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GLAUCOPHANE SCHISTS AND ASSOCIATED ROCKS OF KOPINA MT. (LASOCKI RANGE, SUDETEN)

UKD 552.43:549.643.31 + 553.541.061.4(438—14:234.57 góra Kopina)

Abstract. The specimens of glaucophane-rich schists, including anchimono-mineralic rocks, were found on the southeastern slope of Kopina Mt, Lasocki Range, Sudeten. Glaucophane appears there as a polymorph II (high pressure-low temperature), associated with garnet, epidote, quartz, albite, sphene, and barroisitic actinolite-hornblende. Caledonian ocean-floor metamorphism of the initial-stage volcanites and subvolcanites during the ocean-floor spreading and the Late Caledonian or even Early Hercynian burial metamorphism, reaching glaucophane schist facies as the result of subductional thrusting, are postulated.

INTRODUCTION

Many writers have commented upon the remarkable tectonic setting of glaucophane schists. Glaucophane schist belts are significantly confined to eugeosynclinal, late or more often post Paleozoic structures. This is explainable due to secular decrease of the Earth's geothermal gradient.

Though the mentioned tectonic structures are not infrequent in Poland the true glaucophane schist occurrences, as far as the recognition from published sources reaches, have not yet been examined. Despite this statement, older and newer papers (*vide* Juskowiak, 1957) report the existence of glaucophane-bearing metamorphites, especially in southeastern surroundings of Karkonosze Mts (Lasocki Range, Rychorskie Mts). The Cambro-Silurian up to Silurian-Ordovician age of the source rocks and Caledonian stage of main metamorphism is usually postulated (Teisseyre, 1973) for the so-called Niedamirów Series and Rychorskie Mts crystalline regions.

The rocks collected by Juskowiak (*op. cit.*) were classified as epidote-chlorite-glaucophane schists (with garnet, sphene, albite, common horn-

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blende and rare magnetite, quartz, clinozoisite) indistinguishable from greenschists. The origin by the transformation of basalt-type lavas and tuffs under low temperature — directional pressure conditions and in the presence of mineralisators derived from Karkonosze granitoid massif was implied.

According to the lately published observations made by Teisseyre (1973) in undetermined localities of Lasocki Range or Rudawy Janowickie Range, glaucophane is accompanied by actinolite amphibole, epidote, chlorite, albite (An_7), quartz and sporadically by garnet, stilpnomelane, sphene and magnetite. Besides, this author states, as following: „glaucophane schists are badly exposed and therefore unsatisfactorily investigated. The determination of optical properties was executed on small grains of this mineral and may be faulty” (α — violet, β — green-violet, γ — gray-blue, $c/\gamma = 6-9^\circ$, $n_\gamma - n_\alpha = 0.013-0.015$).

Numerous further occurrences of glaucophane-bearing rocks have been recorded from the adjacent Czechoslovak territory. The alluvial deposits of Rychorskie Mts supplied Berg (1912) with rocks, which as divergently granular Epidotfels, was composed of epidote, albite, quartz and glaucophane (α — light violet, β — grey-violet, γ — deep blue). Pelikan (1928) gives a detailed description of a glaucophane schist from Labske Udoly, (Horní Vrchlabí), consisting of dominant blue and green hornblende, rarer epidote, zoisite, chlorite, muscovite, plagioclase, orthoclase, magnetite and quartz. The so-called, by this writer, pseudoglaucophane is in reality a crossite ($\gamma = b$, $c/\beta = 12^\circ$, $2E = 52^\circ(-)$, α — nearly colourless, β — ultramarine blue, γ — violet), which continually passes into common hornblende (γ — blue-green, $c/\gamma = 18^\circ$), forming rims in zoned amphiboles. Similar blue alkali amphiboles Tuček (1949) found at Vichové (NNW of Jilemnice) in quartz-epidote rocks associated with hematite deposits in greenschists, especially if rich in quartz. There is no evidence to name these amphiboles as glaucophanes, taking into account new schemes of optic classification. The optic data, like: $b \cong \gamma$, $c/\beta = 4-5^\circ$, $2V \cong 0^\circ$, $n_\gamma - n_\alpha = 0,020$, $n_\gamma = 1,660$, α — light yellow-green or yellowish, β_s ultramarine blue, γ — violet, favour the term — crossite. Further announcements are of little value for the correlative aims.

PETROGRAPHIC NOTES

In the alluvial deposits of southeastern slope of Kopina Mt (908.8 m) a quantity of loose blocks (up to 30 cm in diameter) could be excavated for microscopic and chemical studies. In their number some represented typical (e.g. sample $K_{1,2}$) blueschists of grey-blue tint. The associated rocks were identified as actinolite-chlorite-epidote (K_3), chlorite-actinolite-epidote \pm garnet \pm ferrostilpnomelane (K_4), epidote-chlorite (K_5), epidote-chlorite-phengite (K_6) and phengite-chlorite schists (K_7), as well as, epidote rocks (= epidosite, K_8) and albite-quartz rocks (K_9). All the mentioned varieties of greenschists, except the specific components, contain various amounts of albite and quartz as essential minerals.

Glaucophane schists. These fine- to medium-grained schists contain variable amounts of glaucophane, epidote, quartz and albite as essential constituents (type K_1). The quantitative proportions of minerals oscillate between anchi-monomineralic glaucophane glomeroblasts with up

to 90 per cent of glaucophane content to epidote-or albite and quartz-rich segregations. Sometimes in quartz- and albite-poor varieties (K_2) appears the blue-green (barroisitic) hornblende in scarce amounts. The average modal composition of the two glaucophane schist varieties is tabulated below (Table 1).

The dominant glaucophane grains in form of slender prisms with mean breadth equaling 0.15 mm and maximum reaching 0.30 mm, are responsible in accordance with the mean elongation ratio = 1:12—1:15 for the employment of terms — nematoblastic or even fibroblastic texture. With increasing admixture of quartz and albite grains assemblages the schist assumes the features of nematogranoblastic and glomeroblastic fabric.

Table 1

Quantitative proportions of mineral constituents in the glaucophane schists from Kopina Mt (in vol. per cents after planimetric data)

| Rock-type | Glaucophane | Bluish hornblende | Epidote (zoisite) | Garnet | Quartz | Albite | Chlorite | Sphene | Pyrite |
|-----------|-------------|-------------------|-------------------|--------|--------|--------|----------|--------|--------|
| K_1 | 49.0 | — | 12.1 (0.4) | 6.3 | 20.5 | 9.3 | 0.6 | 1.4 | 0.8 |
| K_2 | 56.9 | 0.3 | 34.0 | 2.1 | 1.2 | 0.8 | 2.5 | 1.8 | 0.4 |

Epidote and sphene are spatially connected with glaucophane, whereas zoisite appears only in quartz-albite segregations. Epidote exhibits up to 1.4 mm long but less elongated (1:4—1:10) prisms, parallel to b-axes. These being concordantly oriented with c-axes of glaucophane individuals (b-axes being positioned in glaucophane concordantly with the foliation) take part in the development of well expressed lineation. On the contrary, euhedral or subhedral autoblasts or nearly porphyroblasts of garnet, measuring 1—2 mm in diameter, are irregularly distributed. Chlorite is a late mineral, interstitial in relation to glaucophane grains and infilling dilatation fractures of stretching haloes. Albite composing almost monomineralic or albite-quartz assemblages belongs also to synkinematic, interstitial minerals, though postkinematic albite microporphyroblasts (np. to 1.05 mm large) were also detected. Absent inclusions and exsolution phenomena, as well as, the high structural ordering and pure sodic composition support neoblastic nature of this mineral. The similar provenance may be implied for the mineral, namely quartz, which though easily deforming shows no distinct symptoms of structural incoherence. Pyrite, abundant in shear-zones, replaces all other minerals as the latest mineral, excluding secondary goethite, the alteration product of pyrite.

The list of deuteric minerals comprises also barroisitic actinolite hornblende, a sporadic component, constituting epitactic overgrowths and interstitial fillings in relation to the glaucophane grains. It transforms into chlorite, or vice versa, preceding only pyrite in the crystallization sequence of mafic minerals from hydrothermal solutions.

Among the associated schists the most common are the *actinolite-chlo-*

rite epidote (type K_3) and chlorite-actinolite-epidote schists with albite but without quartz \pm garnet and sporadic ferrostilpnomelane (type K_4).

