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PARACRYSTALLINE MICROBOUDINAGE OF ZONED GRAINS AND OTHER CRITERIA FOR SYNKINEMATIC GROWTH OF METAMORPHIC MINERALS

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ABSTRACT. The long-known snowball porphyroblasts and certain microfolds prove synkinematic recrystallization for stages postdating the formation of schistosity. Recrystallization synchronous with elongation parallel to the schistosity is demonstrated by microboudinage of complexly zoned Na-amphiboles in the Shuksan Greenschist (Northern Cascades, Washington). Ruptures across prisms stretched parallel to schistosity did not open beyond submicroscopic dimensions, as rate of filling by amphibole accretion equalled rate of stretching, successive zones growing both on the crystal surfaces and across the ruptures. A regionally consistent zoning sequence allows one to determine stages of initial rupture and history of stretching, demonstrating that the whole metamorphism and the crystallization schistosity were synkinematic. Similar patterns occur in zoned epidote, in zoned hornblende of other Cascades units, and in certain zoned Na-amphiboles in California. Where rate of stretching exceeded rate of amphibole growth, delicate bridges of amphibole formed across the gaps.

Microboudinage of relatively rigid lenticles and large grains of epidote in Shuksan Greenschist predominantly is postcrystalline in respect to the epidote but is paracrystalline in respect to schistose matrix that flowed into the gaps and to mineral precipitation in the gaps. Similar patterns occur in garnet in amphibolite, et cetera.

Paracrystalline microfolding is demonstrated rigorously by polygonal arcs composed of crystals still weakly bent on the same fold pattern. This feature was observed in rocks greatly varying in composition and grade.

A Shuksan crossite schist displays recrystallization controlled by pressure gradients operative during microfolding, with transfer of chlorite and muscovite from the limbs into the hinges, resulting in incipient secondary compositional layering parallel to the axial plane.

Analysis of metamorphic history commonly reveals an intricate interplay of broadly simultaneous deformation and recrystallization. Crystallization schistosity more commonly is synkinematic than static-mimetic.

1. INTRODUCTION

Views on the role of tectonic deformation in regional metamorphism vary widely. If penetrative deformation is recognized as an integral element in most regional-metamorphic situations, its time relations to recrystallization become a major issue (discussed by Sander, 1930, especially p. 262-276; and in some other classical works). If one is interested in the hypothesis that in most, though not necessarily all, cases of regional metamorphism deformation and recrystallization were synchronous at least during a major portion of the metamorphic cycle, then reliable petrographic criteria for synkinematic recrystallization are needed to test this hypothesis. Certain theoretical and experimental aspects of synkinematic recrystallization, illustrated by artificially deformed marbles, have been discussed by Turner and Weiss (1963, p. 353-355, 407, 409, 441-442).

A conclusive criterion for synkinematic recrystallization is provided by porphyroblasts containing S-shaped traces of included schistosity. Snowball garnets, first described by Flett (1912) and subsequently discussed by Schmidt (1918) and Krige (1918), recently were systematically reviewed by Spry (1963). Snowball structure in chloritoid porphyroblasts was first described by Niggli (1912). The same structure has been reported in porphyroblasts of albite, staurolite, and a few other minerals. General discussions on rotated porphyroblasts and especially those of snowball type are found in the classical works of Grubenmann and Niggli (1924, p. 469-470), Sander (1930, p. 264-269), and Harker (1931, p. 220-221). Numerous additional data are found in the more recent literature. In view of the ample documentation available, examples encountered by the writer can be dispensed with here, except to add, as a kind of curiosity, that snowball structure was noted in some small sphene porphyroblasts in a Northern Cascades phyllite (no. 7.18.49.1, Jack Mountain Phyllite (Misch, 1966, p. 115)).

While rigorously demonstrating synkinematic recrystallization, snowball porphyroblasts postdate the act of formation of the schistosity which they include. A similar limitation applies to the record provided by paracrystalline microfolds; they are discussed in section (3) of this paper. Data that demonstrate recrystallization synchronous with elongation parallel to the schistosity are presented in part (2) of the paper (briefly outlined by Misch, 1961).

Rock designations used here list the minerals in the order of increasing abundance. Where abbreviated rock names are used, the most distinctive mineral is selected. Rock samples are identified by numbers and are deposited at the University of Washington.

Drs. N. L. Christensen and R. L. Gresens read the manuscript and offered constructive critical comments. Further, the paper was materially improved by a critical review by Dr. J. L. Rosenfeld.

2. PARACRYSTALLINE MICROBOUDINAGE

2A. Crystal boudinage during growth recorded by zoning, and implications regarding crystallization schistosity.[1]—Snowball porphyroblasts and certain microfolds provide evidence for synkinematic recrystallization at various stages after formation of the original schistosity. Evidence for recrystallization synchronous with deformation on the original schistosity is more elusive. Yet, if it can be found, such evidence has a critical bearing on the origin of crystallization schistosity—which may be attributed either to synkinematic or postkinematic recrystallization.

If homogeneous in composition, the aligned but individually undeformed crystals of a given phase rarely yield any clue as to whether they grew while deformation parallel to *s*[2] and/or stretching along linea-

[1] Crystallization schistosity = *Kristallisationsschieferung* (Becke, 1913, p. 37, 51) is used in a purely descriptive sense here, for schistose (or gneissose) rocks characterized by disregarded orientation of elongate crystals which, however, individually lack mechanical deformation in terms of lattice distortion.

[2] "*s*" is used here as defined by Sander (1930; compare, Knopf and Ingerson, 1938), except that bedding is not included as in Sander's original usage. Thus, *s* stands for metamorphically produced planar schistosity and/or foliation, whether it parallels or transects inherited bedding, if any. Following Sander, coexisting *s* planes are referred to, from older to younger, as s_1, s_2, et cetera.

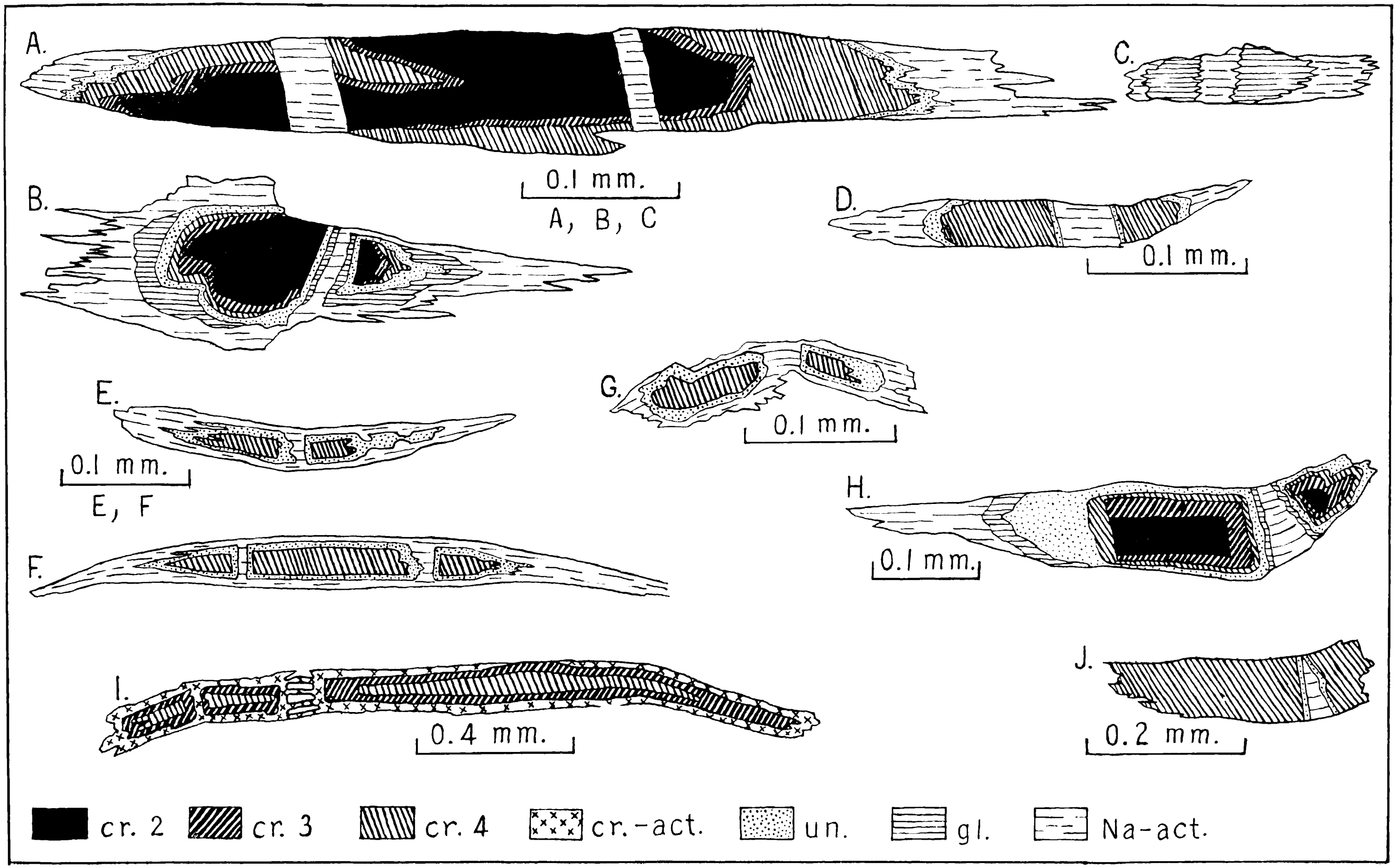
tion[3] were active, or whether they represent static annealing after deformation (mimetic recrystallization = *Abbildungskristallisation,* Sander, 1930, p. 172). If, however, the aligned crystals are zoned, they contain a record of their growth history which might be checked against the record of deformation, provided such a record can be found in the crystals. In this manner, it may be demonstrated whether crystallization schistosity represents synkinematic or postkinematic recrystallization.

