Geological Society of America
Special Paper 339
1999

Emplacement geometry of the Sudbury Igneous Complex: Structural examination of a proposed impact melt-sheet

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ABSTRACT

The main mass of the 1.85-Ga Sudbury Igneous Complex (SIC) has been recently interpreted as a 2.5-km-thick impact melt-sheet that differentiated into norite, gabbro, and granophyre layers. This interpretation requires the SIC to have been emplaced as a horizontal sheet ponded in a complex impact crater whereby orogenic folding is regarded as the cause of its synformal geometry. However, three independent lines of structural evidence from the SIC and its Huronian host rocks indicate that the SIC was not a horizontal sheet at the time of its consolidation.

1. Planar mineral fabrics of the unstrained norite and gabbro layers are subparallel to the synformal base of the SIC and mineral lineation plunges toward the center of the SIC. This radial lineation pattern is inconsistent with an initial horizontal sheet geometry of the SIC, but is consistent with preconsolidation strain caused by gravitational reorientation of crystals on inclined magma chamber walls.

2. Anisotropy of magnetic susceptibility (AMS) of the granophyre reveals a magnetic lineation that is orthogonal to the basal contact of the SIC. This fabric is correlated to acicular plagioclase crystals and is thus interpreted as a wall-orthogonal crystallization texture. Fold-induced strain is expected to overprint such textures most severely where the curvature of the SIC is greatest, e.g., in the North Lobe. However, the angular departure of this lineation from its initial contact-orthogonal orientation is minimal in this area. Shortening strains estimated from AMS numerical modeling and microstructural analysis are significantly lower than strains expected from orthogonal flexural folding, <15 vs. 50%, respectively. The observed low strain levels are in agreement with a primary parabolic geometry of the SIC, but are inconsistent with folding of a consolidated horizontal melt-sheet.

3. Structural analysis of Huronian host rocks shows that deformation of these rocks can be explained without invoking rotation of Huronian strata as a consequence of impact cratering. Moreover, the absence of pervasive, post-SIC ductile strain in Huronian rocks and the adjacent norite, the uniform northwest-southeast–directed, late-orogenic compression, and the regional tectonometamorphic correlation suggest that shortening of the SIC was not accomplished by noncylindrical buckle folding but rather by imbrication of the southern SIC on thrust surfaces of the South Range Shear Zone.

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Cowan, E. J., Riller, U., and Schwerdtner, W. M., 1999, Emplacement geometry of the Sudbury Igneous Complex: Structural examination of a proposed impact melt-sheet, *in* Dressler, B. O., and Sharpton, V. L., eds., Large Meteorite Impacts and Planetary Evolution II: Boulder, Colorado, Geological Society of America Special Paper 339.

If the SIC is accepted as an impact melt body, a nonhorizontal initial configuration of the SIC has far-reaching implications for the emplacement mechanism of impact melts in large craters. Published theoretical models of crater formation invariably predict a horizontal emplacement geometry for the impact melt-sheet. In the light of our structural results, such models and the fractionation mechanism of the SIC require revision.

INTRODUCTION

The 1.85-Ga Sudbury Igneous Complex (SIC), in central Ontario, Canada is a 2.5-km-thick layered igneous body whose main mass consists of a lower norite layer overlain by gabbro and granophyre sheets, respectively (Figs. 1 and 2). The main mass is underlain by a discontinuous sulfide-rich noritic unit called the Sublayer, and radial and concentrically oriented quartz dioritic Offset Dikes extend out from the Sublayer, transecting the basement lithologies. Although studied for more than a century, the mechanism of SIC emplacement has been debated since the first quarter of this century when Coleman (1905, 1907) interpreted the SIC as an intrusion that differentiated in situ. Coleman's interpretation was followed by a hypothesis in which the norite and the granophyre were regarded as separate intrusions (Phemister, 1925). Subsequent studies have supported either, or a combination, of these two views (Naldrett et al., 1970; Peredery and Naldrett, 1975; Naldrett and Hewins, 1984).

The interpretation that Sudbury was a site of extraterrestrial impact was first suggested by Dietz (1964), but he regarded the SIC as a mantle-derived igneous body triggered by the impact. Recently, however, a radically new interpretation, i.e., an impact melt origin, was introduced for the entire SIC (Faggart et al., 1985; Grieve et al., 1991). Prior to these publications, the SIC

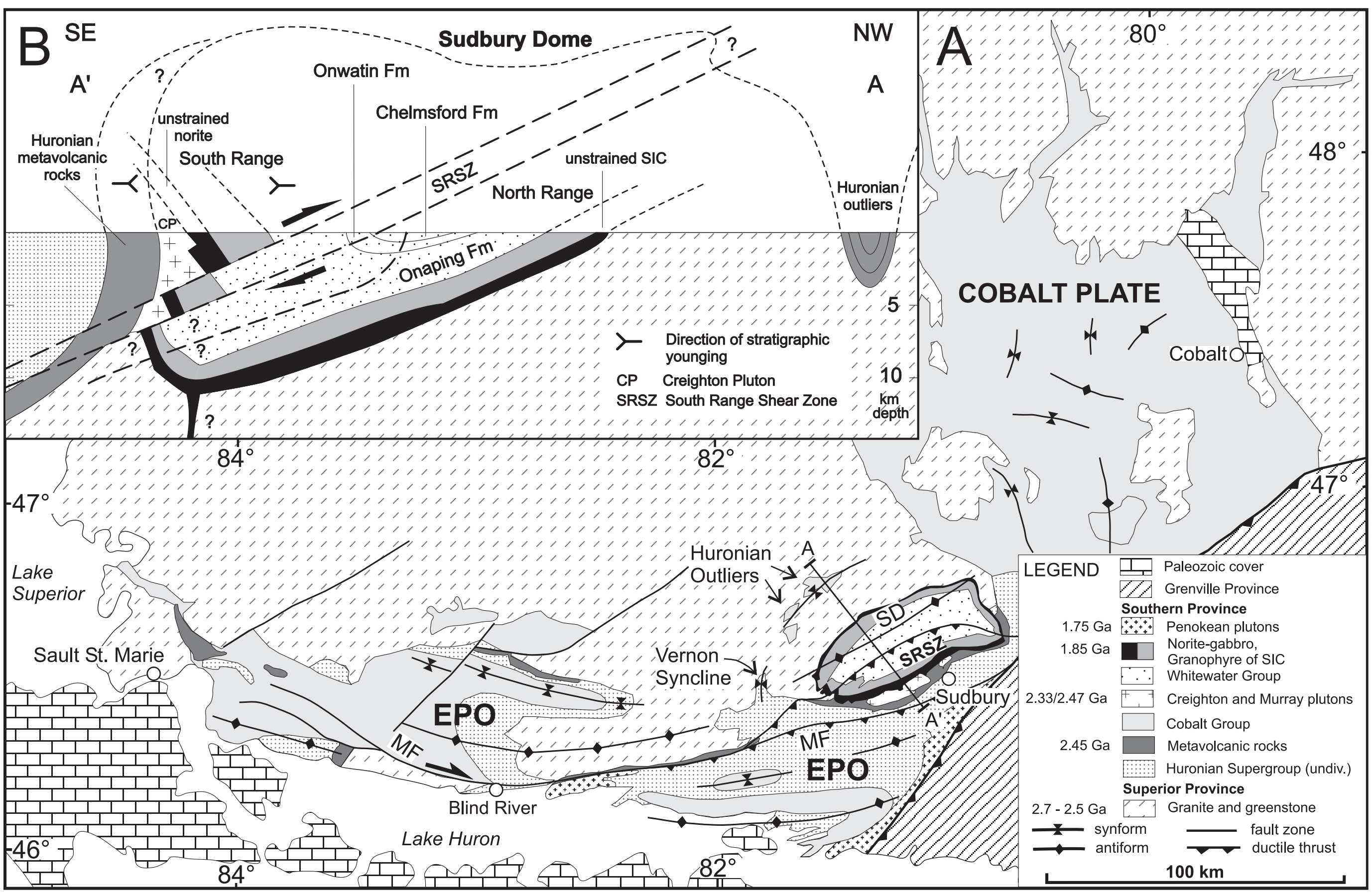


Figure 1. The Sudbury Structure and its geologic setting. A, Major structures and geologic units of the Eastern Penokean Orogen (EPO) in central Ontario. SD = Sudbury Dome (Riller and Schwerdtner, 1997); MF = Murray Fault; SRSZ = South Range Shear Zone (Shanks and Schwerdtner, 1991a). B, Northwest-southeast profile of the Sudbury Basin and the Sudbury Dome based on the Lithoprobe seismic profile (Milkereit et al., 1992). Y-shaped arrows indicate the reversal in stratigraphic younging between the Whitewater Group and the Huronian strata.

