American Mineralogist, Volume 64, pages 1294–1299, 1979

An albite–anorthite assemblage in low-grade amphibolite facies rocks

HANS-RUDOLF WENK

Department of Geology and Geophysics
University of California, Berkeley, California 94720

Abstract

Poikiloblastic amphibole schists from an ophiolite series in the vicinity of the Tertiary Bergell granite contain the assemblage albite (An 0)–anorthite (An 95), actinolite–pargasite, together with clinozoisite. TEM illustrates how large andesine crystals with a periodic APB (anti-phase boundaries) structure of *e* plagioclase change over a few hundred angstroms to pure albite and pure $P\bar{1}$ anorthite. Anorthite formation from andesine is accompanied by changes in the APB microstructure. Adjacent APB's combine, form loops, and finally annihilate to reduce strain energy along the boundaries. The continuous transition from *e* to *b* plagioclase and the chemical phase separation are cooperative processes. APB's provide favorable surfaces for large-scale diffusion. The TEM investigation documents that anorthite is definitely not a relict from an earlier high-grade metamorphic episode and thus appears to be stable at low metamorphic grade together with albite, which puts new constraints on the plagioclase phase diagram. Albite–anorthite assemblages are restricted to amphibole schists with pargasitic hornblende coexisting with actinolite. A striking correlation of (Na + K) and Al^{IV} suggests that the amphibole assemblage also is the result of decomposition.

Introduction

Intergrowths of plagioclase with different compositions are an expression of the complex subsolidus stability relations of this mineral series. Several miscibility gaps have been established, with lamellar structures forming by exsolution during cooling of igneous rocks, and compositional zoning, alternating growth structures, and two-feldspar assemblages in metamorphic rocks (for general reviews see *e.g.* Smith, 1974; Champness and Lorimer, 1976). At medium metamorphic grade albite coexists with oligoclase (An 15–20) (*e.g.* Evans, 1964), andesine (An 30–35) with labradorite (An 60–70), and labradorite (An 60–70) with anorthite (An 90–95) (*e.g.* E. Wenk and H. R. Wenk, 1977).

In general there is a maximum An content for a given metamorphic grade which is usually attained in calcareous schists. At higher normative An content or lower temperature other minerals form instead of calcic plagioclase, most importantly clinozoisite. This holds true for most regionally metamorphic rock suites (*e.g.* E. Wenk and H. R. Wenk, 1977) and has also been confirmed experimentally (Goldsmith, 1978). But a crucial question has always remained unsolved. Is the endmember anorthite stable at low temperature? There is no clear documentation for this except for a short abstract by Voll (1971) which has never been elaborated. During a study of amphibolites in the Central Alps I recently found albite–anorthite assemblages in fibrous amphibole schists of the border zone between amphibolite and greenschist facies. Even though I am far from understanding all implications either for regional geology or plagioclase phase relations, the observation seems important enough to report it in some detail.

Geological setting and petrography

The Tertiary Bergell granite has been emplaced for the most part conformably in the Upper Pennine nappes. However, along its NE edge there are some pronounced discordant contacts (Fig. 1). This area is characterized by contact metamorphism with andalusite–cordierite hornfelses. To the west metamorphism was more of a regional type (H. R. Wenk *et al.*, 1974). Along the granite contact amphibolite series dominate. They are associated with lenses of ultramafic rocks and locally display pillow structures. Further south they grade into tonalites which were mobilized along with the Bergell granite (H. R. Wenk *et al.*, 1977). All these calcic rocks, together

0003–004X/79/1112–1294$02.00

with ultramafic rocks of nearby Val Malenco and quartzites at Muretto Pass are considered to be members of a fairly extensive ophiolite series separating the Pennine realm from overlying Austroalpine (*sensu lato*) units. Amphibolites are variable in texture and composition. Some have equidimensional mosaic texture, others are crystalloblastic with large plagioclase porphyroblasts depicting an older mica fabric. Many of them have complicated poikiloblastic textures indicating different stages of crystallization, with the phases present certainly not representing an ideal equilibrium situation.