Evidence of this type was found in zoned sodic amphiboles in blueschist layers of the Shuksan Greenschist of the Northern Cascades of Washington (Misch, 1959, 1961, 1966). The mineralogy of these amphiboles (briefly outlined by Misch, 1959) need not be discussed here except for those features which provide a relative time sequence in terms of amphibole growth history.

The dominant sodic amphibole is *crossite,* arbitrarily subdivided into *"crossite 1" through "crossite 4"* with decreasing Fe^{3+}/Al ratio, "crossite 1" attaining the Fe^{3+}-content (but not the optic orientation!) of riebeckite. Crossite is followed by *"uniaxial" blue amphibole* in which Fe^{3+}/Al is close to 1 and by still relatively Fe^{3+}-rich *glaucophanes,* highly aluminous glaucophane not being stable in the particular subfacies of a broadly defined blueschist facies developed in this area (Misch, 1959, 1966). Further, there is *"soda-actinolite",* a solid solution of actinolite and glaucophane or relatively Fe^{3+}-poor crossite; and *"crossactinolite",* a solid solution of actinolite and Fe^{3+}-richer crossite, which shares the normal-symmetric orientation of crossite.

Most of the sodic amphiboles are zoned; relations between contiguous zones are gradational, as a rule. *"Normal" zoning* involves decreasing Fe^{3+}/Al; crossite 1→2→3→4→ uniaxial → glaucophane, with part or all of this series present in a given rock, depending on bulk composition. A variant of "normal" zoning involves increasing actinolite admixture; crossite → crossactinolite or soda-actinolite, glaucophane → soda-actinolite; also, crossite → crossactinolite → soda-actinolite, and soda-actinolite → actinolite. Though more rarely preserved, *"reverse" zoning* also occurs, both in terms of Fe^{3+}/Al ratio and of actinolite admixture. Where found, "reverse" invariably predates "normal" zoning ("reverse" cores, "normal" rims). This zoning sequence is consistent throughout the area studied, that is, for several dozen miles, and it may be interpreted in terms of gradually changing physical conditions (briefly discussed by Misch, 1959). Thus, the zoned amphiboles provide a regionally valid relative time sequence. Further, the "amphibole history" of the blueschists can be correlated with their overall metamorphic history. For instance, in the northern parts of the area, the reverse →

[3] Lineation may represent *a* (the direction of "tectonic transport") or, more commonly, *b*—as defined by Sander (1930). Though representing stretching at many places, *b* lineation may form in other ways also, as by distributed rotational motion like microfolding or "rolling of pencils", either of which commonly, but not necessarily, is accompanied by stretching along *b*. Where *b* is referred to in this paper, it has been identified on the basis of being parallel to axes of minor folds.


A.
B.
C.
D.
E.
F.
G.
H.
I.
J.
0.1 mm.
A, B, C
0.1 mm.
0.1 mm.
E, F
0.1 mm.
0.1 mm.
0.4 mm.
0.2 mm.
cr. 2
cr. 3
cr. 4
cr.-act.
un.
gl.
Na-act.

normal zoning sequence seen in the sodic amphiboles is matched by the sequence, prochlorite → greenish biotite → prochlorite. The metamorphism recorded by the amphiboles and associated minerals was preceded by a hypothetical pre-blueschist-facies stage[4] and followed by minor retrogression chiefly characterized by late- and, dominantly, postkinematic stilpnomelane.

In addition to providing a consistent relative time sequence, the zoned amphiboles in the Shuksan blueschists contain a record of deformation, in terms of "stretching" of growing crystals parallel to the schistosity. This involves elongation on the *s* plane (commonly with preferred orientation of amphibole (100) parellel to *s*) and, in rocks having *b* lineation, maximum stretching along *b* (with amphibole tending to align itself parallel to *b*).

The results of "stretching" of growing zoned amphibole crystals are illustrated by the examples shown on figure 1. The process visualized is pictured on figure 2. "Stretching" was initiated by rupture across the prism axis and involved pulling-apart of the fragments. However, the rupture was healed as soon as it occurred, and continued pulling-apart of the original fragments was compensated by continuous filling of the developing gap. Thus, successive amphibole zones were deposited not only on the outer surface of the crystal but also grew normal to the walls of the opening rupture. The continuity of the amphibole structure was maintained throughout. Where this pattern is developed, obviously the width of the actual opening rarely, if ever, exceeded submicroscopic dimensions. Being a site of reduced pressure, the extensional rupture attracted diffusing amphibole constituents and favored their precipitation.

The pattern described proves that amphibole crystallization was exactly synchronous with deformation that involved elongation parallel to the schistosity. If the amphiboles were homogeneous instead of zoned, no visible record would remain of what actually happened. Undoubtedly, this applies to the generally (optically) unzoned actinolites which charac-

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Fig. 1. Paracrystalline microboudinage of aligned grains of zoned soda-amphiboles in fine-grained blueschists from 8 localities in the metabasaltic Shuksan Greenschist between Skagit River and Mount Shuksan, Northern Cascades, Washington. cr. 2 = "crossite 2"; cr. 3 = "crossite 3"; cr. 4 = "crossite 4"; cr.-act = "crossactinolite"; un. = "uniaxial" blue amphibole (in crystal J, "uniaxial" zone has actinolite admixture, is green-blue); gl. = glaucophane; Na-act. = soda-actinolite. Crystal A from soda–actinolite–bearing crossite schist (no. Sh 114). B and C from soda–actinolite–glaucophane–crossite schist with minor soda-pyroxene (Sh 115). D from soda–actinolite–bearing crossite schist (Sh 125). E and F from glaucophane–soda–actinolite–crossite schist (Sh 26). G from soda–actinolite–bearing crossite schist (Sh 131). H from glaucophane– and soda–actinolite–bearing crossite schist (Sh 83). I from crossactinolite–bearing crossite schist (Sh 78). J from soda–actinolite– and crossactinolite–bearing crossite schist (Sh 77). All rocks carry pistacite, albite, and subordinate prochlorite; quartz and phengitic mica occur in part of the rocks.

[4] This is suggested by such metamorphically produced compositional banding as predates the blueschist assemblage and, locally, is transected by the schistosity associated with that assemblage.

