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The origin of ribbon lineation within the southern Adirondacks, U.S.A.

JAMES M. MCLELLAND

Department of Geology, Colgate University, Hamilton, NY 13346, U.S.A.

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Abstract—Multiply deformed metamorphic rocks of the southern Adirondacks exhibit a pronounced linear fabric consisting of elongate, flat ribbons oriented parallel to early fold axes and lying within foliation planes. The ribbons, which are often monomineralic, consist of quartz, feldspar and mafic minerals. As seen in transition from least to most deformed rocks, these ribbons appear to be the result of elongation of grains, or grain aggregates, in response to a regional rotational strain which also rotated early fold axes into parallelism with the lineation. A consistent sense of asymmetry of feldspar tails with respect to foliation suggests that simple shear was the dominant component of strain. The long dimension of these ribbons is believed to mark the maximum elongation direction (X) of the finite strain ellipsoid.

INTRODUCTION

THE SOUTHERN and central Adirondacks (Figs. 1 and 2) are underlain by multiply deformed plutonic, sedimentary, and volcanic rocks metamorphosed to granulite facies conditions during the 1100–1000 Ma Grenville Orogeny (McLelland & Isachsen 1980). The entire region has been affected by at least four sets of folds whose sequence is known but which may represent successive events in a deformational continuum (Wiener *et al.* in press). The earliest recognized set, F_1, consists of large E–W trending isoclinal, recumbent folds that verge to the south. These folds rotate an earlier foliation of uncertain origin. Coaxial to the F_1 folds are large, upright folds, F_2, which are open throughout most of the area but which tighten and become isoclinal towards the northwest (Wiener *et al.* in press). The third fold set, F_3, trends NW and dies out towards the east and the south. The fourth fold set, F_4, trends NNE and is developed only in the eastern Adirondacks. Neither the third nor the fourth fold-sets make significant contributions to the rock fabric in the area under consideration.

Throughout the southern Adirondack region rocks are strongly lineated and foliated. The foliation is defined by compositional layering as well as by oriented mineral platelets that exhibit extensive parallelism. The earliest, and most pronounced, foliation is oriented parallel to compositional layering. Foliation axial planar to F_1 is only slightly less intense and parallels the earliest foliation except in F_1 hinges. As a result, it is usually impossible to distinguish between the two early foliations. Foliations axial planar to F_2, F_3 and F_4 are weak and only locally developed.

Lineations in the region are of several kinds and result from different mechanisms. Intersection lineations occur where foliations intersect. Most commonly these are due to intersections between compositional layering, the earliest foliation, and foliation axial planar to F_1. These intersections result in pencil gneisses (Fig. 3a). Locally, foliation axial planar to F_2 can further enhance this lineation, since F_1 and F_2 are coaxial but have almost perpendicular axial planes. Rodding may be the result of widely spaced intersections, but more commonly rods can be shown to be the detached and isolated hinge regions of highly flattened F_1 minor folds whose limbs have been attenuated and disrupted (Figs. 3a & b). Oriented prismatic minerals are also common elements of the linear fabric. In most instances, these oriented, prismatic minerals, notably hornblende, appear to be undeformed. The orienting mechanisms of the apparently undeformed prismatic minerals are uncertain, although syntectonic recrystallization may play a large role. The most striking linear fabric of the Adirondacks consists of ribbon lineations whose origin is the subject of this paper and which are described below. These are generally accompanied by parallel, small amplitude crenulations which contribute to the linear fabric.

Throughout the southern Adirondacks ribbon lineations are aligned parallel to axes of the coaxial sets F_1 and

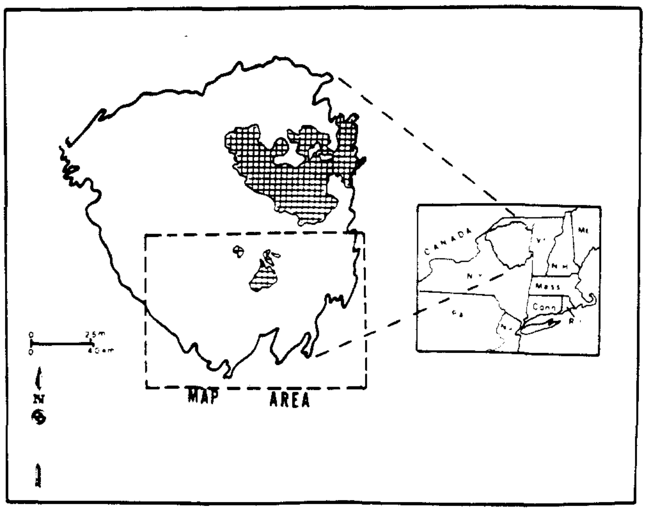

Fig. 1. Location of the Adirondack Mountains. The southern Adirondacks lie within the dashed rectangle labeled Map Area. Patterned areas are anorthosite.

