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Recognition of pervasive prestrain in the total-strain pattern of large folds

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Abstract—Two methods are introduced for identifying states of pervasive prefold strain in the total-strain field of large domes or basins. The first method relies on the symmetry rule and is restricted to structures in which the planes of effective symmetry of the total-strain field are non-coincident with those of the fold form. The second method seeks to demonstrate the existence of a strain-induced anisotropy (foliation or lineation) prior to upright folding, and utilizes narrow décollement zones within homogeneous rock units of domes or basins. The methods are applied to large oval structures in two Precambrian gneiss terranes of Ontario.

INTRODUCTION

THE *total strain* is accumulated *throughout* the deformational history of lithologic units and is generally recorded by primary geologic features (e.g. inclusions with isotropic initial fabrics). Geologists recognized many years ago that the total-strain pattern of cylindrically folded units constrains the range of potential mechanisms of natural folding (Ramberg 1963a). This led to the publication of model-strain patterns for those fold mechanisms deemed most realistic geologically (Ramsay 1967, pp. 345–437). The models assume that the original units were perfectly tabular and had not been strained prior to folding. Based on this assumption, folding by a mechanism such as flexural flow leads to a pattern of total strain (Ramsay 1967, p. 391) that differs from those produced by other potential mechanisms.

The model makers realized that: (1) several mechanisms can be involved in any natural folding, either acting simultaneously or consecutively; and (2) the same total-strain pattern may be produced, at least in theory, by many combinations of mechanisms. Nonetheless the concept of model-strain patterns appears to have great potential in discriminating among rival hypotheses advanced for the large-scale folding in mountain chains and Precambrian shields.

The rock units of most ancient and modern orogens were folded several times and on vastly different scales (Ramsay 1967, pp. 518–556). Each generation of folds contributed to the final fold form and the total strain, which may have commenced prior to the first folding. Examples of prefold strain are the compaction of sediments or concordant ductile shearing of horizontal strata. The earliest large-scale folding is often tightly recumbent and, because of hinge zone destruction, difficult to ascertain in redeformed metamorphic rocks. Such early folding strain will be included in the prestrain when considering upright and potentially refolded structures. The combined strain of all upright foldings will be called the fold-generating strain. How can one recognize the existence of pervasive prestrain in prominent large folds?

SYMMETRY OF FOLDS AND STRAIN FIELDS

An important geometric attribute of ideal physical systems and processes is their symmetry, which can be specified by isometric transformations called symmetry operations (e.g. Verhoogen *et al.* 1970, p. 26). In each operation or combination of operations, certain collections of points, such as those on specific lines in space, remain fixed and are called symmetry elements. The symmetry of an ideal geometric body can therefore be specified in terms of its symmetry elements (rotation axes, mirror planes and inversion point), whereby the symmetry of the body increases according to type and number of symmetry elements. Isotropic bodies or ideal spheres have the highest symmetry of all.

A set of symmetry operations characterizing a finite geometric body, such as an ideal fold, is called a point group and a similar set characterizing an infinite periodic pattern, such as an infinite system of ideal buckle folds, is called a space group. Real bodies have no truly identical parts so that the strict definition of symmetry operations must be relaxed to apply to effectively identical parts, such as the hands of a human body (Verhoogen *et al.* 1970, p. 28).

This paper deals with individual large folds or parts of large folds whose effective symmetry may be specified by point groups and represented by International Symbols (Verhoogen *et al.* 1970, p. 33). For example, the effective symmetry of nearly circular domes or basins is represented by ∞ mm and that of orthorhombic oval domes and basins by 2 mm. The same symbols apply to three-dimensional strain fields of folds. Because of their three-dimensional character, orthorhombic strain fields are difficult to display by conventional methods. Axially-symmetric strain fields, on the other hand, can be depicted by two-dimensional plots of strain ellipsoids (Fletcher 1972) or by strain trajectories plus contour maps of strain intensity ($\bar{\gamma}_0$ or r values) and prolateness (ν or k values, Schwerdtner *et al.* 1983).

According to the symmetry rule in structural geology (Paterson & Weiss 1961), also known as Currie's principle in general physics (Verhoogen *et al.* 1970, pp. 130

and 531) or Neumann's principle in crystal physics (Nye 1960, p. 20, Verhoogen *et al.* 1970, p. 97), any symmetry element common to all contributing factors, causes or influences must be present in the final result or physical response. Symmetry elements absent from the final result must also be absent from at least one contributing factor.

The symmetry rule applies to the final form of folds as well as their total-strain field (spatial array of strain ellipsoids). For kinematic purposes, the total-strain field can be defined as the result of the superposition of: (i) a field of prestrain; and (ii) the field of fold-generating strain. In practice, the geologist may only know the fields of mineral-aggregate foliation and mineral-aggregate lineation. Only if these structural elements were produced by passive deformation of effectively isotropic mineral fabrics can we equate the lineation trajectories with total-extension trajectories.