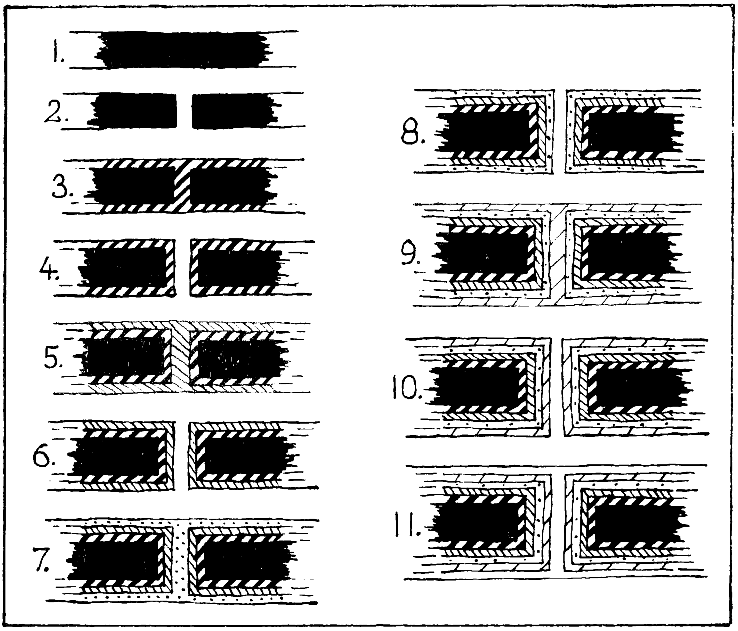

Fig. 2. Deformation-growth sequence involved in paracrystalline microboudinage of zoned crystals. A single site of rupture across a prism is shown. To allow graphic representation, stretching and accretion have to be treated as alternating finite steps. Actually, both occur simultaneously, the steps, as a rule, being infinitesimal.

terize the predominant rock types of the Shuksan Greenschist[5]. For it would seem highly unlikely that overall deformation-crystallization history in the actinolite-rich greenschists was different from that in the blueschist intercalations, their structures being identical and their mineralogical differences merely reflecting rock-compositional variation.

The pattern discussed above is modified if the rate of pulling-apart of segments of an amphibole prism exceeds the rate of amphibole crystallization in the gap, due to accelerated deformation and/or insufficient diffusion of amphibole constituents to the site of rupture. Instead of solid filling, only delicate amphibole bridges form across the gap (fig. 1-I). The remainder of the opening space is filled by precipitation of other phases (for example, albite, quartz, et cetera) that diffuse to the site of reduced pressure. This bridge pattern is very rare in the Shuksan blueschists but was found to predominate at a Californian locality (fig. 5). Such bridge patterns would be diagnostic in an unzoned, homogeneous crystal also.

In some of the zoned amphiboles, paracrystalline stretching was accompanied by rotational movement between segments, resulting in bent or kinked prisms (fig. 1-G, H, J; by contrast, crystals D, E, F, I show ordinary postcrystalline bending).

[5] Owing to lower Fe^{3+}/Fe^{2+} ratios in these rocks (Misch, 1959).

The regionally consistent amphibole zoning sequence in the Shuksan blueschists and regional distribution of crystals showing paracrystalline microboudinage make it possible to determine when initial rupture and subsequent stretching took place in individual crystals, in different crystals and rocks from the same locality, and in samples from different localities. For the few examples depicted on figure 1, crystallization-deformation history is plotted on figure 3. Regional integration of all available data indicates: (1) initial rupture occurred throughout the "amphibole history" of the rocks, including the early stage recorded by reverse zoning; (2) once initial rupture had occurred, stretching usually continued at the ruptured site during the remainder of the growth history of the crystal. It follows that all the blueschist metamorphism was synkinematic.

Though the data presented above are provided by one rock unit, they may have broad application. Similar patterns were noted in aligned zoned hornblendes in a few amphibolites from other rock units in the Northern Cascades (fig. 4). Paracrystalline microboudinage is also displayed by prisms of glaucophane zoned to crossite in a lawsonite-blue amphibole schist collected by Dr. G. A. Davis in the Klamath Mountains

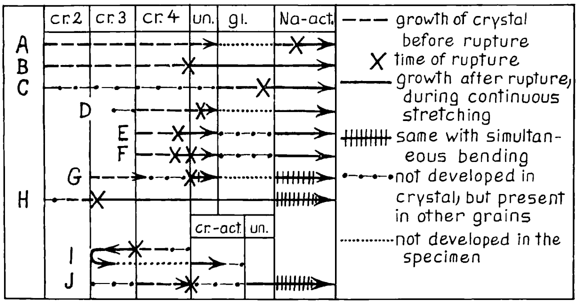

Fig. 3. Interpreted history of zoned soda-amphibole crystals shown on figure 1. Arrows point from cores to rims.

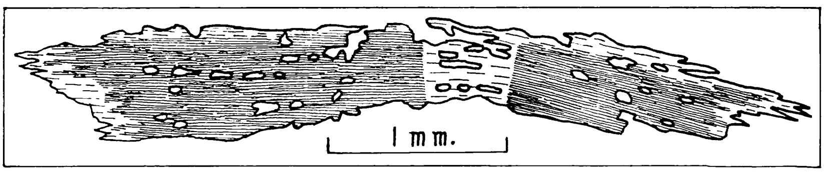

Fig. 4. Paracrystalline microboudinage of aligned porphyroblast of zoned hornblende in quartz- and pistacite-bearing chlorite-biotite-oligoclase-hornblende schist (very fine-grained except for hornblende). Cascade River Schist (Misch, 1966, p. 112) southeast of Marblemount, Northern Cascades, Washington (no. 9.22.54.16). Close lining: medium blue-green (Z) common hornblende. Widely spaced lining: Light bluish-green (Z) actinolite-rich hornblende. Patterns of this type can also be produced by retrogressive alteration of hornblende to actinolite along late, crosscutting strain zones. However, this does not apply to the crystal pictured here, as the "gap" is not lined up with any crosscutting alteration zone.

