89 0.11 7.83 13.71 27.01 |
| | | | | | | | | Spe | cimen nur | nber | | | | | | | | | | | | | |
| : | | ື ຍິ | ن ه-و | | d | Che Che | | | | Tok- | 9/2 | | Ċ | | Tok | -18 | 6 | | | | | | |
| Mineral SiO ₂ SiO ₂ Al ₂ O ₃ Al ₂ O ₃ MgO MnO K ₂ O K ₂ O Total | Gr ₁ 41.09 22.78 21.77 0.46 0.91 0.91 99.64 | Opx ₁ 52.50 5.36 17.09 24.53 24.53 24.53 0.02 99.57 | Gr ₂ 40.62 22.98 12.08 0.66 0.63 100.10 | Opx ₂ 53.07 5.63 15.53 25.41 15.53 99.64 | Gr ₁ 40.33 0.09 222.85 20.13 14.54 0.48 0.48 0.88 0.88 | Opx1 50.92 0.18 8.22 14.56 25.07 14.56 25.07 1 - | Gr ² 40.32 0.09 22.74 21.87 13.44 0.79 0.88 0.88 | Opx ₂ 50.11 8.88 8.88 14.16 25.31 0.33 0.33 98.78 | Offi 40.55 22.41 20.62 14.91 0.32 1.00 | Opx1 50.20 7.96 16.49 24.80 0.09 99.53 | Gr ₂ | Opx ₂ 50.30 8.06 8.06 14.70 0.10 0.10 99.42 | | Opx1 51.44 0.14 6.07 17.10 24.91 0.26 0.08 99.86 | 012 | Opx2 52.47 6.83 6.83 14.27 25.89 0.13 0.13 99.59 | 40.58 40.58 22.27 12.76 0.32 1.38 1.38 1.38 | Opx ₃ 50.83 0.07 8.01 15.61 15.61 15.61 0.10 0.10 0.10 | | | | | |







Fig. 6. N_{Mg} variations in garnets from some cordierite-bearing metapelites of different parts of the Aldan shield (Maxima N_{Mg} refer to cores, minima refer to rims). Numbered localities are: (1) western Aldan (samples: Ald-9, Ald-11, Ald-15, Ald-18), (2) eastern Aldan (samples: Ald-20, Ald-21, Ald-27, Ald-49), Sutam (samples: Sut-72 and Sut-74 (3), sample Sut-81 (4), samples Sut-2, Sut-3, Sut-4, Sut-6 (5), samples Sut-10, Sut-14, Sut-26 (6), samples Sut-60 and Sut-61 (7), (8) Tok (samples Tok-9 and Tok-10).

in metapelites from western Aldan. Their morphology is rather diverse, with typical segregations of the garnet grains in certain bands in gneisses and crystalline schists. Large garnet grains usually contain inclusions of biotite, quartz, ilmenite and, in some cases, cordierite. At contacts with other Fe-Mg minerals, garnet shows a distinct diffusion zoning, with the almandine content increasing towards the contacts.

Garnet grains from metapelites of eastern Aldan are isometric and contain large inclusions of cordierite, biotite, quartz, magnetite and ilmenite, with the size of inclusions being more than 2 mm. Segregations of garnet grains, formed as a result of splitting of the larger grains, are observed in the thin sections. Each part of the split grain forms a new grain with diffusion zoning, which develops at the contacts with the Fe-Mg minerals, but is lacking at the contact with quartz. This difference implies a diffusion origin for the zoning. At the same time, garnets from metapelites of eastern Aldan provide many



Fig. 7. Morphology of the garnet grain (sample Ald-58) showing the growth zoning. Numbers denote N_{Mg} for biotite and garnet.



Fig. 8. Garnet grain with kelyphitic overgrowth consisting of Cor + Qz. The altered Cor is patterned, ilmenite is black.

examples of overgrowth zones. These garnets usually have isometric forms, and compositions of inclusions change regularly from garnet core to rim. The composition of the zones of garnet grains does not depend on the other minerals in contact with the garnet. An example of garnet with an overgrowth zone is shown in Fig. 7, where one can see a garnet grain enclosed in a matrix consisting of quartz, biotite and sillimanite. The garnet grain consists of a core with $N_{Mg} = 26$ and an overgrown zone with $N_{Mg} = 23-24$. Though the difference in composition is not significant, the zones can be distinguished optically in the thin section.

 N_{Mg} values of garnets from the northern part of the Sutam block vary within relatively wide limits, but variations of N_{Mg}^{Gr} within one sample do not exceed 10 mol. % and garnet grains have very irregular forms, as shown in Fig. 8. The garnet here is surrounded by a kelyphitic corona of Cor + Qz. Cordierite in this sample is not fresh and is replaced by sericite.

Garnets of metapelites from the southern part

of the Sutam block have the same morphology as garnets from the northern part, but are more Mgrich. Zoning in these garnets is weaker than in the garnets from the northern Sutam block. Coronas of plagioclase ($N_{An} = 24-30$) commonly separate the garnet grains from orthopyroxene as shown in Fig. 9. In such cases, plagioclase develops together with quartz manifesting the beginning of plagiogranitization (enderbitization). Similar relations were observed in metapelites of the Tokskii block (Fig. 10). The garnets richest in Mg were predominantly found in sapphirine-bearing rocks of the Sutam and Tokskii blocks. Garnet with $N_{Mg} = 62-64$ was found, however, in a biotitegarnet gneiss (sample Sut-61). The garnet grains in this sample show almost no zoning and contain inclusions of quartz and biotite. Unlike most garnets from the other samples, the Sut-61 garnet is characterized by an increase of N_{Mg} towards contact with the biotite inclusions. The relationships between the Bi inclusion and a large unzoned grain of garnet, surrounded by the matrix of K-feldspar and quartz, were studied with the



Fig. 9. Sketch of the garnet grain surrounded by plagioclase, N_{Mg} of the Fe-Mg minerals and anorthite content (N_{An}) in plagioclase are marked by numbers.



Fig. 10. Sketch of thin-section of metapelite from the Tokskii block (Tok-9/2). Numbers denote N_{Mg} of the Fe-Mg minerals and anorthite content (N_{An}) in plagioclase.

microprobe analyser. The N_{Mg} profile across the contact is presented in Fig. 11. While N_{Mg}^{Bi} decreases towards the garnet grain across the biotite cleavage, no significant change was found along the cleavage, where variations are within analytical error (91.2 < N_{Mg}^{Bi} < 92.7). N_{Mg}^{Bi} of the rims is a little lower than that of the inclusion centre, indicating a weak increase of the metamorphic temperature (Perchuk, 1968, 1969).

Biotite

Biotite is abundant in different granulites and varies in N_{Mg} , and in TiO₂, Al₂O₃ and F contents.

The majority of the Aldan granulitic biotites deviate from the tri-octahedral stoichiometry due to an increase in the content of siderophylliteeastonite. In addition, the variation of TiO₂ contributes to a deviation from tri-octahedral stoichiometry. In general, biotites from Sutam and Tok are more Mg-rich than those from the other zones of the Aldan massif (Fig. 12). No distinct correlation between the Al₂O₃ content and N_{Mg}^{B} was found. Random isomorphic substitution in octahedral sites (Bohlen, Peacor & Essene, 1980) is typical of biotites of all units of the Aldan shield. However, N_{Mg} and TiO₂ are



Fig. 11. N_{Mg} variations in co-existing garnet and biotite from metapelite (sample Sut-61) of southern Sutam. N_{Mg} in the biotite inclusion decreases towards the contact with garnet while N_{Mg}^{Gr} increases to the contact with the inclusion.

inversely correlated, in some biotites, from metapelites. Results of the microprobe analyses of biotite from the rock matrix, and from inclusions in garnet and cordierite in sample Sut-81, are presented in Fig. 13. A negative correlation between N_{Mg} and TiO₂ is demonstrated for the biotite matrix (for rims and cores), in contrast to biotite from the inclusions. High TiO₂ content (6-8 wt %) in biotite included in garnet may reflect the TiO₂ concentration in biotite formed at the maximum of the P-T conditions of metamorphism. Similar data were obtained for high-temperature inclusions of biotites in garnet from sample Sut-61 (see Fig. 11): the TiO_2 content in biotite increases up to 8 wt %. The Mg/Fe ratios might have changed due to the exchange reaction between the biotite inclusion and the host garnet. The TiO₂ content in biotite has not changed, however, because the TiO₂ concentration in pyralspite is limited.

High fluorine content is typical of biotite from the Aldan granulites, as a whole, and from the Sutam and Tok granulites, in particular. Munoz & Ludington (1974) reported on a possible correlation between F and Mg in biotite due to a high chemical affinity of these elements. These authors did not attempt to quantify this correlation and selected biotites from different igneous, metamorphic and hydrothermal environments, probably formed under different conditions. We have chosen biotites from the Sutam granulites presumably metamorphosed under similar P-Tconditions (Table 3). The F content and the Mg mole fraction of biotite were fitted by linear regression to give an equation

$$C_F^{Bi} = 5.442 X_{Mg}^{Bi} - 2.592 \text{ wt }\%, \quad (r^2 = 0.828) (1)$$

This correlation (Fig. 14) is important for Bi-Gr thermometry (Perchuk, 1967, 1969, 1977; Perchuk & Lavrent'eva, 1983; Perchuk & Aranovich, 1984).

Orthopyroxene

Orthopyroxenes occur in metapelites as well as in two-pyroxene gneisses of all the blocks of the Aldan shield. In metapelites, orthopyroxene shows rather regular compositional variations (Fig. 15). The highest Fe/Mg ratio was found in orthopyroxenes from biotite-garnet gneisses and, in some cases, from cordierite-garnet metapelites of eastern Aldan (Kitsul, Beriozkin, Damaskina & Shkodzinskii, 1983). For example, the $Cr_{39-42} +$ $Opx_{63-64}^{6,2-6,9} + Bi + Pl + Qz + II (subscripts are N_{Mg}$ and superscripts Al₂O₃ wt %) assemblage wasobserved in the cordierite-garnet gneiss from



Fig. 12. Compositions of biotites from granulites. The biotite compositions from gneisses of western and eastern Aldan are marked by crosses and those from the Sutam granulites are shown by solid circles.



Fig. 13. N_{Mg} and TiO₂ content in biotites from the gneiss matrix (\bigcirc) and from inclusions in garnet (\blacktriangle). (\bigcirc) correspond to the rim compositions of biotite contacting cordierite and garnet (sample Sut-81).



Fig. 14. Correlation of the Mg mole fraction with the fluorine content of biotites from the Sutam metapelites. (---) is a linear regression of the analytical data.

Precambrian granulites of Siberia

| Specimen number | F (wt %) | X _F | X _{Mg} | Specimen number | F (wt %) | X _F | X _{Mg} |
|--------------------|-------------|----------------|-----------------|--------------------|-------------|----------------|-----------------|
| 3-393/8 | 1.30 | 0.149 | 0.839 | B-624/1b | 0.16 | 0.019 | 0.505 |
| B-616a | 0.50 | 0.060 | 0.683 | B-132/2 | 1.35 | 0.158 | 0.648 |
| π-69-23 | 1.90 | 0.230 | 0.793 | B-136/2 | 0.71 | 0.086 | 0.589 |
| π-69-04 | 1.80 | 0.220 | 0.902 | B-136/3 | 0.84 | 0.100 | 0.595 |
| π -5778/1 | 2.40 | 0.265 | 0.893 | B-139 | 0.64 | 0.078 | 0.573 |
| C-97r | 3.55 | 0.401 | 0.951 | B-139/1 | 0.60 | 0.073 | 0.592 |
| C-97r | 2.66 | 0.290 | 0.946 | B-138/1 | 0.21 | 0.025 | 0.628 |
| C-96 | 2.32 | 0.268 | 0.819 | B-138/2 | 0.87 | 0.105 | 0.618 |
| E-Kop | 2.42 | 0.265 | 0.926 | 3-82/1 | 1.90 | 0.221 | 0.770 |
| E-7989/17 | 2.80 | 0.307 | 0.897 | 3-93/4 | 1.49 | 0.182 | 0.631 |
| 3-311 | 1.33 | 0.149 | 0.822 | Ka-M-5332/1 | 1.74 | 0.206 | 0.652 |
| B-614-11a | 1.72 | 0.099 | 0.749 | Ka-M-2358 | 1.19 | 0.143 | 0.607 |
| 3-358 | 0.76 | 0.87 | 0.641 | Ka-M-6230 | 3.20 | 0.358 | 0.852 |
| Ka-M-200/2 | 3.46 | 0.371 | 0.939 | Ka-M-5253/1 | 1.13 | 0.133 | 0.704 |
| Ka-M-2327/3 | 1.72 | 0.200 | 0.715 | B-105-5 | -1.97 | 0.230 | 0.674 |
| Ka-M-5278/14 | 0.90 | 0.106 | 0.678 | B-105-4 | 1.55 | 0.183 | 0.714 |

Table 3. Fluorine content in biotites from gneisses of the Sutam complex, Aldan shield (after Kitsul, 1983)

eastern Aldan (sample LB-208/1). The upper diagram of Fig. 15 shows that N_{Mg} and N_{Al} , in Opx from western Aldan, are noticeably higher in comparison to those from eastern Aldan. Meanwhile, orthopyroxenes from Sutam and Tok reveal practically no difference in composition, but they are richer in MgO and Al₂O₃ than those from other units of the Aldan shield.