Amphiboles are frequently fibrous, with a composition ranging from pargasitic hornblende to actinolite–tremolite (Fig. 2). Similar amphiboles have been reported by Wetzel (1974) from greenschists of the Western Alps. An amphibole rich in (Na + K) and Al^{IV} often coexists with one which approaches actinolite composition. Two-amphibole assemblages are connected by tie lines which show remarkably similar slopes. Its significance and the general problem of amphibole composition are not the subject of this paper. However, Figure 2 documents a correlation with tectonic setting, and of particular interest are amphibolites of the Cavloccio zone which all contain pargasite. Sphene, quartz, clinozoisite, and

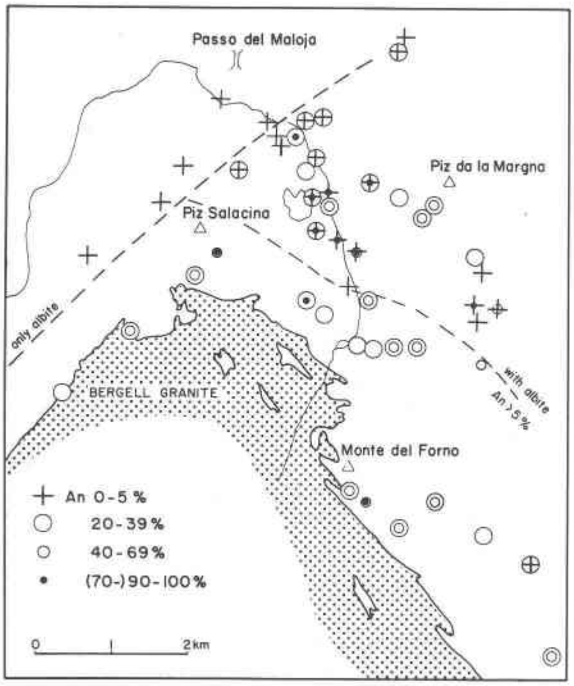

Fig. 1. Map illustrating plagioclase compositions in amphibolites around the NE contact zone of the Bergell granite (Central Alps).

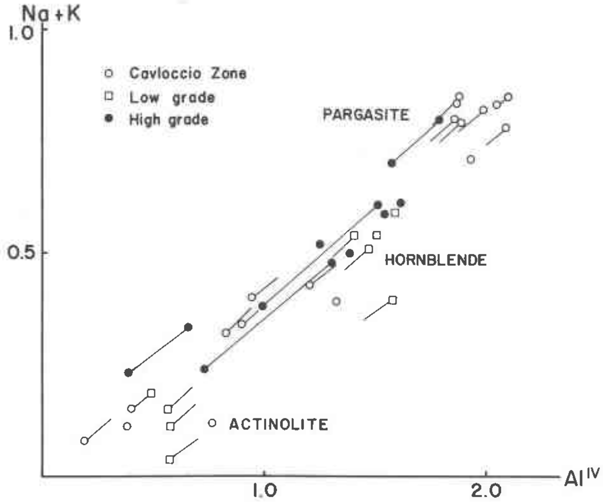

Fig. 2. Amphibole composition in amphibolites. Two-amphibole assemblages are common and tie lines are indicated. Notice that the tie lines are surprisingly parallel, suggesting that the two-amphibole assemblages formed by exsolution. Different symbols are used to characterize the geological setting.

epidote are frequent accessories. Occasionally prehnite veins crosscut the fabric.

A major component is plagioclase, and Figure 1 shows the regional distribution of compositions. Two contours are indicated on the map. The first is an isograd beyond which *only albite* has been observed. It follows the general pattern of regional metamorphism and is well defined in the northwestern part of the area north of the Engadine line. In the northeastern zone, which shows most typical evidence of contact metamorphism, one might expect this isograd to be closest to the granite contact, as implied in the compilation of E. Wenk and Keller (1969). This is not the case. Calcic plagioclase occurs far eastwards, beyond Piz da la Margna, not only in amphibolites but also in tremolite-bearing marbles of Mesozoic stratigraphic age. This intermediate plagioclase was probably formed during a Cretaceous phase of metamorphism whose intensity and extent are rather poorly defined (*e.g.* Bucher and Pfeifer, 1973). It is unrelated to the granite emplacement.