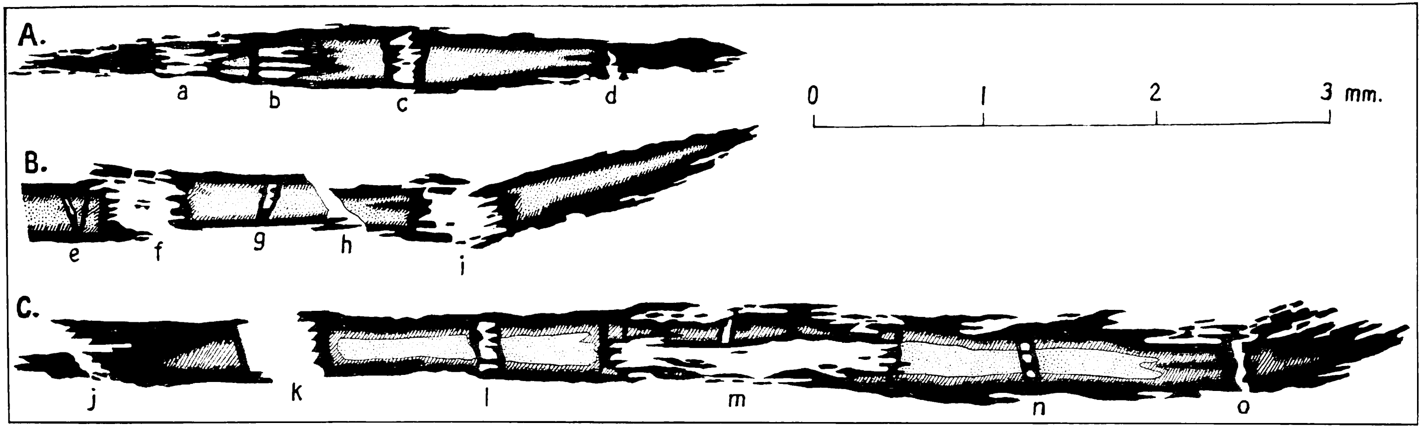

Fig. 5. Paracrystalline microboudinage of aligned porphyroblasts of "reversely" zoned soda–amphibole in fine-grained, albite–, garnet– and aegirine–bearing stilpnomelane–crossite–quartz schist (derived from impure chert?). Tiburon Peninsula, Bay Area, California (no. lab 177). Zone 1 (dotted): actinolite--crossite solid solution (optic plane = (010)); grades rapidly, through narrow "uniaxial" zone (not shown), into Zone 2 (diagonally lined): intermediate crossite ("crossite 2-3"); best developed in crystal C. Zone 3 (black): iron-rich crossite ("crossite 1"). *Rate of stretching* exceeded *rate of amphibole growth*. Hence, developing gaps were only partially filled by amphibole that formed "bridges" and "fingers" = "incomplete bridges". Amphibole growth was favored in exterior portions of gaps, amphibole constituents being supplied from the outside and depletion being most severe in the interior of the gaps. Ratio between stretching rate and amphibole growth rate varied widely for different gaps. Portions of gaps not occupied by amphibole (blank) were filled by precipitation of very fine-grained quartz mosaic, in places with minor stilpnomelane. This quartz mosaic is directionless, in contrast to schistose fabric outside the amphibole porphyroblasts. Gaps h, j, k are partially continued by late quartz veinlets outside the porphyroblasts. *Time of initial rupture* varies: b probably at late stage of growth period of zone 1, rather than at end of 1; i during latest part of period 1 or at end of 1; f after 1 and prior to 2; m initial rupture during middle of period 2, subsequent ruptures across bridges after 2 and prior to 3; l during latest part of period 2; c, e, g, k, n after 2 and prior to 3; a, d probable rupture during middle of period 3; h, j, o latest part of 3. Each rupture initiated more or less continuous stretching which locally outlasted amphibole growth, as at k.

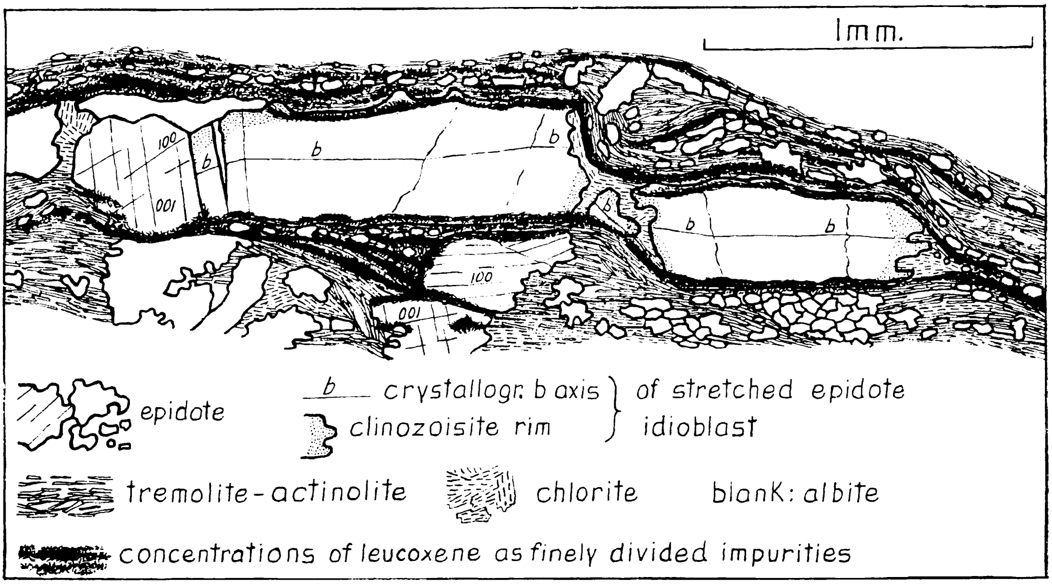

Fig. 6. Paracrystalline microboundinage of zoned epidote idioblast in actinolite-rich greenschist. Shuksan Greenschist, southwest face of Mount Shuksan, Northern Cascades (no. Sh 11). Note rotated small epidote fragment between mutually displaced large fragments, partially surrounded by clinozoisite rim. Rate of stretching exceeded growth rate of clinozoisite zone.

of northern California[6]. The bridge pattern of paracrystalline microboudinage, discussed above, is well developed in aligned porphyroblasts of zoned sodic amphibole in some quartzose schists the writer collected in central California (fig. 5). In these latter rocks, incomplete filling of the developing extensional gaps by amphibole substance reflects both a high rate of stretching and a limited supply of amphibole constituents, and much of the fill was provided by precipitation of quartz.

In the Shuksan Greenschist, paracrystalline microboudinage locally was noted in zoned epidote crystals also, though not as spectacularly developed as in the amphiboles. The epidote porphyroblast depicted on figure 6 shows relatively little growth after rupture, but the basic relationship is the same as in the amphiboles. Part of the developing extensional gap was filled by precipitation of chlorite, and at the same time the schistose matrix of the rock tended to flow toward the gap while continuing to recrystallize.

In Chiwaukum Schist of the North-Central Cascades (Page, ms), currently under investigation by the writer's student, C. C. Plummer, paracrystalline microboudinage locally is shown by small biotite porphyro-

[6] This rock was shown to the writer by Dr. R. L. Gresens as an additional example of paracrystalline microboudinage, and Dr. Davis gave permission to refer to it here.

blasts[7]. No zoning is involved there, but the stretched biotites comprise an earlier-formed (pre-rupture) part characterized by a graphitic internal *s*, and a later-formed part that filled the developing gaps and is clear of graphitic inclusions. Part of the filling was provided by phases other than biotite.

2B. Microboudinage defined as paracrystalline in terms of associated minerals.—In section 2A, evidence for paracrystalline microboudinage was provided by the deformed crystals themselves through their zoning history. The present section is concerned with microboudinage of aggregates and grains that is defined as paracrystalline in terms of associated minerals rather than those that suffered microboudinage. In respect to the microboudinaged aggregates and grains themselves, deformation varies between late-paracrystalline and postcrystalline; in the absence of a zoning sequence, only morphological elements are available to distinguish between these two variants. Excellent examples for the relationships outlined above are found in the Shuksan Greenschist (figs. 7-10). In this unit, epidote-rich aggregates and large epidote grains tended to respond to deformation in a relatively brittle manner, while associated fine-grained schistose matrix responded plastically[8].

Figure 7 shows microboudinage of a pistacite-rich segregation lenticle. The crossite-rich schistose matrix flowed plastically into the opening gap, as well as around the termination of the lenticle. This was accomplished by simultaneous deformation and recrystallization, the diagnostic amphibole fabric being that discussed in section 3A. Those parts of the developing gap not filled by schistose matrix attracted diffusing muscovite and chlorite constituents. Muscovite-chlorite precipitation also occurred inside the segregation lenticle, in sites where pistacite crystals were ruptured and their fragments pulled apart. Figure 8 illustrates paracrystalline plastic adjustment of amphibole-rich schistose matrix to growth and stretching of an epidote glomeroblast. Marginal splitting and stretching of the glomeroblast were accompanied by some further epidote growth, but most of the developing gap was filled by precipitation of albite and amphibole. Figure 9 shows a simple case of rotational splitting and stretching of a pistacite porphyroblast, postcrystalline in respect to the pistacite, but paracrystalline in terms of adjustment in the adjacent schistose fabric and of quartz precipitation in the developing gaps between pistacite fragments. Figure 10 depicts late-metamorphic microboudinage of pistacite, late-paracrystalline and postcrystalline as regards pistacite, but paracrystalline in terms of quartz and retrogressive stilpnomelane precipitated in the opening gaps.

Patterns similar or related to those discussed above occur in a great variety of metamorphic rocks examined by the writer; more commonly

[7] Details will be given by Plummer in his Ph.D. thesis. He agreed to reference to the microboudinage being made here.

[8] "Plastic" is used broadly here, for any non-ruptural, non-cataclastic response of grains and grain aggregates. This includes the combination of mechanical grain deformation with synchronous annealing recrystallization.