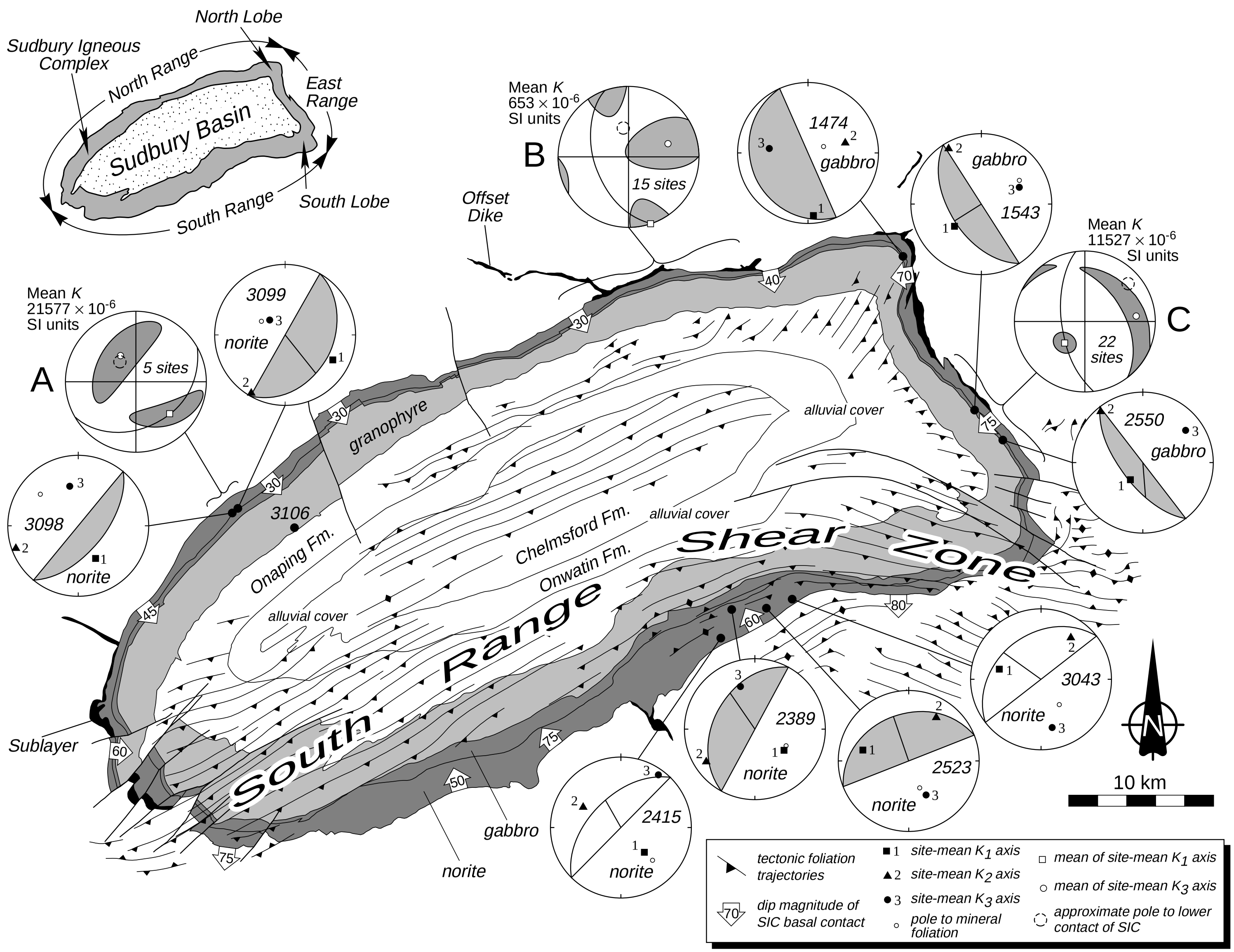


Figure 2. Sites and mean fabric data from image analysis plotted on lower hemisphere equal-area stereonets (shaded great circle indicates mean mineral foliation; line indicates mean mineral lineation) of gabbro and norite samples. Mean principal axes of the AMS ellipsoid K_1, K_2 and K_3 are labeled 1, 2 and 3 on the stereoplots. Small open circles indicate poles to the mean mineral foliation determined from image analysis as described in text. Mineral L-S fabric determined from sites 2415 and 3043 were visually estimated from hand samples without the aid of AMS (see text; unshaded great circle shows mean mineral foliation; line shows mean mineral lineation). Lower hemisphere equal-area stereoplots (A), (B) and (C) are magnetic fabrics obtained from hand samples at several stations (numbers of sites indicated), with each sample site consisting of two to eight core samples: (A) is from sample domain *A*, (B) from domains *B* and *C*, and (C) from domains *H* and *I* of Figure 5. The mean of the site–mean magnetic foliation is shown as a great circle, as well as its pole as an open circle. The mean of the site–mean magnetic lineation is indicated by an open square. Both are shown with shaded 95% confidence cones, and their mean site–mean susceptibilities (*K*) are indicated. The magnetic foliation poles in (A) and (C) are subparallel to the inferred basal contact of the SIC (large dashed open circles are approximate poles). The departure of magnetic foliation pole from the SIC contact, and the large 95% confidence cones of (B) is due to the very low susceptibility values of the samples. The mean site–mean magnetic lineation nevertheless point in a radial orientation with respect to the center of the Sudbury Basin. Dips of the outer contact of the SIC are from Rousell (1984, Fig. 5.1). The foliation trajectories of strained lithologies were constructed from more than 2,500 measurements of individual foliation data, and objectively interpolated by a spatial averaging method (Cowan, 1996). The location of site 3106 (Fig. 3B) is shown in the North Range.

was interpreted as a magmatic intrusion, regardless of whether it was emplaced as a consequence of endogenetic volcanism or impact-induced magmatic activity. More recent geochemical studies (Chai and Eckstrand, 1993a,b; Norman, 1994), in situ magmatic fractionation modeling of the SIC (Ariskin, 1997), field observations (Dressler et al., 1996), and radiometric data from the Sublayer (Corfu and Lightfoot, 1996) cast doubt on the validity of the impact melt model for all or part of the SIC. However, geochemical and impact theoretical arguments in support for the entire SIC as an impact melt are nevertheless favored by many workers (e.g., Grieve et al., 1993; Deutsch and Grieve, 1994; Grieve, 1994; Deutsch et al., 1995; Ostermann and Deutsch, 1997).

Prior to the impact melt hypothesis, the discussion centered frequently on evidence for the predeformational geometry of the SIC. Proponents of the differentiation model assumed the SIC as a horizontal sheet, which was modified by folding during the Penokean Orogeny (e.g., Collins and Kindle, 1935). By contrast, workers favoring the multiintrusion model viewed locally steep contacts of the SIC to be original, and thus supportive evidence for their hypothesis (Thomson and Williams, 1959). The impact melt model of Grieve et. al. (1991) requires that the SIC formed in a horizontal melt-lake, a scenario that is geometrically equivalent to those in which the SIC intruded as a horizontal sheet. Horizontal geometry is required because the tripartite compositional variation of the SIC is interpreted by Grieve et al. (1991) to be the result of magmatic differentiation. Large, complex impact craters are also known to possess a subhorizontal crater floor in which the impact-melt body ponds as a flat sheet (Grieve, 1975; Floran et al., 1978); in addition, numerical models of large impact craters predict a horizontal sheet geometry for impact melts (O'Keefe and Ahrens, 1994; Ivanov and Deutsch, 1997). Only noncylindrical folding can produce the present geometry of the SIC if the initial horizontal configuration is accepted, regardless of its origin (Cowan and Schwerdtner, 1994).

The rivalry between the various emplacement hypotheses of SIC continues today. Still, it may be useful if the emplacement of the SIC can be examined independent of geochemical data and arguments based on impact theory. Knowledge of the predeformational geometry of the SIC may provide independent tests of proposed emplacement mechanisms, and consequently, of the origin of the SIC. It is therefore our intention to summarize in this chapter recently obtained structural information on the primary geometry of the SIC, without expounding on the technical details of the structural analysis that are presented elsewhere (Cowan, 1996, 1999; Riller, 1996; Riller et al., 1996, 1998; Riller and Schwerdtner, 1997). We present three sets of structural evidence data: (1) on the structural petrology of the norite and the gabbro (Cowan, 1996), (2) on the strain levels in the granophyre (Cowan, 1996, 1999), and (3) on the deformation of Huronian host rocks (Riller, 1996). All the data sets, together with published field observations made by previous workers, point to a parabolic, or dish-shaped, primary geometry for the SIC.

GEOLOGIC OVERVIEW

The synformal SIC is part of the Paleoproterozoic Eastern Penokean Orogen, which lies at the southern margin of the Archean Superior Province (Fig. 1). The orogen formed by folding and thrusting of Archean granitoid rocks and volcano-sedimentary sequences of the Huronian Supergroup mainly during the Blezardian (ca. 2.47–2.2 Ga) and Penokean (ca. 1.9–1.8 Ga) tectonic pulses (Card et al., 1972; Zolnai et al., 1984; Riller and Schwerdtner, 1997). Strained Archean greenstone, granitoids, and 2.7-Ga-old high-grade gneisses of the Levack Gneiss Complex (Krogh et al., 1984) underlie the area north of the SIC (Fig. 1). By contrast, southward overturned Huronian metavolcanic strata underlie the South Range and form the cover to Archean granitoid basement rocks west of the SIC (Card, 1965; Card and Palonen, 1976). Synformal keels of Huronian rocks within Archean basement rocks, known as Huronian outliers (Pye et al., 1984), occur at a distance of approximately 20 km to the west and north of the SIC (Fig. 1) (Dressler, 1984). East of the SIC, folded Huronian strata of the Cobalt plate exhibit an east-dipping fold enveloping surface (Fig. 1). These structural relationships suggest that the synformal SIC is superimposed on a crustal dome structure, herein called the Sudbury Dome (Fig. 1), which is cored by high-grade metamorphic Archean basement rocks and which is larger than the SIC at surface.