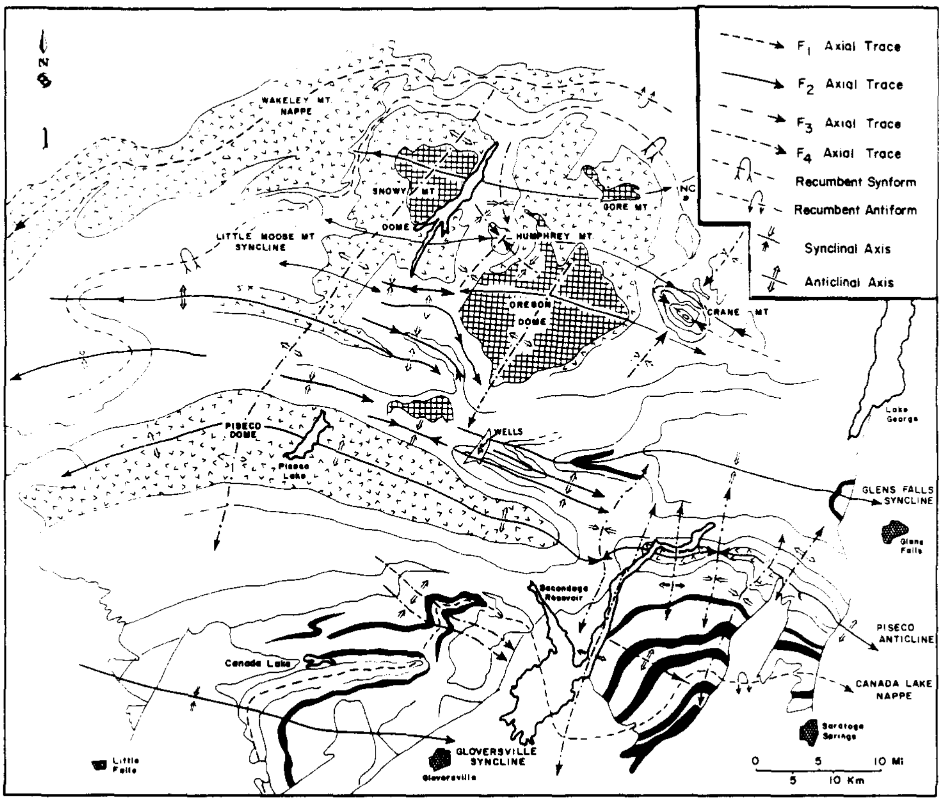

Fig. 2. Structural geology of the southern Adirondacks (from McLelland & Isachsen 1980) Black, meta-quartzites; v-pattern, basal quartzofeldspathic gneisses; grid pattern, meta-anorthosites; unpatterned, undivided metamorphic rocks.

F_2 (McLelland & Isachsen 1980). The intensity of both foliation and lineation appears to vary with rock type and to be more pronounced within quartzofeldspathic lithologies, particularly near the base of the lithologic sequence where it is exposed in the Piseco Dome (Fig. 2).

RIBBON LINEATION

Typical ribbon lineations are shown in Figs. 4–8. Individual ribbons may consist of quartz, K-feldspar, or aggregates of biotite–hornblende rich material. The dimensions of the ribbons vary, but length is always far greater than width or thickness. Typically, the length of an individual ribbon is from 10 to 20 cm, although lengths as great as 40 cm have been observed. Widths vary from 1 mm to 1 cm with the average ribbon being 0.5 cm wide. Thicknesses are commonly 0.5–2 mm for quartz and biotite–hornblende ribbons and from 1 mm to 1 cm for K-feldspar ribbons. In almost all instances the ribbons lie within the plane of foliation. Their characteristically rectangular cross-sections (Fig. 8b) serve to distinguish them from rods and pencils.

Two types of ribbon lineation have been recognized. The first of these is referred to as 'transposition ribbons' and is the least common. The second, more abundant variety is referred to as 'elongation ribbons'. On foliation surfaces the two types are indistinguishable. Each is described below.

Transposition ribbons

Examples of transposition ribbons are shown in Figs. 4 (a) & (b). They appear to be the result of attenuation, dismemberment, and transposition of quartz stringers and veinlets during isoclinal folding. This results in quartz ribbons aligned parallel to fold axes and lying in, or very close to, the axial planes of the folds involved. The resulting lineation does not necessarily mark the direction of maximum elongation although it may be parallel to it.

Ideally, transposition lineation could be distinguished by the fact that the apparent elongation suggested by the ribbons may not be present in the surrounding fabric. In addition, the ribbons are associated only with quartz veins and do not occur pervasively throughout the rock.

Elongation ribbons

Lineations of this sort are shown in Figs. 5–8. They are characterized by thin ribbons of alternating mineralogy. Most often individual ribbons are approximately monomineralic, consisting generally of quartz or feldspar. Less commonly, biotite or biotite–hornblende ribbons are encountered. Their long dimension parallels local F_1 and F_2 fold axes, and they lie within surfaces that are parallel to F_1 axial planes. Many of the best lineated gneisses are quartzofeldspathic and exhibit little compositional layering. They are well foliated, however, and tend to cleave into flaggy segments whose cleavage surfaces exhibit pronounced ribbon lineation.