In the first variety the albite may be more frequent component than the actinolite, prevailing over other mafic minerals. Untwinned, anhedral albite is peculiar by poikilitic intergrowths of amphibole fibres and mosaic albite aggregates. Only in the stretching haloes of garnet crystals the inclusions are absent in this low-temperature feldspar. Actinolite, or more strictly, actinolitic hornblende sometimes occurs in two generations, namely, of relict actinolitized hornblende and of neoblastic actinolite in the form of slender prisms and fibres. The lastly mentioned modification may also be the only present variety. Chlorite appears in divergent or subparallel aggregates of flakes. Epidote shows systematically a pronounced zoning with Fe^{3+} content decreasing from core outwards, indicating as the association of more sodic plagioclases with less ferric epidotes the retrogressive metamorphism or decreasing oxidation grade. Sometimes epidote is accompanied by chlorite creating cummuloblasts or independently — small rotating microporphyroblasts, reaching 0.9 mm in diameter. Garnet in small amounts (up to 5 per cent) or absent, demonstrates well developed holoblasts (measuring up to 0.55 mm) with chloritized biotite or chlorite forming coronas and albite infilling stretching haloes. Lenticular sphene and highly goethitized pyrite are the only representatives of accessories. Texture of the schist may be defined as grano-lepidofibrolastic, as well as, blastocataclastic and tectonoblastic. The arrangement of the actinolite fibres and prisms decides of the appearance of well developed lineation.

The second variety (K_4), namely, the chlorite-actinolite-epidote schist contains in the prevailing chlorite matrix slender prisms of actinolite, epidote and sphene grains. Between aggregates of subparallelly arranged flakes of chlorites occur granoblastic assemblages of albite grains with independent or poikilitic grains of epidote. This mineral may also take form of glomeroblasts of porphyroblasts, undergoing rotation and disintegration during differential movements. Occasional ferrostilpnomelane (up to 0.13 mm in diameter) is associated with pyrite, implying low-stage and late position in the metamorphic processes. Grano-fibro-lepidoblastic and tectonoblastic texture, as well as, planar structure distinguish these schists from the formerly described.

Epidote-chlorite schists (type K_5) differ from the schists containing additional actinolite by the predominance of epidote over all other minerals, including here chlorite, rare albite and quartz. The anhedral epidote prisms (up to 1.1 mm long) being almost divergently oriented show usual zoning with cores enriched in ferriepidote molecule. Also divergent or sheaf-like are aggregates of chlorite plates (up to 0.25 mm large). Albite usually coexists with strongly deformed quartz, especially in vein-like segregations. Among accessory minerals only the lenticular sphene and secondary goethite and leucoxene could be observed. Blastocataclastic texture and brecciated structure are well developed.

With appearance of small amounts of phengite in compositionally related epidote-chlorite-phengite schist (K_6) rises the content of chlorite and the texture passes from the blastocataclastic to more distinctly tectonoblastic one, whereas the structure becomes laminated to lenticular and folded. The lineation and crenulation is discernable even without hand lens. Phengite (up to 0.6 mm in diam.), as well as, chlorite (up to 0.1 mm

in diam.) occur in bands with changing quantitative proportions of components in the laminae. Albite exhibits isometric shape in the larger (up to 2.5 mm) holoblasts, though frequently is also observed as rubbish-like grain assemblages. The sphene and pyrite are the most remarkable accessories.

Phengite-chlorite schist (type K_7) is composed in preponderance of quartz-albite aggregate. Albite tends here to remain partly in the form of larger (up to 1.9 mm) holoblasts, simply twinned (albite twins). These metablasts, judging from helicitic structure produced by hematite, rutile and garnet inclusions, disclose also rotational movement and synkinematic crystallization. Chlorite and phengite lepidoblasts show oriented, parallel intergrowths. Large (up to 0.35 mm as in phengite) plates of hematite, small needles of rutile, dodecahedrons of garnet and nearly isometric prisms of apatite close the list of discerned rare minerals. Lepidogranoblastic and porphyroblastic texture with well visible lenticular structure and crenulation are prominent features of this kind of schists.

Epidote rock (epidosite) (K_8) with strongly prevailing epidote (mean content amounting 70 per cent) and well developed divergent and brecciated structure, more than epidote-chlorite schist (type K_5) approaches to the typical vein rocks, products of the metamorphic differentiation (the so-called venites). The subordinate constituents embrace quartz, albite, rare chlorite, goethitized pyrite and sporadic sphene. Albite and quartz appear together in fine-mosaic aggregates or separately, especially if filling small fissures. Peculiar for the epidote are anhedral, isometric grains to subhedral prisms (up to 2.0 mm long) in sheaf-like, radiate groups or even spherocrysts, showing sectoral extinction of the polarized light. The highest Fe^{3+} contents were noted in vein-like segregations of the central parts of grains and in the zoned crystals — in cores and peripheries. This statement implies twofold, extremal enrichment in ferric ion, connected with varying $p-t$ conditions or more probably — oxidation-grade of solutions (usual phenomenon in the hydrothermalites). Sphene coexists normally with albite vein-like segregations, whereas pyrite is associated with similar but of quartzose composition hydrothermalites.

Albite-quartz rock (type K_9), contrarily to the simple quartz venites (with relicts of phengite schists enriched in leucoxene) shows quartz crystals devoid of zonally distributed liquid inclusions (hooded milk-quartz). Moreover, quartz individuals in albite-quartz venites are stronger deformed (granulation, sectoral and wavy extinction) to the degree proper for the cataclases with mylonitic streaks. Albite of lightly rose colour displays in thin sections simple or polysynthetic albite-twins and pure sodic composition, as well as, low-temperature thermic state. Inclusions of phengite-chlorite schists are present.

MINERALOGIC DATA

The above presented short descriptions of the rock-types show that in each case the mineral assemblage of associated components is rather simple. Summarizing all components may be divided, as follows: glaucophane, blue-green actinolite hornblende (barroisite), epidote, chlorite, phengite, albite, quartz — the essential minerals; garnet, zoisite and ferro-

Spacings and relative intensities of reflections in glaucophane, epidote and albite from Mt Kopina glaucophane schist (K_1)

| Glaucophane | | | Epidote | | | Albite | | |
|-------------|--------|------------------|-------------|---------|------------------|---------|--------|------------------|
| (hkl) | d(Å) | I/I ₀ | (hkl) | d(Å) | I/I ₀ | (hkl) | d(Å) | I/I ₀ |
| 020 | 8.908 | 10 | 100 | 8.020 | 12 | 001,020 | 6.376 | 9 |
| 110 | 8.246 | 100 | 101,102 | 5.012 | 25 | 111 | 5.591 | 5 |
| 001 | 5.151 | 6 | 002 | 4.596 | 5 | 201 | 4.027 | 40 |
| 111 | 4.847 | 14 | 200 | 4.011 | 29 | 111 | 3.853 | 8 |
| 200 | 4.645 | 5 | 202 | 3.986 | 26 | 111 | 3.779 | 26 |
| 021 | 4.457 | 21 | 111 | 3.763 | 16 | 130 | 3.684 | 21 |
| 040 | 4.453 | 29 | 211 | 3.491 | 20 | 131,130 | 3.66 | 20 |
| 131 | 3.845 | 8 | 102 | 3.403 | 25 | 112 | 3.495 | 7 |
| 221 | 3.601 | 12 | 201 | 3.205* | ? | 112 | 3.369 | 9 |
| 131 | 3.383 | 16 | 003 | 3.060 | 25 | 202 | 3.215* | 50 |
| 041 | 3.371* | 6 | 301 | 2.924* | 18 | 002 | 3.194 | 100 |
| 150 | 3.327 | 4 | 112 | 2.920 | 18 | 220 | 3.171 | 35 |
| 240 | 3.220 | 3 | 113 | 2.897 | 60 | 220 | 3.140 | 30 |
| 310 | 3.051 | 100 | 020 | 2.809.6 | 30 | 131 | 2.966 | 20 |
| 221 | 2.934 | 15 | 021 | 2.685 | 100 | 222 | 2.954 | 12 |
| 151 | 2.908 | 5 | 300 | 2.678 | 40 | 022,041 | 2.930 | 8 |
| 330 | 2.745 | 30 | 120 | 2.655 | 15 | 131 | 2.863 | 6 |
| 151 | 2.693 | 45 | 311 | 2.597 | 32 | 132 | 2.638 | 4 |
| 002 | 2.667 | 5 | 103,202 | 2.531 | 26 | 241 | 2.561 | 6 |
| 331 | 2.575 | 4 | 121 | 2.454 | 12 | 241 | 2.442 | 5 |
| 061 | 2.572 | 10 | 022 | 2.402 | 20 | 331 | 2.318 | 3 |
| 202 | 2.519 | 27 | 004,220 | 2.298 | 10 | 060 | 2.125 | 4 |
| 351 | 2.288 | 22 | 122 | 2.164 | 10 | 241 | 2.078 | 2 |
| 312 | 2.246 | 12 | 123 | 2.160 | 15 | 422 | 1.892 | 5 |
| 171 | 2.167 | 7 | 221 | 2.116 | 15 | 113,260 | 1.830* | 10 |
| 261 | 2.150 | 10 | 223 | 2.107 | 22 | 043,062 | 1.824 | 5 |
| 332 | 2.114 | 5 | 412,023 | 2.072 | 18 | 400 | 1.820 | 4 |
| 202 | 2.060 | 4 | 203 | 2.046 | 10 | 204 | 1.783 | 10 |
| 351 | 2.012 | 3 | 213 | 1.927 | 25 | 442 | 1.742 | 2 |
| 242 | 1.868 | 6 | 123,114,222 | 1.879 | 17 | 242 | 1.668 | 1 |
| 191 | 1.847 | 6 | 115,124,224 | 1.875 | 23 | 353,424 | 1.585 | 2 |
| 191 | 1.784 | 5 | 312 | 1.864 | 8 | 024,081 | 1.572 | 1 |
| 512 | 1.712 | 3 | 132 | 1.641 | 10 | 351 | 1.560 | 2 |
| 461 | 1.632 | 12 | 420 | 1.634 | 10 | 424 | 1.531 | 1 |
| 1-11-0 | 1.599 | 4 | 124 | 1.625 | 10 | 281 | 1.507 | 1 |
| 153 | 1.585 | 3 | 115 | 1.578 | 10 | 533 | 1.501 | 1 |

*Coincidence of reflections. Rigaku-Denki X-ray diffractometer, CuK_α radiation, Ni filter.

stilpnomelane — the subordinate or occasional minerals; sphene, rutile, apatite, hematite, and pyrite \pm goethite — the accessory minerals.