The Sudbury Basin consists of the synformal SIC that encloses, in the map pattern, folded sediments of the Whitewater Group (Fig. 2) (Clendenen et al., 1988; Hirt et al., 1993). Shock-metamorphic structures, such as shatter cones, pseudotachylytes, and planar deformation features in quartz, feldspar, and zircon, are documented from the Archean Superior and Proterozoic Southern Province lithologies that envelope the 60- × 27-km elliptical outline of the Sudbury Basin at the surface (Dietz and Butler, 1964; French, 1967; Dressler et al., 1991; Lakomy, 1990; Krogh et al., 1984, 1996; Spray and Thompson, 1995). The presence of these structures in the host rocks of the SIC suggests shock-induced deformation associated with the hypervelocity impact of an extraterrestrial mass.

In addition to the shock metamorphic features, it has been known for some time that devitrified glass of impact origin is preserved in the Onaping Formation of the Whitewater Group (Peredery, 1972a; Muir and Peredery, 1984; Dressler et al., 1996). This unit consists of heterolithic breccia fragments derived from nearby Archean and Proterozoic rocks and is interpreted as an impact-generated suevite deposit (Peredery, 1972a,b; Avermann, 1994), or an impact-generated pseudovolcanic sequence of pyroclastic and hydroclastic deposits (Ames and Gibson, 1995; Ames et al., 1998). In agreement with impact melting, recent studies of the SIC indicate high levels of crustal contamination of its igneous rocks (Faggart et al., 1985; Grieve et al., 1991; Grieve, 1994). Accordingly, Grieve et al. (1991) have argued that the SIC differentiated into its tripartite composition by in situ differentiation of an impact-generated melt-lake. The impact melt model for the SIC consequently constrains the initial geometry of the SIC to a horizontal sheet (Cowan and Schwerdtner, 1994). This is because an impact melt-sheet with a thickness of several kilometers such as the SIC can be generated only by a large impact that results in a multi-ring complex crater with a horizontal floor (Cintala and Grieve, 1994). Thus, the impact-melt hypothesis as presented by Grieve et al. (1991) excludes magma chamber geometries and emplacement mechanisms such as lopolithic intrusion of the SIC along steep walls (cf. Hamilton, 1960; Peredery and Morrison, 1984).

STRUCTURAL PETROLOGY OF THE GABBRO AND NORITE

Fabric studies of granitic plutons have shown that the last increments of magma strain are recorded by the fabric of magmatic minerals (Paterson et al., 1989; Cruden and Aaro, 1992; Bouchez et al., 1992; Nicolas, 1992). Thus, the orientation, shape, and symmetry of these mineral fabrics can yield information on the flow of a magma just prior to its consolidation in a pluton, which, in turn, may provide information on the geometry of the pluton (Cruden and Launeau, 1994). Similarly, as the mineral fabric data obtained from sheet-like igneous bodies may constrain its geometry, attitude, and magmatic flow characteristics (Cruden, 1998). Mineral fabrics in portions of the SIC, which were not affected by solid-state deformation, can be used to unravel its original geometry and aid in discriminating among rival emplacement models of the SIC. Mineral fabrics of the gabbro and norite units were obtained using the latest methods available in digital image analysis. The results are discussed in terms of fabric patterns expected in a melt-lake, and in an igneous body that intruded along parabolic contacts with the host rock.

Analytical methods

Nine oriented block samples of gabbro and norite devoid of solid-state tectonic deformation features were collected in the field (sample sites 3098, 3099, 1474, 1543, 2550, 3043, 2523, 2389, and 2415 in Fig. 2). Two samples were taken from both the North and East Ranges, four from the South Range, and one from the North Lobe of the SIC (Fig. 2). Six to 10 cores (2.2 cm long, with a 2.54-cm diameter) were drilled from each sample. The anisotropy of magnetic susceptibility (AMS) was determined for each core at low magnetic field strength using a Sapphire SI-2 induction coil instrument. Statistical site averaging of the magnetic fabric was done using the matrix averaging routines of Hext (1963) and Jelinek (1978).

Determination of AMS is an established physical method used in the field of petrofabric studies of igneous rocks (Guillet et al., 1983; Cruden and Launeau, 1994; Archanjo et al., 1995). Mineral fabrics are rarely measurable with conventional tools such as a compass but can be rapidly estimated by measuring the AMS. AMS is a symmetric second-rank tensor that relates the intensity of the applied magnetic field (H) to the acquired magnetization (M) of a material:

$$M_i = \boldsymbol{K}_{ij} H_j \, ,$$

The dimensionless susceptibility tensor $\boldsymbol{K}_{ij}$ has the principal components $K_1 \geq K_2 \geq K_3$, which correspond to the principal radii of a triaxial magnetic fabric ellipsoid (Hrouda, 1982). The K_1 axis and the K_3 axis are commonly found to parallel the mineral lineation axis and the pole to mineral foliation plane, respectively. Accordingly, the rock samples were cut parallel to the principal planes of the magnetic fabric resulting in three orthogonal sections for each sample. If the magnetic fabric was subconcordant to the mineral fabric, then polished, large thin-sections were made parallel to the principal planes for further petrofabric analysis. The thin-sections were labeled according to the principal axes of the magnetic fabric (Fig. 2) (K_1 = magnetic lineation axis; K_2 = intermediate axis; or K_3 = magnetic foliation–normal axis).

The determination of the mineral foliation (S) and lineation (L) of the gabbro and norite samples was done by digital image analyses conducted on multiple electron microprobe x-ray maps of the thin-sections (Cowan, 1996). Multi-channel image analysis technique utilized in this study is based on multi-spectral classification using principal component analysis, extensively used in remote sensing (Drury, 1993), but can be used on all types of multi-channel digital images (Launeau et al., 1994). This technique allowed the identification of all mineral phases within the scanned area, and mineral alignment data for each orthogonal face was quantitatively resolved using the intercept method of Launeau and Robin (1996). Figure 3A shows such a well-defined L-S fabric in a norite sample of the North Range, characterized by the alignment of tabular plagioclase crystals (in white) on three orthogonal sections that were assembled to a block diagram (other identified mineral phases were omitted for clarity). The reader is referred to Cowan (1996) for details of electron microprobe data acquisition and digital image processing.

The magnetic fabric can be substantially discordant to the principal petrofabric planes (sites 1474, 3098, 2389, 2415, and 3043 in Fig. 2), but in some of these cases the mineral L-S fabric can be visually estimated in the rock specimen from preferred orientation of plagioclase laths on orthogonal sections (sites 2389, 2415, and 3043). The orientation of the mineral foliation and the lineation were determined with these methods at each site, with the exception of sites 1474 and 3098, where mineral lineation could not be resolved with confidence.

Results

The mineral foliation is effectively parallel to the basal contact of SIC at most localities (Fig. 2) and is consistent with all of the five reliable samples analyzed with the image analysis technique (samples 3099, 1543, 2550, 2523, and 2389). Similar fabric orientations are also obtained by measuring AMS in other samples from the East and North Ranges, as well as visually determined L-S fabrics in samples 2415 and 3043 from the South Range (Fig. 2). Although the magnetic fabrics are not concordant to the mineral fabric at every site, visual examination and image analysis of samples obtained from apparently unstrained gabbro and norite in the East and North Ranges confirms that AMS yields reliable results. Both magnetic and mineral foliations of the norite and gabbro dip toward the center of the Sudbury Basin (Fig. 2). These foliations, however, appear to be shallower than the basal contact of the SIC at most localities, as also noted from the South Range norite by Naldrett and Hewins (1984). Both magnetic and mineral lineations plunge consistently toward the center of the Sudbury Basin (Fig. 2) and so, form a radial lineation pattern. It is important to recognize that the center of symmetry of this fabric pattern coincides with the center of the elliptical Sudbury Basin.