Sapphirine

Sapphirines occur only in metapelites from southern Sutam and Tok. They associate with orthopyroxene, cordierite, biotite, garnet and rarely with sillimanite. In places, sapphirine coexists with quartz (Karsakov, 1978). Microprobe analyses of sapphirine are presented in



Fig. 15. Compositions of orthopyroxene and sapphirine from the granulites of eastern Aldan (\times), western Aldan (\bigcirc), Sutam (+) and Tok (\bigcirc).

| Table 4. Micro | probe anal | ses of ; | sapphir | rines fr | om met | apelites c | of the Si | ıtam an | d Tokskii | blocks | | | | | | | | | | | |
|-------------------------------------|----------------|----------------|----------------|----------|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| | Tok 8 | | | Tok 9/. | C1 | | Tok | 10 | Sut 7 | | | Sut 1 | 0 | | | | Sut | 10 | | Sut | 0 |
| si0 ₂ | 13.59 | 12.34 | 12.58 | 12.31 | 12.79 | 12.40 | 13.89 | 13.91 | 13.20 | 11.61 | 11.69 | 11.87 | 1.66 | 1.67 | 1.71 | 12.05 | 11.71 | 11.86 | 11.94 | 13.14 | 13.44 |
| Al ₂ O ₃ | 58.92 | 63.15 | 62.68 | 63.47 | 63.52 | 62.50 | 57.61 | 57.73 | 60.20 | 64.03 | 64.12 | 64.50 (| 3.66 | 64.25 (| 54.34 | 64.38 | 64.45 | 64.74 | 64.48 | 57.48 | 58.47 |
| Fe,O, | 4.41 | 1.30 | 1.42 | 1.42 | 0.56 | 1.84 | 5.22 | 4.90 | 1.86 | 1.41 | 1.76 | 0.77 | 0.54 | 1.42 | 1.42 | 0.67 | 1.42 | 1.09 | 0.45 | 5.20 | 4.11 |
| FeO | 3.69 | 7.03 | 7.37 | 7.06 | 7.30 | 7.48 | 3.38 | 4.13 | 3.83 | 7.12 | 7.03 | 7.74 | 8.28 | 7.51 | 7.11 | 7.58 | 6.60 | 6.60 | 7.51 | 7.30 | 6.27 |
| MgO | 19.37 | 15.86 | 15.85 | 15.76 | 15.83 | 15.68 | 19.30 | 19.31 | 20.91 | 15.31 | 15.51 | 15.02 | 4.39 | 5.14 | 5.40 | 15.22 | 15.71 | 15.77 | 15.05 | 16.88 | 17.49 |
| Totals | 86.66 | 99 .68 | 06.66 | 100.02 | 100.60 | 06.66 | 99.40 | 86.66 | 100.00 | 99.48 | 00.11 | 5 06'66 | 8.53 9 | 66'60 | 86.66 | 06 .66 | 1 68.66 | 00.00 | <i>61.</i> 66 | 100.00 | 99.78 |
| Cations per 20 ox | ygens | | | | | | | | | | | | | | | | | | | | |
| (IV)Si | 1.62 | 1.48 | 1.50 | 1.47 | 1.52 | I.48 | 1.66 | 1.66 | 1.56 | 1.39 | 1.39 | 1.42 | 1.41 | 1.39 | 1.40 | 1.44 | 1.39 | 1.41 | 1.42 | 1.59 | 1.62 |
| (IV)AI | 4.38 | 4.52 | 4.49 | 4.53 | 4.48 | 4.51 | 4.34 | 4.34 | 4.44 | 4.60 | 4.60 | 4.58 | 4.59 | 4.61 | 4.60 | 4.56 | 4.60 | 4.59 | 4.58 | 4.40 | 4.38 |
| IVI)AI | 3.87 | 4.37 | 4.33 | 4.38 | 4.42 | 4.31 | 3.79 | 3.78 | 3.94 | 4,44 | 4.41 | 4.49 | 4.52 | 4.44 | 4.44 | 4.49 | 4.44 | 4.47 | 4.54 | 3.80 | 3.91 |
| (VI)Fe ³⁺ | 0.39 | 0.12 | 0.13 | 0.13 | 0.05 | 0.17 | 0.47 | 0.44 | 0.17 | 0.13 | 0.16 | 0.07 | 0.05 | 0.13 | 0.13 | 0.06 | 0.13 | 0.10 | 0.04 | 0.47 | 0.37 |
| (VI)Fe ^{2 +} | 0.37 | 0.70 | 0.74 | 0.70 | 0.73 | 0.75 | 0.34 | 0.41 | 0.38 | 0.71 | 0.70 | 0.77 | 0.84 | 0.75 | 0.71 | 0.76 | 0.66 | 0.66 | 0.75 | 0.74 | 0.63 |
| (VI)Mg | 3.43 | 2.83 | 2.82 | 2.80 | 2.81 | 2.80 | 3.44 | 3.43 | 3.68 | 2.74 | 2.76 | 2.67 | 2.60 | 2.70 | 2.74 | 2.71 | 2.79 | 2.78 | 2.68 | 3.05 | 3.14 |
| Totals | 14.06 | 14.02 | 14.01 | 14.01 | 14.00 | 14.02 | 14.04 | 14.06 | 14,17 | 14.02 | 14.02 | 14.01 | 4.01 | 4.02 | 4.02 | 14.01 | 14.02 | 14.01 | 14,00 | 14.07 | 14.05 |
| Si Fe ³⁺ +AI | 0.187 | 0.163 | 0.168 | 0.162 | 0.170 | 0.165 | 0.193 | 0.193 | 0.182 | 0.152 | 0.152 | 0.155 | 0.155 | 0.152 | 0.152 | 0.158 | 0.152 | 0.154 | 0.156 | 0.183 | 0.187 |
| $\frac{Mg + Fe^{2+}}{Fe^{3+} + AI}$ | 0.439 | 0.392 | 0.398 | 0.388 | 0.395 | 0.395 | 0.440 | 0.450 | 0.475 | 0.376 | 0.377 | 0.377 | 0.376 | 0.376 | 0.376 | 0.380 | 0.376 | 0.375 | 0.374 | 0.436 | 0.435 |
| N(Fe)* N(Al) | 0.181 0.586 | 0.225 0.634 | 0.234 0.629 | 0.636 | 0.217 | 0.246 0.629 | 0.190 0.579 | 0.198 0.577 | 0.198 0.591 | 0.235 0.645 | 0.237 0.643 | 0.239 0.648 | 0.255 0.649 | 0.246 0.645 | 0.234 0.645 | 0.232 0.646 | 0.220 0.645 | 0.213 0.647 | 0.228 0.650 | 0.285 0.584 | 0.242 0.590 |
| | | | | | | | | | | | | | | | | | | | | | |

• $N(Fe) = Fe^{10t}/Fe^{10t} + Mg$, $N(AI) = AI^{10t}/\Sigma$ cations.

Table 4. The ferric iron content of the sapphirines was calculated, from stoichiometry, by the method of Higgins, Ribbe & Herd (1979). Typical Tschermak Si + (Mg, Fe^{2+}) = 2(AI, Fe^{3+}) isomorphic substitutions in sapphirines are illustrated in Fig. 15.

Cordierite

Cordierite is widespread in metapelites of all zones of the Aldan shield. The N_{MR} content is highest in the southern Sutam and Tok blocks (Fig. 16). Cordierite coexists with garnet, sillimanite, quartz and biotite in all the metapelites, and forms coronas, symplectites and intergrowths with quartz and plagioclase and sometimes, in rocks from Sutam and Tok, with orthopyroxene. Detailed discussion of the textural peculiarities of the cordierite-bearing rocks will be given in a later section. We have to note that cordierite appears at both prograde and retrograde temperature stages of metamorphism. The differences between both of these cordierites can be revealed only by microprobe profiling across cordierite contacts with other Fe-Mg minerals, and by the estimation of the P-T conditions.

Clinopyroxene and amphibole

Clinopyroxenes and amphiboles occur in calcsilicate rocks and basic crystalline schists. In granulites they usually associate with garnet, plagioclase, biotite and orthopyroxene. We have



Fig. 16. N_{Mg} limits of cordierite from the Aldan metapelites.

made microprobe analyses of clinopyroxene and amphibole from samples Sut-31 and Chog-8, which are typical examples of amphiboleclinopyroxene granulites.

In sample Sut-31, clinopyroxene coexists with a titaniferous hornblende that shows pleochroism in red-brown colours resembling the titaniferous biotite pleochroism. Chemical compositions of coexisting clinopyroxene and amphibole are given in Table 5. Clinopyroxene is largely a solid solution of the FeSiO₃, MgSiO₃ and CaSiO₃ end members, poor in Al₂O₃ and TiO₂. Particular emphasis is placed upon the deficiency of Ca in M₂ which implies relatively high temperature conditions of this rock formation. The rock also contains orthopyroxene ($N_{Mg} = 54-55$) with the CaO content about 0.7 wt $\frac{1}{6}$.

Unlike clinopyroxene, amphibole contains significant titanium and potassium (Table 4), with the Na content being relatively low: Na/(Na + K) = 0.49-0.61. Clinopyroxene, orthopyroxene and amphibole coexist in the rock with the KMg_{1.83} $Fe_{0.84}Mn_{0.01}Ti_{0.24}Al_{1.11}Si_{2.97}$ (O, OH, F)₁₂ biotite, Ab₁₅An₈₅ plagioclase, Gros₁₉Pyr₁₉Alm₆₂ garnet and quartz.

Hornblende and, especially, K-rich amphiboles are rare in basic granulites of the southern part of the Alden shield. In sample Chog-8 from Tok, garnet (N_{Mg} =21.5), biotite (N_{Mg} =75) and orthopyroxene associate with clinopyroxene (N_{Mg} =63) Na_{0.04}Ca_{0.87}Fe_{0.37}Ti_{0.01}Al_{0.12}Si_{1.95}O₆ and amphibole (N_{Mg} =45.7) Na_{0.61}K_{0.32}Ca_{1.6}Mg_{2.56} Fe_{2.04}Mn_{0.01}Al_{2.22}Ti_{0.31}Si_{6.19}O₂₁(OH)₂. The Fe-Mg minerals are included in a matrix of plagioclase (N_{An} =50).