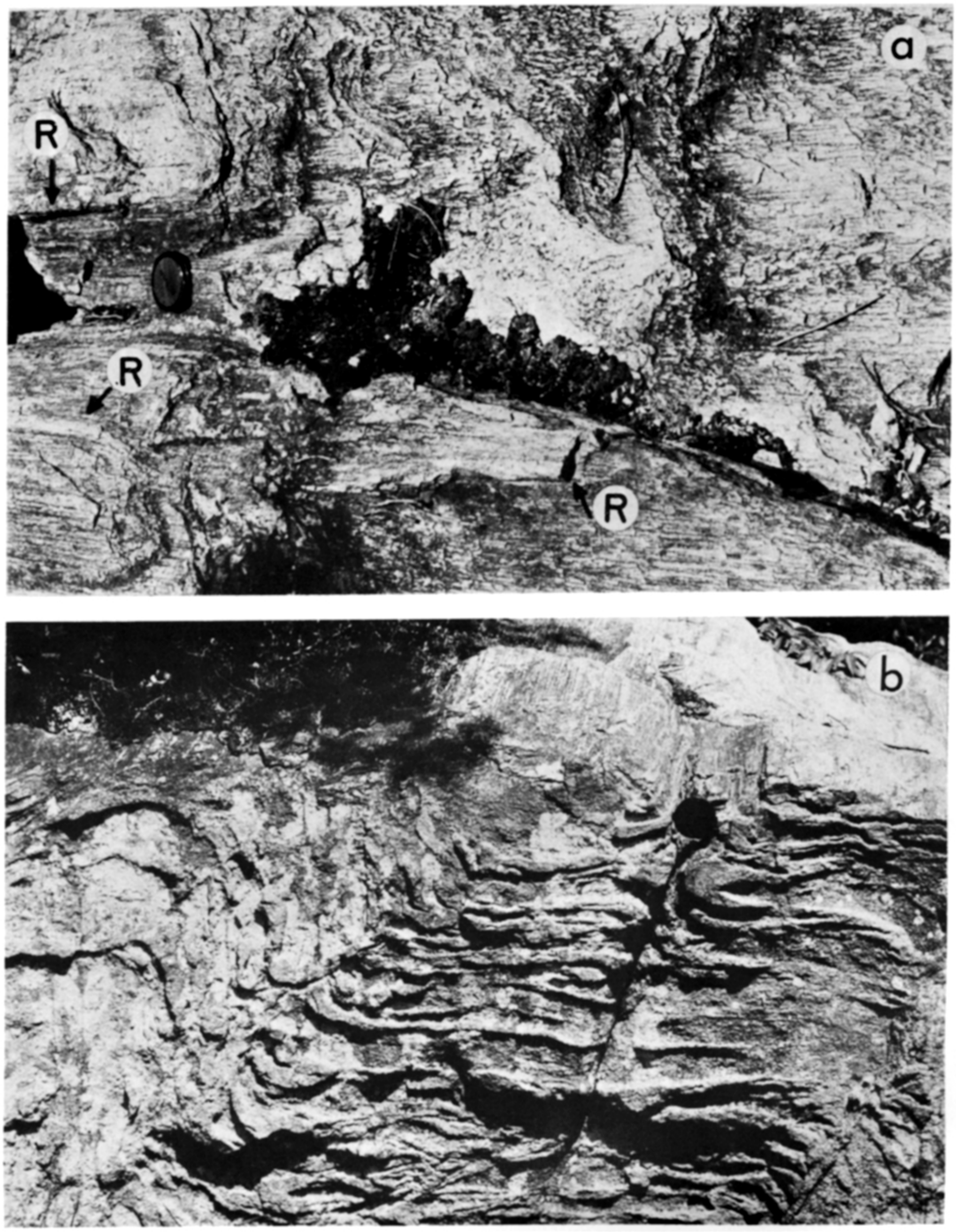

Fig. 3. Lineations developed in multiply folded rocks. (a) Foliation surface exhibiting rods (R) formed by weathered-out F_1 fold hinges. The pervasive, smaller-scale lineation that is best seen in the lower-right corner consists of pencils resulting from the intersection of compositional layering with F_1 and F_2 axial-plane foliations. Lens cap is 5 cm diameter. (b) View of surface perpendicular to foliation and lineation. Isoclinal, recumbent F_1 folds are refolded by coaxial, upright F_2 folds, one of which appears on the left side of the photo and the hinge of the other can be seen in the lower right-hand corner. Attenuated F_1 limbs are best developed just to the right of the steep crack below the lens-cap. The foliation shown in (a) can be seen at the top of the photo. Lens cap is 5 cm across.