The final fold form depends on: (a) the geometry of the lithologic units prior to upright folding; and (b) on the field of fold-generating strain. If the lithologic units were horizontal and effectively planar before upright folding then the final fold form must have the same mirror planes as the field of fold-generating strain. (This will be explained in the next section.) As the fold form and the fold-generating strain field reflect only part of the history represented by the total-strain field, their symmetries may differ drastically. For example, an oval dome may have orthorhombic symmetry (2 mm) while the total-strain field may only be monoclinic (2). This would occur if the prestrain did not share a mirror plane with the fold-generating strain.

Field of fold-generating strain

The folding of sets of horizontal planes is a special application of non-linear transformations (Hobbs 1971, Hirsinger & Hobbs 1983), whereby the symmetry elements of simulated structures are the same as those of the corresponding transformations. This is a direct consequence of the mathematical equations and need not be explained by means of the symmetry rule. Geologists realized many years ago that upright orthorhombic folds must have the same two mirror planes as the fold-generating strain fields (Flinn 1962, Ramsay 1967, pp. 436, 521 and 531). Monoclinic model folds, on the other hand, are produced by strain fields with a single mirror plane (Ramberg 1963b, Cobbold & Quinquis 1980, Hudleston 1986). However, this rule depends critically on the scale between folds and tectonic strain fields, as is illustrated by structural modelling.

Some workers have shown in experiments that very competent buckles are nearly symmetric about their hinge planes, although the folds were generated in oblique layers and regimes of simple shear (Ghosh 1966, Manz & Wickham 1978). This seems to imply that the folds have a plane of symmetry which is absent in the fold-generating strain field. However, there must be a direct correspondence between strain and fold form because the unstrained competent members are virtually up a field of contact strain that is quasi-symmetric about the hinge planes and agrees with the fold form. The buckling of planar competent members under simple shear therefore confirms the rule that, on the scale of individual folds, the field of fold-generating strain has the same mirror planes as the fold form. This relationship is perfectly general and applies to all upright folds developed from coplanar units.

Symmetry criterion. The preceding discussion shows that a lack of vertical mirror planes in the total-strain field of symmetric domes or basins cannot be explained without invoking a field of prestrain that lacks the same vertical mirror planes. This constitutes an important criterion of prestrain that is discordant to symmetric domes and basins. As will be seen in the next section, this simple criterion is difficult to apply in practice, notably to oval structures exposed on erosional peneplains.

Identification of natural prestrain

The application of the symmetry rule to large natural folds is hampered by several major problems: (1) marked curvature of lithologic units before upright folding; (2) slight triclinicity and inclination of prominent domes or basins; and (3) restriction of exposures to the regional erosion surface. As shown by the physical behaviour of pseudosymmetric and dislocation-rich minerals, departures from perfect symmetry and homogeneity do not invalidate Neumann's principle (Nye 1960). Similarly, a slight triclinicity of large folds does not preclude the use of the symmetry rule in the present context. However, we need to find objective techniques for orientating planes of apparent symmetry within large domes or basins.

Problem (1) can lead to significant angles between the mirror planes of the actual folding-strain fields and those of corresponding natural folds. (The effect is akin to the obliquity between the ellipsoids of incremental strain and total strain in progressive non-coaxial deformations.) It also can lead to mirror planes in the total-strain pattern which are oblique to those of the folds and thereby may provide a false indication of prestrain.

Problem (2) can be assessed by analysing large folds mathematically in order to determine: (a) the departure of the natural fold form from one with perfect symmetry; and (b) the geographic orientation of the symmetry elements of the idealized fold. For example, the form of a pericline or oval dome may be represented by a large set of directional and positional data which can be characterized by three orthogonal directions (Robin & Schwerdtner work in preparation). Similarly, the geometry of an orthorhombic or monoclinic field of total-extension trajectories can be characterized by orthogonal directions. Once determined, the characteristic directions of the fold form can be compared with those of the extension trajectories. Given horizontal original boundaries, the rocks are prestrained if the characteristic directions of the fold form are clearly oblique to those of the trajectory field. No decision can be made about a possible prestrain if the characteristic directions of the trajectory field are parallel to those of the fold form.

Problem (3) is most serious and makes it difficult to analyse folds whose hinge planes dip <75°. This is related to the fact that the symmetries of fold form and total-strain pattern cannot be determined from observations on an arbitrary single surface through the three-dimensional structure. Only on a horizontal section or regional peneplain through an upright dome, pericline or basin is it possible to determine the orientation of effective symmetry elements. How can such structures be identified on geological maps?

The map pattern of upright symmetric structures is characterized by concentric oval boundaries of lithologic units, which have the same apparent thickness on opposite limbs. Using the measured attitudes of folded surfaces, the plane bisecting the non-cylindrical fold limbs can be drawn on statistically contoured stereoplots. This bisecting plane coincides with the proper hinge plane of the symmetrical folds, and is approximately vertical in domes, basins and upright periclines.