Plagioclase and scapolite

Plagioclases and scapolites occur together in calcsilicate rocks and rarely in granulites. The plagioclase composition varies from oligoclase to anorthite. The scapolite composition changes within narrow limits (Fig. 17). In calc-silicate





| | | Cli | поругохе | enes | | | | Hornt | lendes | | |
|-------------------|--------------|-------|----------|------|--------------|-------|------------------|-------|--------|-------|-------|
| | 39c | 40r | 36r | 60r | 45ı | | 37r | 42r | 59r | 60r | 61r |
| Weight per c | ent | | | | | | ····· <u>·</u> · | | | | |
| SiO ₂ | 51.1 | 52.8 | 52.9 | 53.1 | 50.3 | 42.4 | 42.6 | 42.4 | 43.5 | 42.46 | 41.66 |
| TiO, | 0.0 | 0.3 | 0.3 | 0.5 | 0.4 | 3.2 | 3.3 | 3.6 | 3.3 | 3.20 | 3.60 |
| Al,Ō, | 0.0 | 0.0 | 0.0 | 0.0 | 2.8 | 12.0 | 12.4 | 13.0 | 11.6 | 12.08 | 12.22 |
| FeO | 7.9 | 9.2 | 9.0 | 9.7 | 13.2 | 13.1 | 13.0 | 12.9 | 12.2 | 12.87 | 12.86 |
| MgO | 14.3 | 14.0 | 13.6 | 14.2 | 12.4 | 11.9 | 11.8 | 11.7 | 12.5 | 12.36 | 12.30 |
| MnO | 0.0 | 0.3 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| CaO | 26.4 | 23.3 | 23.7 | 22.1 | 20.5 | 12.3 | 12.4 | 11.9 | 12.4 | 11.45 | 11.84 |
| к,о | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.5 | 2.3 | 2.5 | 2.4 | 2.25 | 2.03 |
| Na ₂ O | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 1.6 | 1.9 | 1.6 | 1.5 | 1.53 | 1.85 |
| Σ | 99 .7 | 100.0 | 99.9 | 98.2 | 99 .7 | 99.00 | 99.7 | 99.6 | 99.4 | 98.70 | 98.36 |
| Cations | | | | | | | | | | | |
| Si | 1.91 | 1.98 | 1.98 | 1.99 | 1.91 | 6.26 | 6.24 | 6.20 | 6.35 | 6.28 | 6.17 |
| Ti | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.36 | 0.36 | 0.40 | 0.36 | 0.36 | 0.40 |
| Al | 0.00 | 0.00 | 0.00 | 0.00 | 0.12 | 2.09 | 2.14 | 2.24 | 2.00 | 2.11 | 2.13 |
| Fe | 0.25 | 0.29 | 0.28 | 0.30 | 0.42 | 1.62 | 1.59 | 1.58 | 1.49 | 1.59 | 1.59 |
| Mg | 0.79 | 0.78 | 0.76 | 0.79 | 0.70 | 2.62 | 2.57 | 2.55 | 2.72 | 2.72 | 2.72 |
| Mn | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | | _ | | _ | | |
| Ca | 1.05 | 0.94 | 0.95 | 0.90 | 0.83 | 1.94 | 1.94 | 1.86 | 1.94 | 1.82 | 1.88 |
| к | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.47 | 0.43 | 0.47 | 0.45 | 0.42 | 0.38 |
| Na | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.46 | 0.54 | 0.45 | 0.42 | 0.44 | 0.53 |
| Σ | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 15.81 | 15.82 | 15.74 | 15.73 | 15.73 | 15.82 |
| N _{Mg} | 76.3 | 73.1 | 72.9 | 72.4 | 72.5 | 61.9 | 61.8 | 64.6 | 64.6 | 63.1 | 63.0 |
| Oxygen | 6 | 6 | 6 | 6 | 6 | 23 | 23 | 23 | 23 | 23 | 23 |

Table 5. Chemical compositions of associated clinopyroxene and amphibole in the basic granulite Sut-31, from the Sutam complex of the Aldan shield



Fig. 18. Microphoto of wollastonite in equilibrium with Cal + Qz in calc-silicate rock from western Aldan. Partly crossed polarized light. Width of field 2 mm (sample Ald-12).

| | Ald-5 | Ald-4 | Ald-7 | Ald-12 | Ald-17 | Ald-103 |
|------------------|--------|-------|-------|--------|--------|---------|
| Weight per cent | ! | | | | | |
| SiO ₂ | 52.68 | 51.82 | 50.10 | 50.30 | 50.52 | 51.59 |
| $Al_2 \bar{O}_3$ | _ | — | | — | 0.01 | 0.06 |
| FeO | 0.57 | 0.64 | 0.84 | 0.95 | 0.08 | 0.05 |
| MgO | 0.07 | 0.05 | 0.08 | 0.03 | | 0.04 |
| MnO | 0.09 | 0.28 | 0.22 | 0.10 | 0.74 | 0.48 |
| CaO | 46.98 | 46.76 | 47.82 | 48.08 | 49.42 | 47.01 |
| Na,O | | _ | _ | | 0.14 | _ |
| K₂Õ | | — | — | — | 0.06 | 0.03 |
| Σ | 100.40 | 99.55 | 99.06 | 99.46 | 100.97 | 99.26 |
| Cations per 6 o | xygens | | | | | |
| Si | 1.010 | 1.005 | 0.986 | 0.986 | 0.978 | 1.003 |
| Al | | | | | | 0.001 |
| Fe | 0.019 | 0.010 | 0.013 | 0.015 | 0.001 | 0.000 |
| Mg | 0.002 | 0.001 | 0.002 | 0.000 | 0.000 | 0.001 |
| Mn | 0.001 | 0.004 | 0.003 | 0.001 | 0.012 | 0.007 |
| Ca | 0.965 | 0.971 | 1.008 | 1.009 | 1.025 | 0.979 |
| Na | | _ | - | | 0.005 | |
| К | — | | | — | 0.001 | |
| Σ | 1.987 | 1.991 | 2.012 | 2.011 | 2.022 | 1.991 |
| N_{wol} | 98.9 | 98.5 | 98.2 | 98.4 | 98.7 | 99.2 |

Table 6. Composition of wollastonite

rocks plagioclase is generally heterogeneous. For example, in sample Ald-17 (see Table 1), plagioclases $Ab_{2.6}An_{9.7.4}$ and $Ab_{28.5}An_{71.5}$ coexist with Fsp containing 10% Ab. In sample Ald-7 (see Table 1), plagioclases $Ab_{40}An_{60}$, $Ab_{14.4}An_{85.6}$ and $Ab_{2.7}An_{97.3}$ were found. Heterogeneity of plagioclase indicates that recrystallization is likely to take place at retrograde stage of regional metamorphism.

Plagioclase composition in metapelites varies from $Ab_{90}An_{10}$ to $Ab_{60}An_{40}$. In parageneses with quartz, sillimanite and garnet, the albite content in plagioclase increases from eastern Aldan towards Sutam and Tok.

Other minerals

K-feldspar is represented in granulites of the Aldan shield by orthoclase with a very low albite content. Microcline may also be found in some granitic veins and migmatites.

Wollastonite occurs in calc-silicate rocks together with plagioclase, scapolite, clinopyroxene and grossular garnet. In some samples, an assemblage Wol + Cal + Qz was found, without any reaction textures (Fig. 18), that can be explained by noticeable impurities in Wol'(Table 6).

Carbonates are calcite and dolomite (Table 1) co-existing in calc-silicate rocks and marbles. Table 7 shows significant contents of impurities in these minerals. A very low concentration of calcite in dolomite and that of magnesite in calcite, implies a relatively low temperature equilibration of the carbonate minerals.

METAMORPHIC TEXTURES AND REACTIONS IN THE CRYSTALLINE ROCKS OF THE ALDAN SHIELD

Reactions in the Aldan shield rocks have been discussed in many papers (Korzhinskii, 1936, 1940; Marakushev, 1965; Sudovikov, Glebovitskii & Drugova, 1965; Perchuk et al., 1981; Korikovskii & Kyslyakova, 1975; Kastrykina, 1976). Some authors believe the reaction textures to be a result of increasing temperature, exclusively, or pressure; others consider them as indicators of retrograde metamorphism. It is impossible, however, to judge the matter without methods of geothermometry and geobarometry based on systematic microprobe analyses. Such data have not been available, in the past, for granulites of the Aldan shield. Now we have several thousand microprobe analyses of co-existing minerals and an internally consistent system of geothermometers and geobarometers, discussed in the Appendix. On the basis of the system, we deduce, more quantitatively, the metamorphic evolution of the Aldan shield granulites.

Granulites of the Aldan shield provide many examples of the retrograde metamorphic reactions and only few prograde ones (Perchuk,

| | יוווי ביכלוחו | | רו לפומוויריוויור | | רמזרוור? מזוח חו | source a | | | | |
|--------------------------------|---------------|----------|-------------------|----------|------------------|----------|----------|----------|-----------|-------|
| Components | Ald | -3 | Ald-4 | Ald-10 | Ald-17 | Ald-34 | Ald-106 | Ald-111 | Sut | -67 |
| | Cal 2 | 3 Dol | Cal 4 | Cal 5 | Cal 6 | Cal 7 | Cal 8 | Cal 9 | Cal 10 | Dol |
| | | | | | | | | | | : |
| Weight per cent | | | | | | | | | | |
| SiO ₂ | 1 | ł | 1.28 | 1.16 | 1.35 | 0.79 | 1.14 | 0.65 | ł | ļ |
| Al ₂ O ₃ | ł | ļ | Į | I | 0.03 | I | 0.01 | 0.01 | 1 | |
| CaO | 54.28 | 30.32 | 53.38 | 53.38 | 49.47 | 53.81 | 57.93 | 55.94 | 55.42 | 28.12 |
| FeO | 0.22 | 1.05 | ļ | - | 1 | 0.30 | - | ł | I | I |
| MgO | 2.22 | 19.76 | ţ. | ** | ł | 0.18 | 0.03 | 0.04 | 1.09 | 18.2 |
| MnO | 0.29 | 0.27 | 1 | ł | ŀ | 0.12 | 0.05 | ł | 4.00 | 5.8 |
| Na ₂ O | l | ţ | 0.04 | 0.01 | 0.10 | ł | 0.07 | 0.32 | 1 | I |
| K,Ō | I | ١ | 0.07 | 0.07 | 0.03 | ł | 0.08 | 0.06 | | ! |
| Σ | 57.02 | 51.40 | 54.77 | 54.62 | 50.98 | 55.20 | 59.31 | 57.02 | 60.51 | 52.12 |
| Cations per 3 oxygens | | | | | | | | | | |
| Si | ţ | I | 0.021 | 0.019 | 0.024 | 0.013 | 0.018 | 0.010 | I | |
| Ca | 0.940 | 0.515 | 0.956 | 0.960 | 0.949 | 0.963 | 0.961 | 0.972 | 0.922 | 0.485 |
| Fe | 0.003 | 0.014 | - | ł | I | 0.004 | | ļ | | 1 |
| Mg | 0.053 | 0.467 | | ł | I | 0.004 | 0.001 | 0.001 | 0.025 | 0.436 |
| Mn | 0.004 | 0.004 | I | I | Ι | 0.002 | 0.001 | 1 | 0.053 | 0.079 |
| Na | I | 1 | 0.001 | Ι | 0.003 | I | 0.002 | 0.010 | ł | |
| х | I | ŀ | 0.001 | 0.001 | 0.001 | 1 | 0.002 | 0.001 | - | 1 |
| Σ | 1.000 | 1.000 | 0.980 | 0.980 | 0.978 | 0.986 | 0.984 | 0.995 | 1.000 | 1.000 |

Table 7, Microprobe analyses and cation ratios in crystallochemical formulas for calcites and dolomites

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| Specimen | | Garnet | | Orthop | yroxene | | | | | , γ°1 | C/P (kbai | r) | | | |
|----------|---------------|----------|-----------|--------|-------------------------|------------|-------------|--------------------------|------------|------------|-------------------|------------|----------------------------|---------|-------------------|
| number | Pyr 2 | Alm 3 | Gros 4 | 5 5 | AlAIO ₃ 6 | NCor 78 | 8 8 8 | 1+ 9 | 2 10 | 3 11 3 | 4 | 5 13 | 6 14 | 7 15 | Average 16 |
| Sut-2/1 | 45.8* | 51.2 | 2.3 | 64.1 | 6.4 | 84.4 | | 711 6.4 | | 7.1 | $\frac{751}{7.2}$ | 805 7.2 | | | $\frac{744}{7.0}$ |
| | | | | 64.2 | 4.7 | 85.1 | | | | | | <u>679</u> | | | |
| | 43.1 | 53.8 | 2.4 | 67.5 | 6.0 | | | <u>558</u> 2.7 | | | | | | | |
| Sut-2/2 | 46.4* | 50.8 | 1.9 | 64.1 | 5.9 | 84.9 | | 743 8.0 | | 738 7.3 | 740 7.3 | 742 6.9 | | | 741 7.4 |
| | | | | 64.2 | 5.8 | 85.2 | | | | | | 722 6.9 | | | |
| Sut-6 | 46.6 | 50.3 | 2.2 | 64.2 | 6.4 | 85.8 | | $\frac{730}{7.2}$ | | 731 7.3 | <u>726</u> 7.3 | 719 7.5 | | | $\frac{727}{7.3}$ |
| Sut-10 | 50.8* | 45.0 | 3.6 | 67.0 | 7.5 | | | 700 5.5 | | | | | | | |
| | 48.2 | 47.8 | 4.0 | 71.6 | 5.5 | | | <u>552</u> 3.8 | | | | | | | |
| | 43.8 | 51.2 | 3.6 | 67.8 | 7.8 | | | $\frac{512}{0.3}$ | | | | | | | |
| Sut-28 | 52.9* | 45.7 | 0.8 | 63.0 | 8.3 | | | <u>836</u> 8.5 | | | | | | | |
| | 46.7 | 51.4 | 1.1 | 64.8 | 7.7 | | | <u>637</u> <u>3.4</u> | | | | | | | |
| | 53.0 | 45.6 | 0.7 | | | | 11.2 | | | | | | <u>(836)</u> <u>8.7</u> | | |
| Sut-61 | 63.5* | 35.5 | 1.0 | 71.1 | 8.1 | | | 808 9.1 | 807 8.9 | | | | | | 808 9.0 |
| | 63.5 ° | 35.5 | 1.0 | 71.5 | 7.8 | | | <u>823</u> 9.2 | 819 8.8 | | | | | | 821 9.0 |
| | 61.4 | 37.3 | 0.9 | | | | 14.3 | | | | | | <u>(820)</u> 8.7 | | |