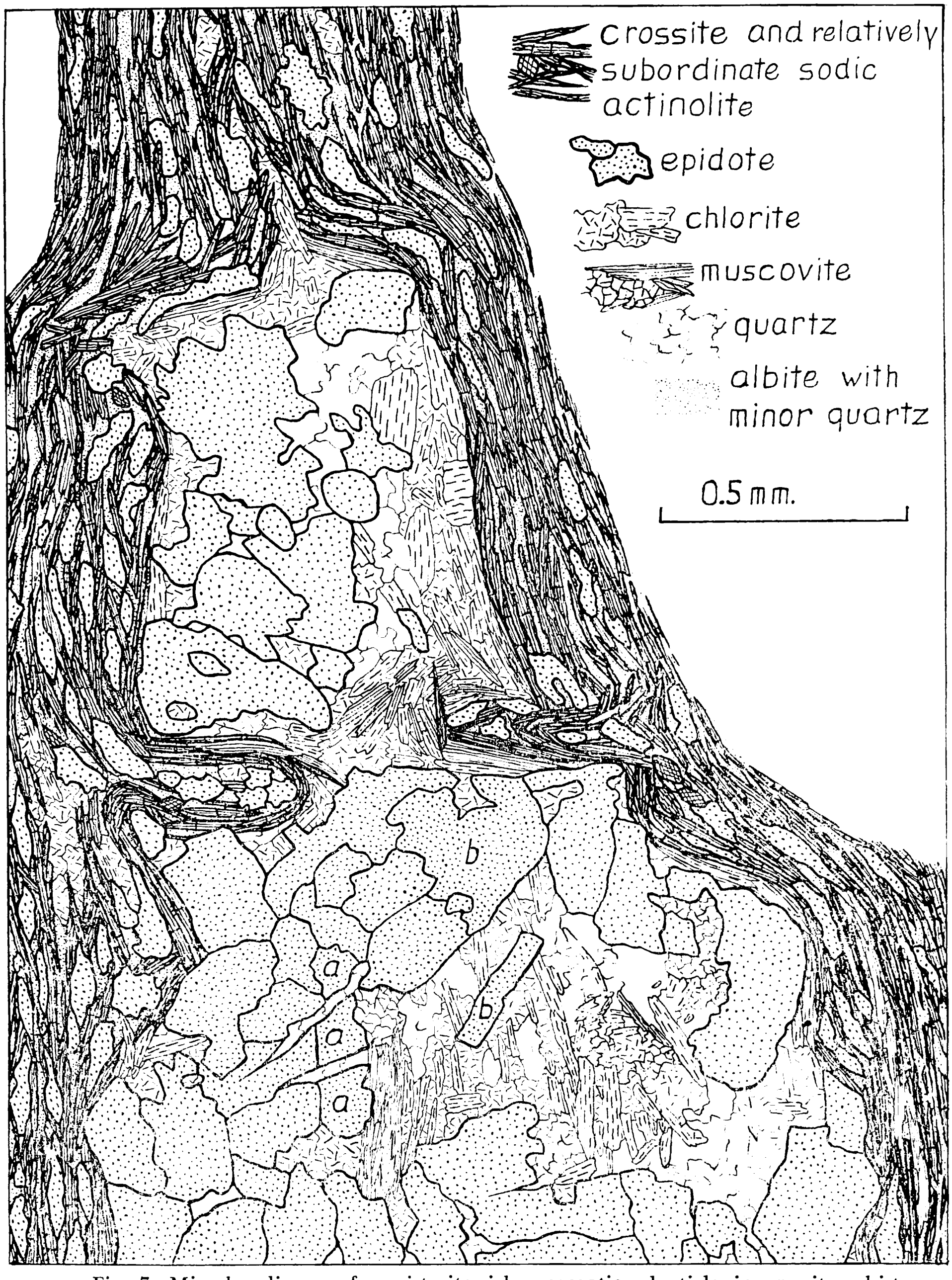

Fig. 7. Microboudinage of a pistacite-rich segregation lenticle in crossite schist. Shuksan Greenschist, north side of Skagit valley near Marblemount (no. Sh 115). Where schistose matrix flowed into gap between fragments of lenticle and around its termination, bent crystals are combined with polygonal patterns, indicating that flow was paracrystalline in respect to crossite fabric. Central part of gap, not filled by schistose matrix, was site of precipitation of non-aligned phengitic muscovite and prochlorite. Some elongation also occurred within fragments of lenticle, as shown by rupture of pistacite filled by muscovite–chlorite–quartz.

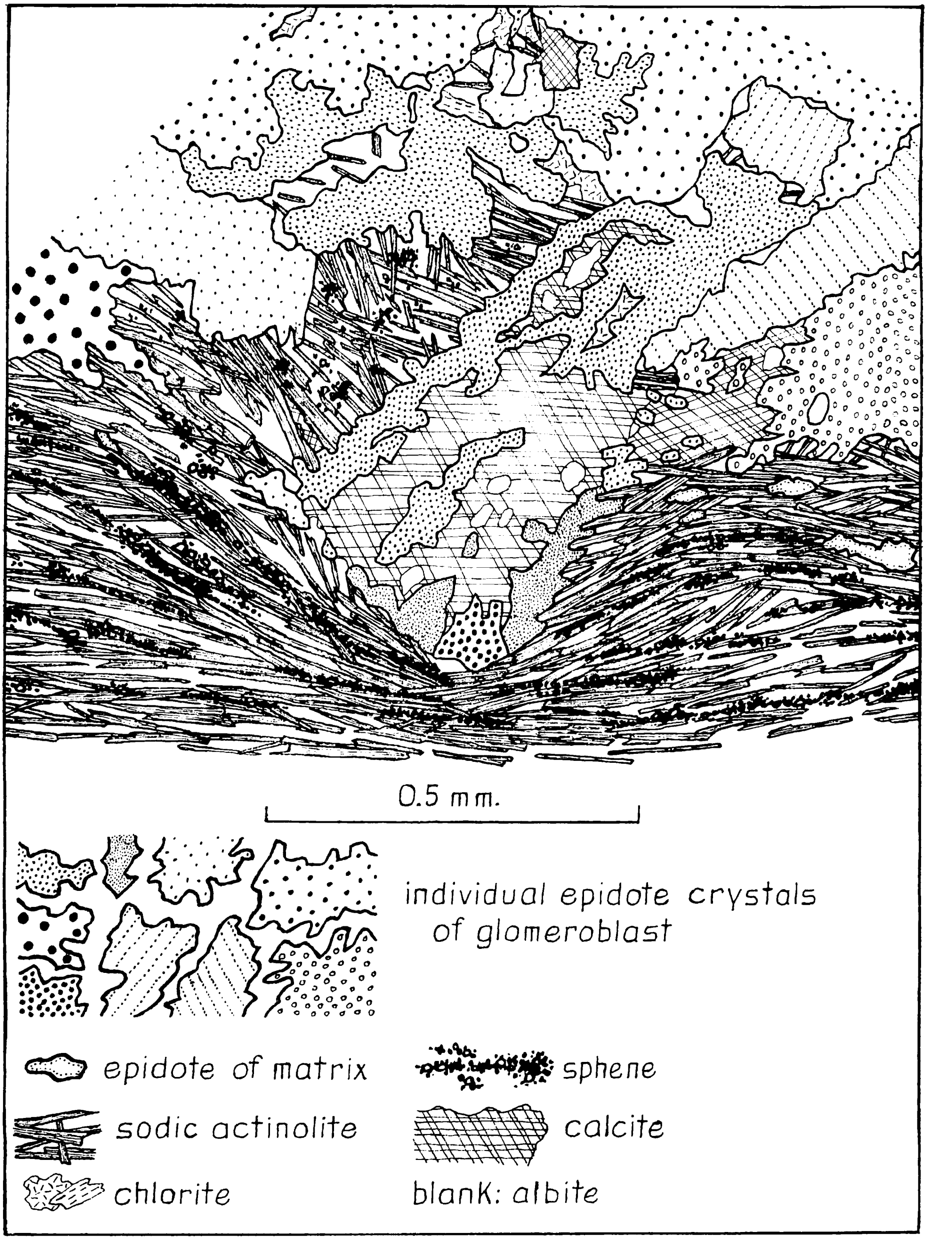

Fig. 8. Part of an epidote glomeroblast in soda-actinolite schist. Shuksan Greenschist, Skagit valley northwest of Marblemount (no. Sh 96). Growing glomeroblast bent out schistosity of matrix. Some epidote in the glomeroblast was ruptured, and the fragments pulled apart (large rupture in center). Some epidote growth continued during this stage, as indicated by non-matching, crenulated epidote borders on opposite sides of gap (center). Schistose matrix adjusted to growth and stretching of glomeroblast by paracrystalline flow (polygonal patterns combined with bent prisms). Most of the gap was filled by albite and amphibole; the latter tended to align itself in the direction of stretching. At some later time, calcite replaced some epidote; calcite also occurs in veinlets cutting the glomeroblast outside the area shown.