The symmetry rule provides no help where the symmetry elements of the prestrain field have the same orientation as those of the upright-fold form and the total-strain field. This may be encountered in coaxially refolded strata where early recumbent folds and associated *L*-fabrics (Flinn 1965) produced a governing linear anisotropy (Cobbold & Watkinson 1981). If the early folds are not detected during the field mapping, then the geologist must find independent structural clues that the rocks were highly strained prior to upright folding. These clues in effect constrain the range of possible kinematic paths and ascertain that the rocks were deformed at least twice.

Two non-cylindrical folds will be described in the following sections that are composed of prestrained rocks. In the first structure, an Archean gneiss dome, the presence of a prestrain can be ascertained by means of the symmetry concept. The second fold is an oval basin in Proterozoic gneiss for which the symmetry concept provides little help but in which the prestrain is revealed by décollement zones within thick lithologic units. Only the inner portion of both folds is effectively symmetric, a common phenomenon throughout folded gneiss terranes.

ASH BAY DOME

The Ash Bay dome is situated in the Rainy Lake granitoid complex of the western Wabigoon Subprovince, southern Canadian Shield (Figs. 1 and 2) (Sutcliffe

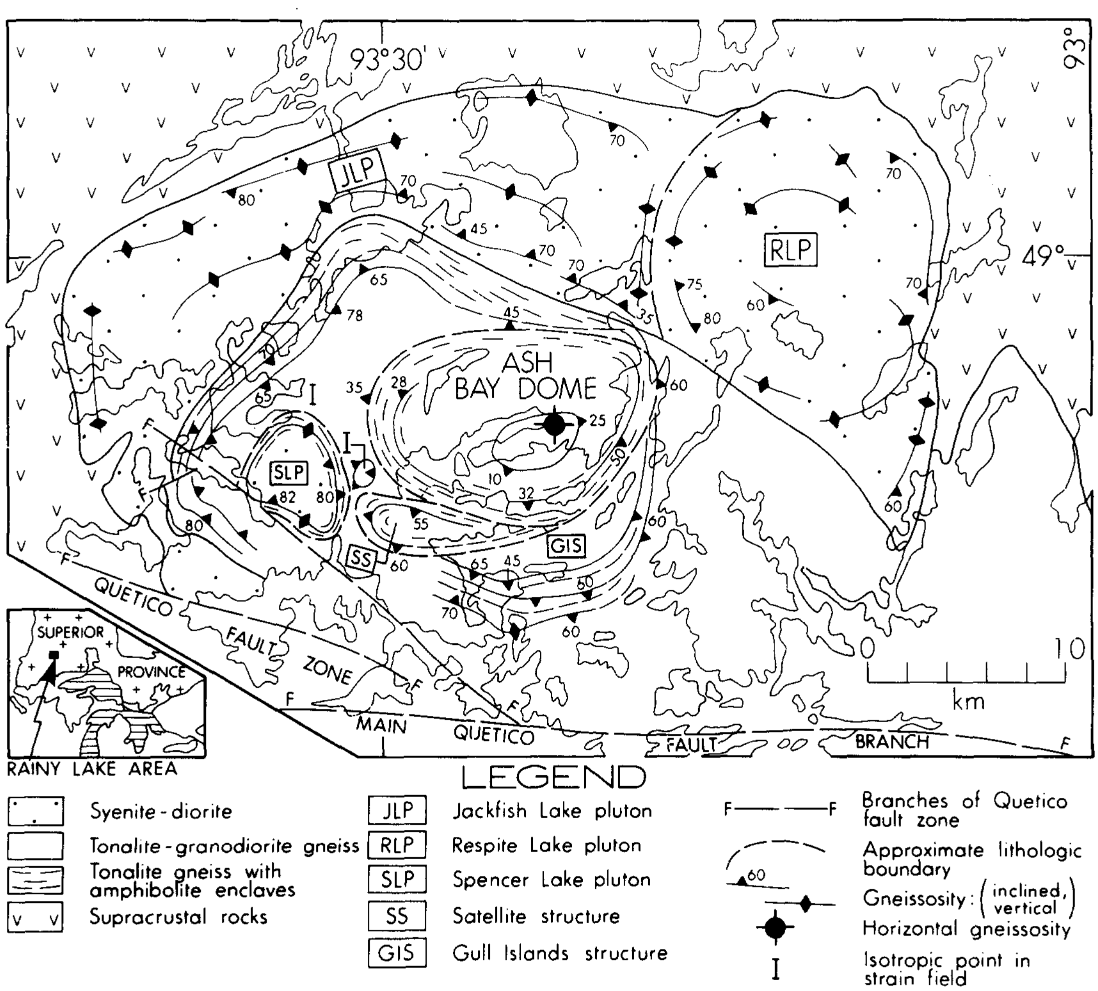

Fig. 1. Rainy Lake granitoid complex showing Ash Bay dome, Satellite and Gull Islands structures and syenite–diorite plutons. Dips of gneissosity are given in degrees.