On the map a second isograd shows the *first appearance of albite* in amphibolites. This isograd is close to the granite contact, and crystallization of secondary albite is probably related to the emplacement of Bergell granite in early Tertiary. Amphibolites between the two albite isograds—particularly those of Alpe Cavloccio and the Orlegna river between Orden and Plan Canin—show considerable variety of plagioclase compositions. A histogram of microprobe

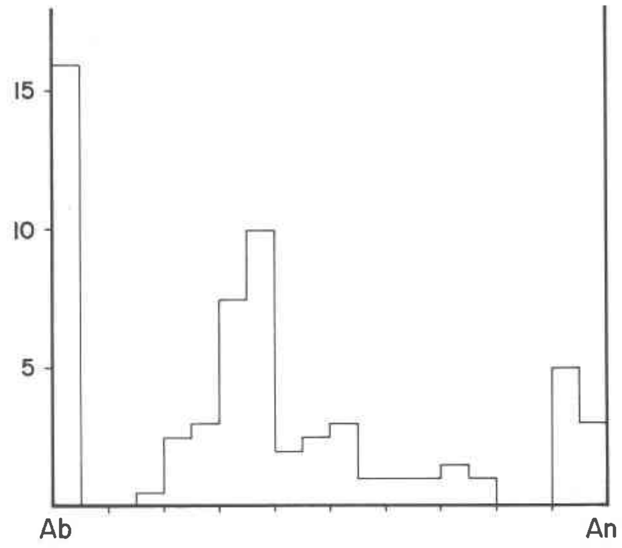

Fig. 3. Histogram showing frequency of plagioclase compositions. Microprobe analyses of only homogeneous areas are represented. Counting intervals are 5% An.

analyses in Figure 3 illustrates a high frequency of compositions An 0–5, An 30–40 and An 90–95. Oligoclase–andesine occurs as large porphyroblasts twinned according to albite and pericline laws. Occasionally two compositions An 25–30 and An 40–45 are intergrown with sharp boundaries representing growth faces, similar in style to andesine–labradorite intergrowths described by E. Wenk and H. R. Wenk (1977). Occasionally less regular intergrowths of albite and oligoclase are observed which resemble those described by Evans (1964) from New Zealand. The large crystals are basically porphyroblasts and not relics of phenocrysts of an original andesite fabric. They formed during a post-Jurassic metamorphism. In a second event fibrous amphibole and fine-grained plagioclase crystallized. Large crystals often show patchy extinction and variations in relief as they decompose to a fine-grained aggregate occasionally containing inclusions of clinozoisite, reminding one of the classical stuffed plagioclases of Cornelius (1935).

Fine-grained plagioclase in amphibolites is a mixture of pure albite and pure anorthite more or less in crystallographic continuity but with small subgrains and very complicated textures (Fig. 4). Anorthite is recognized by its high relief and birefringence. The petrographic microscope does not provide much information about the origin of these assemblages, and many possibilities remain open. Are these crystallites newly nucleated grains or alteration products? Is anorthite a relict? This is unlikely because, even at high-grade metamorphism or in the original volcanic environment, anorthite is not the stable plagioclase in rocks of andesite composition. Another question is whether the phase with anorthite composition and a high relief actually is clinozoisite, which is a common accessory in all these amphibolites. I found that final identification cannot rely on microprobe analyses because the chemical compositions of the two minerals can be almost identical. Further information on textures was obtained with the transmission electron microscope analyzing ion-thinned foils removed from petrographic thin sections.

Electron microscopy

Anorthite and albite were confirmed in many specimens with selected-area diffraction patterns and simultaneous elemental analysis on the same grain by