Glaucophane. In both just mentioned kinds of glaucophane schists (types K_1 and K_2) there is no easily detectable variation in morphological and physical properties. This is also valid in respect to glaucophane from the schists investigated by Juskowiak (1957), (the symbol KJ in Table 2).

Morphologically glaucophanes from Kopina Mt are quite peculiar. They exhibit a prominent long prismatic shape (the mean elongation ratio =

Table 2

Optic properties of Mt Kopina glaucophanes

| Rock-type | Refractivity and pleochroism | | | $n_\gamma - n_\alpha$ | $2V_\alpha$ | Disp. $2V$ | Optic. orient. | Extinct. angle γ/c |
|---------------------|------------------------------|-------------------------------|----------------------------------|-----------------------|-------------|------------|----------------|---------------------------|
| | n_γ | n_β | n_α | | | | | |
| K_1 | 1.648 blue | 1.644 violet ¹⁾ | 1.625 pale yel. ²⁾ | 0.023 | 46— 47° | $v > r$ | $\beta = b$ | 3.5—5° |
| K_2 | 1.646 blue | 1.643 violet ¹⁾ | 1.624 pale yel. ²⁾ | 0.022 | 46° | $v \geq r$ | $\beta = b$ | 3.5° |
| K_3 ³⁾ | — blue | — violet ⁴⁾ | — pale yel. ²⁾ | 0.024 | 46° | $v \geq r$ | $\beta = b$ | 5—7° |

¹⁾ with purplish hue, ²⁾ yellowish to colourless, ³⁾ sample examined by Juskowiak (1957), ⁴⁾ with bluish hue. Absorption scheme: $\gamma < \beta > \alpha$ (K_1, K_2) and $\gamma > \beta > \alpha$ (K_3).

= 1:12—1:15) of subhedral individuals, with well developed lateral ($\{110\}$ and $\{100\}$ forms) but undeveloped terminal faces. Untwinned, they show normal excellent cleavage traces parallel to the vertical prism and the basal parting.

The optic properties of glaucophanes, established using immersion (spindle-stage) and universal-stage techniques, are tabulated above (Table 2). The small differences between actually and formerly (Juskowiak, 1957) studied glaucophanes include only the absorption scheme ($\gamma \leq \beta > \alpha$ in $K_{1,2}$ and $\gamma > \beta > \alpha$ in KJ), birefringence and extinction angle values. The relatively low R.I., high birefringence and large optic axes angle imply rather small to moderate content of ferroglaucophane and riebeckite molecule (see the next chapter).

The content of riebeckite molecule could also be determined basing on the X-ray diffractometer data (Table 3) and on the diagrammatic representation of variation of (310) interplanar distances with composition (Fig. 1). The ordered occupancy of cation sites in Kopina Mt glaucophane, as usually in natural material, is in accord with the Ernst's so-called high pressure-low temperature polymorph (glaucophane II).

Actinolite-hornblende. This is a sporadic component of some glaucophane schists (K_2) and essential one in the actinolite-chlorite-epidote (K_3) or chlorite-actinolite-epidote schist (K_4). In the first variety this amphibole reveals a faint to intensive pleochroism, varying like: γ — green with blue hue to bluish green, β — green with brown hue and α — faintly yellowish. The extinction angle γ/c equals 19° and the bire-

fringence reaches 0.018. O. Juskowiak (*op. cit.*) mentions $\gamma/c = 17-22^\circ$. In the second and third varieties of schists the optic properties, except the extinction angle $\gamma/c =$ up to 24° in K_4 -type, are practically the same, as: $n_\gamma = 1.644$ (with blue hue in the light green absorption), $n_\beta = 1.637$ (with yellow hue in the light green absorption) and $n_\alpha = 1.627$ (nearly colourless with yellow hue). The remaining data are, as follows: $n_\gamma - n_\alpha =$

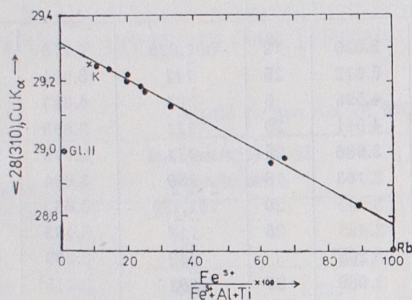


Fig. 1. Variation of (310) interplanar distances with composition of glaucophane-riebeckite series of sodic amphiboles; the letters denote

K_1 — Kopina Mt sample, GL II — high pressure-low temperature synthetic polymorph of glaucophane, Rb — riebeckite (both from Collville *et al.*, 1966). Solid circles and interpolated line correspond to amphiboles from blueschists of Cazadero, California (Coleman and Papike, 1968)

$= 0.017$, $2V_\alpha = 78^\circ$, $r \approx v$, $\beta = b$, $\gamma/c = 16.5-17^\circ$. The regular blue hue suggests a little barroisitic character (tschermakite molecule admixture) of the mentioned amphiboles. Peculiar is also a high elongation ratio of independent neoblasts (1:8—1:20) and smaller one (1; 3—1:6) in the actinolite-hornblende replacing the older common hornblende.

Table 4

Optic properties of Mt Kopina epidotes

| Rock-type | Refractivity and pleochroism | | | $n_\gamma - n_\alpha$ | $2V_\alpha$ | Disp. $2V$ | Extinct. angle a/c | Disp. $\Delta a/c$ |
|-----------|------------------------------|------------------|---------------------|-----------------------|-------------|-----------------|----------------------|-------------------------|
| | n_γ | n_β | n_α | | | | | |
| K_{1-2} | 1.749 p.yel.* | 1.740 p.yel.* | 1.724 colourless | 0.012— 0.030 | 77—84° | $r > v$ high | 1—3°(-) | 0.07 r — 2.07° v |
| K_3 | 1.747 p.yel. | — p.yel. | — colourless | 0.012— 0.030 | 77—85° | $r > v$ high | 1—3°(-) | = 2° |
| K_5 | 1.766 f.yel** | 1.756 f.yel** | 1.730 colourless | 0.026— 0.036 | 70—76° | $r > v$ high | — | — |
| K_6 | 1.765 f.yel. | 1.756 f.yel. | 1.729 colourless | 0.028— 0.036 | 70—76° | $r > v$ high | — | — |
| K_8 | 1.754 f.yel. | — f.yel. | 1.725 colourless | 0.015— 0.032 | 81—82° | $r > v$ high | 2—4°(-) | 3.37 r — 5.37° v |

* Pale yellowish in $K_{1, 2, 4}$.

** Faintly yellow in $K_5, 6, 8$.

Epidote. This is a ubiquitous and sometimes highly preponderant mineral. In epidotes occurring in the glaucophane schists remarkable is the high elongation ratio of anhedral prisms (1:4—1:10), a little flattened according to {001}, as well as, the distinct zonal structure with more ferruginous core and the appearance of rare simple twins with (100) as the composition plane. In the remaining kinds of schists porphyroblastic to glomeroblastic grains or their aggregates of epidote have been observed, showing simultaneously isometric to prismatic shape of the separate individuals. Significantly they are devoid of crystallographic faces with few exceptions, especially in epidotes (K_3), where some epidotes reveal lateral faces. The variability in optic properties is not much advanced (see compilation on the Table 4), as should be expected. The recorded values are, with the exception of birefringence, not the extremal ones, but mean and usually found changing due to zoning. The above presented optic data allowed the determination of Fe_2O_3 percentage or of ferriepidote molecule content, utilizing respective diagrams (Hörmann and Raith, 1971, Figs 2—4). The corresponding values oscillate between 7—12 (K_1, K_2 and K_3) 11—14 (K_5 and K_6) and 8—13 (K_8) per cent of Fe_2O_3 or 14—24, 22—28 and 16—26 mol per cent of ferriepidote molecule, respectively. As a rule the iron content increases towards core of grain.