Interpretation

The mineral foliation is dipping shallower than the basal contact of the SIC at most localities (Fig. 2). Thus the formation of the L-S fabric of the gabbro and norite as a result of noncylindrical folding of a semi-consolidated sheet can be ruled out as consistently steep S fabrics are not observed (Fig. 4A). Emplace-

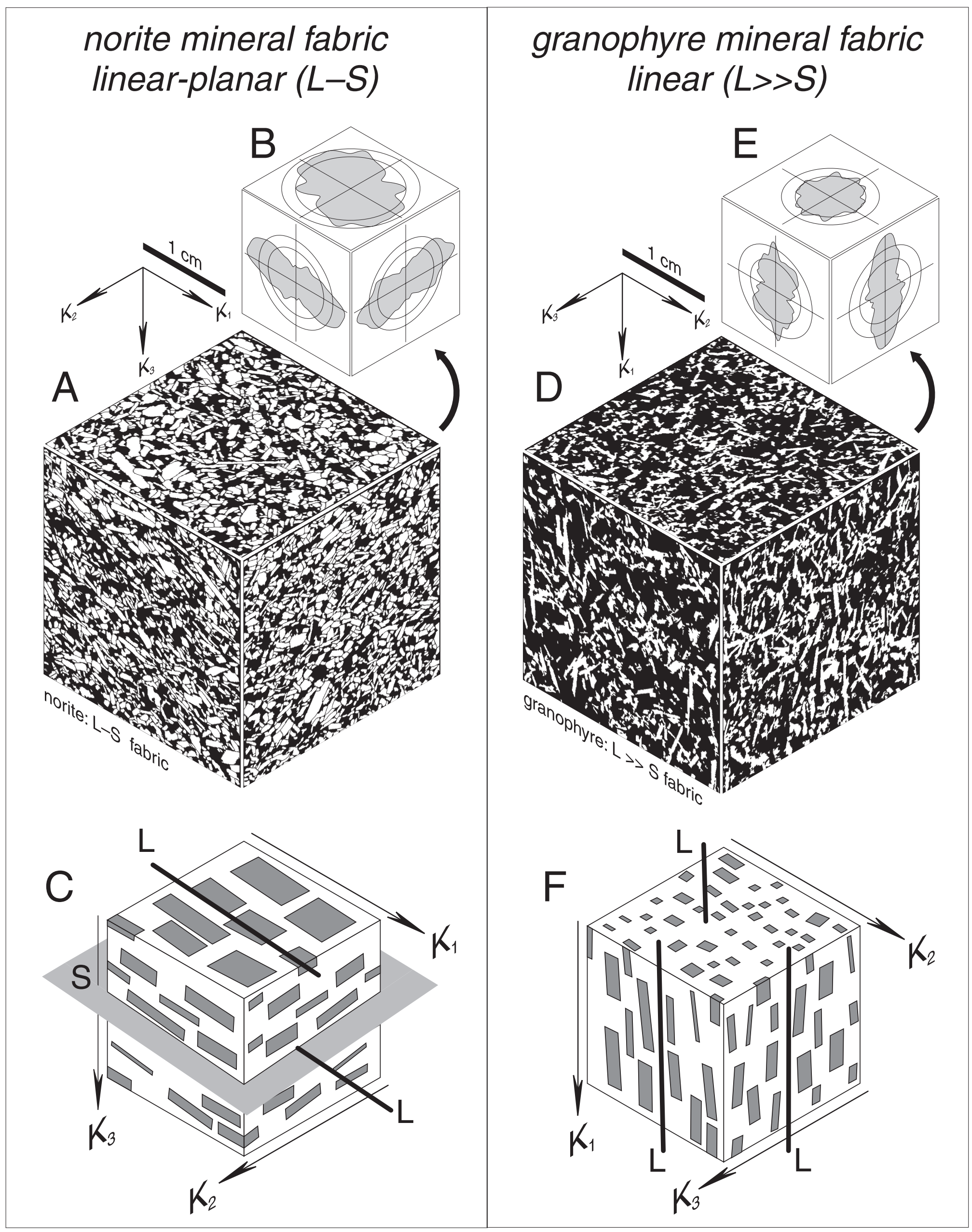


Figure 3. A, Plagioclase fabric of norite from site 3099 in the North Range (Fig. 2, UTM 467240E, 5162260N). As shown in Figure 2, the mineral foliation is subparallel to the K_1– K_2 plane, which in turn is subparallel to the contact of the SIC. D, The plagioclase fabric of granophyre from site 3106 from the North Range near Onaping Falls (Fig. 2; UTM 470700E, 5161060N). The mineral lineation is defined by alignment of acicular plagioclase crystals that parallel the K_1 direction, which in turn is orthogonal to the contact of the SIC. Smoothed histograms of sectional plagioclase long-directions in both (B) and (E) are shown with the inner circle in the histogram plots representing uniform distribution, the outer circle is plus one standard deviation from uniform distribution. Block diagrams in (C) and (F) schematically show the mineral fabric represented in the L-S fabric of the norite (A) and L>>S fabric of the granophyre (D).

ment models for the SIC that may be distinguished by the mineral L-S fabric pattern in the gabbro and the norite include: (1) emplacement as an impact-induced melt-lake (Fig. 4B), (2) viscous drag of magma on intrusive contacts (Fig. 4C), (3) expulsion of magma as a consequence of roof subsidence (Fig. 4D), and (4) postemplacement adjustment of magma due to inclined magma chamber walls (Fig. 4E).

The radial lineation pattern in the gabbro and the norite is difficult to reconcile with a ponded impact melt-sheet. Such a melt-sheet would most likely undergo gravitational settling and compaction of early crystallized mineral phases. This would result in a dominantly foliated mineral fabric devoid of mineral lineation (S>>L fabric) (Fig. 4B), rather than in the observed L-S fabric. Viscous drag along the lower and upper contacts during magma intrusion provides a possible explanation for the obliquity between the contact and the mineral foliation and the radial mineral lineation (Fig. 4C). However, this early formed fabric will be short-lived, and will be destroyed by subsequent magma strain. The presence of identical down-plunging L fabrics in mineral phases of both the gabbro and the norite indicates that fabric formation persisted during the process of igneous fractionation and consolidation. Similar down-plunge L-S fabric geometry is known from large mafic intrusions with inclined basal contacts (e.g., Nicolas, 1992; Quadling and Cawthorn, 1994). In such intrusions, the lineation exhibits a radial symmetry with respect to the intrusive body in map view, comparable to the mineral fabric pattern seen at Sudbury. Gravitationally induced flow and drag within the magma chamber appears to be the most plausible explanation for the L-S mineral fabrics of the gabbro and norite (Fig. 4E). Such a process would occur throughout the fractionation process, thus explaining the presence of identical L-S fabrics in the gabbro and norite (Fig. 2).

In summary, the L-S mineral fabrics of the gabbro and norite are inconsistent with an initial horizontal geometry of these units. The contact-parallel mineral foliation and down-plunging mineral lineation of the norite and gabbro are best explained by igneous strain resulting from gravitational settling of magmatic mineral phases on inclined magma chamber walls. This process occurred over a protracted period of time, commensurate to that of the fractionation process.

MAGNITUDE OF SOLID-STATE STRAIN IN THE GRANOPHYRE

Although the South Range of the SIC is transected by south-dipping thrust surfaces of the South Range Shear Zone (Shanks and Schwerdtner, 1991b), the SIC is reported to be unaffected by solid-state strain elsewhere (Rousell, 1984; Muir, 1984). This is incompatible with the standard impact melt model for the SIC, as solid-body rotation during folding of an initially horizontal, and solidified impact melt-sheet, is required to produce dips of 40°–70° in the North and East Ranges, respectively (Fig. 2). Such rotations must invariably impart solid-state strain to the hinge zones of folds, for example, in the North and South Lobes

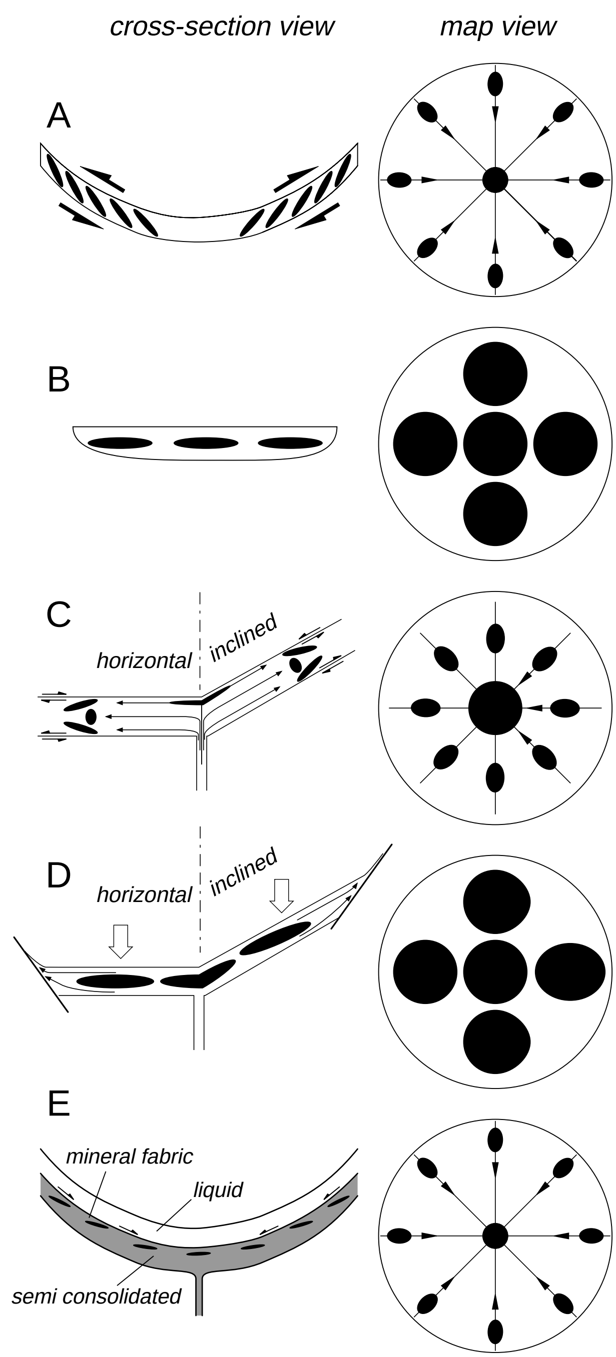


Figure 4. Kinematic and emplacement models for the gabbro and norite bodies and expected fabric patterns. Expected strain fabric resulting from (A) noncylindrical folding; (B) ponded impact melt, which is expected to produce a planar mineral fabric due to gravitational settling of crystallizing species; (C) frictional drag of magma on its wall during intrusion; D largely planar fabrics produced as a result of roof subsidence; and E, layer-parallel L-S fabrics resulting from gravitational strain effects and sedimentation within an inclined magma chamber. Mineral lineation (lines in map view, and arrow indicating plunge direction) is radial and down-plunging with respect to the parabolic shaped igneous magma chamber in the last scenario.