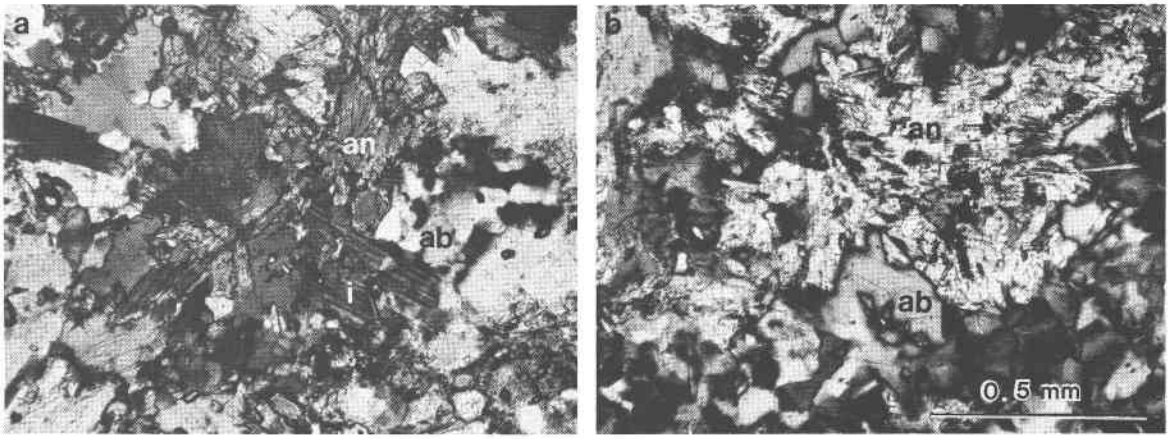

Fig. 4. Photomicrographs of plagioclase assemblages in sample Sci 1583. Albite (ab), anorthite (an), and intermediate plagioclase (i) are indicated. Crossed polarizers. (a) Shows intermediate plagioclase attaining patchy extinction and transforming to anorthite. (b) A region with finely twinned anorthite in direct contact with albite.

an energy-dispersive X-ray detector in the microscope. One crystal (Sci 1649 from A. Cavloccio) was particularly interesting. It contains "*e*" plagioclase with regular "*e*" fringes spaced 40A (Fig. 5a) and an An content of 35%. The fringe pattern is disrupted by boundaries which divide the area into domains. Along these boundaries fringes are kinked and dislocations occur occasionally. The formation of such a microstructure has been explained by Wenk and Nakajima (1979) as due to continuous ordering at conditions of undercooling below the critical ordering temperature which produces periodic APB's (see *e.g.* the discussion in Wenk *et al.*, 1980). Continuous ordering is not homogeneous throughout the crystal but begins in separate local areas which have a high chance to be out of phase. The regular "*e*"-structure decomposes over a distance of less than a micron into albite (An 2.5) with no microstructure but frequent submicroscopic twinning (Fig. 5c). In the transitional region the spacing of APB's becomes smaller and fringes are difficult to resolve, but presence of APB's is indicated by satellites in the diffraction pattern which have a wider spacing. Curved boundaries corresponding to those in Figure 5a can still be imaged in darkfield with "*e*" reflections (Fig. 5b). As one proceeds from andesine towards anorthite, the periodic APB structure changes by the pairwise recombination mechanism which we have documented earlier (Wenk and Nakajima, 1979). Adjacent APB's combine and form loops (Fig. 5d). This process, which reduces strain energy along the planar defects, is analogous to the pinching out of dislocation dipoles into loops. As the microstructure becomes depleted in APB's the An content increases. Changes in the APB microstructure and chemical decomposition are cooperative processes, with APB's apparently providing favorable surfaces for large-scale diffusion. In the end only a few isolated loops remain (Fig. 5e) defining a rather sharp boundary with an anorthite lamella (Fig. 5f). In this the few "*b*"-boundaries are relics of the "*e*"-structure, and not the result of Al–Si ordering from a disordered phase. The latter gives rise to smoothly curved APB's and is observed in volcanic plagioclase (*e.g.* Christie *et al.*, 1971). There are also some straight boundaries oriented parallel to (010) in contrast with "*b*" reflections (Fig. 5f), for which I do not yet have a satisfactory explanation. In places which are free of periodic APB's, composition is An 92–95 and curved "*c*" APB's can be imaged with "*c*"-reflections (Fig. 5g). Diffraction patterns also document albite, "*e*"-andesine, and primitive anorthite over a distance of a few microns and in crystallographic continuity (Fig. 6). In other samples only albite and anorthite are present directly adjacent to each other.

Discussion

These microstructures suggest that anorthite is indeed a stable phase at low-grade metamorphic conditions, and that the anorthite field extends to low temperatures in the plagioclase phase diagram. But its occurrence is rare, and geological conditions conducive to its formation are rather complex and not often achieved. As is demonstrated by changes in the APB microstructure, albite and anorthite form by decomposition of an intermediate plagioclase. The textural evidence of the elimination of APB's by recombination from a regular periodic to a disordered boundary arrangement during the transformation of andesine to anorthite, which is depicted in Figure 5, clearly documents anorthite to be an alteration product and not a relict. Such a conclusion would be difficult to establish on the basis of light-optical observations.