Table 8. The mineral compositions and P-T conditions of metamorphism of the Aldan shield rocks

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| | 56.0 | 42.7 | 1.2 | 67.7 | 8.2 | $\frac{732}{6.0}$ | |
|---|---------------------------|-------------|--------------------------|---------------|---------|--|--|
| | 57.7 | 41.6 | 0.7 | 72.4 | 8.3 | <u>567</u> <u>2.6</u> | |
| Sut-72 | 27.7 | 69.5 | 1.8 | | | 65.9 | $\frac{827}{7.4}$ |
| Chog-2 | 59.8* | 37.2 | 2.2 | 6.9.3 | 8.2 | $\frac{820}{8.7}$ | |
| | \$9.8* | 37.2 | 2.2 | 69.8 | 7.6 | <u>833</u> <u>9.5</u> | |
| | 59.8* | 37.2 | 2.2 | 69.4 | 7.9 | <u>835</u> <u>9.4</u> | |
| | 57.6 | 39.1 | 2.1 | 71.5 | 8.2 | <u>639</u> <u>4.2</u> | |
| Chog-6 | 49.4 | 47.8 | 1.8 | 67.7 | 5.8 | <u>702</u> 7.1 | |
| | 46.7 | 49.5 | 1.8 | 70.0 | 6.1 | <u>522</u> <u>3.0</u> | |
| Chog-6 ^b | 54.6 | 42.2 | 2.1 | 68.6 | 8.9 | 645 <u>3.4</u> | |
| | 50.1 | 45.8 | 2.4 | 68.9 | 9.6 | <u>511</u> 0.04 | |
| Tok-9/2 | 54.5* | 42.2 | 2.6 | 66.7 | 8.5 | <u>753</u> 6.2 | |
| | 53.4 | 42.6 | 3.3 | 69.7 | 8.5 | <u>611</u> <u>2.9</u> | |
| Tok-18 | 51.5* | 43.3 | 3.4 | 67.5 | 6.5 | 768 8.6 | |
| | 54.7* | 42.3 | 2.0 | 70.7 | 7.4 | <u>637</u> <u>4.4</u> | |
| | 47.2 | 48.5 | 3.7 | 67.8 | 8.5 | <u>530</u> 0.6 | |
| * Core compositions. † The <i>P-T</i> parameters' (temperature assumed) | were estin) and (7) r | nated by: (| (1) reaction 2 and 1. | ls 7 and 5 ir | Table A | (2) reaction 7 and 8; (3) reactions 7 and 9; (4) reactions | s 2 and 9; (5) reactions 4 and 3; (6) reaction 6 |

Lavrent'eva, Aranovich & Podleskii, 1983; Korikovskii & Perchuk, 1983). Zoning in the Fe-Mg minerals and in garnet, in particular, is the most spectacular evidence of the retrograde stage. The Fe/Mg ratio in garnet usually increases to the grain rims; this indicates a decrease in temperature (Perchuk, 1969, 1971, 1977), with the composition of other minerals being constant. Sketches of the zoned garnets from metapelites of the Aldan shield are illustrated in Figs 7-10 and discussed above. Unzoned garnets and those with prograde zoning are very rare. Only one such example (sample Sut-61) was found in a metapelite which contains the Opx +Sil + Bi + Qz assemblage (see Fig. 11) and, probably, indicates the maximum P-T conditions of metamorphism in this region.

Extensive development of cordierite around garnet, in an assemblage with sillimanite and quartz (see Fig. 19a), is a result of the reaction

$$2Gr + 8Sil + Qz = 3Cor.$$
 (2)

The stability limits of cordierite expand to the iron-rich compositions with a temperature increase or pressure decrease (e.g. Perchuk, 1973, 1977; Martignole & Sisi, 1981; Aranovich & Podlesskii, 1983), with K_D^{Mg} decreasing. In most Aldan metapelites, however, the distribution coefficient increases with growth of the cordierite coronas and this indicates a decrease of temperature.

Reaction (2) was discussed (e.g. Loomis, 1976; Korikovskii, 1979; Korikovskii & Zuyev, 1970) as an example of prograde metamorphic relations. In zoned metamorphic complexes, reaction (2) actually shifts to the cordierite side with an increase in temperature ($K_{\rm D}$ decreases). In contrast to these complexes, in the Aldan shield metapelites the growth of cordierite between garnet and sillimanite was probably caused by a decrease in pressure and/or temperature. Sample Ald-49 provides a typical example of the retrograde compositional relations. Here, the garnet core contains 27% pyrope, while towards contacts with biotite and cordierite N_{Mg}^{Gr} decreases to 16.7. N_{Mg}^{Cor} varies only from 69.2 to 70.7 and N_{Mg}^{Bi} from 50.7 (core) to 58 (rim), which corresponds to a decrease in temperature and pressure from 780 °C to 600 °C and from 7 to 3-4kbar, respectively (see Table 8). Similar relationships were observed in a thin section, Sut-72. The core assemblage is $Gr_{27.7} + Cor_{65.9}$ and the rim assemblage is $Gr_{21} + Cor_{71}$, which indicates a decrease from $840 \degree C/7.5$ kbar to $650 \degree C/4.5$ kbar (see Table 8).

Symplectites of cordierite + quartz, overgrow biotite in garnet-bearing granulites (containing

no sillimanite) parallel with the appearance of orthopyroxene and K-feldspar. These textural relations have been reported earlier (Korikovskii & Kyslyakova, 1975; Perchuk *et al.*, 1983; Karasakov, 1978) from Sutam and Tok and are interpreted to indicate a prograde stage in the metamorphic evolution.

The orthopyroxene corona, with perthitic K-feldspar on biotite, is extremely rare in the rocks described. We have observed this phenomenon in the thin section Sut-2 (see Fig. 19b). Thus, this replacement can be described by the following prograde reaction:

$$Bi + 3Qz = Fsp + 3Opx + H_2O(+F), \quad (3)$$

which shows an example of the relict reaction texture. In this corona, biotite with the composition $K_{1.03}Fe_{0.64}Mg_{1.94}Ti_{0.28}Al_{1.11}Si_{3.01}O_{10}(O, OH)_2$ is replaced by orthopyroxene with a constant $N_{Mg} = 64$ but with a variable Al_2O_3 content, ranging from 3.45 to 4.26 wt% at different contacts with a biotite tablet. The perthitic K-feldspar consists of $Ab_{22}Or_{78}$ (matrix) + $Ab_{45}Or_{43}An_{12}$ (lamellae). An adjacent biotite grain is replaced by $Cor_{89-85} + Qz$. Thus, the more complex prograde reaction may describe the relationships observed:

$$Bi + Qz = Cor + Opx + Fsp + H_2O(+F).$$
(4)

The P-T conditions estimated from the cores of Opx and Gr of the relict assemblage correspond to 750 °C and 7.3 kbar but those inferred from the rim compositions show 590 °C and 3 kbar (see Table 8, sample Sut-2/2); this reflects the retrograde stage of the metamorphic process. Along with the reactions considered, the Cor + Qz intergrowth, with the plagioclase and orthopyroxene symplectites, replaces garnet in the same sample, Sut-2 (see Fig. 19c). The reaction texture indicates, unambiguously, the decrease in pressure in the course of metamorphic evolution because the reaction

$$Gr + Qz = Opx + Pl$$
 (5)

shifts to the right with a decrease in pressure.

In the gneiss sample Sut-3, collected from a locality near Sut-2, the cordierite-quartz intergrowths appear at contacts of biotite and garnet (see Fig. 19d). K-feldspar lamellae are expected as a product of the prograde reaction (3), but only plagioclase is found at these contacts, even though K-feldspar is present in the matrix of the rock. Orthopyroxene ($N_{Mg} = 67-69$) is in equal amounts with garnet. Plagioclase overgrowths on



partially crossed. Width of field 1.1 mm. (b) Orthopyroxene rim around biotite in metapelite Sut-2. Width of field 1 mm. Plane polarized light. (c) Quartz-cordierite symplectite with separate grains of orthopyroxene around garnet in metapelite Sut-2. Nicols slightly crossed. Width of field 0.8 mm. 0.6 mm. (d) Quartz-cordierite rim between cordierite and garnet in metapelite Sut-3. Nicols slightly crossed. Width of field 0.8 mm.



Fig. 19. Microphotos of reaction textures in granulites of the Aldan shield. (e) Symplectite of Cor + Opx developed together with biotite inside a garnet grain in granulite Tok-18. Plane polarized light. Width of field 0.8 mm. (f) Cordierite-orthopyroxene symplectite in granulite Sut-23/2. Nicols slightly crossed. Width of field 2 mm. (g) Sagenite in orthopyroxene from granulite Tok-19. Nicols crossed. Width of field 1 mm. (h) Intergrowth of orthopyroxene and sillimanite in granulite Tok-20. Plane polarized light. Width of field 2 mm. (g) Sagenite in orthopyroxene from granulite Tok-19. Nicols crossed. Width of field 1 mm. (h) Intergrowth of orthopyroxene and sillimanite in granulite Tok-20. Plane polarized light. Width of field 2 mm.



Fig. 19. Microphotos of reaction textures in granulites of the Aldan shield. (i) Cordierite reaction rim between orthopyroxene and sillimanite in granulite Tok-18. Plane polarized light. Width of field 1.1 mm. (j) Cordierite reaction rim between sapphirine and orthopyroxene in granulite Sut-10. Plane polarized light. Width of field 1.9 mm. (k) Intergrowth of feldspar, sapphirine and sillimanite in metapelite Sut-18. Plane polarized light. Width of field 2.2 mm. (l) Intergrowth of sapphirine, cordierite and sillimanite Sut-10. Plane polarized light. Width of field 1.4 mm.





garnet are very common (see Fig. 19c and Fig. 9). The composition of plagioclase changes inside a corona ($N_{An} = 24$ -40). This texture also indicates a decrease in pressure as in the case of the symplectitic intergrowth of Opx + Cor + Qz in sample Sut-2.

Not all garnet grains are overgrown by plagioclase or Cor + Qz coronas in granulites Sut-2 and Sut-3. Moreover, intergrowths of Cor + Qz were observed outside the reaction textures forming thin chains in the plagioclase-quartz matrix away from garnet.

The Cor+Opx+Fsp±Bi symplectites mantling garnet were reported from many granulite localities of Sutam and Tok (e.g. Kastrykina, 1976; Korikovskii & Kyslyakova, 1975; Karsakov, 1978; Perchuk *et al.*, 1983). An example of the texture is shown in Fig. 19e. It is possible for symplectites to develop from the reaction between osumilite and garnet as has been reported from Enderby Land, Antarctica, by Ellis, Sheraton, England and Dallwitz (1980),

$$Os + Gr + H_2O \rightleftharpoons Cor + Opx + Bi + Qz$$
, (6)

that proceeds to the right with a decrease in temperature. The microprobe investigations, however, gave no evidence of reaction (6) in the Aldan shield metapelites; no osumilite relics were found among cordierite-orthopyroxene symplectites.

The spectacular symplectites of cordierite and orthopyroxene were observed in granulite of sample Sut-23/2 (see Fig. 19f) composed practically of the cordiertite matrix with irregular distribution of biotite, quartz and sillimanite. Orthopyroxene has no contacts with sillimanite. In general, there appears to be a stable association of orthopyroxene and sillimanite which begins with segregation of the elongated sillimanite crystals in the large crystals of orthopyroxene during the formation of a sagenite texture (see Fig. 19g). As a rule, orthopyroxenesillimanite symplectites are well developed in these granulites (see Fig. 19h), but this assemblage breaks down, with decreasing pressure, to cordierite ($N_{M_R}^{Cor} = 92$) according to the reaction

$$2MgSiO_3 + 2Al_2SiO_5 + SiO_2 \neq Mg_2Al_4Si_5O_{18}.$$

In some granulites, thin coronas of cordierite appear between the grains of orthopyroxene and sillimanite in symplectites.