(Fig. 2). The strain magnitudes in rocks of these areas are very low (e.g., Dressler, 1987) but have never been estimated quantitatively. The aim of the following study is to quantify strain intensity of the granophyre in the North Lobe, and to compare these estimates with shortening strains expected to result from folding of a consolidated igneous sheet with the curvature equivalent to that of the North Lobe.

Analytical methods

The level of tectonic strain is difficult to estimate in igneous rocks that have been affected by a minor solid-state overprint. Magnetic fabric can, however, be used to quantify the tectonic strain. The magnetic fabric in weakly strained igneous rocks arises from the combination of strain acquired in the igneous state before consolidation and superposed solid-state strain. The igneous component of the AMS fabric is destroyed only if the imposed solid-state strain is large enough; otherwise, the igneous fabric will be detectable by AMS. The amount of shortening strain required to modify, and eventually obliterate, an AMS fabric due to igneous strain can be modeled numerically, assuming magnetic grain reorientation due to distortion of the host rock mass (Richter, 1992; Benn, 1994). Such a numerical method was used to estimate the amount of shortening strain resulting in the measured magnetic fabric anisotropy of the granophyre (Cowan, 1996, 1999). In order to compare these strain estimates with strains expected to result from folding of a consolidated igneous sheet, the interlimb angle of the SIC in the North Lobe was calculated by down-plunge projection. As in the fabric study of the gabbro and norite samples, the mineral fabrics of the granophyre were first estimated with AMS and supplemented by digital image analysis.

Results

Combined magnetic fabric and image analyses indicate that the microstructure of the granophyre is characterized by *comb-layering* or *crescumulate* crystalline texture (Moore and Lockwood, 1973; McBirney and Noyes, 1979). Crescumulate texture forms by wall-orthogonal crystal growth due to a temperature gradient and preferential crystal nucleation in the magma chamber (Lofgren and Donaldson, 1975; Lofgren, 1983). In the SIC, this fabric is distinguished by a mineral lineation oriented orthogonal to its basal contact and is best seen by eye in the plagioclase-rich granophyre (Peredery, 1972b) close to the upper contact with the Onaping Formation (Fig. 3B). The fabric is also readily identified by the contact-orthogonal magnetic lineation determined from nine sampling domains of the North and East Ranges (Fig. 5).

Interpretation

The crescumulate texture in the granophyre serves as an ideal natural strain gauge, as the initial orthogonality between its linear fabric element and the SIC contact will be destroyed if subjected to even minor tectonic shortening (Fig. 6). This is particularly relevant to the North Lobe if its curvature formed by flexural folding. This fold mechanism seems unlikely because the mean magnetic lineation is perpendicular to the basal contact of the SIC in all domains (Fig. 5). The orthogonality may, however, have been preserved during folding if strain axes were coaxial to the petrofabric, i.e., parallel to the axis of mineral alignment and the contact plane of the SIC such as by orthogonal flexure (Twiss and Moores, 1992, p. 240–241). In such a scenario, large shortening strains in the order of 30% in the outer arc and 50% in the inner arc of the fold are expected to be present in the host rock of the granophyre (Fig. 7).

Microstructural examination of host rocks revealed only minor distortion of quartz by dislocation creep (Cowan, 1999, Fig. 13). This indicates a low level of solid-state overprint and is therefore inconsistent with high shortening strains expected from folding by orthogonal flexure in the North Lobe (Fig. 7B). These observations are consistent with a maximum of 15% shortening in the granophyre, but are most likely much less based on numerical modeling of the magnetic fabric (Cowan, 1996, 1999). Further, the absence of layer-parallel stretching in the outer arc negates the orthogonal flexure mechanism in the North Lobe (Fig. 7).

In summary, the preservation of contact-orthogonal mineral and magnetic fabrics in the granophyre and overall low strain magnitudes in the North Lobe are inconsistent with a fold origin of the SIC in this area.

PALEO-PROTEROZOIC TECTONISM IN THE SUDBURY AREA

Three features have been attributed to either the formation of a multi-ring basin by meteorite impact (Grieve et al., 1991; Deutsch et al., 1995; Spray and Thompson, 1995) or crustal doming due to orogenic deformation (Cooke, 1948; Card et al., 1984; Riller, 1996; Riller and Schwerdtner, 1997) (Fig. 1): (1) circumferencial distribution of Huronian synforms around the SIC; (2) southward overturned Huronian strata exposed south of the South Range norite and (3) the presence of high-grade metamorphic rocks below, and north of, the SIC in the North Range. Dietz (1964) attributed the reversal of stratigraphic younging between the Whitewater Group and Huronian strata immediately south of the South Range SIC (Fig. 1B) to recumbent folding, analogous to overturning of strata at the collars of impact and explosion craters (Shoemaker, 1960; Jones, 1977; Roddy, 1977; Shoemaker and Kieffer, 1978). Consequently, the age and mechanism of tilting of Huronian strata are critical for deciphering impact-induced from orogenic deformation and thus for constraining the primary geometry of the SIC. In the impact model, the SIC was emplaced as a subhorizontal melt-sheet that cooled at the surface and acquired its synformal geometry by noncylindrical buckle folding prior to northwestward thrusting of the South Range (Grieve et al., 1991; Deutsch et al., 1995). Synformal buckling must have

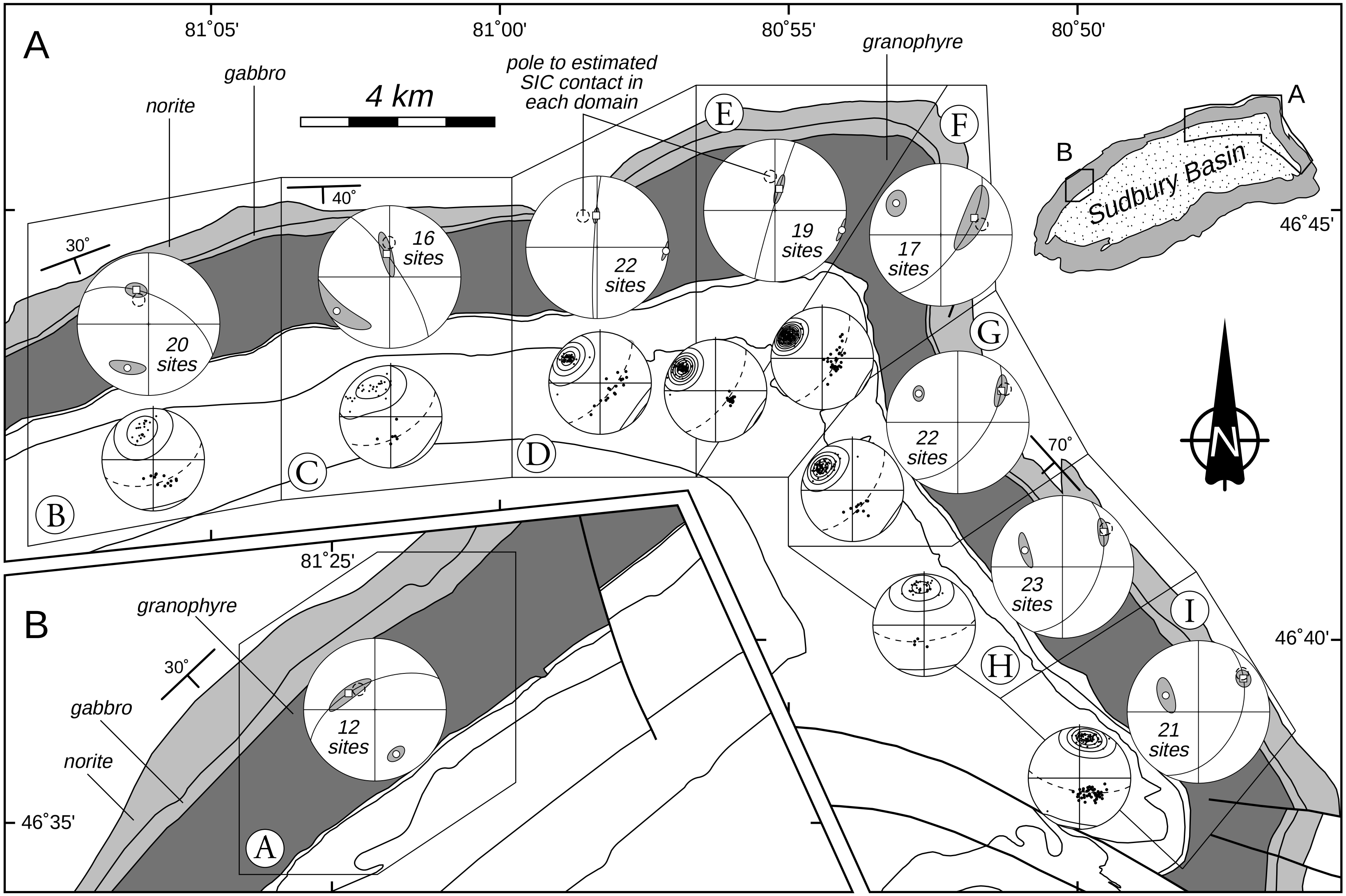


Figure 5. Mean magnetic foliation and lineation from the granophyre (dark shading; light shading indicates gabbro/norite). Each domain consists of as many as 23 sample sites, and each site has 3–12 core samples in which AMS fabrics were determined. Domain means of site-means were calculated according to statistical site averaging method of Jelinek (1978). Mean magnetic lineation (K_1) is shown in open square, and mean foliation pole (K_3) as open circle on the lower hemisphere stereonets with shaded 95% confidence cones about the mean values. Mean magnetic foliation also shown as solid great circle. Stereoplots are divided into Domains *A* through *I*, and the number of station means used to calculate the domain mean is shown in the stereonets. The dips of the North and East Ranges are also shown in map view and their estimated pole orientations are plotted as large dashed open circles for each domain on the stereonets. Note that the pole to the basal contact of the SIC in each domain is subparallel to the direction of the magnetic lineation in the same domain (see text). Smaller stereoplots show the tectonic foliation in the Onaping Formation (contoured) and lineation (not contoured). Mean tectonic foliation is drawn as a dashed great circle.