Fig. 9. Rotational stretching of pistacite porphyroblast in quartz–pistacite–rich segregation lenticle in crossite schist. Shuksan Greenschist, northwest of Marblemount (no. Sh 80). The following stages are indicated: 1. Synkinematic schistose fabric, comprising crossite- and muscovite-rich fabric and train of aligned pistacite grains (b); also marked by leucoxene. 2. Porphyroblastic pistacite growth (a), engulfing train (b), and others. 3. Rupture and rotational stretching of porphyroblast (a); rupture made use of (001) cleavage; another fragment of (a) is on the left of the area shown. Opening gaps (largest one on left) were filled by precipitation of clear quartz. Response of crossite- and muscovite-rich schistose fabric to this deformation was plastic with recrystallization continuing, as shown by lack of rupture and by combination of shallow polygonal pattern with slightly bent crystals.

in those of low or medium than in those of high grade. An example is a quartz–garnet–labradorite amphibolite (no. 8.24.60.6) from the Skagit Gneiss of the Northern Cascades (Misch, 1966, p. 112-113). This rock contains garnet porphyroblasts up to 2 cm in size that include an internal *s* of hornblende not displaced relative to external *s*. The garnets were ruptured normal to *s*, and their fragments pulled apart. The developing

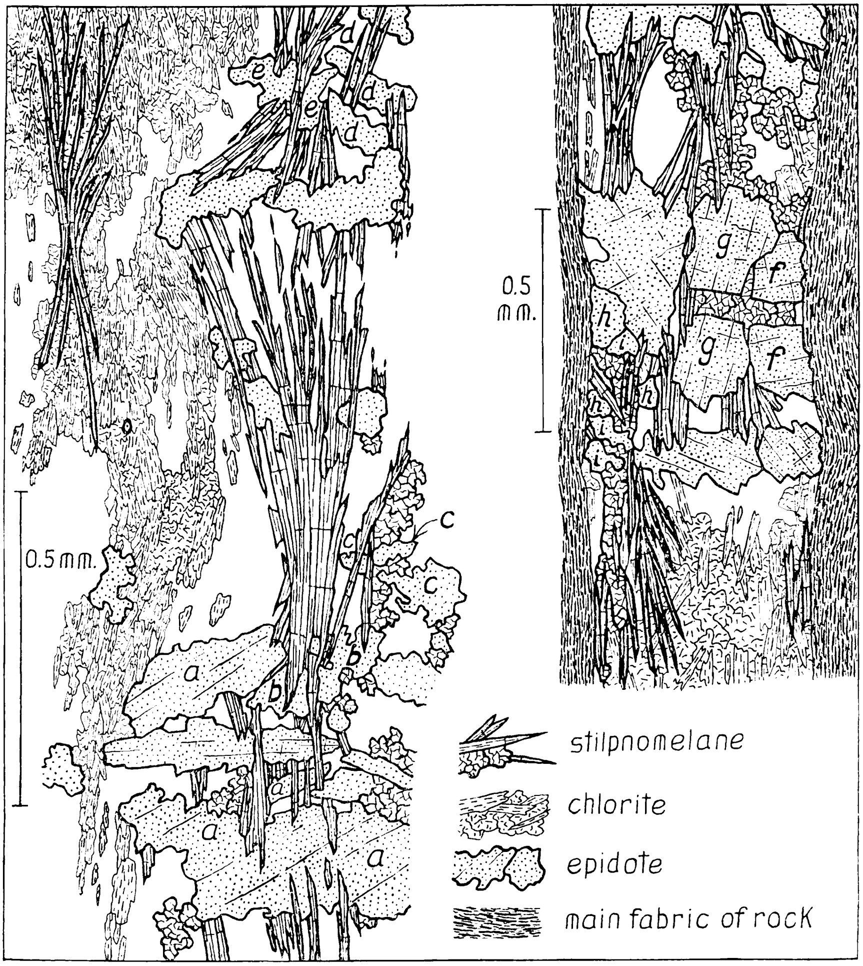

Fig. 10. Microboudinage of pistacite accompanied by growth of stilpnomelane, in quartz–chlorite–pistacite segregation layers in extremely fine-grained, chlorite-rich soda-actinolite schist with accessory glaucophane and crossite. Shuksan Greenschist, north side of Skagit valley near Marblemount (no. Sh 101). Blank: quartz. Letters refer to fragments of individual pistacite crystals. Rupture and stretching in part were entirely postcrystalline in respect to pistacite (crystals f, g), but in part stretching was still accompanied by some pistacite growth, as shown by non-matching, crenulated borders of fragments. Stilpnomelane and quartz filled most of the opening gaps. Stilpnomelane tended to align itself in the direction of stretching parallel to the schistosity (analoguous to amphibole in center of fig. 8). Stilpnomelane postdates and has replaced chlorite. It also has pierced pistacite fragments. This late-synkinematic stilpnomelane differs in its fabric from postkinematic, non-aligned stipnomelane in other samples.

gaps were filled by precipitation of hornblende-rich fabric which is aligned normal to the walls of the ruptures, that is, parallel to *s* (comparable to patterns on figs. 8 and 10). Next to the microboudinaged garnets, the matrix of schistose amphibolite adjusted plastically while continuing to recrystallize.

Ruptures of microboudinage type such as described above tend to be approximately normal to *s* and, in lineated rocks, to lineation that most commonly represents *b*. Opening and simultaneous filling of synkinematic (commonly, late-kinematic) fractures, commonly across *b*, is believed to be widespread in metamorphic rocks, on the mesoscopic as well as microscopic scale. Crosscutting veinlets in schistose rocks (for example, kyanite-quartz veinlets) cannot automatically be regarded as postkinematic.

Filling of gaps opening during microboudinage was found to involve precipitation of mineral phases that diffused to the site of extension (sec. 2A and B) and plastic flow of schistose fabric under paracrystalline conditions (sec. 2B). These two processes are analoguous to those operating between megascopic boudins. There, however, it may be difficult to determine whether flow of crystalline fabric was paracrystalline, owing to the different scales of megascopic structure and microtexture. Microboudinage may contribute to the understanding of megaboudins, as well as of crystallization schistosity.

3. PARACRYSTALLINE MICROFOLDS

3A. Polygonal arcs containing bent crystals.—Postcrystalline microfolds are easily recognized, deformation of the component crystals conforming with the curvature of the fold. On the other hand, polygonal arcs—that is, microfolds consisting of individually undeformed crystals in polygonal arrangement—may be attributed either to precrystalline or paracrystalline folding, the first case involving static mimetic recrystallization (*Abbildungskristallisation*, Sander, 1930, p. 172). Grubenmann and Niggli (1924, p. 471) emphasized that polygonal arcs are not necessarily static-mimetic. Sander (1930, figs. 110 and 111) presented two patterns as evidence for paracrystalline microfolding: (1) The core of a fold consists of a polygonal arc, and its outer portion, of deformed crystals. (2) A fold made up of deformed crystals is laterally contiguous with a polygonal arc. Both cases would involve highly uneven annealing which, however, might also be interpreted as static-mimetic. Further, case 2 might be attributed to a different age of the adjacent but separate microfolds, one being pre- or paracrystalline, and the other, postcrystalline.