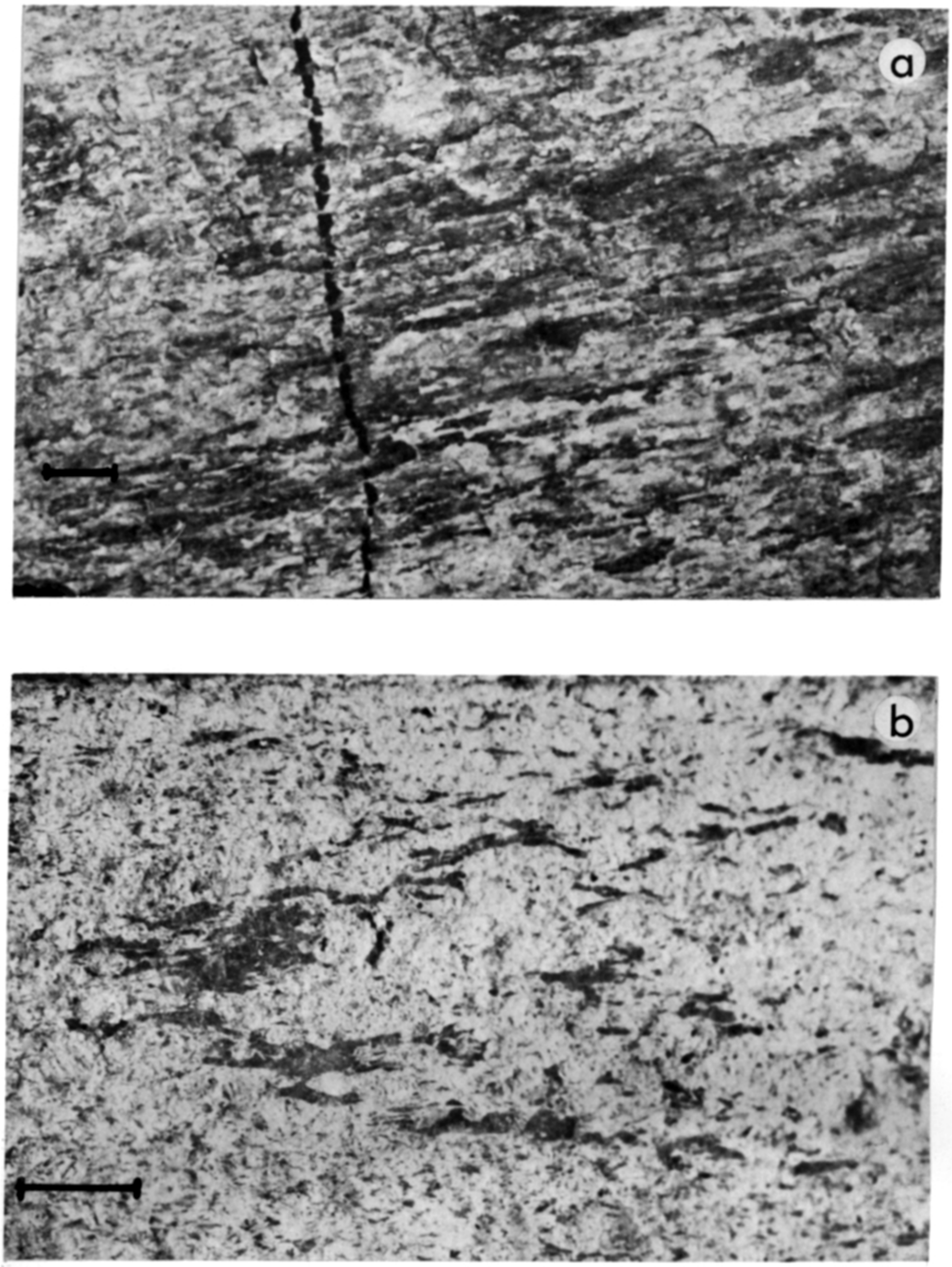

Fig. 4. Transposition lineation associated with a folded quartz vein in a quartzofeldspathic gneiss. (a) Foliation surface showing quartz ribbons, each of which is a transposed segment of an originally continuous quartz vein. Scale bar is 1 cm. (b) View perpendicular to foliation and lineation showing disrupted and transposed quartz vein. Fold axes oriented parallel to lineation in (a). Scale bar is 1 cm long.

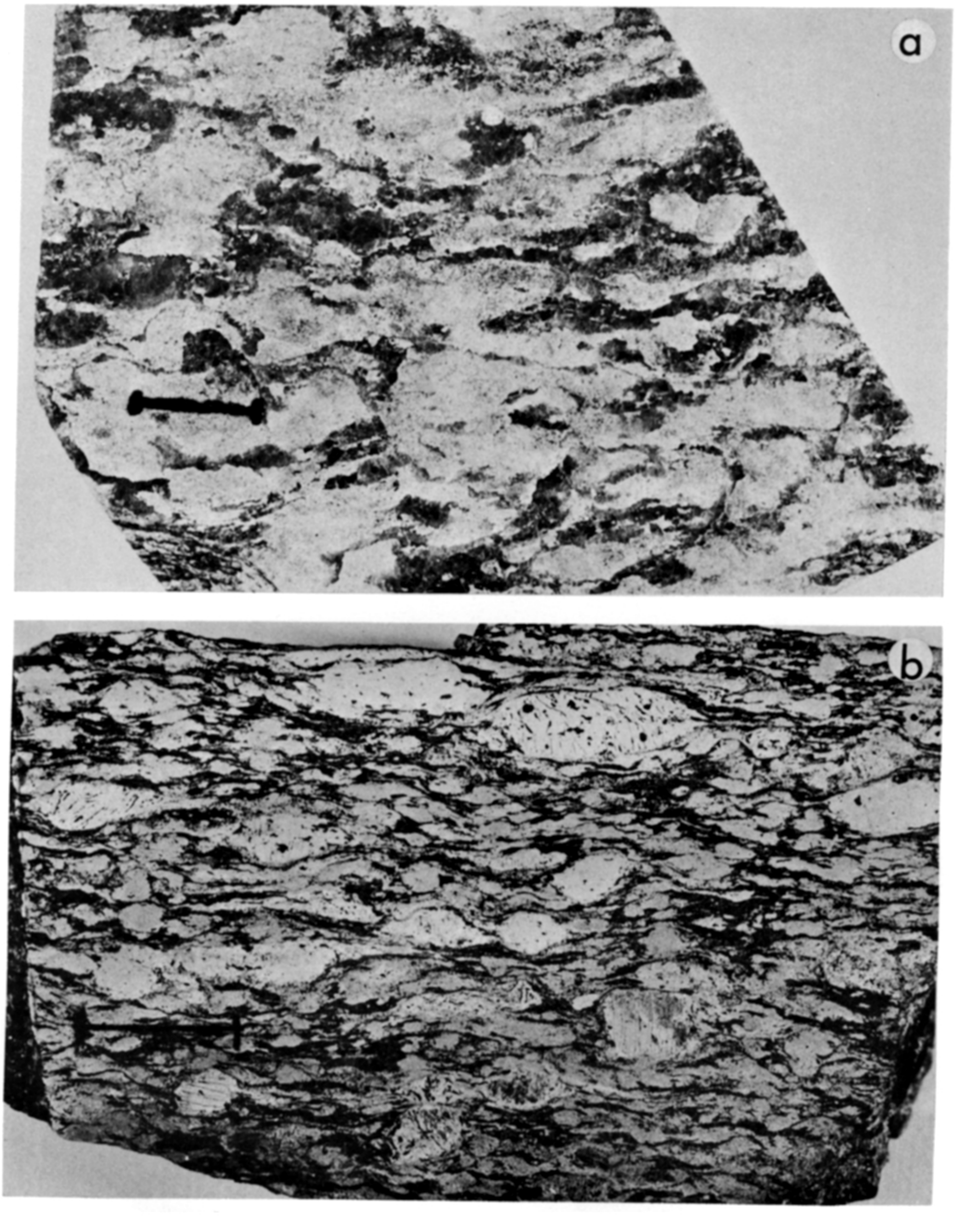

Fig. 5. Least deformed quartzofeldspathic augen gneiss collected from the Piseco Dome. (a) View of foliation surface showing K-feldspar augen (white) and quartz aggregates (dark). Lineation has begun to develop but is not pronounced and ribbons have not yet formed. Scale bar is 2 cm. (b) Surface cut parallel to lineation and perpendicular to foliation. K-feldspar augen exhibit the development of tails that show a consistent sense of asymmetry with respect to foliation. The originally euhedral to subhedral form of the feldspars is still recognizable. The dark regions consist of quartz; almost no mafic minerals are present. Scale bar is 2 cm long.