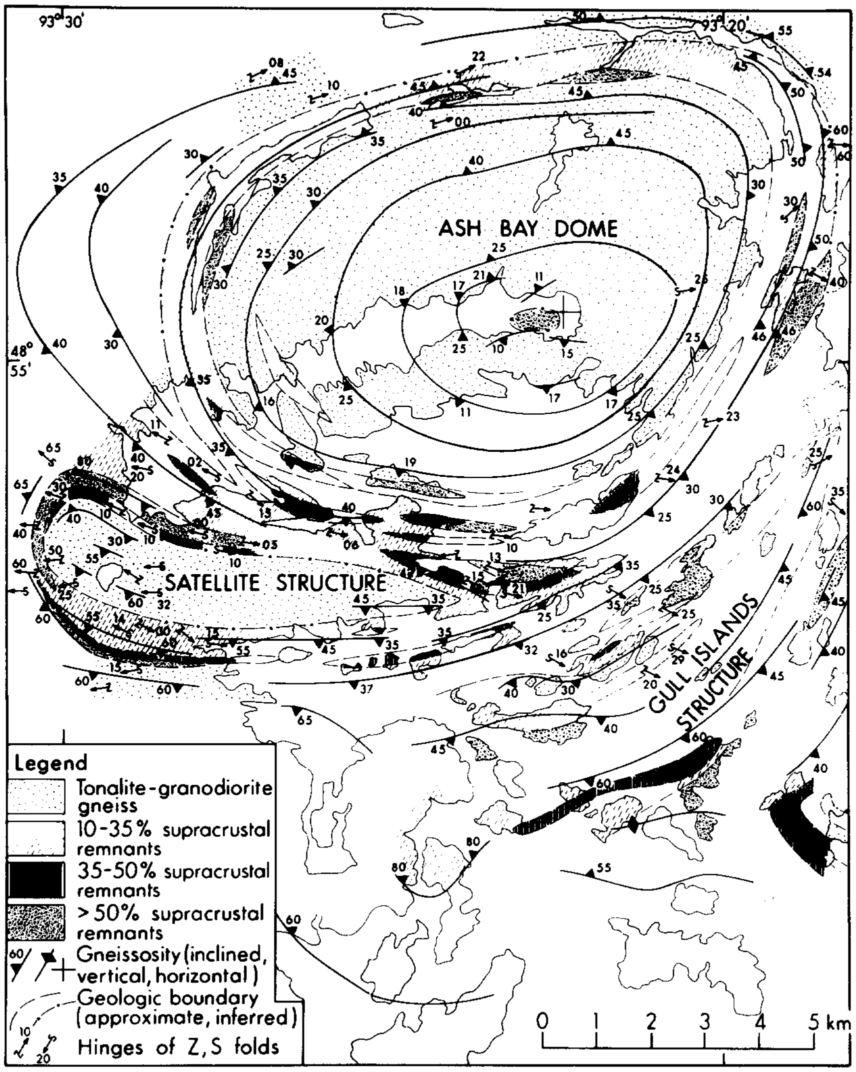

Fig. 2. Ash Bay dome with trajectories of gneissosity. Dips of gneissosity and plunges of fold hinges are given in degrees.

& Fawcett 1979, Schwerdtner 1984, Blackburn *et al.* 1985). The dome lacks a definite boundary, but has a leucocratic core of gneissic granodiorite–tonalite and a ring of tonalite gneiss with strained enclaves of amphibolite ranging in length from a few centimetres to hundreds of metres. Some enclaves have relict volcanic textures and strained primary structures which point to a volcanic origin of the protolith of the amphibolite. Biotite is the dominant mafic mineral of gneiss that lacks amphibolite enclaves. Amphibole, on the other hand, abounds in the tonalite gneiss containing >20% angular enclaves. This suggests that the fragmentation of the metavolcanics was a plutonic process which led to contamination of the original tonalitic magma. Prior to deformation, the amphibolite-rich tonalite seems to have been the roof zone of a tabular batholith composed of leucocratic granodiorite–tonalite. It will be assumed that the roof zone had boundaries that were originally planar and horizontal. When was the granodiorite–tonalite changed to gneiss, during the growth of the Ash Bay dome or in an earlier tectonic episode?

Several hundred attitudes of gneissosity were measured throughout the oval dome and utilized in the construction of Fig. 2. On a scale of >10 m, the gneissosity trace is generally parallel to the overall boundary between the core region and the encompassing zone of amphibolite-rich gneiss (Fig. 1). These regions make up the inner Ash Bay dome. Mafic lenses, narrow amphibolite enclaves and gneissosity are folded (Fig. 2), on the scale of a few metres or less, and this may be seen as evidence that the granodiorite–tonalite had been strongly deformed and converted into a gneiss prior to the doming. Yet no proof is available that the small-scale folds actually predate the Ash Bay dome. The oval map pattern of the inner dome is non-elliptical and seems to lack an obvious plane of symmetry (Figs. 1 and 2). The ratio of extreme horizontal diameters is only about 1.3, not a very large departure from circularity. However, the dome is part of, and virtually aligned with, an ENE–WSW chain of oval structures (Fig. 1). This subparallelism cannot be fortuitous, and supports the notion that the inner Ash Bay gneiss dome comes close to having two vertical mirror planes which strike approximately ENE and SSE. The inferred orientation of the planes is being checked numerically by using all available measurements of gneissosity (Robin & Schwerdtner work in preparation).