Sapphirine co-existing with quartz and Al-poor hypersthene, from quartzites of the Tokskii block, was originally reported by Karsakov (1978) who suggested the following reaction:

 $10(Mg, Fe)_{1.8}Al_{0.4}Si_{1.8}O_6$ Aluminous orthopyroxene

$$\rightleftharpoons^{8(Mg, Fe)_{2}Si_{2}O_{6}}_{Bronzite} + \frac{(Mg, Fe)_{2}Al_{4}SiO_{10}}{Sapphirine} + \frac{SiO_{2}}{Quartz}.$$

This reaction may explain the coronas of sapphirine + quartz on the aluminous orthopyroxene grains (see Fig. 190).

Calc-silicate rocks are exposed in each tectonic unit of the Aldan shield. They usually contain scapolite, calcite, diopside, quartz, wollastonite, sphene and, in places, dolomite. Grossular very rarely appears in these rocks as a primary mineral. Usually grossular forms coronas (see Fig. 19p) around scapolite and separates it from diopside, calcite, and quartz. The following reaction may be proposed, to explain the appearance of the grossular coronas around scapolite:

$$\frac{\text{CaAl}_2\text{Si}_2\text{O}_8\text{CaCO}_3}{\text{Scapolite}} + \frac{\text{SiO}_2 + \text{CaCO}_3}{\text{Quartz calcite}}$$
$$= \frac{\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12} + 2\text{CO}_2}{\text{Grossular}}.$$
 (10)

Korzhinkskii (1940) suggested the following rule: 'CO₂ pressure increases with increasing depth of granulitic metamorphism, thereby promoting carbonation reactions'. Applying this rule to the decarbonation reaction (10), we can conclude that a pressure decrease had to occur. This is another example of reaction textures which result from a pressure drop in the course of metamorphic evolution of the Aldan shield granulites.

P-T TRAJECTORY AND COMPOSITION OF FLUIDS DURING THE RETROGRADE STAGE OF METAMORPHISM

An internally consistent system of minerological thermometers and barometers, based on our experimental and theoretical data (see Appendix), were applied to microprobe analyses of coexisting minerals, to estimate changes in P-T conditions during metamorphism. Our P-T estimates are based on several thousand electron microprobe analyses; selected analytical data are listed in Table 8. These data were largely obtained on metapelites, because the methods of mineral thermometry and barometry for these rocks are

more developed. Three hand-samples of metabasites from Sutam and Tok, were also studied in detail.

The following mineral assemblage, Am_{62-65} + $Bi_{64}+Gr_{27-18.6}+Cpx_{62-71}+Opx_{54-55},$ was analysed in sample Sut-31. Several dozen probe analyses have shown that rims of garnet and pyroxene grains have higher Fe/Mg ratios than their cores, while the cores of amphibole and biotite grains have higher Fe/Mg than their rims. Plagioclase $(Ab_{10}An_{90})$, quartz and ore minerals also occur in this metabasite. The highest temperatures were estimated for cores of clinopyroxenes and amphiboles (750°C, see diagram A2 in Appendix), and the lowest estimates were obtained for contacting rims of the amphibole and garnet grains (Gr_{18.6} + Am₆₅ yields 470°C according to diagram A1 in the Appendix). The other mineral contacts show a wide range of temperatures between 750°C and 470°C (mean value, 630 °C) which reflect the retrograde stage of metamorphism of the rock.

Metabasite Sut-37 contains garnet ($N_{Mg} = 15-23$), biotite ($N_{Mg} = 66-68$), clinopyroxene ($N_{Mg} = 51-52$), plagioclase ($N_{An} = 90-93$), orthopyroxene (with 1.3-1.5 wt % Al₂O₃), quartz and ore, but no amphibole. According to Figs A2-A4 in the Appendix, the temperatures estimated from cores of Fe-Mg minerals range from 755°C to 690°C, and from rims of contacting grains, from 640 to 575°C.

Assemblage $Gr_{37} + Bi_{70} + Cpx_{63} + Opx + Pl + Qz$ was analysed in sample Chog-8 from Tok. Garnet and clinopyroxene grains are rimmed by plagioclase. Thermometers give 790°C (according to Fig. 4 in the Appendix) and 778°C (by biotite-garnet thermometer, see equation A20 in the Appendix), as well as 700°C—for contacting amphibole and clinopyroxene rims and 690°C—for contacting biotite and clinopyroxene rims.

Thus, the retrograde stage of metamorphism of the Aldan shield granulites, is clearly defined for metabasites as well as for metapelites. This stage shows itself as composition zoning in Fe-Mg minerals and as the appearance of the reaction rims of plagioclase around garnet and clinopyroxene grains.

The data from Table 8 are plotted in Fig. 20. Though textures of the Aldan shield granulites reflect both prograde and retrograde stages of the metamorphism, thermometry and barometry almost always show a decrease in temperature and pressure. This fact may be attributed to changes in the mineral compositions due to ionic exchange at the retrograde stage. Only in the case of sample Sut-61 did we find an increase in temperature accompanied by a slight decrease in pressure.

Thus, the results of geothermometric and geobarometric measurements, of mineral equilibria, reflect mainly a retrograde stage of metamorphism (see Fig. 20). These data are in good agreement with fluid inclusion studies; to be discussed below. By contrast, the data on reaction textures indicate a progressive stage of metamorphic process although P-T parameters have not been estimated quantitatively.

Evaluation of H₂O and CO₂ activities

The water fugacity has been estimated using equilibrium conditions for the mineral assemblage Gr + Bi + Fsp + Sil + Qz (Perchuk, 1973; Froese, 1973; Lee & Holdaway, 1977). Thermodynamic parameters for the corresponding reaction have been recently refined by Aranovich (1983) (see Appendix, equations from (A34) to (A37)). Results are given in Table 9. In addition to sample Sut-72 and Ald-49, this table shows the results of other samples from eastern Aldan which have been described in detail by Aranovich (1984). The last column of Table 9 lists the values of H₂O activity rather than H₂O mole fraction because there are no accurate data on composition of the metamorphic fluid phase. The assumption of ideality seems not to be valid even for the relatively simple case of H2O-CO2-NaCl fluids (Shmulovich, 1983; Shmulovich & Kotova, 1982).

The data of Table 9 indicate a surprisingly constant H_2O activity during the retrograde stage of metamorphism. Moreover, comparison of the

Table 9. H_2O activities estimated for the Gr + Bi + Fsp + Sil + Qz assemblage from the Aldan shield granulites

| Sample number | t (°C) | P (kbar) | <i>.f</i> н,о | a _{H20} |
|------------------|--------|----------|---------------|------------------|
| Ald-49 (core) | 780 | 6.5 | 1402 | 0.21 |
| Ald-49 (rim) | 615 | 4.0 | 384 | 0.17 |
| Sut-72 | 660 | 5.5 | 809 | 0.20 |
| Ald-51* | 630 | 5.1 | 570 | 0.17 |
| Ald-48* | 700 | 5.9 | 950 | 0.19 |
| Ald-52* | 745 | 6.8 | 1220 | 0.18 |
| Ald-20* | 670 | 5.7 | 990 | 0.23 |
| Ald-27* | 764 | 7.2 | 1490 | 0.19 |
| Ald-53* | 630 | 5.2 | 460 | 0.15 |
| | | | | |

* Data for these samples are from Aranovich (1984).

 H_2O activity values with those calculated by Lee & Holdaway (1977) for granite melting in the presence of $H_2O + CO_2$ fluid shows that anatectic melting of granites *in situ* did not take place at the retrograde stage. Some of the migmatite layers which occur in the Aldan shield granulites can be interpreted to be premetamorphic, similar to those reported by Grew (1981) for migmatite layers in granulites at Molodezhnaya Station, east Antarctica.

To evaluate the activity of CO_2 in the metamorphic fluid, the following end-member reactions have been used:

$$\frac{\text{CaCO}_3}{\text{Calcite}} + \frac{\text{SiO}_2}{\text{Quartz}} = \frac{\text{CaSiO}_3 + \text{CO}_2}{\text{Wollastonite}}$$
(11)

and

$$\frac{\text{CaAl}_{2}\text{Si}_{2}\text{O}_{8}}{\text{Anorthite}} + \frac{2\text{CaCO}_{3}}{\text{Calcite}} + \frac{\text{SiO}_{2}}{\text{Quartz}}$$
$$= \frac{\text{Ca}_{3}\text{Al}_{2}\text{Si}_{3}\text{O}_{12}}{\text{Grossular}} + 2\text{CO}_{2}. \quad (12)$$

The association of wollastonite with calcite and quartz was observed in many calc-silicate rocks alternating with metapelites both in western Aldan and in eastern Aldan. Estimates of metamorphic temperatures and pressures, obtained for the metapelites, fall within the wide P-T range shown in Fig. 20.

To simplify the estimation we accepted wollastonite and calcite to be pure $CaSiO_3$ and $CaCO_3$,



Fig. 20. P-T trajectories of metamorphic evolution of the Aldan shield granulites with the data of fluid inclusions.

respectively. This enabled us to use reaction (11) to estimate the evolution of the metamorphic fluid in respect of activity of CO_2 . Assemblages of garnet with plagioclase, calcite and quartz are also found widespread in calc-silicate rocks from these parts of the Aldan shield (see Table 1). However, as shown above, compositions of the garnet and plagioclase are variable. Grossular garnets (~95% Gros) and anorthite plagioclases (~95% An) are characteristic of the rocks of the highest metamorphic grade, with Fe-rich garnets and acid plagioclases corresponding to lower grades. Due to this fact, we used reaction (12) to estimate the CO_2 activity only at high temperatures.

According to the latest experimental data by Shmulovich (1983) the temperature (T) dependence of the Gibbs free energies (ΔG) of reactions (11) and (12) can be expressed as:

$$\Delta G(11) = 19327 - 35,143T, \tag{13}$$

and

$$\Delta G(12) = 26358 - 54.012T, \tag{14}$$

Using data on molar volumes of the solids, from Robie, Hemingway & Fisher (1978) we get equations which describe the equilibrium of reactions (11) and (12) (where K = the activity product of the solid phases):

$$RT \ln K(11) + RT \ln f_{CO_2} + 19327 - 35.143T - 0.47068(P-1) = 0 \quad (15)$$

and *R*

$$RT \ln K(12) + 2RT \ln f_{CO_1} + 26358 - 54.021T - 1.72206(P-1) = 0 \quad (16)$$

Estimates of pressure and temperature of metamorphism of western Aldan and eastern Aldan have been found to fit a linear equation (Fig. 20),

$$P(bar) = -6538 + 12.5T.$$
(17)

The simultaneous solution of equation (17) and equations (15) and (16) has given the following estimates of the metamorphic conditions: T = $832 \,^{\circ}$ C, P = 7281 bar, $f_{CO_1} = 34471$ bar. With regard to the CO₂ fugacity coefficient (γ_{CO_1}) equalling 16.5 (Shmulovich & Shmonov, 1978) this CO₂ fugacity value (f_{CO_1}) corresponds to the CO₂ activity ($a_{CO_1} = f_{CO_1}/\gamma_{CO_1}P_{FL}$) of 0.3.

For 590 °C and 4 kbar (conditions corresponding to minimum depth of metamorphism of the Aldan rocks), the f_{CO_1} calculated from equilibrium conditions of reaction (11) equals 1883 bar, implying the CO₂ activity of ~0.1. The evaluation of the CO₂ activity shows that with decreasing pressure a role of CO_2 in the metamorphic process has probably become less important, due to increasing water content in the fluid. This conclusion is supported by data on fluid inclusions in minerals from granulites of western and eastern Aldan (Tomilenko & Chupin, 1983).

Fluid inclusions

Fluid inclusions, in two Sutam samples, were studied for determining the evolution of P-T parameters. Both samples Sut-61 and Sut-10 were preferentially examined with a microprobe (see Table 1) and the equilibrium T and P was then determined by mineralogical thermometry and (see Table 8).

In the sapphirine-garnet-biotite-cordieriteorthopyroxene-plagioclase gneiss, about 340 measurements of fluid inclusions have been made to determine the homogenization temperatures (see the histogram at the top of Fig. 20). These inclusions are represented by almost pure liquid CO_2 : the cavity walls do not contain any visible H_2O , but the gas-hydrates are rarely crystallized at freezing. The most dense inclusions ($V_{CO_1} =$ 0.9-0.99) occur in plagioclases. However, the bulk of the fluid inclusions occurs in recrystallized garnet grains. Their specific volume, V_{CO_1} , ranges from 0.99 to 1.12 cm³/g. The least dense ($V_{CO_1} =$ 1.42), but vast inclusions can also be observed only in garnets.