More conclusive evidence for paracrystalline microfolding is provided by a pattern noted first in Northwest-Himalayan mica schists (Misch, 1949, p. 692) and subsequently in many other metamorphic rocks (brief reference in Misch, 1961). In this case, the crystals making up a polygonal arc are still weakly bent on the same fold pattern defined by the polygonal arc, as illustrated diagrammatically by figure 11A (stage 2); actual examples are shown on figures 12 and 13 (compare also, figs. 14 and 7). Two interpretations may be considered: (A) The polygonal arc formed by mimetic recrystallization of a precrystalline microfold, and

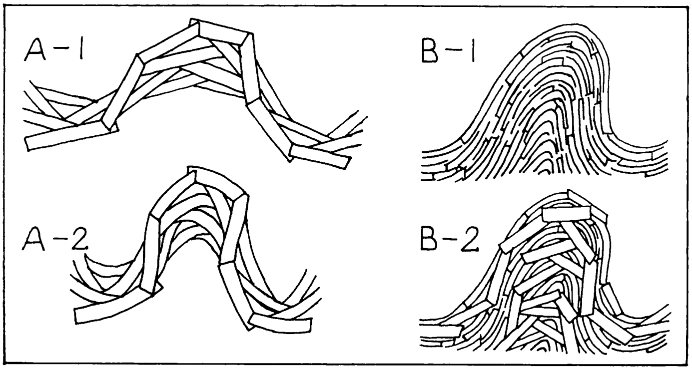

Fig. 11. Diagrams illustrating two different ways in which polygonal patterns and bent crystals may be combined in the same microfold. Explanation in the text.

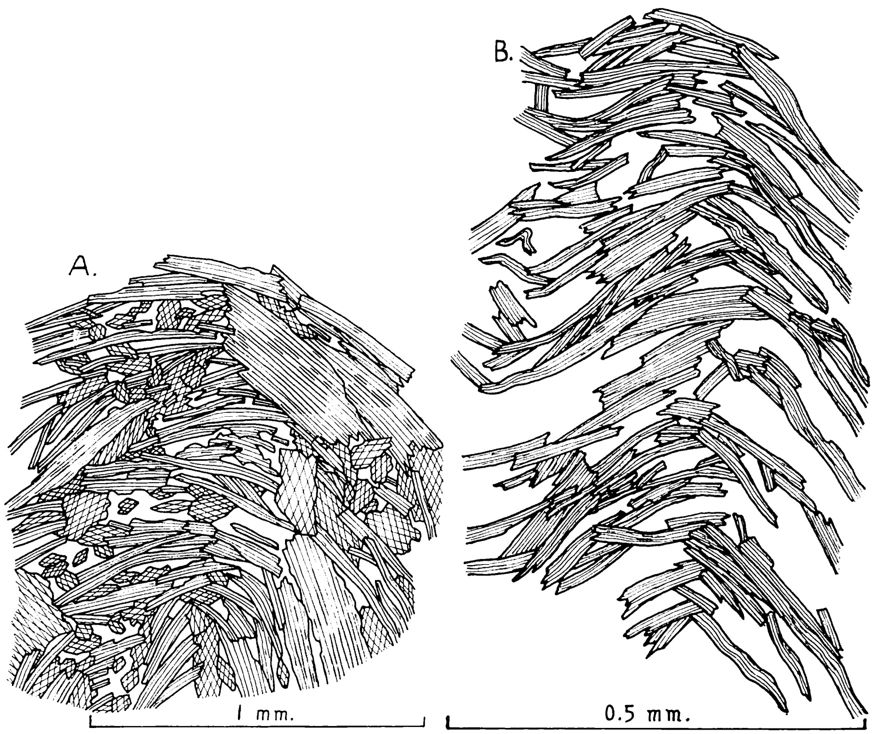

Fig. 12. Paracrystalline polygonal arcs in which crystals are still bent. A. Hornblende fabric in fine-grained, medium-grade amphibolite. Cascade River Schist (Misch, 1966, p. 112), Skagit valley northeast of Marblemount, Northern Cascades (no. 8.28. 61.12). B. Mica fabric in poorly garnetiferous, fine-grained, medium-grade biotite-muscovite schist. Eastern base of Okanogan Range north of Okanogan, north-central Washington (no. 7.10.48.15).

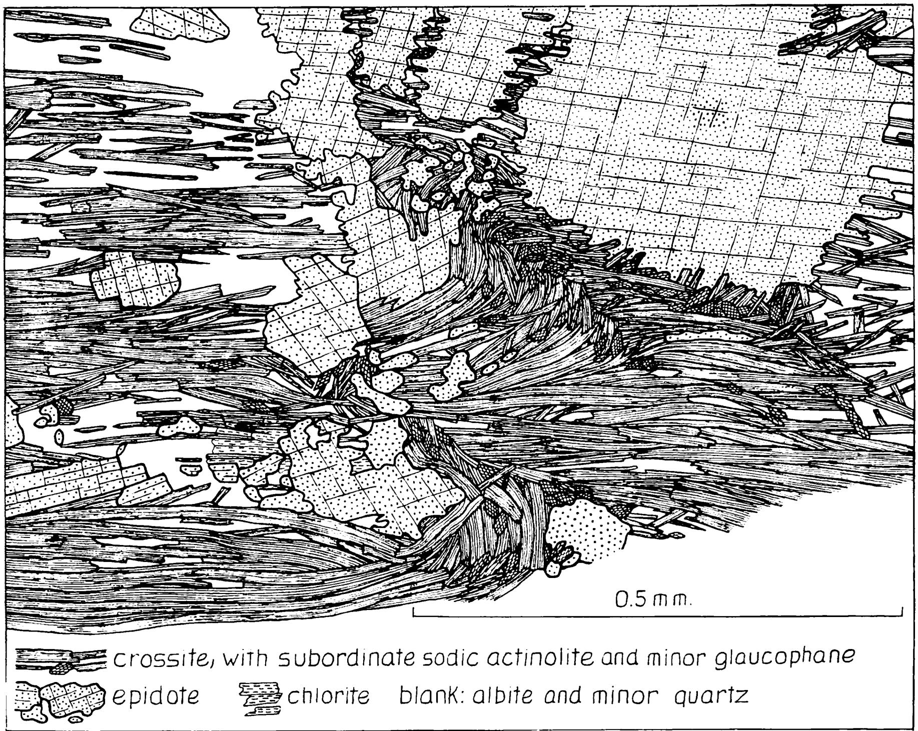

Fig. 13. Complexly microfolded crossite schist, showing paracrystalline polygonal patterns in which crystals are still bent. Note also paracrystalline stretching of large pistacite porphyroblast in upper part. Shuksan Greenschist, south of Baker Lake northwest of Marblemount (no. Sh 45).

the bending of the crystals was caused by a later, postcrystalline act of folding. It seems rather improbable that two separate, independent deformational events should have contributed harmonically to one and the same delicate microfold, without the structure resulting from the second deformation being discordant to that produced by the first deformation. (B) The polygonal arc is paracrystalline, lattice distortion being annealed as soon as it occurred (fig. 11A, stage 1), but recrystallization lagged or ceased near the end of the act of folding so that minor bending of crystals remains (fig. 11A, stage 2). This is considered the correct interpretation.

This pattern was observed in schistose and some gneissose rocks greatly varying in grade, facies, and composition. A few examples may be added to those shown on the figures: amphibole fabric in a lawsonite–crossite–glaucophane schist, Coast Range, central California (no. lab 21); chlorite fabric in fine-grained matrix of a hornblende garbenschiefer, southeast of Nanga Parbat, Northwest Himalayas (no. 19.6.S. Gurikot 4); fabric of a chlorite schist formed from talc schist, south of Skagit valley northeast of Marblemount, Northern Cascades, Washington (no. 8.25.

59.2); mica fabric in a high-grade pelitic schist, south of Conconully, Okanogan County, north-central Washington (no. lab 55).