The Ash Bay dome bears a large flanking sheath-like structure (Figs. 1 and 2) which is incompatible with an ENE–WSW mirror plane. This satellite structure may be a squashed oval diapir or an early recumbent fold. It will be seen, however, that neither origin would greatly affect the application of the symmetry rule to the inner Ash Bay dome.

Satellite diapirs grow slowly while being starved for low-density material, and may be deformed by their fast-growing neighbours (e.g. Ramberg 1981, p. 47). The existence of a squashed southwesterly satellite would merely confirm the dominance of the ENE–WSW chain of structures in the western Rainy Lake granitoid complex (Fig. 1). An early recumbent fold, on the other hand, would attest to a large prestrain, as well as to subhorizontal predomal attitudes of the amphibolite-rich zones.

Except where folded on a small scale, the mineral aggregates (flattened quartz eyes and mafic clots) are normal to the minor axis of the total-strain ellipsoid (Schwerdtner 1984). Throughout the Ash Bay dome, there is only one penetrative stretching lineation in the mineral constituents—the major axis of the total-strain ellipsoid. This lineation is parallel to the hinges of small-scale asymmetric folds and lies in the enveloping plane to gneissosity if buckled on the scale of a few metres or less. Because of widespread buckle folding, the gneissosity of the amphibolite-rich zone cannot coincide with a principal plane of the total-strain ellipsoid. (This follows from the requirement that principal fabrics be reconstituted progressively rather than deformed actively while a non-coaxial strain accumulates, cf. Schwerdtner 1973.) Owing to the high strain recorded in gneissosity and the scarcity of tight folds, an oblique superposition of the folding strain may have failed to produce a large angle between the minor axis of the total-strain ellipsoid and the normal of the enveloping plane to the folded gneissosity.

The total-strain pattern of the Ash Bay dome is presented by three elements (Figs. 2–4): Flinn's (1962) k-value as crudely estimated by visual inspection of strain fabrics, the direction of mineral lineation and the enveloping surface to gneissosity. The k-values are plotted on a topographic map (Fig. 3), the attitudes of the envelope to gneissosity are shown in Fig. 2, and lineation trend lines are displayed in Fig. 4. Note that the trend lines do not correspond to three-dimensional extension trajectories projected onto the horizontal plane. Instead they are obtained by drawing a set of form lines through a field of closely-spaced arrows—the plotted lineation directions. Nonetheless, the trend lines are very helpful in assessing the symmetry of the total-strain pattern. This may be appreciated by comparison with the imaginary trend-line pattern of theoretical stretch lineations in simulated circular domes (Fletcher 1972). Regardless of the dynamics and the mechanism of folding, the radial trend line pattern will be axially symmetric if the model strata were planar and undeformed at the onset of doming.

The k-value map of the Ash Bay dome seems to lack a simple pattern (Fig. 3), and cannot be readily interpreted. By contrast, the trend line system of the stretching lineations has no plane of symmetry but shows a Z-like azimuth pattern and a skewed plunge pattern (Fig. 4). Accordingly, the lineation pattern has at best a vertical two-fold symmetry axis as opposed to the vertical mirror planes of the idealized dome form. This situation implies that the granodiorite–tonalite was markedly strained before the gneiss doming. This conclusion remains unchanged if the dome is regarded as circular and the lineation pattern as symmetric about the NNE–SSW vertical plane. Research is underway to ascertain the mechanism of doming (Schwerdtner 1984) and unravel the structural history of the gneiss, but these topics are beyond the scope of the present paper.

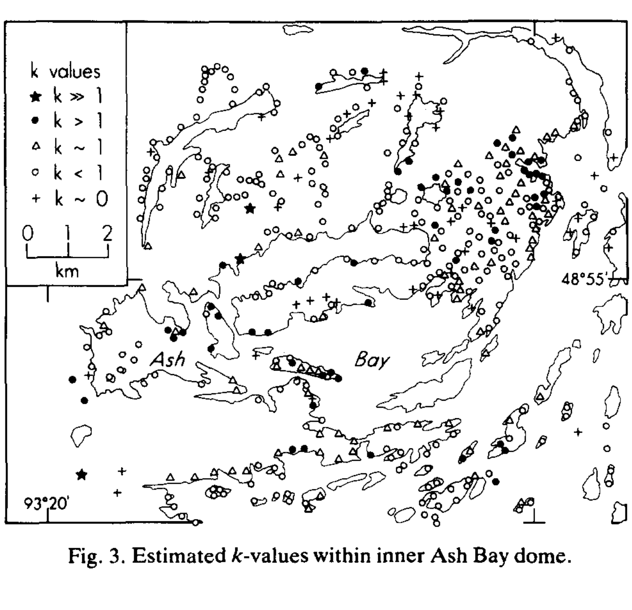

Fig. 3. Estimated k-values within inner Ash Bay dome.