In hypersthene-sillimanite granulite Sut-61 the most dense carbonic inclusions (V_{CO} , == 0.89-0.9 cm³/g) were discovered in the first generation quartz formed at 850 °C (see Table 7). Close values were determined for inclusions from the first generation garnets. The inclusions contained no visible water. Possibly, they would contain no more than 10 % HF, HCl and/or H₂S.

Figure 20 shows histograms of 228 homogenization temperature measurements. We have suggested that the most dense inclusions should correspond to the highest temperatures obtained from the mineral geothermometry (see Table 8), and the corresponding pressure values were estimated using isochors of Fig. 20. Similarly, the least dense inclusions should correspond to the lowest temperatures. The points were also plotted onto the diagram of Fig. 20. As is seen from the diagram, these data are in good agreement with the results obtained independently by mineralogical barometry.

Tomilenko & Chupin (1983) reported the data on homogenization temperature measurements and compositions of gas-liquid inclusions in

Table 10. Homogenization temperatures and specific volumes of CO₂ inclusions (\bar{V}_{CO_2}) in minerals from granulites of the Aldan shield (after Tomilenko and Chupin, 1983)

| Fluid bearing | (min hom | I max hom | ν̄ _{co,} |
|---------------|-------------|--------------|-------------------|
| Western Aldan | | | |
| Garnet | 3 | + 5 | 1.0666-1.12 |
| Sillimanite | - 3 | + 5 | 1.066-1.12 |
| Quartz | - 3 | + 5 | 1.066-1.12 |
| Sutam | | | |
| Sapphirine | - 27 | - 25 | 0.94-0.95 |
| Plagioclase | 27 | - 23 | 0.94-0.95 |
| Garnet | 222 | -10 | 0.96-1.02 |
| Sillimanite | - 18 | -10 | 0.978-1.02 |
| Quartz | - 20 | - 10 | 0.97-1.02 |
| Tok | | | |
| Quartz | - 42 | - 27 | 0.89-0.94 |

minerals from the Aldan shield granulites. Some of these data are listed in Table 10. Although both chemical compositions and zoning of these coexisting minerals have not, as yet, been studied, the densities of inclusions in these minerals are roughly the same as in samples Sut-61 and Sut-10. Hence, P-T parameters of metamorphism might also have been similar.

A microchemical analysis of the gas extracts, from enclaves in minerals made by Tomilenko & Chupin (1983), indicates that this fluid contains essentially CO₂ (90%) with small amounts of H₂O, GF, HCl, SO₃, CH₄, CO and N₂. The H₂O/CO₂ ratio is higher only in the granulites which developed markedly during the amphibolite facies metamorphism. Highly concentrated salt solutions are not typical of the inclusions and the bulk content of salts does not exceed 10 wt % (Na, K, Mg, Ca chlorides). Quartzes of the western Alden granulites occasionally contain liquid methane (+CO₃).

A TECTONIC MODEL OF METAMORPHIC EVOLUTION OF THE ALDAN SHIELD

The Aldan shield is characterized by a relatively similar petrochemistry within each of its units. Each unit consists predominantly, of metapelites with subordinate amounts of metabasites and calc-silicate rocks. On the basis of lithology and paleogeography, of the region, we can propose the following hypothesis. In early Archaean times a large shallow sea was surrounded by volcanic ridges where dacitic and rhyolitic lavas were ex-

truded (Fig. 21A). Submarine volcanism was characterized by more basic compositions (andesites and basalts). This basin developed on the border between the eastern-Siberian and Mongolo-Okhotskaya plates and sediments accumulated from an extensive territory. This conclusion is based on the large thickness of metamorphosed terrigeneous sediments. Accumulation of the sediments was accompanied by subsidence of the basin, elevation of isotherms in the underlying upper mantle towards the Moho boundary, and increasing volcanic activity. During late Archaean time, vertical movements were affected by a subduction of the Mongolo-Okhotskaya plate under the eastern Siberian plate. During the middle Archaean the present-day Stanovoy foldbelt existed as a bridge of volcanoes (in part subaqueous) giving rise to an island arc (Fig. 21B). The crust thickness of that territory was 2-3 times greater than that beneath the Aldan sea basin, but heat flows were similar in both areas.

The Stanovoy fold-belt was completely formed and uplifted during the early Proterozoic following the retrograde stage of Archaean metamorphism, as was shown in the previous section for southern Sutam. In this belt, the high pressure and moderate temperature conditions were probably created by subduction of the Mongolo-Okhotskaya plate under the eastern Siberian continental plate. While the folding and formation of blastomylonites took place, the chemical reactions between minerals created assemblages of kyanite series in the fold-belt. At the same time, some of the rigid deep-seated granulite blocks, of the marginal part of the continental plate, were forced up from a higher pressure zone along the blastomylonite zones (Karsakov, 1980) of the Stanovoy fold-belt (Fig. 21C). Due to such a mechanism, the original textures, described above, were preserved in the granulites.

From the P-T diagram of Fig. 20 we can conclude that the maximum P-T conditions beneath the Aldan sea basin corresponded to a lesser depth than those beneath the Tok and Sutam areas where the crust was thicker. The maximum P-T conditions of metamorphism were probably attained about 3.4 b.y. ago and mark the first metamorphic event. The second event corresponds to an age of 2.6 b.y. There are no isotopic data on the retrograde stage which may have occurred in the same period. According to Gerasimov's unpublished experimental data on the rate of the Fe and Mg diffusion in garnets, the width of diffusion zones in garnets described in this paper indicates that the retrograde stage lasted 0.8 m.y. During this time, the metamorphic



complexes of the Aldan shield were uplifted by 16 km and cooled by 300 °C (Fig. 20).

Thus, three main tectonic stages may be distinguished in the metamorphic evolution of the Aldan shield:

(1) The stage of prograde metamorphism of terrigenous sediments accumulated in the marginal sea rimmed from the south by an island arc. This stage may be referred to as the upper Archaean and it involved the most highly metamorphosed granulites of the shield.

(2) The stage of the retrograde regional metamorphism coinciding in time with transformation of the island arc to the Stanovoy fold-belt during subduction of the Mongolo-Okhotskaya plate (The Archaean Proterozoic boundary).

(3) A second metamorphic event (early Proterozoic), within the Stanovoy fold-belt, leading to the development of kyanite series rocks from Mg-Al-rich granulitic rocks. Relics of fresh granulites are found as rare tectonic blocks uplifted from great depths.

All three stages of the tectonic and metamorphic evolution of the Aldan shield rocks are schematically shown in the geodynamic pattern of Fig. 21.

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Fig. 21. Sketches illustrating geological evolution of the Aldan shield and Stanovoy fold-belt (North is on the left). MOP = Mongolo-Okhotskaya Plate; ESP = Eastern-Siberian Plate.

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APPENDIX

Thermodynamic symbols

| X_i^{ϕ} | Mole fraction of component i in phase ϕ . |
|-------------------|---|
| K _D | Distribution coefficient of Fe |
| | and Mg betwen ϕ_1 and ϕ_2 . |
| | $K_{\rm D} = \left(\frac{\rm Mg}{\rm Fe}\right)^{\phi} / \left(\frac{\rm Mg}{\rm Fe}\right)^{\phi}$ |
| K, | Partition coefficient of com- |
| | ponent i. |
| f_{i} | Fugacity of component i. |
| a_i^{ϕ} | Activity of component i in phase |
| · | ϕ . |
| γ_1^{ϕ} | Activity coefficient of com- |
| | ponent i in phase ϕ . |
| Т | Temperature, K. |
| t | Temperature, °C. |
| P | Pressure, bar. |
| R | A gas constant, 1.987 cal/K, |

A gas constant, 1.987 cal/K, mole.

- C_p Heat capacity at constant pressure.
- ss Subscript denoting the phase represented by solid solution.

One of the main purposes of this paper was to find and describe the evolution of metamorphic processes of the Aldan shield granulites in terms of P, T, f_{CO} , and $f_{H,O}$. Mineralogical thermometry and barometry, on the one hand, and the position of some well determined univariant mineral reactions, on the other, were used for solving this problem. Firstly, we have to consider some thermodynamic models of the mineral solid solutions.

Activities of components in mineral solid solutions

Cordierite (Fe, Mg)₂Al₄Si₅O₁₈(l - n)H₂O

For cordierite, an ideal two-site model has been assumed that takes into account H_2O in the structural channels (Aranovich & Podlesskii, 1983):

$$RT \ln a_{\text{COTM}_{0}} = 2RT \ln X_{\text{Mg}} + RT \ln n, \quad (A1)$$

$$RT\ln a_{\text{Corre}} = 2RT\ln X_{\text{Fe}} + RT\ln n, \qquad (A2)$$

$$\ln n = 1.006 - 1260/T - 0.18205(P-1)/T.$$
(A3)

Garnet (Mn, Ca, Fe, Mg)₃Al₂Si₃O₁₂

Thermodynamic properties of multicomponent Gr_{ss} were estimated using experimental data on phase equilibria and thermochemical measurements in the binary boundary systems. We have, per one mole of isomorphous components:

- $G_{Fe-Mg}^{e} = 0$ (Perchuk & Lavrent'eva, 1983; Aranovich & Podlesskii, 1983; O'Neil & Wood, 1979; Perchuk, 1967, 1970, 1977)
- $W_{Ca-Mg} = 3300 1.5T$ (Newton & Haselton, 1981)

$$G_{\text{Fe-Mn}}^{c} = 0$$
 (Weisbrod, 1974; Hsu, 1968)

Since the Fe-Mg and Fe-Mn solid solutions are

close to ideal, we have assumed that the Mg-Mn solution is also ideal, i.e.

$$G_{Mg-Mn}^{e} = 0.$$

For Ca-bearing garnets we considered the range $0 \le X_{Ca} \le 0.3$, which covers the range of calcium content in metapelitic garnets. This enabled us to markedly simplify the description of their thermodynamic properties. For partial excess molar-volumes of components, we have obtained the following equations from the data of Cressey, Schmid & Wood (1978):

$$V^{\circ}(\text{Gros}) = 0.025 - 1.522(0.2 - X_{Ca})^2$$
, (A4)
 $V^{\circ}(\text{Py}) \approx V^{\circ}(\text{Alm}) \approx 0$.

Excess free energy for the Alm-Gros join has been calculated from the data of Cressey *et al.* (1978) using Darken's (1967a, 1967b) formulation:

$$G^{e}(\text{Gros}) = (2404 + 0.258T)X_{Ca}(2 - X_{Ca}) + (5704 - 1.242T)X_{Mg}(1 - X_{Ca}) - (234 + 0.748T), \quad (A5)$$

$$G^{\bullet}(Alm) = -(2404 + 0.258T)X_{Ca}^{2},$$

(-5704 - 1.242T)X_{Ca}X_{Me}. (A6)

For Ca-Mn garnets there are no experimental data. As far as the Fe-Mn solid solution in Gr is ideal, and the properties of these elements in the +2 oxidation state are similar, we have assumed that the Ca-Mn interaction is equal to that of the Ca-Fe (Aranovich, 1984):

$$G^{\epsilon}_{Mn} \approx G^{\epsilon}_{Fe},$$

 $G^{\epsilon}_{Ca}(Ca - Mn) \approx G^{\epsilon}_{Ca}(Ca - Fe).$

In sum, the equation for the calculation of activity of components may be written as follows, for quaternary Fe-Mg-Ca-Mn garnets:

$$RT \ln a_{\text{Gros}} = 3[RT \ln X_{\text{Ca}} + (2404 + 0.258T)X_{\text{Ca}}(2 - X_{\text{Ca}}) + (5704 - 1.242T)X_{\text{Mg}}(1 - X_{\text{Ca}}) - (234 + 0.748T)] + 3PV_{\text{Gros}}^{e},$$
(A7)

$$RT\ln a_{Alm} = 3[RT\ln X_{Fe}]$$

$$-(2404+0.258T)X_{Ca}^{2}$$

$$-(5704 - 1.242T)X_{Ca}X_{Mg}],$$
 (A8)

$$RT \ln a_{\text{Pyr}} = 3[RT \ln X_{\text{Mg}} + (3300 - 1.5T)X_{Ca}^{2} + (5704 - 1.242T)X_{Ca}X_{Fe}]. \quad (A9)$$

It should be noted that equations (A4)–(A9) are valid only for the ranges $0 \le X_{Ca}^{Gr} \le 0.3$ and $X_{Fe}^{Gr} \ge 0.4$.