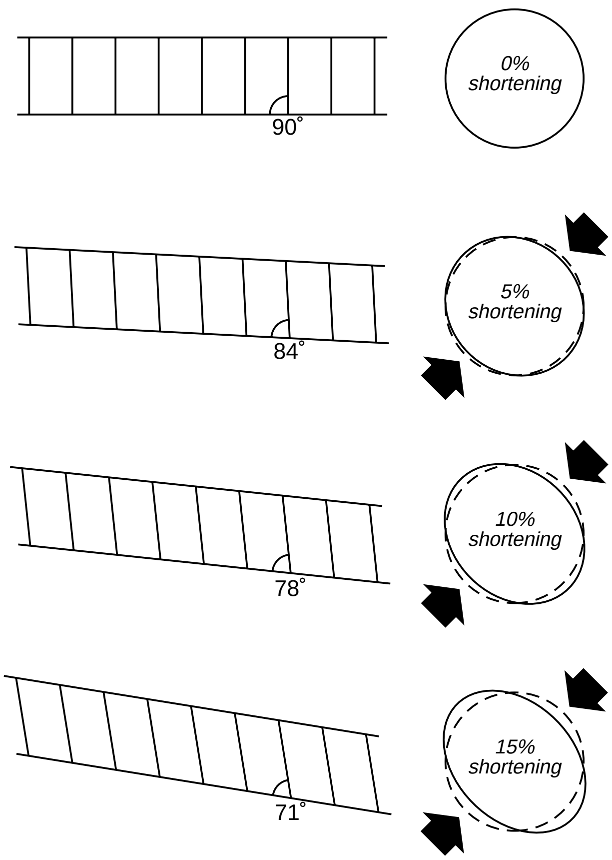


Figure 6. Diagram showing the departure from orthogonality of line elements for different amounts of coaxial homogeneous strain. At 0% total shortening, the vertical lines are analogous to the crescumulate fabric of the granophyre, whereas the horizontal lines represent the contact planes of the SIC. Note that orthogonality between line elements is lost after small amounts of shortening strain (see text for explanation).

imparted ductile strain to the SIC and its host rock unless rotation of these rocks was accomplished bodily. Nevertheless, the attitude of the Huronian strata south of the SIC should differ from that exposed along strike to the southwest of the SIC. Alternatively, orogenic crustal doming occurred prior to emplacement of the SIC. In this scenario, ductile strain in Huronian rocks should be larger and older than those in the SIC. Moreover, northwestward translation of the South Range would be the dominant shortening mechanism of the SIC and consequently ductile strain fabrics in the SIC should be associated spatially with the South Range Shear Zone.

In our previous studies (Riller, 1996; Riller et al., 1996, 1998; Riller and Schwerdtner, 1997), we presented structural evidence strongly supporting the formation of a Sudbury Dome during Blezardian tectonism and a primary synformal geometry of the SIC, which was modified by Penokean thrusting along the South Range Shear Zone. Based on these results, an outline of the effects of individual orogenic pulses on Huronian rocks and the SIC are presented below and complemented with results of a shape fabric and a paleostress analysis.

Blezardian tectonism (2.47–2.2 Ga)

Huronian rocks of the Elliot Lake Group acquired their pervasive tectonic foliation and lineation (Fig. 8B**)** during intrusion of the 2.33-Ga granitoid Creighton Pluton (Frarey et al., 1982) and the 2.47-Ga Murray Pluton (Krogh et al., 1996). Syntectonic intrusive relationships indicate that the pervasive strain fabrics in Huronian rocks formed under lower amphibolite facies conditions in the Blezardian tectonic pulse. The elliptical outline of the plutons at surface and low shape fabric intensities in granitoid rocks are best explained by emplacement of granitoid magma into a dilation zone between Archean basement and Huronian cover rocks during formation of the Sudbury Dome (Riller and Schwerdtner, 1997). Dilation at the basement-cover interface was most likely induced by fold detachment in its hinge zone during regional horizontal contraction. Since 2.2-Ga Nipissing gabbro bodies truncate the Vernon syncline, which is a section of the rim synform to the Sudbury Dome (Fig. 1), crustal doming occurred during Blezardian tectonism (Roscoe and Card, 1992).

Pervasive shape fabrics in ductilely deformed Huronian metavolcanic and metasedimentary rocks are defined by elongate primary markers such as vesicles, lapilli, pebbles, and preferentially oriented metamorphic mineral aggregates (Fig. 8B**)**. Assuming initial sphericity, these markers can be used for estimating total ductile strain imparted to Huronian rocks during orogenic deformation. Aspect ratios of 20–30 markers per station were measured in oriented rock samples cut parallel to the A–B and B–C principal planes of the shape fabric ellipsoid ($A \geq B \geq C$). Since the mineral lineation is subvertical and parallel to A, mean sectional shape fabric ellipse diameter ratios (R) on A–C planes are generally larger than those on the horizontal B–C planes that are shown in Figure 8B (for original data, see Riller and Schwerdtner, 1997). Apart from high diameter ratios ($R \approx 5$) and variable orientation of ellipse long axes near the margin of the Creighton Pluton due to contact strain, ellipses are characterized by moderate diameter ratios ($2 < R < 4$). The preferred orientation of ellipse long axes ($\phi \approx 60°$) parallel to the strike of the pervasive planar strain fabrics (Fig. 8B,C**)** suggests that most of the ductile strain seen in Huronian rocks accumulated during Blezardian tectonism and is therefore related to crustal doming.

Penokean tectonism (ca. 1.9–1.8 Ga)

Penokean ductile deformation occurred under middle greenschist facies metamorphic conditions but is not pervasive in the South Range of the SIC and its Huronian host rocks. A concentration of ductile strain due to competency contrast should be expected at the interface between Huronian supracrustal rocks, Proterozoic granite plutons and the norite if the SIC and its enveloping rocks were subjected to Penokean buckle folding. However, this is not apparent in the field. Kilometer-scale folds in Huronian strata, identified as Blezardian due to their axial-planar foliation formed under amphibolite-facies conditions, are truncated by effectively unstrained South Range norite (e.g., at station 3