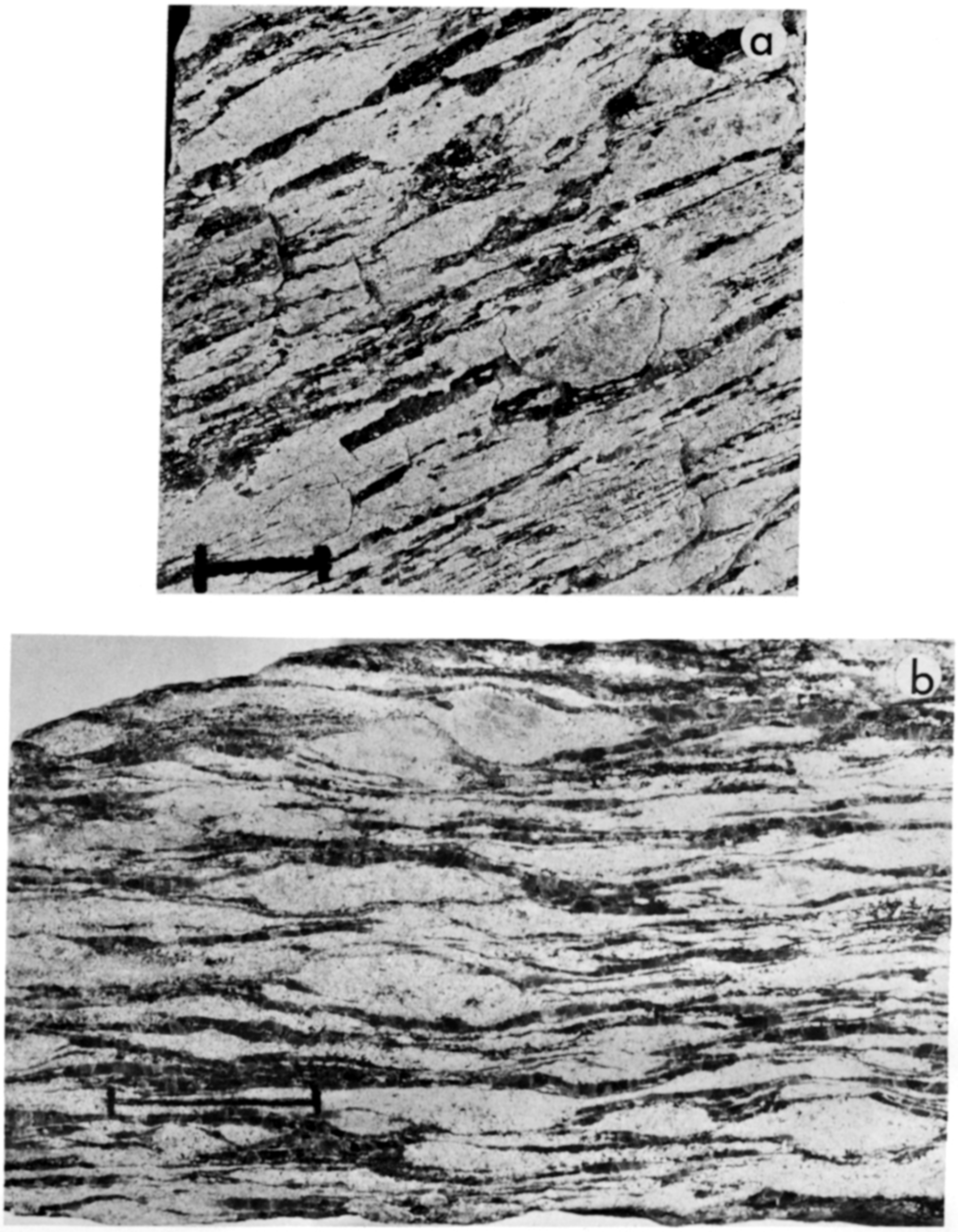

Fig. 6. Moderately deformed quartzofeldspathic augen gneiss collected from the Piseco Dome. (a) View of foliation surface showing good lineation and the development of ribbons of quartz (dark) and K-feldspar (white). Scale bar is 2 cm. (b) Surface cut perpendicular to lineation and foliation. K-feldspar augen have developed extensive tails with a consistent sense of asymmetry to foliation. Quartz aggregates (dark) have undergone considerable elongation. Scale bar is 2 cm long.