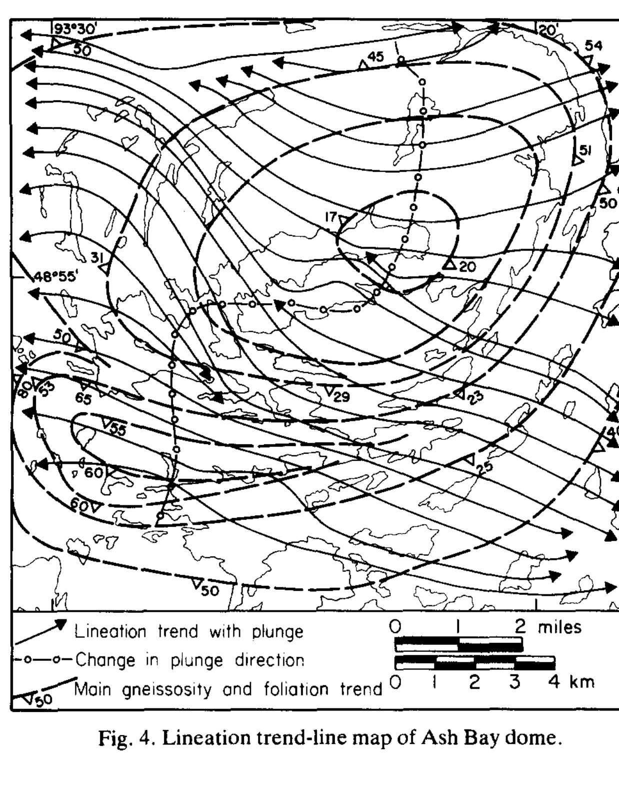

Fig. 4. Lineation trend-line map of Ash Bay dome.

SPARROW LAKE BASIN

The second large fold investigated is composed of Grenville gneiss that contains many small isoclinal folds. Evidence for buckling of gneissosity is widespread on the scale of metres (Schwerdtner 1987), but this does not necessarily mean that gneissosity and small-scale structures actually predate the onset of upright large-scale folding. One may therefore question the presence of pervasive prestrain on the scale of kilometres. The following section describes a case in which the symmetry rule fails to provide conclusive answers.

Folded Grenville gneiss is very well exposed near the shore of Georgian Bay (Lake Huron) and in the adjacent Muskoka region, about 150 km north of Toronto. Here the intricate structure of gneissosity is readily discernible on aerial-photographic mosaics and topographic relief maps (Canadian National Topographic System, Orillia sheet 31D/NW, Parry Sound sheet 41H/SE and Muskoka sheet 31E/SW). The Sparrow Lake basin is one of several oval structures that appear on the Orillia sheet near the southern edge of the Canadian Shield. This area lacks a pervasive simple pattern of fold interference, but exhibits sporadic domes and basins (Schwerdtner & Mawer 1982).

The Sparrow Lake basin, which lacks a definite boundary, is defined mainly by gneissosity, but it contains important lithologic contacts which seem to have controlled the large-scale folding (Fig. 5). A composite body of gneissic diorite–syenite including strained mafic clots (Schwerdtner & Mawer 1982) occupies the core of the basin as well as its southwestern exit near Sidetrack Lake (Fig. 5). The total map pattern lacks a vertical mirror plane on the scale of >3 km, but the dioritic core of the structure is virtually symmetric about a NE–SW plane. This plane is approximately parallel to the Gren-

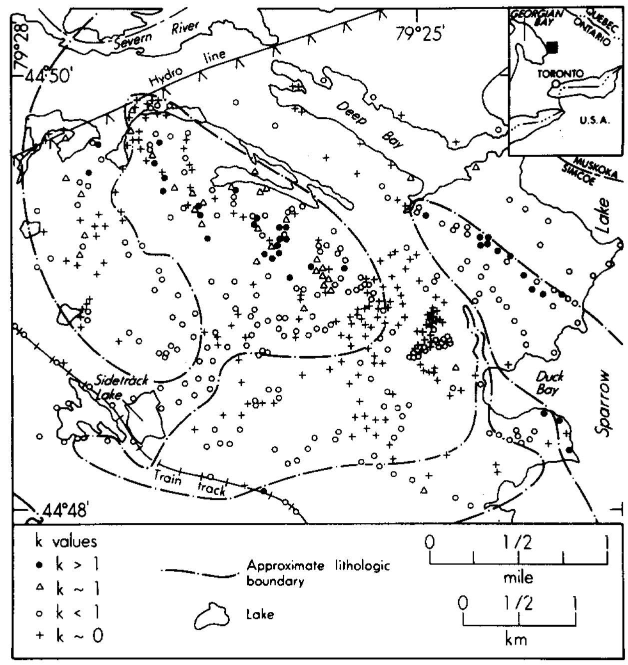

Fig. 6. Pattern of k-values in Sparrow Lake basin.

ville Front (Davidson 1984), perpendicular to the regional structural grain (Schwerdtner 1987), and probably an element of local monoclinic symmetry. The same mirror plane of effective symmetry appears on the k-value map (see central concentration of k >1 in Fig. 6) and in the pattern of lineation trend lines (Fig. 7), whose symmetry group may be 2 mm. However, the gneissosity trajectories, which are an expression of the total-strain field, conform to the folded boundary of the dioritic core. This implies that the total-strain pattern must have the same monoclinic symmetry as the fold form.