Another convenient method is the X-ray diffractometric evaluation (Table 3) of ferriepidote molecule content using diagrams published by Hörmann and Raith (1971), (Fig. 6) and Meyer (1966). The position of epidote 020 reflection and the spacings between Si_{111} and Ep_{020} gave the following values: 2.806—2.812 Å* (K_1), 2.823 Å (K_5) and 2.818 Å (K_8) corresponding to 8—11 (K_1), 14—15 (K_5) and 12—13 (K_8) per cent of Fe_2O_3 or 16—22, 28—30 and 24—26 per cent of ferriepidote molecule, respectively.

Chlorite. In comparison with epidote exhibits a little smaller compositional variation. Though being the product of prolonged crystallization it does not show any remarkable zoning, but due to ability of easy nucleation appears in fine crystalline, chemically differing generations.

In glaucophane schist the latest is the iron-rich variety occurring in interstitial spaces and in veinlets. Besides the presented in Table 5 optic and structural variables, their easy recognition is allowed by stronger pleochroism: γ, β — grass green, α — faintly yellowish and by lavender (subnormal) interference colours. The optic and X-ray data after plotting on the corresponding diagrams constructed by Brindley and Gillery (1956), (Fig. 2 and 3), Albee (1962), (Fig. 4 and 5) and Wetzel (1973), (Fig. 8b and 9—15) and using the well known Hey's diagram gave the following atomic formula coefficients: $Al^{IV} = 2.4$, $Al^{VI} = 2.4$, $Fe_{tot.} = 5.0$ and $Mg = 4.6$. In the older generation the Mg/Mg + Fe ratio (mg) is distinctly higher (55 versus 44—48), what is microscopically accentuated in the change of optic sign and subnormal interference colours. Both varieties of chlorite fall in the field occupied by Brindley's and Hey's ripidolites.

The chlorites from actinolite-chlorite-epidote schist (K_3 and K_4) display either negative (more frequently) or positive optic sign, purple or brown interference colours, very small birefringence (0—0.001) and moderate $n_\beta = 1.621$ (grass green with blue hue) to 1.629. These values are transi-

* 1 Å = 0.1 nm (SI).

Table 5

Optic and structural properties of Mt Kopina chlorites

| Rock-type | n_β | $n_\gamma - n_\alpha$ | d_{001}^* | d_{005} | d_{060} | $\frac{I_{002} + I_{004}}{I_{003}}$ |
|-----------|-------------|-----------------------|-------------|-----------|-----------|-------------------------------------|
| | | | | | | |
| K_1 | 1.624—1.632 | 0.002(+)—0.001(-) | 14.13 | 2.8306 | 1.5477 | 5.8 |
| K_5 | 1.619 | 0.003(+) | 14.14 | 2.8296 | 1.5462 | 5.2 |
| K_6 | 1.621—1.630 | 0.001(+)—0.002(-) | 14.16 | 2.8328 | 1.5479 | 6.0 |

* All spacings in ångstroms.

tional to the owned by chlorites peculiar for epidote-chlorite schists (K_5 , see Table 5). The optical and structural data of the last mentioned chlorites correlate with the Hey's pycnochlorites: $Al^{IV} = 2.3$, $Al^{VI} = 2.5$, $Fe_{tot.} = 4.3$ and $Mg = 5.2$.

In the epidote-chlorite-phengite schist (K_6 , see Table 5) chlorites reveal the properties which are similar to recorded for those from the glaucophane schists. The more ferrigenous varieties, occurring usually as veinlets, yield the following composition: $Al^{IV} = 2.3$, $Al^{VI} = 2.2$, $Fe_{tot.} = 5.3$ and $Mg = 4.5$, corresponding to the Hey's brunsvigite and Brindley's ripidolite. The highest content of total iron ($Fe = 5.8—6.2$) was found in always optically negative and stronger birefringent ($n_\gamma - n_\alpha = 0.003—0.004$) chlorites of epidotes (K_8).

It should be pointed out that the most reliable calculations of chlorite composition were made basing on the following variables, as: refractive indices, birefringence, d_{005} and d_{060} spacings and intensity relations of reflections $I_{002} + I_{004}/I_{003}$.

Phengite. This mineral is essential only in two rock-types, namely in the epidote-chlorite-phengite (K_6) and in the phengite-chlorite schists (K_7). The optic and structural properties of both kinds of phengites are compiled in the following Table 6. The differences in optical and structural data are quite large and may be elucidated by the variation in the Fe^{3+}

Table 6

Optic and structural properties of Mt Kopina phengites

| Rock-type | Refractivity and pleochroism | | $n_\gamma - n_\alpha$ | $2V_\alpha$ | $d_{060}(\text{Å})$ | $b_0(\text{Å})$ |
|-----------|------------------------------|-------------------------|-----------------------|-------------|---------------------|-----------------|
| | n_γ | n_α | | | | |
| K_6 | 1.613 pale green | 1.581 pale yellowish | 0.031—0.032 | 17° | 1.5105 | 9.063 |
| K_7 | 1.596 yellowish | 1.559 colourless | 0.037 | 27° | 1.5063 | 9.038 |

content or partly by the grade of metamorphism. Taking into account the relation between n_β and $Fe_2O_3 + FeO$ content reviewed by Foster *et al.* (1960) in the case of the epidote-chlorite-phengite schists (K_6) it must be rather high (about 0.25 in terms of molecular equivalents). The distinct pale green absorption, usually produced by admixture of both iron cations, supports this conclusion. Faintly yellowish absorption of phengites from the phengite-chlorite schists (K_7) is typical for iron-poor varieties.

Structurally both varieties represent $2M_1$ polytypes with d -values varying in the range typical for phengitic white micas. Actually much favoured use of b_0 -value (or d_{060}) in potassic white mica classification allows the treatment of both varieties as typical phengites (with $b_0 = 9.025—9.065 \text{ Å}$ according to Sassi, 1972).

Albite. Sodic plagioclase of glaucophane schists is usually of anhedral, nearly isometric shape, sometimes a little flattened according to $\{010\}$. Untwinned individuals are less common than simple Albite twins and (or) fragmental Albite lamellae. The orientation of indicatrix in the subindividuals corresponds to purely sodic (An_0) composition. Juskowiak reports (1957) a little different An-content (An_6) in the glaucophane-bearing schists of Kopina Mt. In the examined albites from the glaucophane schists (K_1 and K_2) the values for $2V_\alpha$ indicate simultaneously the structural state proper for low temperature or highest ordering ($2V_\alpha = 105—107^\circ$ corresponding to intermediacy index $\cong 100$). The same results were obtained taking into account X-ray data (from Table 3), like d_{131} , $d_{1\bar{1}1}$, $d_{1\bar{3}2}$, d_{111} , $d_{1\bar{1}1}$ a.o., confirming the pure sodic composition and the same high ordering (I.I. $\cong 100$).

In the actinolite-chlorite-epidote schists (K_3) albite contains up to 4 per cent of anorthite molecule and correspondingly has a somewhat smaller optic axes angle ($2V_\alpha = 103—104^\circ$), whereas mostly untwinned albite grains of epidote-chlorite schists are identical with known from glaucophane schists.

The albites occurring in epidote-chlorite-phengite schists (K_6) in form of large holoblasts show regularly simple or polysynthetic twinning according to Albite, rarely Roc Tourné or Carlsbad rule. The An-content amounting here only 1 per cent is not responsible for low values of $2V_\alpha = 92—94^\circ$ but the smaller degree of ordering (higher temperature of origin?). Similar (An_{1-2}) composition of plagioclase was noted in phengite-chlorite schist (K_7), though $2V$ is relatively higher ($99—100^\circ$).

Pure sodic albites again appear in epidotes (K_8), where they exhibit feebly elongated, mostly untwinned (excl. scarce Albite lamellae) grains. In contrary, the frequently twinned (simple Albite twins or Albite lamellae) pure sodic feldspars abound in albite-quartz vein rocks (K_9).

Quartz. This mineral demonstrates no significant variability, except the changing grade of lattice deformations accordingly with the extent of the differential movements in the growth environment.

Garnet. In the glaucophane schists is developed in the form of subhedral to euhedral dodecahedrons with peculiar orange-rose to salmon-red absorption colour. In the thin slides it shows only a faint, yellowish colouration. The refractive indices are relatively stable (no detectable zoning), averaging 1.792. Unit cell parameters for a_0 established from X-ray diffractograms oscillate between 11.625 and 11.626 Å. Unexpectedly

garnets from actinolite-chlorite-epidote schists (K_3) are almost identical, having $n = 1.792$ and $a_0 = 11.628 \text{ \AA}$ (compare Fig. 2).

Zoisite. It appears in undeformed, euhedral prisms distinguished by optic orientation of zoisite- β ($\alpha = a$, $\beta = b$), small axial angles ($2V_\gamma = 5-7^\circ$) and the absence of subnormal interference colours peculiar for iron-poor varieties. It is a postkinematic mineral occurring in paragenetic association with quartz and albite.