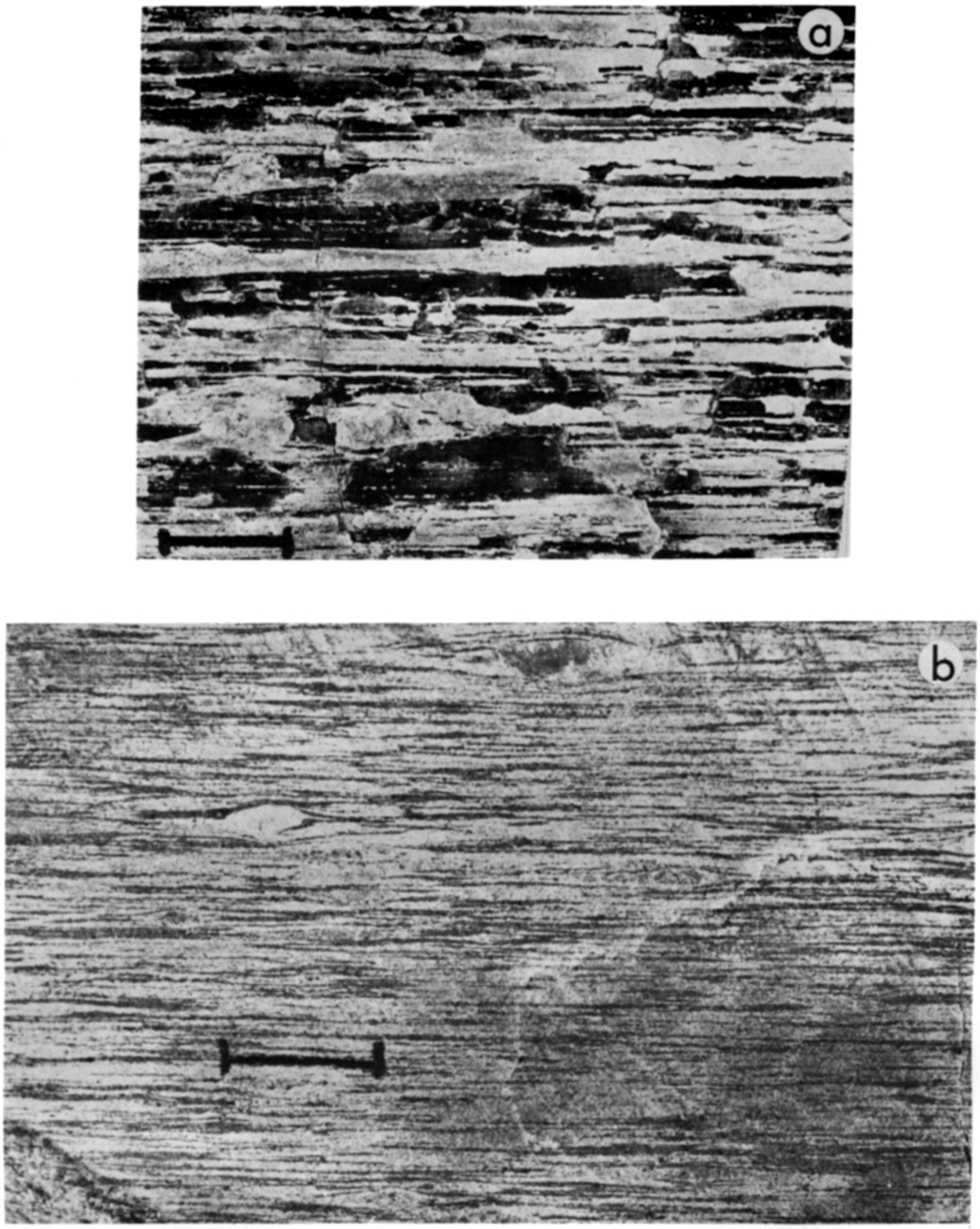

Fig. 7. Highly deformed quartzofeldspathic augen gneiss collected from the Piseco Dome. (a) View of foliation surface showing pronounced ribbons of quartz (dark) and K-feldspar (white). Scale bar is 2 cm. (b) Surface cut perpendicular to lineation and foliation, K-feldspar augen are almost all reduced to tails which appear as white layers and lenses. Dark layers of quartz indicate the large amount of elongation that has taken place. Scale bar is 2 cm long.