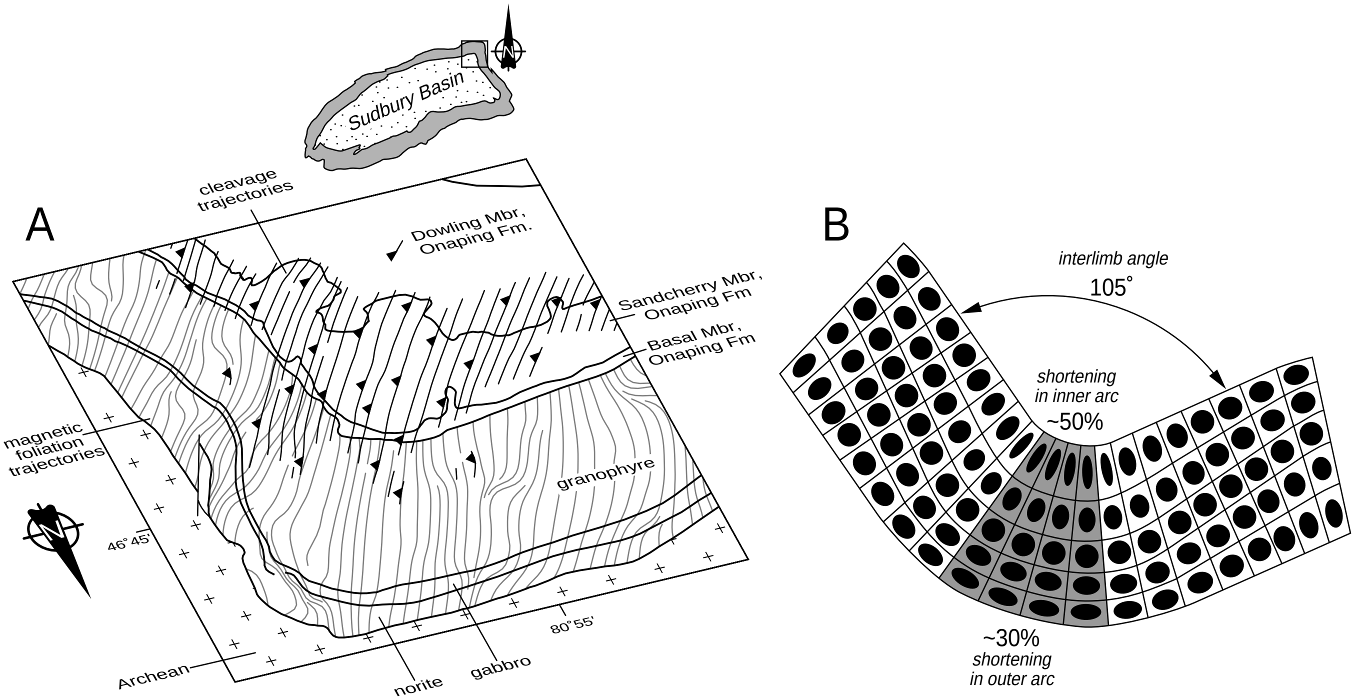


Figure 7. A, Down-plunge projection view of the North Lobe. The boundary between Sandcherry and Dowling Members (formerly Grey and Black Members) are marked by the appearance of shard layers, and not the absence or presence of carbon (see Ames and Gibson, 1995). Solid lines with dip-barbs are cleavage trajectories of the Onaping Formation and parts of the strained granophyre. Most of the SIC is unstrained, however, and the magnetic foliation is the only evidence for deformation (shown as the dashed trajectories). Note that these two sets of trajectories are subparallel to each other (both computer interpolated), and are axial planar to the North Lobe. B, Plane strain buckle fold showing orthogonal flexure in the hinge region (shaded) with the same interlimb angle as the North Lobe (105°). The outer arc must undergo layer-parallel stretch in order to preserve the orthogonality of lines, and conversely, axial planar shortening in the inner arc. This layer-parallel stretch is absent from the North Lobe shown in (A). Strain levels are also incompatible between the North Lobe (A) and the fold model (B), since shortening of ~50 and ~30% is theoretically required in the inner and outer arcs, respectively. Evidence for large degree of solid-state strain, however, is clearly lacking in the North Lobe.

in Fig. 8B). Similarly, hinge zones of mesoscopic Blezardian folds were destroyed by largely unstrained Sudbury Breccia bodies (see below). Finally, undeformed 1.85-Ga quartz-diorite Offset Dikes (Krogh et al., 1984) transect Blezardian shape fabrics in Huronian rocks (Fig. 8B).

Since the formation of pseudotachylyte (Sudbury Breccia) is regarded as penecontemporaneous with emplacement of the SIC (e.g., Spray and Thompson, 1995), shape fabrics of breccia fragments should record post-SIC Penokean strains. As vertical outcrop surfaces are rarely exposed, the mean diameter ratio (R) of these strains in horizontal section was estimated by applying the inertia tensor method (P.-Y. F. Robin, unpublished data) to the orientation and aspect ratio of 30–70 fragments per station (Fig. 8). Fabric ellipse diameter ratios of breccia fragments are considerably lower ($1 \le R \le 1.5$) than those of primary markers ($1.4 \le R \le 5.3$) in the same area (Fig. 8B,C). This confirms that most of the bulk ductile strain was imparted on Huronian rocks prior to emplacement of the SIC and is in agreement with static growth of greenschist-metamorphic mineral assemblages in Huronian metavolcanic rocks during Penokean tectonism (Riller and Schwerdtner, 1997). Consequently, the South Range and its Huronian host rocks were not affected by large amounts of shear-induced rotation due to buckle folding, or shearing on listric faults, during the later stages of Penokean ductile deformation.

By contrast, higher values of fabric ellipse diameter ratios are found on or close to the South Range Shear Zone (Fig. 8A). However, there is no preferred alignment of breccia fragments in Archean rocks north and west of the SIC (e.g., station 2047 in Fig. 8A). Thus, the South Range Shear Zone, and the spatially related ductile strain recorded in the Whitewater Group within the Sudbury Basin, appears to be the northernmost locus of Penokean ductile deformation (Clendenen et al., 1988; Shanks and Schwerdtner, 1991a,b; Hirt et al., 1993). Ductile strain fabrics of the South Range Shear Zone transect the southwestern SIC where they are concordant to the interface of Archean basement with Huronian cover rocks for about 15 km before turning southwest, at location 2310, to join with the Murray fault (Fig. 8A). This indicates that the shear zone is part of a regional thrust system, and is unrelated to local deformation associated with rotation of the North and South Ranges, as invoked by Cowan and Schwerdtner (1994). The sum of the above structural relationships suggest that Penokean shortening of the SIC and the Sudbury Dome was

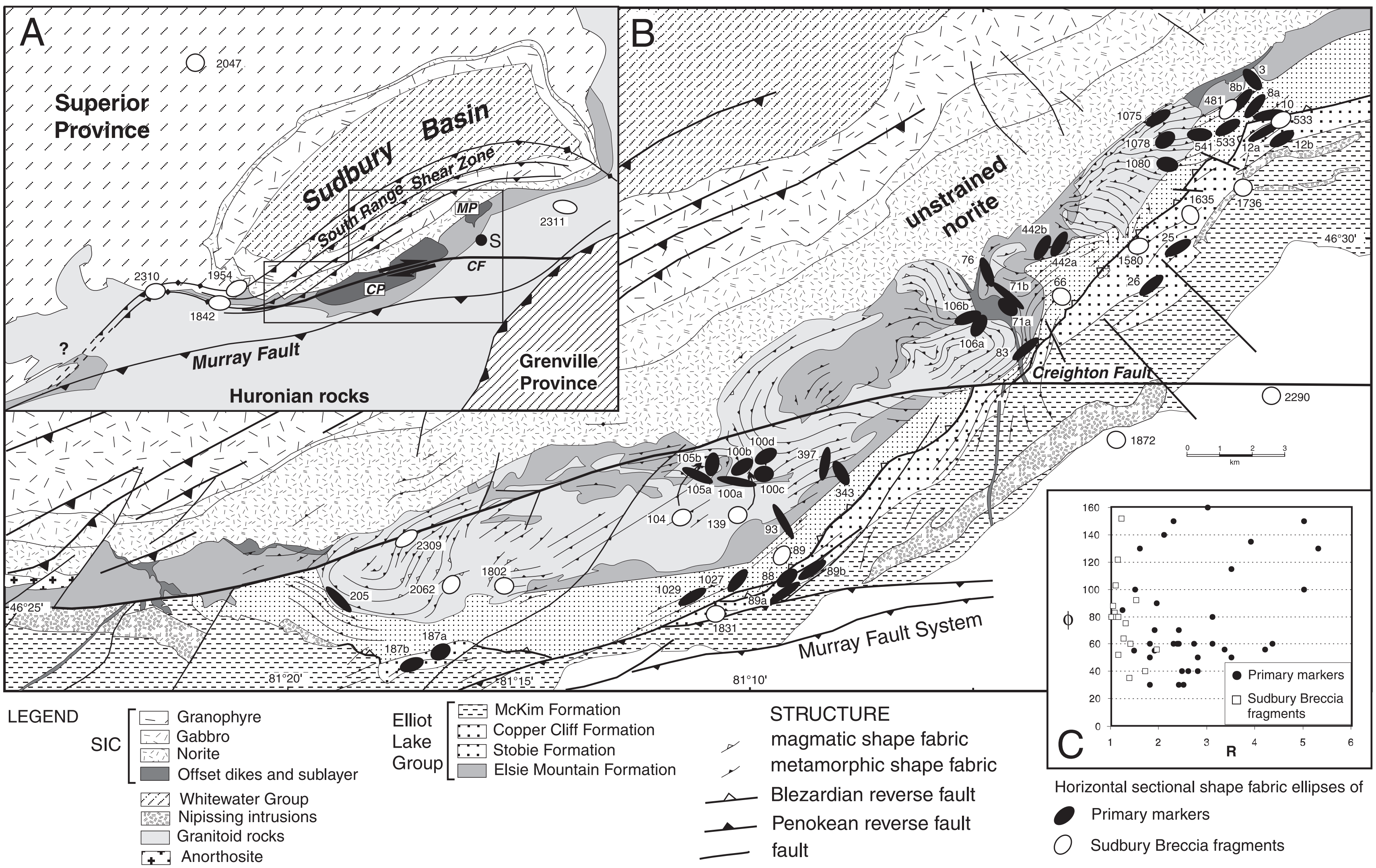


Figure 8. A and B, Ductile strain and shape fabrics in the South Range of the SIC and its host rocks (S = town of Sudbury; CF = Creighton fault; CP = Creighton Pluton; MP = Murray Pluton). Foliation trajectories of the South Range Shear Zone are from Shanks and Schwerdtner (1991a); those in Huronian rocks are from Riller et al. (1996) and Riller and Schwerdtner (1997). Ellipses represent the arithmetic mean of the normalized horizontal sectional aspect ratio of measured primary markers and Sudbury Breccia fragments per station. Unless indicated by arrows, the center of each ellipse is located at the station of data acquisition. C, Plot showing the diameter ratio (R) versus the azimuth (ϕ) of horizontal sectional shape fabric ellipses. Note that primary markers reflect the total strain, whereas shape fabrics of Sudbury Breccia fragments record Penokean strain accumulated after 1.85 Ga.

accomplished chiefly by imbrication of the South Range and its Huronian host rocks. Ductile distortion and rotation of these rocks due to large-scale Penokean buckle folding can be ruled out as an operative mechanism.