Ferrostilpnomelane. It was found only in the chlorite-actinolite-epidote schists (K_4), in the pressure-shadows of synkinematic pyrite metablasts. The pleochroic colours (γ , β = deep green, α = pale yellow) and relatively low birefringence (0.030–0.031) argue alone the identity

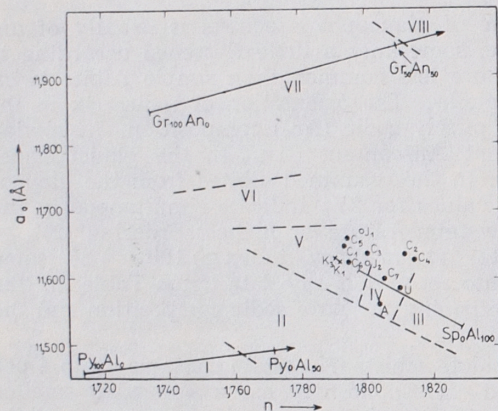


Fig. 2. Unit-cell (a_0) parameter and refractive index variations in garnets from glaucophane schists and associated rocks. Latin ciphers denote after Frietsch (1957) projection areas (between dashed lines) of the following mixed crystals

I — Py(+Al), II — Al(Py+Gr), III — Al(+Sp), IV — Sp(+Al), V — Al(+Gr+An+Py+Sp), VI — Gr(+An+Al+Sp), VII — Gr(+An), VIII — An(+Gr). Solid lines show variations in pyrope-almandine and grossular-andradite series (after Winchell, 1958), as well as, in spessartine-almandine₉₋₁₀₀ (after Hsu, 1968). Other explanations as in

Figure 6

with ferrostilpnomelane having the atomic ratio $Fe^{3+} + Al/\text{total } Fe + Mn + Mg + Al \cong 10$ per cent of stilpnomelane molecule after Deer *et al.* (1963). This variety shows no correlative features with the stilpnomelane described by Teisseyre (1973).

Accessory minerals, like the formerly mentioned sphene, rutile, apatite, hematite and pyrite (usually goethitized) exhibit habits and other properties characteristic for the minerals from low-stage metamorphic rocks. Magnetite recorded by Juskowiak (1957) and Pelikan (1928) as occurring in glaucophane-bearing rocks is lacking in the actually investigated samples.

CHEMISTRY OF GLAUCOPHANE AND GARNET

The mineral separation of moderately crushed samples of glaucophane schist in heavy liquids and hand-picking under binocular microscope were much helpful in the recovery of the externally completely pure glaucophane and garnet. The influence of the still persisting inclusions of sphene and epidote was taken into account by the subtraction from the analytical data of the previously planimetrically established and recalculated volume contents. The chemical analyses in weight per cents and atomic ratios are compiled in Table 7.

The bulk chemical analyses after calculation to fit amphibole — $X_2Y_5Z_8O_{22}(OH, F)_2$ and garnet — $X_3Y_2Z_3O_{12}$ formulae may be represented as follows:

Glaucophane: $(Na_{1.52}, Ca_{0.38}, K_{0.05})_{1.95} (Mg_{1.92}, Fe_{0.88}^{2+}, Fe_{0.21}^{3+}, Mn_{0.14}, Ti_{0.02}, Al_{1.83})_{5.00} (Si_{7.90}, Al_{0.10})O_{22} \cdot (OH_{1.68}, O_{0.32})$.

Garnet: $(Ca_{0.66}, Mn_{0.45}, Fe_{1.82}^{2+}, Mg_{0.01})_{2.04} (Ti_{0.06}, Al_{1.98})_{2.04} (Si_{2.94}, Al_{0.06})_3O_{12}$.

The OH group in glaucophane does not come up to the required 2OH for the formula. This is due to the well known difficulties in determination of amphibole water or resulted from, e.g. — the substitution of O^{2-} for OH, combined with the excess of available Fe^{3+} (Coleman, Papike, 1968). The

Table 7

Chemical analyses (in weight per cents) and atomic ratios of Mt Kopina glaucophane and garnet

| Components | Glaucophane | Garnet | Cations and Anions | Glaucophane | Garnet |
|--------------------------------|-------------|--------|--------------------|-------------|--------|
| | | | | | |
| SiO ₂ | 57.22 | 36.35 | Si | 7.90 | 2.94 |
| TiO ₂ | 0.20 | 0.91 | Ti | 0.02 | 0.06 |
| Al ₂ O ₃ | 11.88 | 21.37 | Al ^{IV} | 0.10 | 0.06 |
| Fe ₂ O ₃ | 2.02 | n.d. | Al ^{VI} | 1.83 | 1.98 |
| FeO | 7.64 | 26.90 | Fe ³⁺ | 0.21 | — |
| MnO | 1.22 | 6.62 | Fe ²⁺ | 0.88 | 1.82 |
| MgO | 9.34 | 0.11 | Mn | 0.14 | 0.45 |
| CaO | 2.56 | 7.62 | Mg | 1.92 | 0.01 |
| Na ₂ O | 5.66 | n.d. | Ca | 0.38 | 0.66 |
| K ₂ O | 0.29 | n.d. | Na | 1.52 | — |
| H ₂ O ⁺ | 1.83 | n.d. | K | 0.05 | — |
| H ₂ O ⁻ | 0.14 | 0.07 | OH | 1.68 | — |
| Total* | 100.00 | 99.95 | | | |

* After subtraction of small amounts of sphene and epidote from the modal composition.

presented formula shows also the high ordering, indicative for high pressure — low temperature polymorph. The cation $M(2)$ position is occupied exclusively by Al^{VI} and Fe³⁺ ($\Sigma = 2.04$) and the $M(1)$ and $M(3)$ positions — by Mg, Fe²⁺, Mn and probably by Ti ($\Sigma = 2.96$). This is consistent with charge balance requirements and the minimization of volume and entropy required by the environmental conditions (high pressure — low temperature). The not small participation of calcium in the glaucophane structure proves the well known partial miscibility of glaucophane and actinolite molecules. Therefore, not surprising is the fact of the coexistence of Carich glaucophane and actinolite in paragenetic mineral pairs in the Sudeten Mts, in California a.o. places (compare points 6 and 14 in Fig. 3). Nevertheless, this is not contradictory to the always persisting compositional miscibility gap. According to Coleman and Papike (1968) glaucophane appears to be more calcium-rich in the higher grade blueschists, and such substitution could be a function of $p-t$ conditions rather than of variation in bulk composition.

In the establishment of the classificational position of the examined glaucophane much useful seems to be the Miyashiro's scheme modified by Borg (1967) showed as Figure 4. The calculation of diagram parameters based on the ratios $Fe^{3+} + Ti/Fe^{2+} + Ti + Al^{VI}$ and $Fe^{2+} + Mg/Fe^{2+} + Mn + Mg$ allowed to define some regularities. The considerable clustering of projection points of over one hundred of plotted analyses in

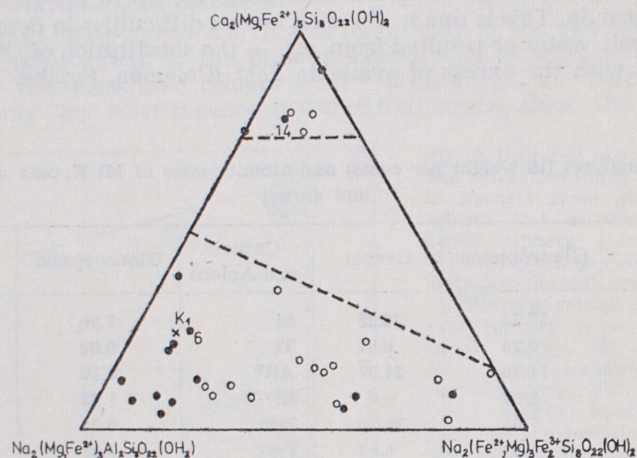


Fig. 3. Triangular plot of California (Cazadero) and New Caledonia sodic amphiboles and actinolites from blueschist facies (solid circles) compared with amphiboles from other similar occurrences (open circles) and Kopina Mt ($x=K_1$). Numbers 6 and 14 concern coexisting glaucophane and actinolite. The dashed lines show limits of miscibility gap

bands can be interpreted by the presence of solid solution series. In the interesting us part of diagram they embrace chiefly glaucophane-riebeckite and glaucophane-ferroglaucophane end member pairs.