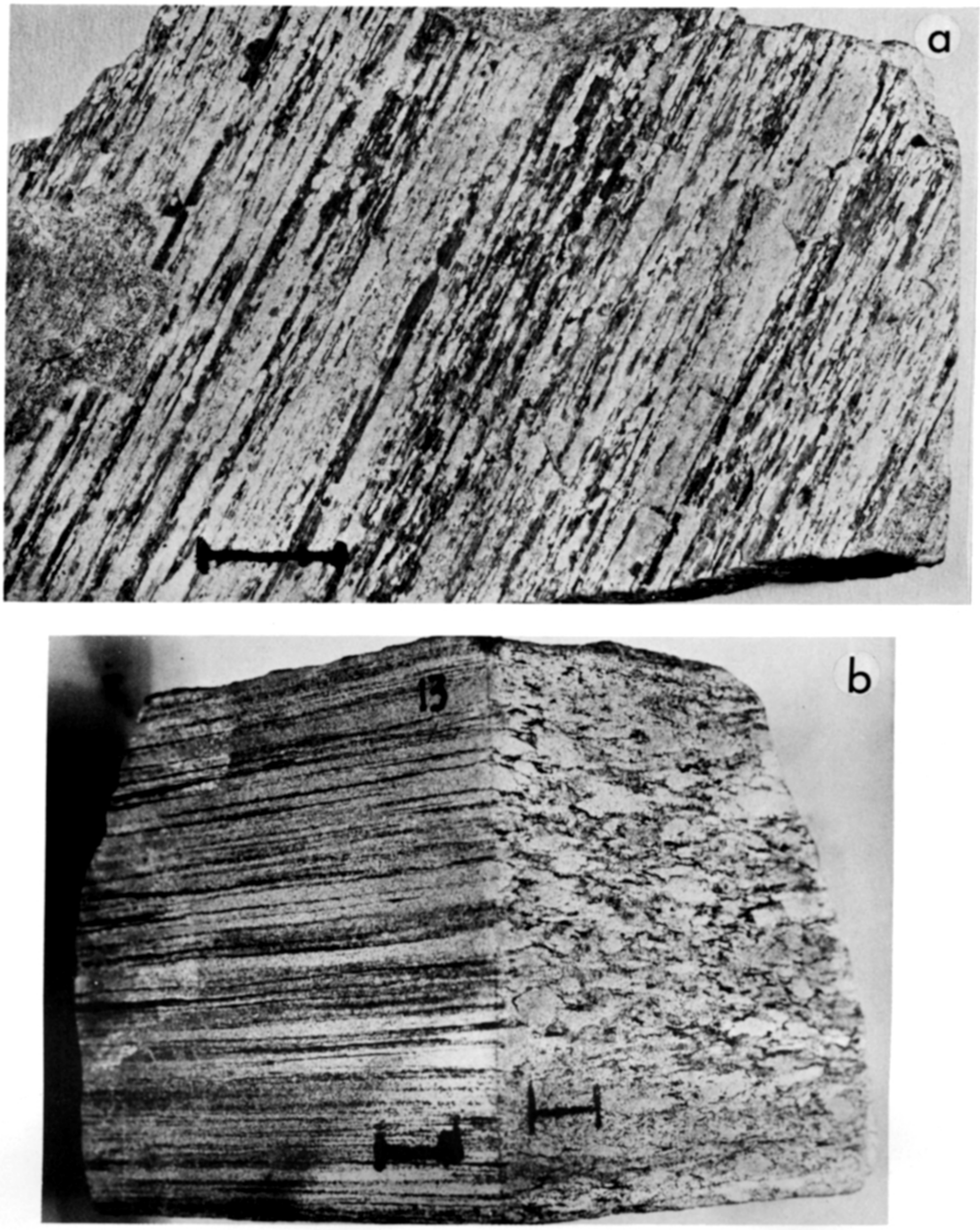

Fig. 8. Most intensely deformed ribbon gneiss collected from the Piseco Dome. (a) View of foliation surface showing intense ribbon lineation defined by quartz (dark) and K-feldspar (white). Some of the quartz ribbons appear to have been boudinaged. Scale bar is 1 cm. (b) Perspective view of surfaces perpendicular to foliation. The white layers of K-feldspar seen on the left-hand faces (parallel lineation) are the result of elongation of augen, the cross-section outlines of which are still recognizable on the right-hand face. No augen are now present; all feldspar is fine grained. Quartz ribbons appear black on the photograph. Scale bar is 1 cm long.

Field mapping in the southern Adirondacks has demonstrated that the intensity of ribbon lineation is variable within a given quartzofeldspathic unit. Figures 5–8 show a typical sequence of ribbon development from least deformed (Fig. 5) to most highly deformed (Fig. 8) examples. These specimens were collected over a distance of several kilometers along strike in the Piseco Dome (Fig. 2). Similar examples exist in numerous other localities. No wholly undeformed rocks have been found in the area, but the least deformed specimen (Fig. 5) appears to be a strained inequigranular metaigneous rock. Although cross-cutting contacts have not been demonstrated in the southern Adirondacks, similar rocks in the northwest Adirondacks have been shown to cross-cut and to contain angular, rotated xenoliths (Wiener *et al.* in press). Modally, the ribbon gneisses consist of 40–50% perthite and microperthite megacrysts; 20–40% sodic plagioclase; 15–30% quartz; and minor amounts of hornblende, biotite and pyroxene. They fall, therefore, into the fields of granites and quartz–monzonites (Streckeisen 1976). Occasional granodiorites are also present. Megacrysts of alkali feldspar are from 2 to 4 cm long and 1 to 2 cm in cross-section. Plagioclase grains average about 5 mm in diameter. Quartz commonly occurs in aggregates averaging about 5 mm across.

Based upon their appearance, mineralogy, and correlatives it is suggested that the precursors of the ribbon gneisses were inequigranular igneous rocks of broadly granitic composition.

Figures 5(a)–8(a) show the progressive development of ribbons on the foliation surfaces of megacrystic quartzofeldspathic gneiss similar to those described above. Figures 5(b)–8(b) show the corresponding faces cut perpendicular to foliation and parallel to lineation. It is clear that with increasing strain, feldspar megacrysts become progressively more elongate and parallel to one another, thus contributing to an increasingly pronounced linear fabric (Figs. 5a–8a). Simultaneously these megacrysts become more augen-shaped and develop tails consisting of fine-grained mosaics of dynamically recrystallized K-feldspar (Figs. 5b–8b). In specimens exhibiting minimal deformation (Figs. 5b and 6b) these tails are asymmetric with respect to foliation, but sweep towards the foliation plane as deformation proceeds (Figs. 7b and 8b). As deformation increases, grain size reduction continues to operate, and fine-grained tails grow at the expense of augen to the point where few, if any, remnant feldspar cores remain (Figs. 7b and 8b). At the stage represented by Fig. 8, the feldspars are represented only by long, fine-grained ribbons (i.e. tails) that constitute an important part of the penetrative linear fabric of the rock.

The development of aligned K-feldspar augen is accompanied by deformation of groundmass minerals. The most important of these is quartz; grains and aggregates of which become elongated and sweep around the less ductile K-feldspar augen (Figs. 5b and 6b). As seen in Figs. 5(a)–8(a), quartz, together with feldspar, defines the ribbon lineation in these gneisses. Examination of Fig. 5(a) suggests that original aggregates of quartz grains may have been nearly equant. Subsequent elongation has resulted in the development of long, thin ribbons. In thin sections cut perpendicular to foliation and parallel to lineation the quartz ribbons are seen to consist of long, narrow layers composed of rectangular segments with contacts oriented at essentially right angles to the upper and lower boundaries of the ribbons. Undulose extinction is not pronounced which suggests that the grains are largely strain free. Preliminary studies of the preferred lattice orientation of these quartz grains indicates that *c*-axes lie in a girdle with a strong maxima perpendicular to lineation and lying within the plane of foliation.

The deformation of quartz and K-feldspar is accompanied by the syntectonic recrystallization of plagioclase into augen with grain-size reduced tails oriented parallel to lineation. Mafic aggregates also become elongated and oriented in the direction of lineation. Some of these include orthopyroxene.

DISCUSSION

Any mechanism accounting for the origin of the ribbon lineations described above must be consistent with the following constraints.

(1) The ribbons are the result of grain size reduction of K-feldspar augen gneisses of probable igneous, plutonic origin.

(2) The tails of feldspar augen exhibit a consistent sense of asymmetry with respect to foliation.

(3) The ribbons are oriented parallel to F_1 and F_2 fold axes.

(4) Ribbon dimensions average 20 cm × 0.5 cm × 1 mm.

(5) The ribbon lineations are developed on a regional scale in the southern Adirondacks and exhibit a parallel orientation throughout the area.