A different pattern combining polygonal arcs and bent crystals is shown diagrammatically on figure 11B. In this case, postcrystalline folds (stage 1) were partially and unevenly annealed during a later event of static recrystallization (stage 2). No examples for this pattern are pictured here, because they do not constitute evidence for paracrystalline folding. However, such patterns were observed; for instance, where microfolded schist has been incompletely annealed by contact metamorphism. Also, some rocks characterized by the pattern of figure 11A contain minor elements that recall figure 11B, indicating that at a late stage annealing tended to become somewhat uneven.

Where, on the contrary, microfolding ceased somewhat earlier than recrystallization, polygonal arcs are likely to consist of entirely undeformed crystals. Such essentially synkinematic polygonal arcs commonly, though by no means everywhere, may be distinguished from static-mimetic polygonal arcs in that the latter tend to contain transverse crystals not following the inherited structure. The same criterion may aid in the distinction of synkinematic and static-mimetic crystallization schistosity.

3B. Paracrystalline microfolding proved by redistribution of mineral phases in response to pressure gradients during folding.— A rigorous demonstration of microfolding synchronous with recrystallization is provided by some rocks in which minerals were redistributed during folding. The best example found is a tightly microfolded crossite schist from the Shuksan Greenschist, shown on figure 14. In this rock, all chlorite has been concentrated in the fold hinges. Muscovite also has been transferred from the limbs towards the hinge regions, but it inhabits wider belts than the chlorite does. The limbs have become almost monomineralic crossite. This pattern of mineral redistribution, conforming with the fold geometry as it does, can be accounted for only in terms of local pressure gradients between the limbs and the hinges of the folds. Such gradients can have existed only while folding was in active progress. Selective diffusive transfer of muscovite and, even more radically, of chlorite into the hinge regions was exactly synchronous with microfolding. Crossite enrichment in the fold limbs essentially was residual; compared to the phyllosilicates, crossite did not markedly respond to pressure gradients. However, crossite, too, recrystallized during folding, as it displays the diagnostic pattern discussed in section 3A.

The redistribution of mineral phases described above represents an incipient stage of a secondary compositional layering parallel to the axial plane. If this process had attained an advanced stage, the earlier layering which coincides with the pre-fold schistosity might have been destroyed. Thus, a microfold-controlled mechanism of metamorphic differentiation may be envisaged. Some other forms of fold-controlled, and therefore likewise synkinematic, metamorphic differentation are well-

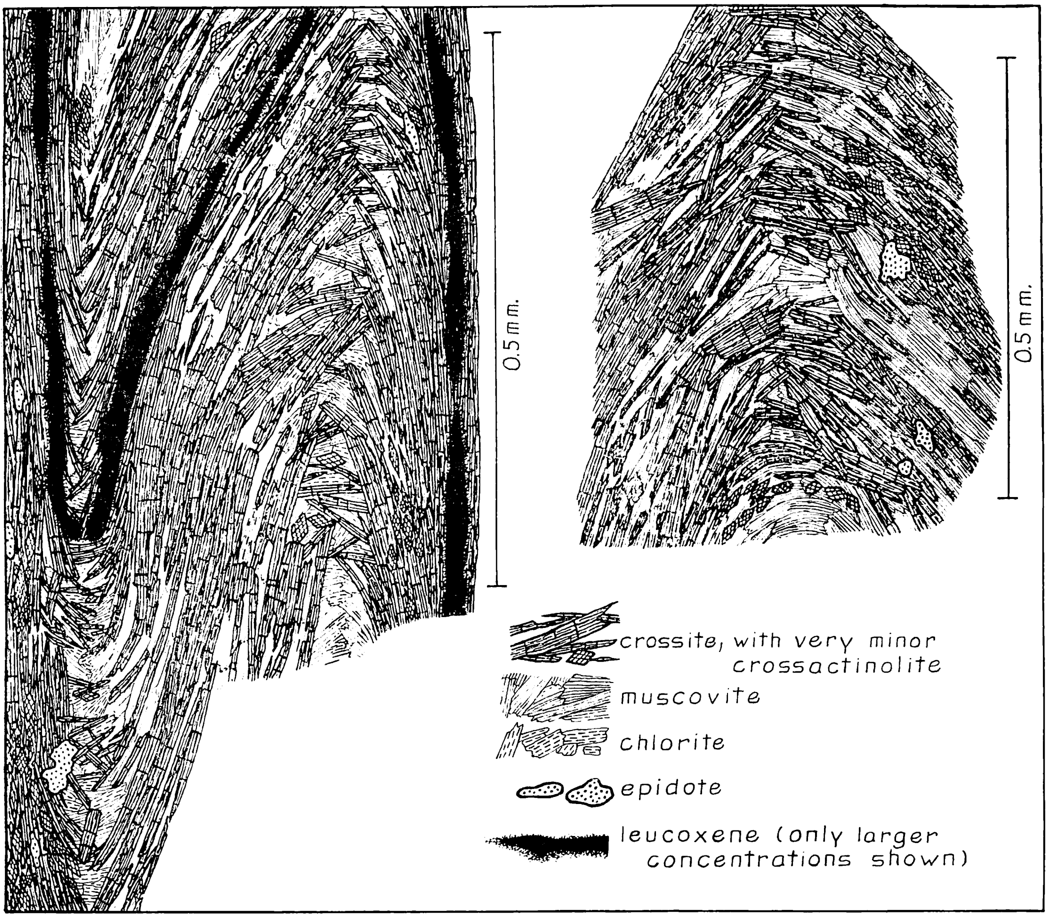

Fig. 14. Paracrystalline microfolds in epidote-poor area of quartz- and prochlorite-bearing pistacite-phengitic muscovite-crossite schist. Shuksan Greenschist, south of Baker River, between Mount Shuksan and Marblemount (no. Sh 136). Schistosity (s_1) is paralleled by pre-folding compositional layering, marked by leucoxene in the area shown but also involving other constituents in other parts of the sample. Evidence for paracrystalline folding is discussed in the text.

known and widespread, such as segregation of quartz or of quartzo-feldspathic material, commonly pegmatitic, in places such as fold crests.

The principle of redistribution of metamorphic mineral phases due to pressure differences was emphasized long ago by Backlund (1918).

4. SYNKINEMATIC RECRYSTALLIZATION INDICATED BY ANALYSIS OF METAMORPHIC HISTORY

Analysis of metamorphic history aims at establishing a detailed time sequence of specific stages of deformation and recrystallization[9] in in-

[9] Such analysis, of course, also involves an interpretation of the mineralogically recorded sequence of physical and chemical conditions, but this aspect is not discussed here.

dividual rocks and, by areal integration, in rock units. Deformational stages may be defined in terms of s_1, s_2, et cetera, of microfolding of s_1, or s_2, of rupture, stretching, shearing, folding, or rotation of certain minerals, and so forth. Crystallization stages may be defined by mineral species the growth of which either was confined to, or attained a climax during a given stage, by different generations of the same mineral (for example, early-formed, thinly platy, aligned biotite, and late porphyroblastic biotite), by compositional zones of solid-solution minerals, or by textures indicating reaction between successive phases, including reactions that involve metasomatism.

In many regionally metamorphosed rocks the writer has seen, such analysis of metamorphic history reveals an intricate interplay of deformation and recrystallization. In some cases, both were exactly synchronous throughout. In other cases, now one prevailed and then the other commonly overlapping in time; there may be several well-defined pulses of each. Still, deformation and recrystallization may be described as broadly synchronous in situations of this kind. Further, a given deformational stage commonly is postcrystalline in respect to one or several mineral phases, paracrystalline in respect to others, or precrystalline in respect to still others.

Not all regionally metamorphosed rocks display histories of the intricacy outlined above, in part because their actual history was simpler, and in part because the record of earlier stages has been destroyed, as in many high-grade rocks. Further, some rocks were reconstituted on a regional scale without undergoing penetrative deformation.

If the evidence obtained by analysis of metamorphic history of schistose and gneissose rocks is weighed as a whole, it may be stated that crystallization schistosity more commonly is synkinematic than static-mimetic, although in many essentially synkinematic rocks recrystallization has outlasted deformation.

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