Albite–anorthite assemblages are conspicuously restricted to amphibolite with pargasitic hornblende which generally coexists with an actinolitic hornblende. The striking linear correlation of (Na + K) and Al^{IV} shown in Figure 2 suggests that the two-amphibole assemblage is the result of decomposition from an intermediate hornblende, and may correspond to the miscibility gap proposed by Klein (1969) and Shido and Miyashiro (1959), but this needs to be further corroborated. It is noteworthy that in these amphibolites there is only occasionally evidence for peristerite compositions, which have been documented in other parts of the Central Alps (Streckeisen and E. Wenk, 1974; E. Wenk and Keller, 1969). The histogram in Figure 3 illustrates three concentrations: albite, An 30–40 (which is older), and anorthite. This is different from labradorites in amphibolites from N. Bavaria described by Voll (1971), which may have exsolved to oligoclase and anorthite. There is some resemblance with Miyashiro's (1961) vaguely defined high temperature–low pressure actinolite–calcic plagioclase facies observed in Japan. But in those rocks albite, clinozoisite, and pargasite are lacking and according to Miyashiro "calcic" plagioclase (An 25–60) may be a relict of an igneous phase.

The observation of albite and anorthite forming by decomposition of intermediate plagioclase is consistent with a model of a thermal regional metamorphism in the Bergell Alps evolving in the Cretaceous to