(1) This constraint requires that the ribbons are the result of strain acting upon the rocks and causing syntectonic recrystallization. The presence of syntectonically recrystallized perthitic feldspar and orthopyroxene in the ribbons suggests that the strain took place at high metamorphic grade.

(2) The asymmetry of feldspar tails (Figs. 5a and 6a) strongly suggests that the strains involved were rotational and consisted of a large, probably dominant, component of simple shear. The quartz *c*-axis maximum approximately perpendicular to lineation and within the foliation plane is similar to that described by Wilson (1975) for quartz ribbon mylonites associated with thrusting in the Sëve–Koli complex of the Swedish Caledonides. These quartz ribbon mylonites developed at upper greenschist or lower amphibolite facies where elevated temperatures enhanced prismatic rather than basal slip in quartz. It is suggested that the grain shapes and lattice orientations of the ribbon lineations of the southern Adirondacks are also the result of high temperature, syntectonic recrystallization occurring in response

to rotational strains. The long dimensions of the ribbons lie parallel to the X direction of the finite strain ellipsoid and are, therefore, elongation lineations similar to those developed during thrust emplacement of the Helvetic nappes (Ramsay 1981).

(3) The parallelism between the ribbon lineation and F_1, F_2 fold axes suggests a genetic relationship between them. However, there does not appear to be any satisfactory mechanism for forming the ribbons parallel to fold axes during folding. The possibility of feldspar rotation about axes parallel to the fold axes (Lister & Price 1981) is precluded by the lack of feldspar asymmetry on faces perpendicular to both lineation and foliation (Fig. 8b). On the contrary, feldspar asymmetry is most pronounced on faces parallel to lineation (Figs. 5b and 6b). It appears most likely that the present parallelism between ribbon lineation and early fold axes is the result of rotation of the fold axes into the maximum elongation direction marked by the lineation. The most satisfactory mechanism for accomplishing this is a regime where the bulk deformation is dominated by a progressive simple shear (Cobbold & Quinquis 1980) that rotates early formed fold axes towards the direction of maximum finite strain (X). The rotation described by Cobbold & Quinquis (1980) may be envisaged as extreme arcuation of fold axes and leads to the formation of sheath folds whose long axes parallel maximum finite strain and, hence, ribbon lineation. Recent field work in the southern Adirondacks has revealed the existence of sheath folds of the F_1 generation (McLelland 1983). These possess E–W long axes together with a down-dip E–W ribbon lineation. It is possible that the early folds were initially formed with their axes oriented at a high angle to shear couples and that progressive rotational strain amplified fold axis deflections into passive sheath folds.

(4) The dimensions of the ribbons provide a further insight concerning the strain responsible for them. If we equate the long dimension (20 cm) of the ribbons with X of the finite strain ellipsoid, then $Y = 0.5$ cm and $Z = 1$ mm. The ratio X/Y equals 40 and Y/Z equals 5. These ratios place the strains within the constrictional field on a Flinn diagram and indicate that the rotational strains were composed of both pure and simple shear components.

(5) The development of ribbon lineation on a regional scale in the southern Adirondacks suggests that the rotational strains were produced by large-scale, regionally coherent tectonic processes. A simple and reasonable mechanism for transmitting this strain is by the emplacement of thrust slices. While no thrust offsets have yet been demonstrated in the Adirondacks, a number of N–S and NE-trending high strain zones have been identified (Geraghty *et al.* 1980, Foose 1980, Berry 1958). The largest and best known of these is the Carthage–Colton Mylonite Zone which separates the Adirondack Highlands from the Adirondack Lowlands (Geraghty *et al.* 1980). This zone is characterized by a belt of high ductile strain that varies in width from a few meters to several kilometers across. It shows a pronounced down-dip lineation plunging NW to WNW and may represent one of the postulated thrust slices (Y. Isachsen pers. comm.).

The suggestion of N–S to NE-striking thrust slices in the Adirondacks is consistent with recent investigations in the Grenville Province of Ontario where Davidson & Morgan (1980) have demonstrated the existence of NW-directed thrusts in the vicinity of Georgian Bay on Lake Huron. These are accompanied by extensive mylonitization. Many of the mylonites possess NW-trending ribbon lineations on their foliation surfaces. Rotated feldspar porphyroblasts indicate that the sense of displacement was the SE side up and to the NW. Southeast from Georgian Bay to the Adirondacks a number of other NE-trending high strain zones have been identified and lithologic discontinuities may exist across several of these (A. Davidson pers. comm.). These thrust slices, as well as those postulated in the Adirondacks, may have played a major role in the crustal thickening that accompanied the Grenville Orogeny and would therefore be related to the granulite facies conditions inferred for much of the terrane (McLelland & Isachsen 1980).

The ribbon lineations discussed above are one manifestation of a more general grain-size reduction process that has operated over much of the southern Adirondacks. Many quartzofeldspathic gneisses are fine grained and are composed of thin, regular layers that contain E–W oriented quartz blades and ribbons that, on a smaller scale, are similar to those developed from megacrystic meta-igneous rocks. This difference probably arises from the originally simpler mineralogy and coarser grain size of the megacrystic lithologies. Despite these differences all of the rocks attest to widespread ductile deformation and syntectonic recrystallization throughout the region. The causal mechanism invoked in all these instances is rotational strain operating at high metamorphic grade and possibly resulting from the stacking of thrust slices moving from east to west. Strains may have been focused into quartzofeldspathic mineralogies because of their greater ability to undergo syntectonic recrystallization.

A very rough estimate of the magnitude of strain involved can be made by assuming that quartz aggregates in the megacrystic gneisses were originally equant. The average dimensions of quartz ribbons then corresponds to a spherical volume of 1 cm^3, or a sphere of 0.6 cm radius. Compared with the 20 cm length of the ribbons, this indicates elongations of 300–400%.

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