According to the symmetry rule (Paterson & Weiss 1961), the absence of a NW–SE mirror plane from the

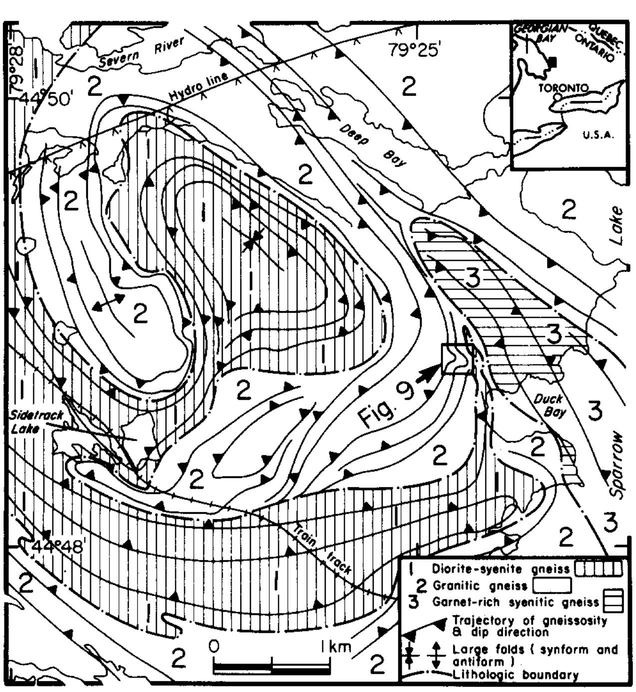

Fig. 5. Sparrow Lake basin with gneissosity trajectories.

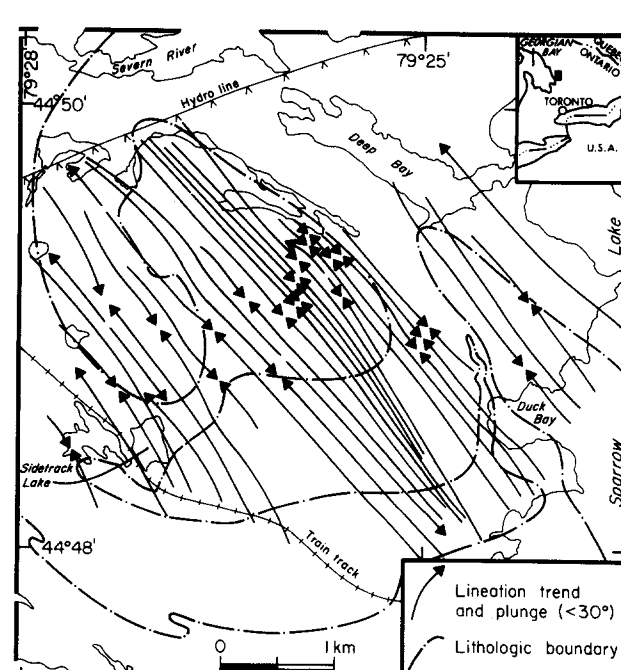

Fig. 7. Lineation trend-line map of Sparrow Lake basin.

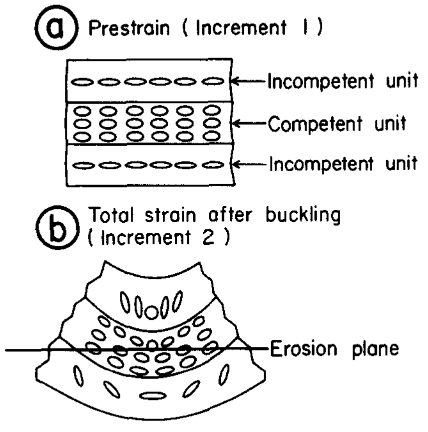

Fig. 8. Two-stage evolution of the total-strain pattern of the Sparrow Lake basin in a NE–SW vertical schematic section. Apparent strain incompatibility between units was compensated by boundary slip and volume change.

total-strain field implies that the same plane is absent from at least one contributing factor. Owing to the absence of this plane from the basin form, we need not involve an oblique prestrain to explain the missing symmetry element in the total-strain pattern (Figs. 5–7). However, this does not rule out the possibility that the diorite–syenite gneiss was strained before the upright folding. For example, the northwestern terminus of Unit 3 (Fig. 5) may be interpreted as the closure of a recumbent fold predating the Sparrow Lake basin. If the basin developed under lateral compression and buckling is the chief mechanism of large-scale folding, then the syenite–diorite must have been preflattened, as explained in the following paragraph and in Fig. 8.