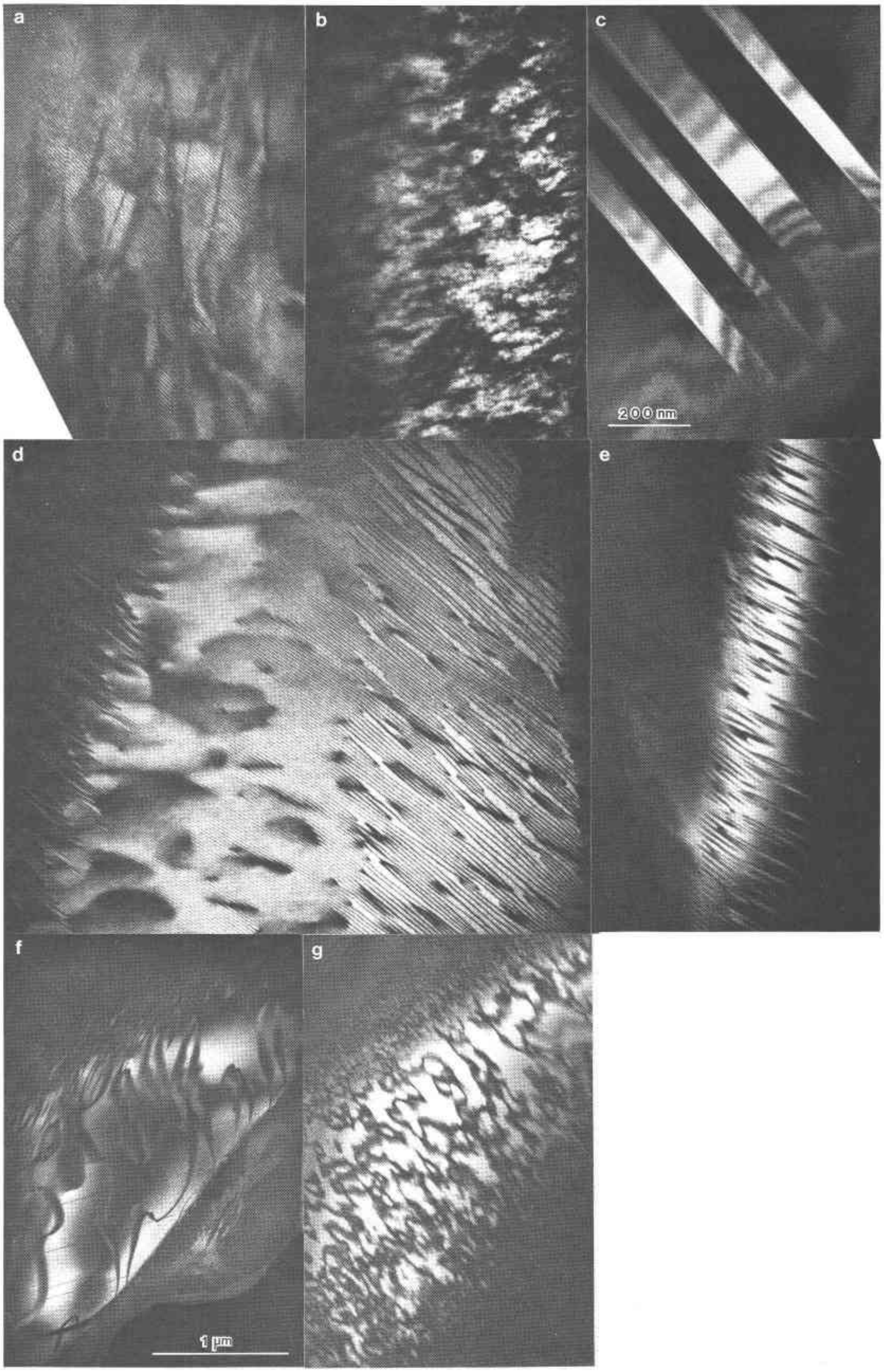

Fig. 5. Darkfield electron photomicrographs illustrating changes in microstructure during decomposition of andesine (a) into albite (b–c) and anorthite (d–g) in specimen Sci 1649. (a) Intermediate plagioclase with periodic APB's, "*e*"-fringes resolved; (b) more sodic area with "*e*"-structure still present but with a narrower fringe spacing; (c) albite with submicroscopic albite (010) twins; (d) opening of the periodic APB structure by pairwise recombination leaving only a few isolated loops in the An-rich region (e); (f) lamella of anorthite with a few relic "b" APB's in intermediate plagioclase with a periodic "*e*" structure; (g) "*c*" APB's in anorthite imaged with "*c*"-reflections. (Fringes are visible on the original photograph but cannot be distinguished in this reproduction due to the coarse screen. ***e*** fringes in Fig. 5b are roughly parallel to those in Fig. 5a, and are spaced 35A).

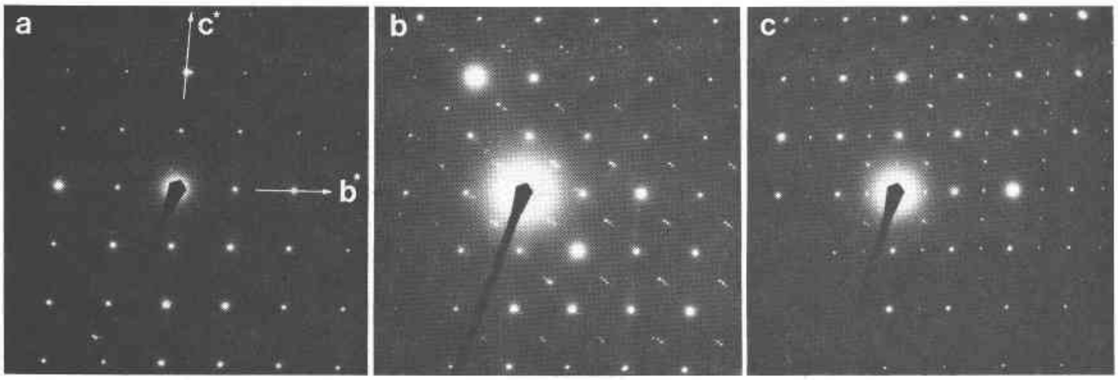

Fig. 6. Selected-area electron diffraction patterns of albite (a), andesine (b), and anorthite (c) in the same specimen as Figure 5. Fig. 6a corresponds to region in Fig. 5c, 6b to 5a, and 6c to 5e-g.

the east (Bernina–Malenco), and increasing in intensity and moving westwards, where it culminates in late Miocene in the Lepontine metamorphism. This regional metamorphism is overprinted in the Oligocene by a brief event of contact metamorphism caused by the emplacement of the Bergell granite during intense tectonic movements. The contact metamorphism is younger than the regional metamorphism in the east but is postdated by the Lepontine metamorphism further west.