Orthopyroxene (Mg, Fe, Al)(Al, Si)O₃

The Opx solid solution is presented as a regular

mixture of simple components MgSiO₃(En), FeSiO₃(Fs) and fictive end-member 'ortho- Al_2O_3 (A). The calculations made by Aranovich & Kosyakova (1985) have shown that this model fits experimental data on the orthopyroxene equilibria in the systems MgO-Al₂O₃-SiO₂ (MAS) (Perkins, Holland & Newton, 1981; Aranovich, Kosyakova & Van, 1983; Gasparik & Newton, 1984) and FeO-MgO-Al₂O₃-SiO₂ (FMAS) (Aranovich & Kosyakova, 1984; Kawasaki & Matsui, 1983) in the same way as a two-site model (Wood & Banno, 1973; Sack, 1980; Kawasaki & Matsui, 1983). Using experimental points the following parameters have been calculated (Aranovich, Podlesskii & Kosyakova, 1985):

$$W_1 = W_{MgAl} = -1237,$$

 $W_2 = W_{FeMg} = -2533 + 1.86T,$ (A10)
 $W_3 = W_{FeAl} = -6441.$

Using equation (A10) and neglecting the pressure dependence of activities in Opx solid solutions, we have:

$$RT \ln a_{\text{En}} = RT \ln X_{\text{Mg}} + X_{\text{Fe}}^{2}(-2533 + 1.86T) + X_{\text{Fe}}X_{\text{Al}}(2671 + 1.86T) + X_{\text{Al}}^{2}(-1237)$$
(A11)

$$RT \ln a_{Fs} = RT \ln X_{Fe} + X_{Mg}^{2}(-2533 + 1.86T) + X_{Al}^{2}(-6441) + X_{Mg}X_{Al}(-7937 + 1.86T),$$
(A12)

$$RT \ln a_{AI} = RT \ln X_{AI} + X_{Fe}^{2}(-6441) + X_{Fe}X_{Mg}(-6145 - 1.86T) + X_{Mg}^{2}(-1237).$$
(A13)

Plagioclase $(Ca_xNa_{1-x})(Al_{1+x}Si_{3-x})O_8$

The activity of An in the Pl solid solution has been calculated by the equation of Newton, Charlu & Kleppa (1980):

$$RT \ln a_{An} = RT(\ln X_{An} + 2\ln(1 + X_{An})) - 1.386) + (1 - X_{An}^{2}) \times (2050 + 9392X_{An}).$$
(A14)

The excess molar-volume of anorthite, in plagioclase, is close to 0 (Newton *et al.*, 1980; Newton & Haselton, 1981).

Biotite (Na, K)(Mg, Fe²⁺, Mn, Fe³⁺, Al, Ti)₃ (Al, Si)₄O₁₀(O, OH, F)₂

Biotite has been treated as an ideal multi-site solid solution (Bohlen, Peacor & Essene, 1980;

Aranovich, 1983). The thermodynamic model of reciprocal solutions (Wood & Nicholls, 1978; Aranovich & Kosyakova, 1980) has been used for formulation of Phl and Ann activities in biotites with F-OH substitution. Values for the parameters of the model have been calculated from the experimental data of Munoz & Ludington (1974) on the F-OH exchange between Phl and fluid and Ann and fluid:

Phl(OH) + Ann(F) = Phl(F) + Ann(OH),
(A15)
$$\Delta G^{\circ}(A15) = -4905 - 6.588T + 0.081P.$$

(A16)

The equations for the activities of components in the biotite solid solution may be written as follows:

$$a_{\rm PhI} = X_{\rm K} X_{\rm Mg}^3 n_{\rm AI^{\rm IV}} (n_{\rm Si}/3)^3 X_{\rm (OH)}^2$$

$$\times \exp \{X_{\rm Fe} X_{\rm F} \Delta G^{\circ}({\rm A15})/RT\}, \qquad (A17)$$

$$a_{\rm Ann} = X_{\rm K} X_{\rm Fe}^3 n_{\rm AI^{\rm IV}} (n_{\rm Si}/3)^3 X_{\rm (OH)}^2$$

$$\times \exp \{-X_{\rm Mg} X_{\rm F} \Delta G^{\circ}({\rm A15})/RT\},$$

where $n_{A^{\mu\nu}} = [Al(i\nu)]/4$; $n_{S_i} = 4 - n_{A^{\mu\nu}}$, $A^{\mu\nu} =$ the number of tetrahedral Al-atoms in the formula unit of biotite per 22 negative charges.

Mineralogical thermometry and barometry _

A large number of experimental, theoretical and empirical calibrations for mineralogical thermometers and barometers has appeared in geological literature during the last 10 years (reviewed by Essene, 1982). However, these thermometers and barometers are not based on an internally consistent set of thermodynamic data and, consequently, their precision and accuracy is difficult to assess.

In the present paper, we have used an internally consistent set of mineralogical thermometers and barometers that is based on the general principle of the phase correspondence formulated by Perchuk (1969, 1970, 1977). Nearly all of the geothermometers and geobarometers were calibrated experimentally or treated thermodynamically to be consistent with the available experimental data on different mineral equilibria. The mineral reactions and corresponding thermodynamic data are listed in Table A1.

Cordierite-garnet and biotite-garnet geothermometers

For estimating temperatures of metamorphism of the Aldan granulites, the cordierite-garnet and

| No. | Reaction | Number of reaction in text | ΔH°_{970} cal | Δ <i>S</i> [°] ₉₇₀ eu | ΔV° calbar ⁻¹ |
|------------|--|----------------------------------|------------------------------|--|-----------------------------|
| 1 | $\frac{1}{3}\operatorname{Pyr} + \frac{2}{3}\operatorname{Sil} + \frac{5}{6}\operatorname{Qz} = \frac{1}{2}\operatorname{Cor}_{M_R}$ | A25 | 51 | 4.62 | 0.63827 |
| 2 | $\frac{1}{3}$ Pyr + $\frac{1}{2}$ Cor _{Fe} = $\frac{1}{3}$ Alm + $\frac{1}{2}$ Cor _{Mg} | A26 | -6134 | -2.668 | - 0.03535 |
| 3 | $\frac{1}{2}$ Cor _{Me} = En + $\frac{3}{2}$ Qz + AlÅIO ₃ | A27 | 6096 | - 4.897 | -0.42628 |
| 4 | $\frac{1}{2}$ Cor _{Ma} + Fs = $\frac{1}{2}$ Cor _{Fe} + En | A22 | 1368 | 0.014 | 0.0193 |
| †5 | $Pyr = 3En + AlAlO_3$ | A33 | 2785 | -1.869 | 0.32855 |
| 6 | $\frac{1}{3}$ Gros + $\frac{2}{3}$ Sil + $\frac{1}{3}$ Qz = An | A31 | 2722 | 10.266 | 0.435 |
| 7 | $\frac{1}{3}$ Pyr + Fs = $\frac{1}{3}$ Alm + En | A21 | -4766 | - 2.654 | -0.02342 |
| ‡ 8 | $\frac{1}{3}$ Pyr + $\frac{1}{3}$ Qz = En + $\frac{1}{3}$ Sil | | - 1681 | - 0.796 | 0.06328 |
| 9 | $Pyr + \frac{3}{2}Qz = 2En + \frac{1}{2}Cor_{Mg}$ | _ | -3311 | 3.028 | 0.76483 |

Table A1. Thermodynamic constants of reactions involving garnet, cordierite, orthopyroxene and plagioclase*

* The sources of thermodynamic parameters: reactions 1 and 2—Aranovich & Podlesskii, 1983; 3-5, 7 and 8— Aranovich *et al.*, 1985; 6—Aranovich, 1983; 9—linear combination of 1 and 8. Sources of experimental data are given in text.

 $\dagger \Delta Cp = 5.88$ (calculated from the experimental data of Perkins *et al.*, 1980).

 $\pm \Delta Cp = 1.96$ (mean value in the temperature range 1000-1600 K).

biotite-garnet mineralogical thermometers were used. Results of experimental calibration have been discussed by Perchuk & Lavrent'eva (1983).

Cordierite-garnet geothermometer can be expressed by the following equation:

$$T = \frac{3087 + 0.018P}{\ln K_{\rm P} + 1.342}.$$
 (A18)

Precision of the thermometer is estimated to be $\pm 12^{\circ}$ C.

According to experimental data on the Capoor system mentioned above, and taking into account equations (A4)–(A9), we can record the biotite-garnet thermometer as follows:

$$T = \frac{3720 + 2871X_{Ca}^{Gr} + 0.038P}{\ln K_{\rm D} + 0.625X_{Ca}^{Gr} + 2.868}.$$
(A19)

A statistical precision of equation (A19) is within ± 15 °C. Biotites from the majority of depth granulites of the world usually contain significant fluorine. For biotites from the Sutam granulites, equation (1) expresses correlation between X_{Mg}^{Bi} and C_{F}^{Bi} . This correlation indicates that the introduction of fluorine in biotite decreases the Mg activity coefficient and facilitates an increase in the Mg concentration in biotite at a constant temperature. This substitution shifts the exchange equilibrium, $\frac{1}{3}$ Pyr + $\frac{1}{3}$ Ann = $\frac{1}{3}$ Alm + $\frac{1}{3}$ Phl, to the right and, as a consequence, leads to an artificial underestimation of the temperature values by the Gr-Bi thermometer. Perchuk & Aranovich (1984) used the experimental data of Munoz & Ludington (1974) to correct the garnetbiotite thermometer for F in biotite. The corrected biotite-garnet geothermometer equation is:

$$T = \frac{3720 + 2871 X_{Ca}^{Gr}}{(0.38 - 0.02 X_{F}^{Bi}/n)P} + 2469 X_{F}^{Bi}/n}{\ln K_{D} + 2.868} + 0.625 X_{Ca}^{Gr} - 3.27 X_{F}^{Bi}/n}, \quad (A20)$$

where $X_F^{Bi} = F/(F + OH)$ and the coefficient *n* equals (Mg + Fe) in the crystallochemical formula of biotite; calculated per 22 negative charges. Equation (1) was used to calculate X_F for biotites from the Aldan shield granulites.

Garnet-orthopyroxine geothermometer

The standard entropy and enthalpy effects of the exchange reaction

$$\frac{1}{3}$$
Pyr + Fs = $\frac{1}{3}$ Alm + En (A21)

are given in Table A1. They have been obtained (Aranovich *et al.*, 1985) by linear combination of the thermodynamic parameters for equilibrium (A18) and equilibrium

$$\frac{1}{2}Cor_{Mg} + Fs = \frac{1}{2}Cor_{Fe} + En,$$
 (A22)

that has been studied experimentally by Aranovich & Kosyakova (1984). Using ΔH° and ΔS° from Table A1 and corresponding activity expressions, the following equation of the garnet-orthopyroxene geothermometer has been derived:

$$t = \frac{4766 + 2533(X_{F_{5}} - X_{En})^{O_{PX}}}{R \ln K_{D} + 2.65} - 273, \quad (A23)$$

+ 0.023*P*
- 273, (A23)
+ 1.86(X_{F_{5}} - X_{En})^{O_{PX}} + 1.242X_{C_{4}}^{C_{4}}

where

$$\begin{split} & K_{\rm D} = (X_{\rm Fe}^{\rm opx} X_{\rm En}^{\rm opx}) / (X_{\rm Mg}^{\rm opx} X_{\rm Fs}^{\rm opx}); \\ & X_{\rm Fs}^{\rm Opx} = {\rm Fe} / ({\rm Fe} + {\rm Mg} + {\rm Al}/2); \\ & X_{\rm En}^{\rm Opx} = {\rm Mg} / ({\rm Fe} + {\rm Mg} + {\rm Al}/2); \end{split}$$

and

$$X_{\rm Al}^{\rm Opx} = 1 - X_{\rm Fs} - X_{\rm En}.$$

It should be noted that for garnets with a high Cr_2O_3 content (which is characteristic of garnet in mantle xenoliths) an additional term must be added to the right hand side of equation (A23) (Aranovich & Kosyakova, 1980, Aranovich *et al.*, 1985). Although at low to intermediate pressures, the pressure term in equation (A23) could be neglected, in most cases this equation should be solved simultaneously with one of the geobarometric equations to be considered in the next section.

Garnet-cordierite-sillimanite-quartz geobarometer

Experimental and theoretical problems, on using this assemblage for estimates of pressure, have been discussed by Aranovich & Podlesskii (1983).