Throughout the Muskoka region and surrounding areas of Grenville rocks, most types of mafic gneiss were prone to boudinage and small-scale buckling. If the Sparrow Lake basin is indeed a large buckle fold then the syenite–diorite gneiss of its core region is a thick competent member. The concave boundary of this member has been removed by erosion, but its hinge line may be close to the centre of the present map pattern. Only a trace of the convex boundary is exposed on the erosional peneplain (Fig. 5), with dip values of typically <20°. This must be kept in mind when considering the strain pattern of the dioritic core region, whose inner portion appears to be stretched ($k > 1$) and outer zone highly flattened (Fig. 6). On the NE–SW vertical mirror plane, the principal ratio of sectional strain is therefore greatest at the convex hinge and decreases systematically toward the concave hinge of the syenite–diorite unit. The opposite strain gradient is found in competent members of model structures (e.g. Ramsay 1967, p. 403) produced by compression of undeformed strata. Buckling of severely pre-flattened units leads to the total-strain pattern and inferred vertical gradient of the inner Sparrow Lake basin (Fig. 8).

The granitic gneiss was redeformed in an active manner, and this furnishes independent evidence that the gneissic fabric (planar anisotropy) predates the large upright folds. For example, intrafold décollement zones (Ramsay 1967, p. 420) were identified throughout the basin, and they seem to have developed during upright folding. Such décollement zones are common within active folds produced by buckling or bending of uniform anisotropic rocks and/or multi-layered sequences (Ramberg 1963a, b, Hudleston 1986).

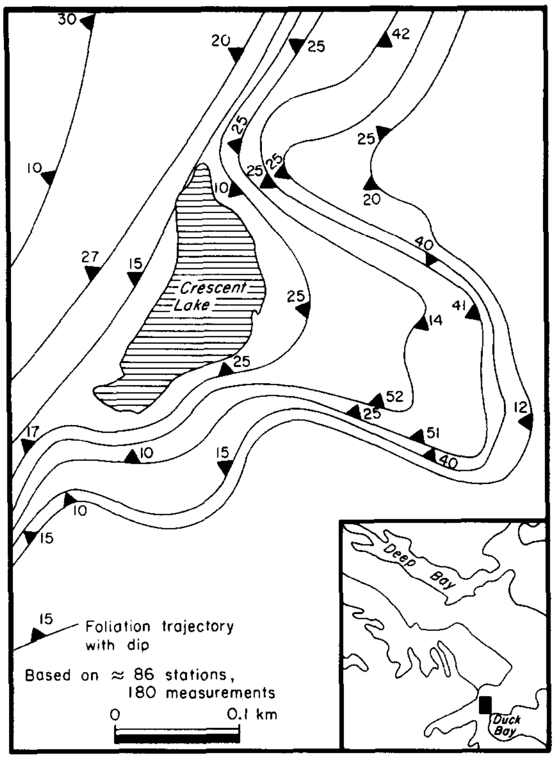

Fig. 9. Gneissosity trajectories in part of the southern hinge zone of the Sparrow Lake basin (see Fig. 5).

A well-defined zone of décollement occurs NW of the thin syenite–diorite unit at the box shown in Fig. 5, within the granitic gneiss of the hinge zone trending NW–SE near Duck Bay (Fig. 9). The degree of curvature of the trajectories of gneissosity increases at first, as one moves from Crescent Lake in a southeasterly direction within the hinge zone of the NW-plunging fold (Fig. 9). However, a decrease in curvature is encountered among the last three trajectories in the granitic gneiss (Fig. 9). This reveals that the décollement zone resulted from buckling of granitic gneiss and that the thin branch of syenite–diorite (Fig. 5) near Duck Bay did not govern the active deformation. Had the granite rock been isotropic prior to the upright folding then the degree of curvature of gneissosity would increase continuously (cf. Ramsay 1967, fig. 7–81A) away from Crescent Lake (Fig. 9) until the concave boundary of the competent syenite–diorite gneiss is reached (Fig. 5). Such a gradual increase leads to a fold style that characterizes isotropic incompetent units: (1) in the cores of single-layer buckle folds and (2) between the competent members of multi-layer structures (Ramsay 1967, pp. 417–434).

CONCLUSIONS

Oval domes and basins dominate the map pattern of typical gneiss terranes in many Precambrian Shields.

The overall form of such large structures is defined by gneissosity and lithologic boundaries, and can come close to having two vertical symmetry planes. Yet a concordant gneissic fabric need not predate the upright folding of the principal lithologic units (cf. Ramberg 1963a).

Commonly the gneissic fabric records the total strain of tabular lithologic units, possibly including a stratiform simple shear before the onset of regional folding. This can lead to total-strain fields whose symmetry elements do not coincide with those of the upright fold forms. Such non-coincidence is therefore indicative of pervasive prestrain, and it affects the application of conventional folding-strain models to natural domes and basins. Symmetry elements common to natural folds and total-strain fields are non-discriminant in regard to pervasive prestrain. This prompts the use of direct indicators of strain-induced anisotropy, such as narrow décollement zones within homogeneous rock units.

Mathematical formulae will be used (Robin & Schwerdtner work in preparation) to: (1) assess the degree of asymmetry of large upright folds; and (2) fix the orientation of effective symmetry elements within the total-strain pattern as well as the fold form. Such formulae should prove valuable in characterizing the state of prestrain in the total-strain pattern of upright large folds.

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