As a result of reduced thermal motion of ions and contraction of structural sites of ions, taking place in low temperature-high pressure environmental conditions, among amphiboles glaucophane shows the closest packed crystal structure and most reduced Gibbs free energy. It is clear that this peculiarity has some consequence, like small allowance of ion exchange in the glaucophane and special distribution of ions between glaucophane and accompanying minerals. The chemical analyses of glaucophane and garnet co-occurring in the same rock may serve in finding some systematic distribution of ions, especially in the partitioning of manganese and magnesium. Taking as comparative material similar compositional relations in the glaucophanes and garnets from low-grade schists of Eastern Shikoku, Japan, demonstrated on respective diagrams (Fig. 5a and 5b) by Ernst (1964), the following conclusions are obligatory in both metamorphic terranes. The cationic proportions $Mn^{2+}/Mn^{2+} + Ca$ in glaucophane-garnet pair exhibit a high and functional (see the partition curve of Fig. 5a) concentration of manganese in garnets from E Shikoku. The same pair from Sudeten Mts shows resembling trend. Manganese, in con-

trast to 8-fold coordination of Mn^{2+} in garnet, is assigned to 6-fold structural sites in the glaucophane and alkali amphiboles. In accordance with the size of these sites in glaucophane they can not be occupied by Mn^{2+} in such a degree as they are in garnet. Reversely, 8-fold cation positions in garnet are of adequate size to accommodate greater amounts of both Mn, as well as, Ca and Mg. Therefore, the well visible equilibrium in the partition of Mn and Ca in glaucophane-garnet pair from Japan (Fig. 5a), accentuated by clustering of points along the partition curve for mole fraction quotient, is probably in force in all metamorphic regions. The projection point for Kopina Mt example, showing the same affinity, do not much deviate from the partition curve. After Ernst's (1964) investigations in white micas and chlorites it may be induced, that Mn^{2+} is also, or even more, not so strictly diadochic with Mg and Fe^{2+} as in the case of sodic amphiboles.

Diametrically different relations exist in the partitioning of magnesium in glaucophane-garnet pair (Fig. 5b). Except much lower value for distribution coefficient K_D , the dispersion of points in the samples from the same metamorphic terrane is indisputably larger. The position of Kopina Mt sample proves almost total transition of Mg ions to the glaucophane structure.

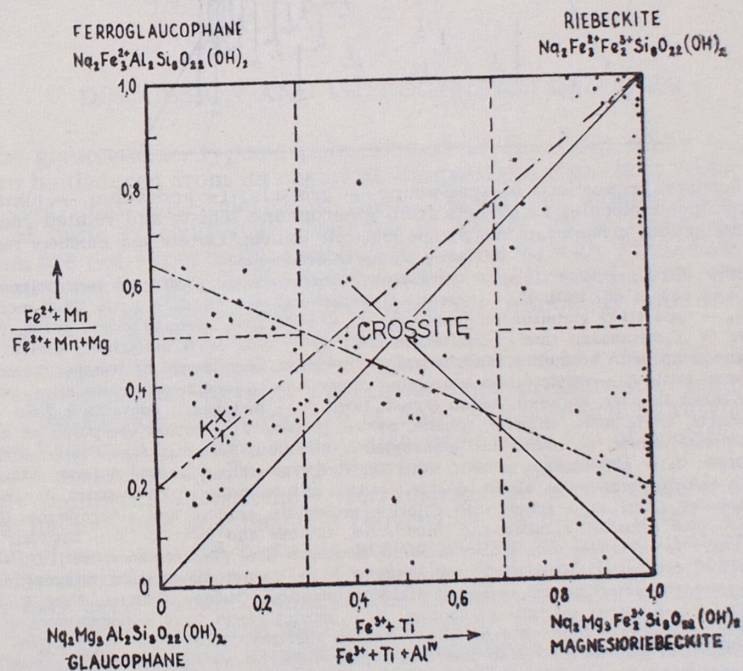


Fig. 4. Quantitative relations of octahedrally coordinated cations in glaucophane-riebeckite-magnesioriebeckite-ferroglaucophane solid solutions. Dots signify chemical analyses as assembled by Borg (1967) and letter x — position of Mt Kopina glaucophane. The dashed lines delineate projection areas for Miyashiro's end members and subglaucophane (here crossite); solid lines — possible isomorphous mixture series

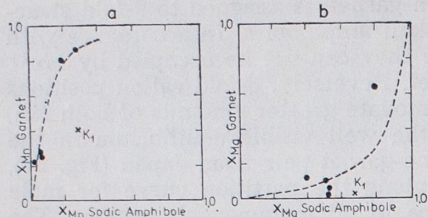


Fig. 5. Compositional variations of analyzed glaucophane-garnet pairs
 $X_{Mn} = Mn^{2+}/Mn^{2+}+Ca$ in *a* and $X_{Mg} = Mg^{2+}/Mg^{2+}+Fe^{2+}$ in *b* are given in cationic proportions. Dots and ideal distribution curves ($K_D = K$) refer to Eastern Shikoku examples (Ernst, 1964) and letter *x* — to Kopina Mt

The regular poverty of pyrope molecule in the garnets (see Fig. 6) from low-metamorphic rocks, and specially from the glaucophane schist facies, suggests (Ernst, 1964) that the pyrope solid solution limits may have

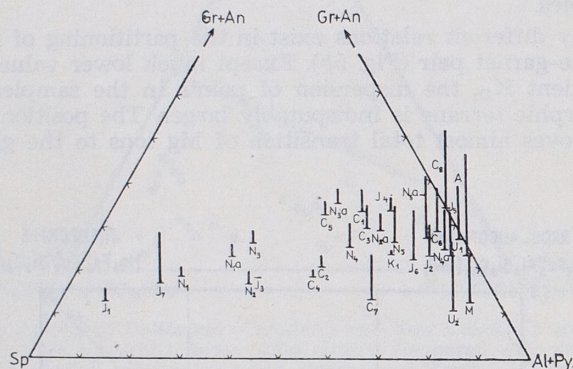


Fig. 6. Ternary proportions of spessartine — grossular (+ andradite) — almandine (+ pyrope) molecules in garnets from glaucophane schists and related rocks
 The heights of rods demonstrate the pyrope molecule content. Letters and numbers represent the following modes of occurrence

K_1 — Kopina Mt; C_1 — type III — A metabasalt, Cazadero Area, California (see Coleman and Lee, 1963 and Lee et al., 1963); C_2 — type III-B metachert, *ibidem*; C_3 — type III-C metashale, *ibidem*; C_4 — type III-D metaironstone, *ibidem*; C_5 — type III-E metacarbonate rocks, *ibidem*; C_6 — type IV-A metabasalt (incl. eclogite), *ibidem*; C_7 — type IV-B metachert, *ibidem*; C_8 — glaucophane schist with actinolite, chlorite and white mica, near mouth of Russian River, California (Pabst, 1931); J_1 — silicic schist containing piemontite, glaucophane, white mica, hematite a.o., Kôtu-Bizan District, Shikoku, Japan (Ernst, 1964); J_2 — metabasalt containing glaucophane, epidote, quartz, white mica, chlorite, sphene, pyrite, *ibidem*; J_3 — schists composed of epidote, sericite, chlorite, albite, actinolite and glaucophane, Shishibu, Saitama, Japan (Miyashiro, fide Sobolev, 1964); J_4 — glaucophane schist, Kôtu District, Tokushima, Japan (Banno, 1959); J_5 — schist with chlorite, muscovite, albite, quartz, epidote and tremolite, Omi District, Japan (Banno, fide Sobolev, 1964); J_6 — schist with chlorite, muscovite, epidote and glaucophane, *ibidem*; J_7 — schist with aegirine, glaucophane, muscovite, epidote and quartz, Kôtu District, Japan (Iwasaki, 1960); U_1 — glaucophane schist, Shubino, Southern Ural (Tschesnokov, 1961); U_2 — glaucophane schist with quartz and muscovite, *ibidem*; N_1 — garnet (core) from metasediment of lawsonite zone characterized by lawsonite-albite association, Ouégoa District, New Caledonia (Black, 1973); N_{1a} — garnet (periphery), *ibidem*; N_2 — garnet (core) from metasediment of transition (lawsonite-epidote) zone, *ibidem*; N_{2a} — garnet (periphery), *ibidem*; N_3 — garnet (core) from metabasalt of transition zone, *ibidem*; N_{3a} — garnet (periphery), *ibidem*; N_4 — garnet (core) from metasediment of epidote zone characterized by epidote-albite-glaucophane association, *ibidem*; N_{4a} — garnet (periphery), *ibidem*; N_5 — garnet (core) from metabasalt of epidote zone characterized by epidote-omphacite-sodic hornblende association, *ibidem*; N_{5a} — garnet (periphery), *ibidem*; A — glaucophanites and eclogites (4 analyses), Zermatt, Alps (Bearth, 1973); M — mean molecular proportions in garnets from phyllites, chlorite and mica schists, mostly of Barrovian-type of metamorphism

been reached. It may be even postulated that negligible amounts of Mg-garnet molecule simultaneously with the increased content of Mg-garnet molecule could serve as an indication for both retrogressively and progressively metamorphic origin of glaucophane. The retromorphic garnets from California (C_6 and C_8 in Fig. 6), Alps (*A*) and Ural (U_1 and U_2) developed in glaucophanized eclogite differ clearly, having relatively high Mg- and small Mn-content. Moreover, these garnets show as others found in glaucophane-schist facies much higher Ca-garnet molecule participation in comparison with average composition of normal (mostly Barrovian-type) low-grade garnets (*M* in Fig. 6). Noteworthy is also rather high content of Ca-garnet and smallest participation of Mg-garnet molecule in the eclogite garnets discerned by Smulikowski (1965) as components of ophiolitic eclogites, geologically connected with glaucophanites and prasinites.