The entropy and enthalpy effects of the reaction with anhydrous cordierite,

$$\frac{1}{3}Pyr + \frac{2}{3}Sil + \frac{5}{6}Qz = \frac{1}{2}Cor_{Mg}, \qquad (A25)$$

are given in Table A1. When these values of ΔH° and ΔS° are combined with activity equations for Pyr and Cor, respectively, and after re-arrangement, we get:

$$P(\text{bar}) = 2605 + (t + 273)(7.855 - 4.310 \ln K_{\text{Mg}})$$
(A26)

where $K_{Mg} = X_{Mg} = X_{Mg}^{Cor} / X_{Mg}^{Gr}$.

Solving equations (A18) and (A26) simultaneously gives the equilibrium values for P and tfor the Gr + Cor + Sil + Qz assemblage.

The corrections connected with the Ca content in garnet are not included in equations (A18) and (A26) because the Ca contents of garnets associated with cordierite are generally very small.

Cordierite-orthopyroxene-quartz geobarometer

Experimental data on equilibrium

$$\frac{1}{2}\text{Cor}_{Mg} = \text{En} + \text{AlAlO}_3 + \frac{3}{2}\text{Qz} \quad (A27)$$

in the systems MgO-Al₂O₃-SiO₂ (MAS) and FeO-MgO-Al₂O₃-SiO₂ (FMAS) were obtained by Aranovich & Kosyakova (1983, 1984). The values of ΔH° and ΔS° calculated from these data are given in Table 1A. Using (A1), (A11) and (A13) we get the geobarometric equation

$$P = [7348 + 3.90T + (X_{Fe}^{Opx})^{2}(-8974 + 1.86T) - X_{Fe}^{Opx}(X_{Mg}^{Opx} - X_{Al}^{Opx})(3918 + 1.86T) - 1237X_{Al}^{Opx}(1 - X_{Mg}^{Opx}) - 1237X_{Mg}^{Opx}(1 - X_{Al}^{Opx}) + RT \ln K]/ (0.250 + 0.142(X_{Fs} + X_{En})^{2} + 0.142X_{Al}^{2}), (A28)$$

where

$$K = (X_{\rm Mg} X_{\rm Al})^{\rm Opx} / X_{\rm Mg}^{\rm Cor}.$$

It should be noted, however, that the use of equation (A28) leads to relatively large uncertainties because (i) it is difficult to estimate the equilibrium T value, as the constant of exchange equilibrium,

$$\frac{1}{2}Cor_{M_{R}} + Fs = \frac{1}{2}Cor_{Fe} + En,$$
 (A29)

is nearly temperature independent ($\Delta H^{\circ} = 1368 \text{ cal/mol}$, see Table A1); and (ii) pressure estimates are markedly affected by the value of X_{Al}^{Opx} , which is usually analysed with uncertainty about $\pm 10 \text{ rel} \%$.

Garnet-orthopyroxene geobarometer

The geobarometer is based on the precise experimental data of Perkins *et al.*, (1981) for the reaction

$$Pyr = 3En + AlAlO_3$$
 (A30)

in the system MAS. We have treated their data, to calculate the thermodynamic parameters for reaction (A30), using the following equation for the molar-volume of Opx in the En-AlAlO₃ join (Aranovich *et al.*, 1985):

$$V(\text{Opx}) = 0.7484 - 0.1016X_{\text{Al}} + 0.1425X_{\text{Al}}^2$$

The results are given in Table A1.

In applying data from the MAS system to more complex natural compositions, one should calculate the activities of Pyr, En and AlAlO₃ with equations (A9), (A11) and (A13), respectively. Even with the activity corrections, the precision of the Gr-Opx geobarometer is only $\pm 2-5$ kbar. This low precision may be attributed to the long extrapolation of the experimental data of Perkins *et al.* (1981) to lower pressures and to uncertainties in the determination of $X_{AIAIO_3}^{Opx}$; mentioned above.

Garnet-plagioclase-aluminium silicate-quartz geobarometer

Experimental data on the reaction

$$\frac{1}{3}Gros + \frac{2}{3}Ky + \frac{1}{3}Qz = An$$
 (A31)

have been obtained by Schmid, Cressey & Wood (1978) and Goldsmith (1980) using different methods for bracketing of equilibrium.

The discrepancies between the two determinations of the P-T equilibrium conditions appear to be associated with differences in the corrections of nominal run pressures used in these papers.

Applying the friction corrections recommended by Perkins *et al.* (1981) to the data of Schmid *et al.* (1978) and Goldsmith (1980), we have arrived at the following equation, for (A31), in the P-t plane (Aranovich, 1983):

$$P = -961 + 23.01t, \qquad (A32)$$

that corresponds to $\Delta H^{\circ} = 2722$ cal and $\Delta S^{\circ} = 10.266$ eu (Table A1) for reaction (A31) with sillimanite. Using these values and the equations for the activity of grossular (A7) and anorthite (A14), one can obtain the following geobarometric equation:

$$P = \{A + BT + 1.987T \\ \times [\ln X_{Ca}^{Pl} + 2\ln(1 + X_{Ca}^{Pl}) - \ln X_{Ca}^{Gr}] \\ + (1 - X_{Ca}^{Pl})^{2}(2050 + 9392X_{Ca}^{Pl}) \\ - [(5704 - 1.242T)X_{Mg}^{Gr}(1 - X_{Ca}^{Gr}) \\ + (2404 + 0.258T)X_{Ca}^{G})(2 - X_{Ca}^{Gr})]\}/$$

$$[C - 1.522(0.2 - X_{Ca}^{Gr})^{2}], \qquad (A33)$$

where A, B and C depend on the Al_2SiO_5 polymorph present:

Polymorph of

| Al ₂ SiO ₅ | A | В | С |
|----------------------------------|------|---------|--------|
| Кy | 4053 | 14.139 | -0.502 |
| Sil | 2956 | -12.273 | -0.410 |
| And | 3334 | -12.635 | -0.384 |



Fig. A1. Amphibolite-garnet thermometer (after Perchuk, 1967, 1969, 1970).

Thermometers for metabasites

To estimate P-T conditions of mineral equilibria in metabasites we have used amphibole-garnet, amphibole-clinopyroxene, amphibole-orthopyroxene and biotite-clinopyroxene geothermometers (Perchuk, 1969) and clinopyroxenegarnet barometer (Perchuk, 1968).

Amphibole-garnet geothermometer

The amphibole-garnet geothermometer was first calibrated on the basis of an amphibole-plagioclase thermometer (Perchuk, 1966). Both of these thermometers were widely used for amphibolebearing rocks (Perchuk, 1967; Mottana, 1970; Hubregste, 1973). A slightly modified version of amphibole-garnet thermometer is presented in Fig. A1. The 1000 °C isotherm has been deduced from the data on amphibole-garnet assemblages from peridotite inclusions in alkaline basalt. Some lower-temperature isotherms have been also modified. The geothermometer is constructed for the following average compositions of co-existing amphibole and garnet:

 $\begin{array}{rl} Am \colon & (Ca_{1.54}Na_{0.55}K_{0.15})_{2.24} \\ & (Mg, Fe^{2+}, Mn, Fe^{3+}_{0.49})_{4.5}Ti_{0.16} \\ & Al_{0.34}[Al_{1.82}Si_{6.18}]_8O_{22}(O, OH, F)_2, \end{array}$

$$\begin{array}{rl} Gr: & Ca_{0.65}(Mn, Mg, Fe)_{2.35} \\ & (Fe_{0.17}^{3\,+}Al_{1.81}Ti_{0.02})Si_{3}O_{12}. \end{array}$$

Above 500 °C the Fe-Mg distribution between these minerals can be considered as ideal and the temperature dependence of $\ln K_D$ may be described by the following equation:

or

$$\ln K_{\rm D} = 3.33 \times 10^3 / T - 2.333$$

$$T = 3330/(\ln K_{\rm D} + 2.333)$$

In calibrating the geothermometer we took into account that (1) X_{Ca}^{Gr} differs very little from 0.212, (2) Mn-content in Gr is very low and (3) composition of Am varies over a wide range.

Amphibole-clinopyroxene geothermometer

The amphibole-clinopyroxene geothermometer



Fig. A2. Amphibole-clinopyroxene thermometer (after Perchuk, 1969, 1970).

was calibrated in one version for magmatic and regionally metamorphosed rocks and another for eclogites and glaucophane schists (Perchuk, 1968, 1969). The first version (Fig. A2) is valid for amphiboles and clinopyroxenes, with an average formulae as follows:

- $\begin{array}{rl} Am: & (Ca_{1.70}Na_{0.65}K_{0.23}) \\ & (Mn,Fe^{2+},Mg)_{3.81}Fe^{3+}_{0.53}Ti_{0.25}Al_{0.41} \\ & (Al_{1.71}Si_{6.29})O_{22}(OH)_2; \end{array}$
- Cpx: $(Na_{0.15}Ca_{0.73})$ $(Fe^{2+}, Mg)_{1.0}Fe^{3+}_{0.12}Ti_{0.02}Al_{0.03}$ $(Al_{0.1}Si_{1.9})O_6.$

As can be seen in Fig. A2 the Fe-Mg distribution is not ideal. Resolution of the geothermometer is high enough, particularly, in the low temperature range.

Amphibole-orthopyroxene geothermometer

The amphibole-orthopyroxene geothermometer (Perchuk, 1969) is efficient for the rocks from the granulitic and, partly, the amphibolitic facies of metamorphism. The Fe-Mg distribution between Am and Opx is also not ideal (Fig. A3). The average compositions of coexisting minerals can be presented by the following crystallochemical formulae:

$$\begin{array}{rll} Am \colon & (Ca_{1.73}Na_{0.44}K_{0.17}) \\ & (Mg,Fe^{2+},Mn)_{4.32}Fe^{3+}_{0.34}Ti_{0.17}Al_{0.17} \\ & (Al_{1.7}Si_{6.3})O_{22}(O,OH,F)_2; \end{array}$$

$$Opx \colon & Ca_{0.03}(Fe^{2+},Mg,Mn)_{0.92} \\ & Fe^{3+}_{0.01}Ti_{0.01}Al_{0.05}Si_{0.97}O_6. \end{array}$$

Clinopyroxene-biotite geothermometer

The clinopyroxene-biotite geothermometer (Fig. A4) has been calibrated (Perchuk, 1970) for the following average compositions:

- Cpx: $(Na_{0.02}Ca_{0.91})$ (Mn, Mg, Fe²⁺, Fe³⁺_{0.03})_{1.0} Al_{0.05} (Al_{0.08}Si_{1.92})₂O₆.



Fig. A3. Amphibole-orthopyroxene thermometer (after Perchuk, 1969, 1970).



Fig. A4. Biotite-clinopyroxene thermometer (after Perchuk, 1969, 1970).

Relative errors associated with the four thermometers do not exceed 10%.

Calculation of the H₂O activity

For this purpose we have used the reaction

$$Phl + Sil + 2Qz = Pyr + Fsp + H_2O. \quad (A34)$$

The equilibrium conditions for this reaction are as follows:

$$RT \ln\left(\frac{a_{Pyt}a_{Saa}^{Pyp}}{a_{Phl}}\right) + RT \ln f_{H_2O}$$
$$= -(\Delta G^\circ + P\Delta V_s). \quad (A35)$$

The equations for the activities of pyrope and phlogopite were given above (see equations (A9) and (A17), respectively).

For feldspar we used the equation

$$RT \ln a_{Fsp} = RT \ln X_{K} + G^{e}$$
(A36)
$$G^{e} = (5075 - 1.91T)(1 - X_{K})^{2}$$

derived by Aranovich (1983) for the compositional range $1 \le X_{\rm K} \le 0.7$, based on the experimental data by Zyryanov, Perchuk & Podlesskii (1978). The volume change of reaction (A34) has been calculated according to the data tabulated by Helgeson, Delany, Nesbitt & Bird (1978), $\Delta V_{\rm s} = -0.3205$ cal/bar.

The equation for ΔG° (A34) has been obtained by Aranovich (1983) through thermodynamic treatment of data from experimental and natural systems on equilibria including garnet, biotite, muscovite, plagioclase, sillimanite, K-feldspar and quartz:

$$\Delta G^{\circ}(A34) = 36475 - 47.038T. \quad (A37)$$

In combination with (A37), (A36), (A9) and (A17), (A35) could be easily solved for f_{H_2O} at known *T*, *P* and compositions of the co-existing minerals. The f_{H_2O} values have been recalculated to a_{H_2O} using the fugacity coefficients of H_2O which were tabulated by Burnham, Holloway & Davis (1969).