Acknowledgments

This research was supported by NSF grant EAR76-14756. Use of a JEM 100C electron microscope obtained with grant EAR77-00127 has been essential in this study. I am most indebted to F. J. Turner for stimulating discussions and some light-optical analyses and to R. Coleman and P. H. Ribbe for efficient and constructive editing and reviewing of the manuscript.

References

Bucher, K. and H. R. Pfeifer (1973) Uber Metamorphose und Deformation der östlichen Malenco-Ultramafitite und deren Rahmengesteine (Prov. Sondrio, N. Italien). *Schweiz. Mineral. Petrogr. Mitt., 53,* 231–242.

Champness, P. E. and G. W. Lorimer (1976) Exsolution in silicates. In H. R. Wenk *et al.*, Eds., *Electron Microscopy in Mineralogy,* p. 174–204. Springer, Heidelberg.

Christie, J. M., J. S. Lally, A. H. Heuer, R. M. Fisher, D. T. Griggs and S. V. Radcliffe (1971) Comparative electron petrography of Apollo 11, Apollo 12 and terrestrial rocks. *Proc. 2nd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl., 2,* 69–89.

Cornelius, H. P. (1935) Zur Deutung gefüllter Feldspäte. *Schweiz. Mineral. Petrogr. Mitt., 15,* 4–30.

Evans, B. W. (1964) Coexisting albite and oligoclase in some schists from New Zealand. *Am. Mineral., 49,* 173–179.

Goldmith, J. R. (1978) Experimental plagioclase–zoisite phase relations (abstr.). *EOS, 59,* 402.

Klein, C. (1969) Two-amphibole assemblages in the system actinolite–hornblende–glaucophane. *Am. Mineral., 54,* 212–237.

Miyashiro, A. (1961) Evolution of metamorphic belts. *J. Petrol., 2,* 277–311.

Shido, F. and A. Miyashiro (1959) Hornblendes of basic metamorphic rocks. *Tokyo Univ. Fac. Sci. J., sec. 2, 12,* 85–102.

Smith, J. V. (1974) *Feldspar Minerals,* vol. 2. Springer, Heidelberg.

Streckeisen, A. and E. Wenk (1974) On steep isogradic surfaces in the Simplon Area. *Contrib. Mineral. Petrol., 47,* 81–95.

Voll, G. P. (1971) Entmischung von Plagioklasen mit An 50–55 zu An 18 + An 93 (abstr.). *Fortschr. Mineral., 49,* Beiheft 1, 61–63.

Wenk, E. and F. Keller (1969) Isograde in Amphibolitserien der Zentralalpen. *Schweiz. Mineral. Petrogr. Mitt., 49,* 139–152.

——— and H. R. Wenk (1977) An-variation and intergrowths of plagioclases in banded metamorphic rocks from Val Carecchio (Central Alps). *Schweiz. Mineral. Petrogr. Mitt., 57,* 51–57.

Wenk, H. R. and Y. Nakajima (1979) Periodic superstructures in calcic plagioclase. In J. M. Cowley *et al.*, Eds. *Modulated Structures-1979 (Kailua Kona, Hawaii),* p. 317–320. American Institute of Physics, Conference Proceedings No. 53.

———, J. Hsaio, G. Flowers, M. Weibel and A. Ayranci (1977) A geochemical survey of granitic rocks in the Bergell Alps. *Schweiz. Mineral. Petrogr. Mitt., 57,* 233–265.

———, W. Joswig, T. Tagai, M. Korekawa and B. K. Smith (1980) The average structure of An 62–66 labradorite. *Am. Mineral.,* in press.

———, E. Wenk and J. Wallace (1974) Metamorphic mineral assemblages in pelitic rocks of the Bergell Alps. *Schweiz. Mineral. Petrogr. Mitt., 54,* 506–554.

Wetzel, R. (1974) Hornblenden aus der Albit–Albitoligoklaszone zwischen Zermatt und Domodossola. *Schweiz. Mineral. Petrogr. Mitt., 54,* 151–207.

Manuscript received, April 16, 1979;
accepted for publication, July 5, 1979.