The rising progressive metamorphism and more open environment usually causes contemporaneous decrease of oxygen fugacity. This is especially visible in the glaucophane-garnet association in metacherts, cited by Iwasaki (1960), in form of reaction: $2Mg\text{-crossite} + 3\text{ piemontite} + 5/2\text{ hematite} + 3\text{ quartz} = 2\text{ magnesioriebeckite} + 3\text{ epidote} + 1\text{ garnet} + 3/4\text{ O}_2$. Only under more reducing conditions Mn^{2+} ion would enter into garnet lattice. Regular occurrence of pyrite as accessory mineral in the garnet-bearing glaucophane schists is much significant.

DISCUSSION AND PETROGENETIC REMARKS

The glaucophane, typomorphic mineral of blueschist facies originated (as can be deduced from its chemical composition) from host rocks rich in H_2O , Na_2O and MgO relative to Al_2O_3 . Though the similar rocks in the form of basic volcanites are common in nature, these rocks, excluding spilites, are not abnormally enriched in Na_2O and H_2O . These two important components could be derived from fresh marine sediments, especially if the basic rocks and marine sediments are intimately intermingled in form of mixed rocks or of intercalations.

Not surprising is the fact, that glaucophane schist facies is bounded with eugeosynclinal terrains undergone high pressure-low temperature in e.g., subduction zones and are of Paleozoic or much more commonly of post-Paleozoic age. The usually associated rocks are of specific composition, represented by Fe- and Mn-rich cherts (jaspers) and calcareous, pelagic sediments. Occasionally, ferromanganese accumulations of exhalative, halmyrolitic and biogenic provenance have been noted. The association of crossite with hematite accumulations in the equivalent to the here described formation on the Czechoslovak side of Sudeten Mts (Tuček, 1949) may serve as an example. The mentioned rocks accompanied by episodic, clastic (esp. graywacke) sediments are responsible for whole chemical variance with all possible combinations of mineral constituents according to the grade and kind of metamorphism.

Glaucophane is reported (Ernst, 1961, 1963) as stable (but not originates in nature) over a wide *p-t* range in lime-deficient rocks, rich in Na_2O and MgO relative to Al_2O_3 . The calcium component, as was formerly established, can be in a limited extent incorporated in the glaucophane struc-

ture. The surplus crystallizes in the shape of actinolitic amphibole \pm epidote usually as rims. Judging from the gradual enrichment in Ca of plagioclase series minerals with temperature, this factor is most probably responsible also for the formation of glaucophanes with increased calcium substitution (Fig. 7).

Glaucophane-bearing blueschists may be the products of prograde, as well as, of retrograde metamorphism, e.g. glaucophanization of amphibolites, eclogites a.o. rocks derived from suboceanic basement. It may be

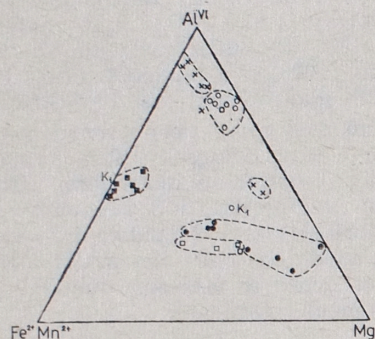


Fig. 7. Ternary proportions of octahedrally coordinated cations in analyzed minerals from Kopina Mt (indicated by letter K) and Eastern Shikoku (Ernst, 1964)

Projection points symbolize: solid circles — glaucophane, open circles — white mica, solid squares — garnet, open squares — chlorite, crosses — pyroxene, letters x — epidote

stated as a broad generalization that blueschists have bulk composition identical to many typical epidote amphibolites and greenschists. Therefore, the p - t conditions assume special importance in the formation of glaucophane schist facies.

Under high pressure-low temperature conditions glaucophane formation may be preceded by the appearance of jadeite with the lime component of rocks contained in lawsonite and magnesia — in chlorites or serpentines. How important is the last component for the formation of glaucophane is well evident from one Californian example (Bloxam, 1960): in the diabase sill (with feldspar converted to jadeite, lawsonite and chlorite) glaucophane is particularly abundant at its margins. Towards diabase the jadeite-bearing metagraywackes become richer in glaucophane and pass into jadeite-free, schistose glaucophane rocks. The jadeitization of metagraywackes was independent of proximity with igneous bodies. Metasomatism (probably hydrothermal) might precede and coincide with metamorphic transformation and differentiation (e.g. lawsonite-rich layers and veinlets). Hydrothermal action conception is supported by the presence of fugitives, a.o. in the form of omnipresent pyrite.

Mentioned Bloxam's observations suggest a important role of hydro- and/or pneumostatic pressure in the glaucophanization processes. The conditions of high lithostatic pressure of kinematic nature in the presence of adequate amounts of relict water (activity pressure) may conduct to the same results. Retrograde glaucophanization of residual blocks of eclogite, recorded by Bloxam (1959) should be here mentioned as an example.

Coleman and Lee (1963) are adherents of progressive metamorphism of Californian basalts and sediments, which have been transformed to glaucophane-bearing rocks under isochemical conditions of crystalloblastesis, except for fugitive and subordinate components. Chiefly basing on

textural and mineralogical criteria they discern three types of glaucophane-bearing metamorphic rocks (II, III and IV) with non-foliated, foliated and gneissic texture.

The complete lack of coexisting albite and chlorite in all above mentioned types of the glaucophane-bearing metabasalts is, as commonly, interpreted by the reaction: albite + antigorite molecule in chlorite = glaucophane + H_2O or albite + chlorite + actinolite = glaucophane + epidote + H_2O .

The relatively iron-rich rocks (e.g., ferrobasalts and their derivatives) will modify the mentioned reactions to the more complex interdependences (Black, 1973), as follows: ferroglaucophane + Fe-rich chlorite + lawsonite = glaucophane + Mg-rich chlorite + epidote + almandine. Conversely, the rather iron-rich amphiboles, as actinolitic or barroisitic hornblendes, could evolve from low-grade Fe-Al chlorites after interreaction with quartz, highly ferruginous almandine garnet and a more magnesiumiferous chlorite.

In the later stages, prograde metamorphism (especially if in a more open environment) commonly favours the phases stable under reducing conditions. This is well visible in the case of Fe- and Mn-rich metacherts (Iwasaki, 1960): $2Mg$ -crossite + 3 piemontite + $5/2$ hematite + 3 quartz = 2 magnesioriebeckite + 3 epidote + 1 garnet + $3/4 H_2O$. Only under reducing conditions Mn^{2+} ion would enter into garnet lattice. Regular occurrences of pyrite and sometimes of ferrostilpnomelane as late accessory minerals give another confirmation for this conclusion.

On the other hand, the first reaction members of blueschist facies formation, embraced as the crossite subfacies and ferric glaucophane subfacies (Misch, 1959), show high oxygen activity in relation with the surrounding greenschists. In the presence of epidote, albite and chlorite in both blue- and greenschists, the zoning of Na-amphiboles, based on transition from more to less ferric and to increasingly actinolitic varieties, may be interpreted supposing that the generation of Na-amphiboles depends not on high Na^{1+} but on Fe^{3+} ion content (Misch, 1959). The same sequence of zoning in Na-amphiboles, as well as, the steady decrease of the Fe^{3+}/Al^{3+} ratio in epidotes in the actually examined examples (K_1 , K_2) induce the earlier rise of p - t values and oxygen activity followed by later drop of temperature and oxygen activity. Higher hydro- and/or pneumostatic pressures possibly favoured the decomposition of water molecules and in this way the oxidation of iron (electron exchange). At lower local pressures actinolitic greenschists could exist without transformation into crossite- and glaucophane-bearing rocks. Nevertheless, in all cases the influence of the original composition of source material must always be taken into account. Unweathered and secondarily enriched in iron through weathering and volcanic exhalations basalts and their derivatives show an example. Another indication elucidating the provenance of source rocks presents the relict, usually poikilitic material. The constant and rather magnified content of sphene inclusions in Sudeten glaucophane is much striking. The best interpretation seems to be the recrystallization of leucosene derived from the decomposition of titania-rich pyroxenes (e.g. Ti-augites, common in ferrobasalts).

All these considerations will be incomplete if neglecting the significance

of the metasomatism and metastable recrystallization, examined by Ernst (1971). These processes and the absence of lawsonite in blueschists of Old Paleozoic or earlier age (secular alteration?) remain till now enigmatic.

GEOLOGIC CONCLUSIONS

Presented analytical data and petrogenetic considerations lead to the assumption that the investigated glaucophane schists of Kopina Mt, likely to other glaucophane- or crossite-bearing schists with associated rocks from Polish and Czechoslovak side of Sudeten Mts, generated in the low to high grade chlorite zone of green- and blueschist facies. Their source rocks most probably included basaltic rocks and their tuffaceous derivatives. The appearance of abundant phengites in some of the mineral assemblages implies clastic (pelitic) original nature of the admixed material.

The many-sided geologic studies of Leszczyniec Formation (containing glaucophane-bearing schists), conducted by J. H. Teisseyre (1973), provided numerous data supporting Ordovician-Silurian age of the parental rock series. The facial composition of this almost exclusively magmatogenic formation varies between hypabyssal and volcanic rocks, including tuffs, tuffites, a.o. pyro- and volcanoclastic rocks. The assemblages of such rocks, like: metadiabases, metabasalts, metaspilites, keratophyres, albite amphibolites, zoisite amphibolites, prasinities, greenschists, chlorite-calcite schists, chlorite-albite schists, a.o., are very significant. Also the petrographic descriptions (Teisseyre, 1973) allow here presentation of some important new generalizations. They yield evidence of ocean-floor type metamorphism, contemporaneous with ocean-floor spreading and initial phase of magmatic cycle. The main metamorphic events, culminating in the blueschist facies generation, took place later, in liaison with compressional tectonic displacements, supposedly simultaneously with the final stages of Caledonian orogeny. Teisseyre (*op. cit.*) admits even oldest phases of Hercynian orogeny. These movements might release in the form of the subductional thrusting, directed towards (westwards and northwards in actual orientation) and under pre-Caledonian crystalline complex of Isera-Kowary gneisses, called Early-Assyntian Isera block or massif by Oberc (1960, 1965, 1966). The last mentioned author reasonably identifies the magmatic phenomena of Leszczyniec Formation (unit) with initial volcanites of Caledonian eugeosyncline.

Concluding the most important features of the geological environment of investigated glaucophane occurrences emerge from the two-stage metamorphism, namely — ocean-floor metamorphism of initial volcanites during ocean-floor spreading and later burial metamorphism (*Versenkungsmetamorphose*), a consequence of subductional thrusting.

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LUPKI GLAUKOFANOWE I SKAŁY TOWARZYSZĄCE Z GÓRY KOPINA (GRZBIET LASOCKI, SUDETY)

Streszczenie

Znalezione na południowo-wschodnim zboczu góry Kopina (grzbiet Lasocki, Sudety) łupki glaukofanowe wyróżnia z poznanych dotąd w Sudetach przykładów skał z glaukofanami, obfitość i jednorodny skład amfibolu sodowego umożliwiającego rozbiory analityczne. Cechami rentgenograficznymi glaukofan odpowiada polimorfowi II Ernsta. Towarzyszące mu minerały obejmują granat, pasowy epidot, kwarc, albit, tytanit i niekiedy barroisytową hornblendę aktynolitową. Skład chemiczny almandynowego granatu znamionuje duże ubóstwo molekuly piropowej i stosunkowe bogactwo — grossularowej i spessartynowej, właściwe łupkom glaukofanowym i prasinitom chlorytowego pasma metamorfizmu.

W asocjacji z łupkami glaukofanowymi występują łupki chlorytowo-aktynolitowo-epidotowe (czasem z ferrostilpnomelanem), łupki epidotowo-chlorytowe ± fengit, łupki fengitowo-chlorytowe, epidosyty i wenity albitowo-kwarcowe i kwarcowe.

Łupki glaukofanowe powstały w warunkach wysokiego ciśnienia i niskich temperatur w łączności z ruchami subdukcyjnymi, późnokaledońskimi lub nawet wczesnohercyńskimi. Metamorfizm z tego etapu poprzedzał wcześniejszy, również kaledoński, powiązany z rozsuwaniem się dna oceanicznego i inicjalną aktywnością wulkaniczną. Produktami jej były meta-diabazy, metabazalty, metaspility, metatufy, amfibolity zoisytowe i albitowe i in. typowe dla eugeosynklin skały.

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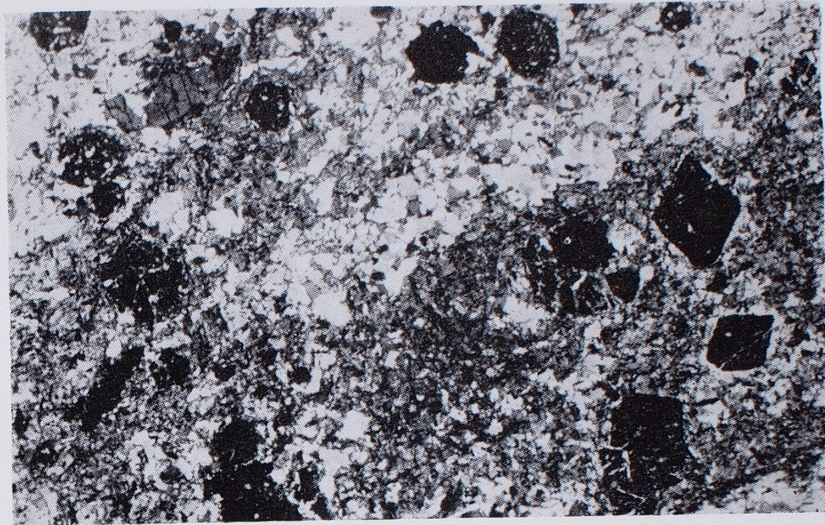
ГЛАУКОФАНОВЫЕ СЛАНЦЫ И СОПУТСТВУЮЩИЕ ПОРОДЫ ИЗ ГОРЫ КОПИНА (ЛЯСОЦКИЙ ХРЕБЕТ, СУДЕТЫ)

Резюме

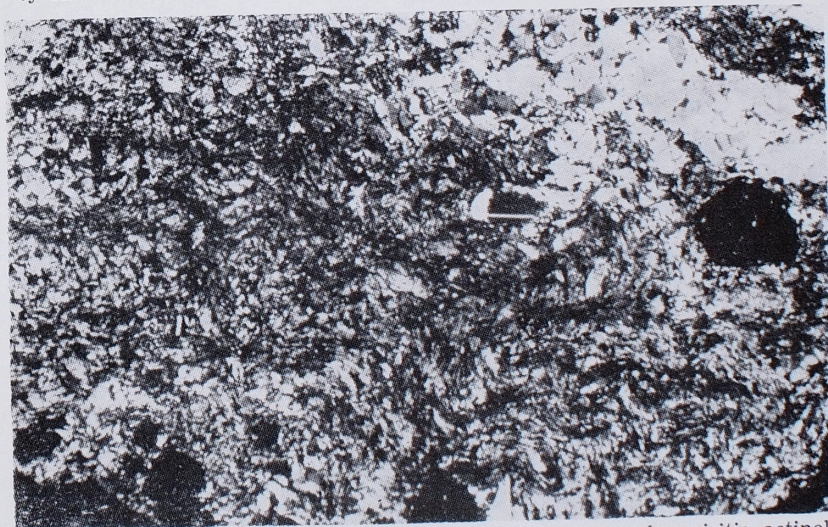
Обнаруженные на юго-восточном склоне г. Копина (Лясоцкий хребет, Судеты) глаукофановые сланцы выделяет из известных до сих пор примеров пород с глаукофаном из Судетов обилие и однородный состав натриевого амфибола, который делает возможным аналитическую разборку. По рентгенографическим характеристикам глаукофан соответствует II полиморфу Эрнста. Сопутствующими минералами являются гранат, полосатый эпидот, кварц, альбит, титанит и иногда барроиситовая актинолитовая роговая обманка. Химический состав алмандинового граната свидетельствует о ничтожном присутствии пироповой молекулы и об относительном обогащении в grossularовую и спессартиновую молекулы, которые свойственные глаукофановым сланцам и празинитам хлоритной полосы метаморфизма.

В ассоциации с глаукофановыми сланцами присутствуют хлорито-актинолитово-эпидотные сланцы (иногда вместе с ферростилпномеланом), эпидот-хлоритовые сланцы с фенгитом, фенгито-хлоритовые сланцы, эпидозиты, албито-кварцевые и кварцевые вениты.

Глаукофановые сланцы образовались в условиях высокого давления и низких температур совместно со субдукционными движениями позднекаледонского или даже раннегерцинского времени. Метаморфизму этой стадии предшествовал более ранний, тоже каледонский, связанный с наступлением океанического дна и первичной вулканической активностью. Её продуктами были метадиабазы, metabазальты, метаспилиты, метатufы, зоиситовые и альбитовые амфиболиты и другие, характерные для эвгеносинклиналей, породы.



Phot. 1. Glaucophane-epidote-quartz-albite-garnet schist from Kopina Mt. Glomeroblastic structure is accentuated by the nearly monomineralic segregations of slender glaucophane nematoblasts. Subhedral to euhedral dodecahedrons of garnet are slightly rotated with the simultaneous development of small stretching haloes, occupied by chlorite. Section normal to lineation. Not fully crossed nicols. Magn. $\times 10$



Phot. 2. Glaucophane-epidote-chlorite-garnet schist with rare barroisitic actinolite-hornblende. The last mineral occurs only as small (epitactic) rims surrounding glaucophane grains. Well developed nemato- to fibroblastic texture and lineation resulting from the subparallel arrangement of elongated amphibole individuals. Section normal to lineation. Not fully crossed nicols. Magn. $\times 10$