Late-Penokean contraction

Folding of the SIC and its host rocks may have been accomplished by rigid-body rotation under brittle conditions, i.e., at a late stage of Penokean deformation. This requires the presence of mainly layer-parallel discontinuities with substantial offsets (Cowan and Schwerdtner, 1994), which should be particularly apparent where the curvature of the SIC is greatest (i.e., the North and South Lobes and the southwestern part of SIC). Faults transecting the SIC in the North Lobe occur only in its eastern limb (Fig. 2), and strain patterns associated with the faults in the South Lobe are consistent with dip-slip displacements (Cowan, 1996). These strain patterns, cannot explain the sharp curvature of the SIC at these localities. Similarly, large strike separations on faults transecting the southwestern SIC are attributed to northwestward translation of the South Range on thrust surfaces of the South Range Shear Zone (Shanks and Schwerdtner, 1991a).

To further explore the possibility of late-orogenic, noncylindrical buckling of the SIC, we analyzed the principal paleostress directions using small-scale shear fractures with known slip sense (slickensides). The orientation of 1,100 fault surfaces and their respective slip sense was recorded at 55 stations in the Sudbury area (Fig. 9). The orientation of compressive principal paleostresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) was calculated using the algorithm by Sperner and Ratschbacher (1994) based on the numerical dynamic analysis of calcite twin lamellae by Spang (1972). Assuming that deformation was coaxial and occurred under a homogeneous stress field and that the striation on a fault surface is parallel to the direction of the maximum resolved shear stress, the direction of the calculated maximum compressive stress (σ_1) will be close to the incremental shortening direction (Bott, 1959; Pollard et al., 1993). Taking into account field observations on mineralization and cross-cutting relationships, successive brittle deformation increments can then be distinguished by separating a given fault population into homogeneous subsets. Noncylindrical buckling of the SIC requires the presence of at least two such subsets, which are expected to differ substantially in their respective σ_1 directions.

Calculated σ_1 directions in Huronian rocks and the SIC are subhorizontal and show a strong preferred orientation in northwest-southeast direction, whereas σ_2 and σ_3 directions delineate a great circle perpendicular to the mean σ_1 direction (Fig. 9C). By contrast, σ_1 in the Grenville Province indicates east-west compression (Fig. 9A). The paucity of such σ_1 directions north of the Grenville Front and the fact that mineralized fault surfaces have not been observed in 1.23-Ga Sudbury dikes (Krogh et al., 1987) suggest that brittle deformation in Huronian rocks and the SIC is unrelated to Grenvillian tectonism and likely to be late Penokean in age. Moreover, fault surfaces in the Sudbury area are generally decorated by single sets of chlorite fibers that are parallel to occasional calcite or quartz fibers on the same surfaces. This indicates a constant direction of shear stress during fault reactivation and is in agreement with uniform northwest-southeast orientation of σ_1. The calculated stress states are correlate well with late Penokean reverse shear on the South Range Shear Zone and dextral strike-shear on the Murray and Creighton faults. However, uniform northwest-southeast–directed compression is incompatible with noncylindrical folding of the SIC.

Grenvillian tectonism (ca. 1.2–1.1 Ga)

Owing to the parallelism of structures in Huronian rocks with those in the adjacent Grenville Front in the Sudbury area, shortening of the Sudbury Structure has also been attributed to Grenvillian contraction (e.g., Wynne-Edwards, 1972). However, the structural and thermal effects of the Grenvillian orogeny on Huronian rocks were insignificant on a regional scale. The strike of first-order structures in the eastern Penokean Orogen changes progressively from east-southeast between Sault St. Marie and Blind River to north-northeast near Sudbury and to dominantly north in the Cobalt Plate (Fig. 1A). This structural grain is truncated by, but not deflected near, the northeast-striking Grenville Front. Furthermore, dikes of the 1.23-Ga Sudbury Swarm are effectively undeformed and unmetamorphosed and transect Penokean ductile strain fabrics such as the South Range Shear Zone. Metamorphic temperatures due to Grenvillian overprint of Huronian rocks, exposed about 60 km northeast of Sudbury, decrease to less than 400°C beyond a distance of 2 km from the Grenville Front (Hyodo et al., 1986).

In summary, the structure and distribution of Huronian rocks as seen at the current level of erosion in the Sudbury area can be explained without invoking rotation of strata as a consequence of impact-related deformation. The lack of structural evidence for ductile and brittle folding strain in the SIC and its host rocks after 1.85 Ga during the Penokean and Grenvillian tectonism suggests that the parabolic geometry of the SIC is mostly primary.

SYNTHESIS

Historical interpretations

Several lines of independent structural evidence presented herein lead us to regard the shape of the SIC as parabolic or funnel-shaped at the time of its consolidation (Fig. 10): (1) the presence of radial igneous fabrics of the gabbro and norite dipping toward the center of the synformal SIC, (2) the preservation of crescumulate petrofabrics of the granophyre in the North Lobe, (3) steep attitudes of Huronian strata prior to the emplacement of the SIC, and (4) the absence of structures indicating strain imparted to the SIC and its Huronian host rocks by buckle folding. Such interpretation of structural field relationships with regard to the primary shape of the SIC is not new. About 40 yr ago, in situ differentiation was commonly accepted as the origin

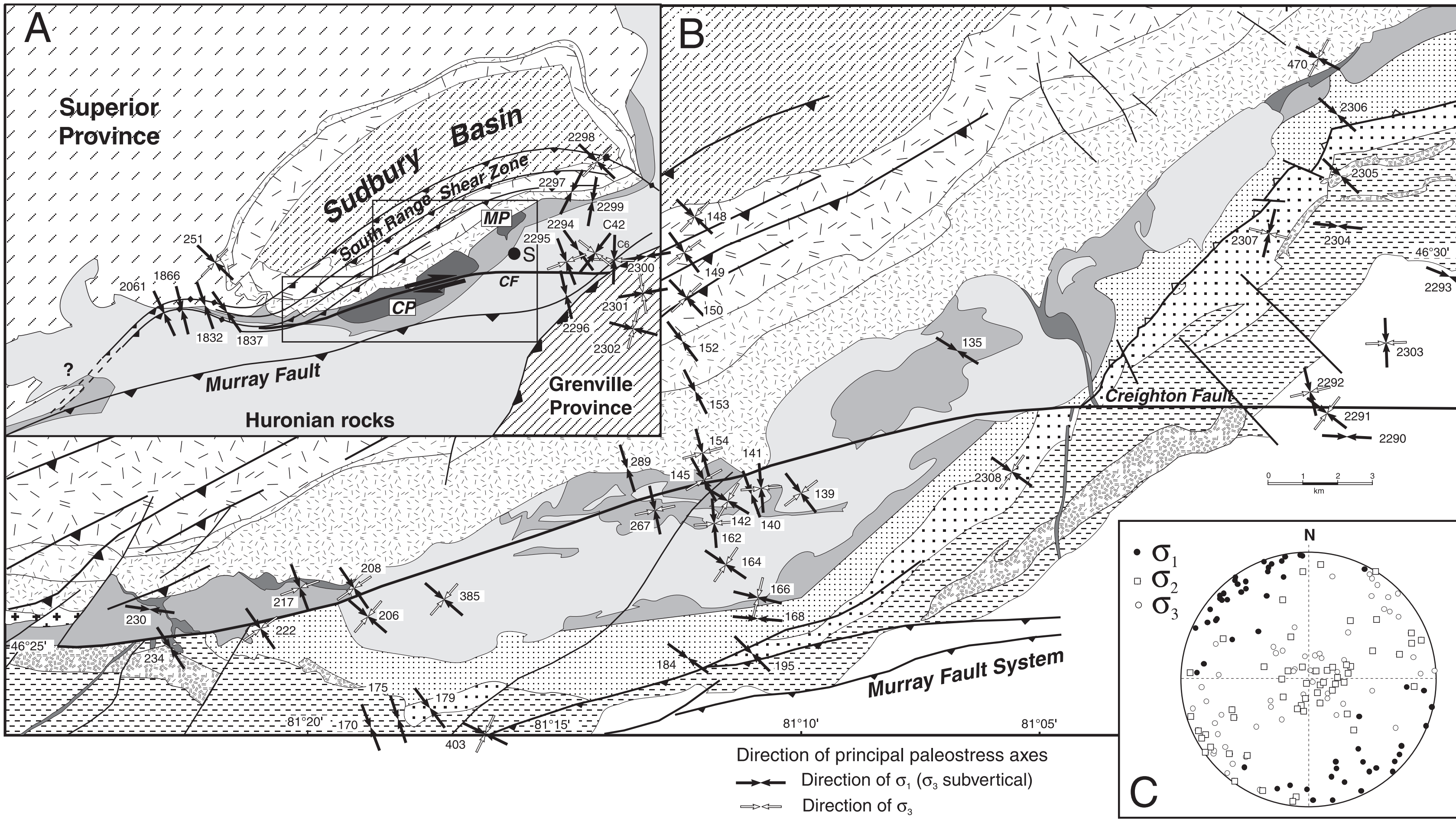
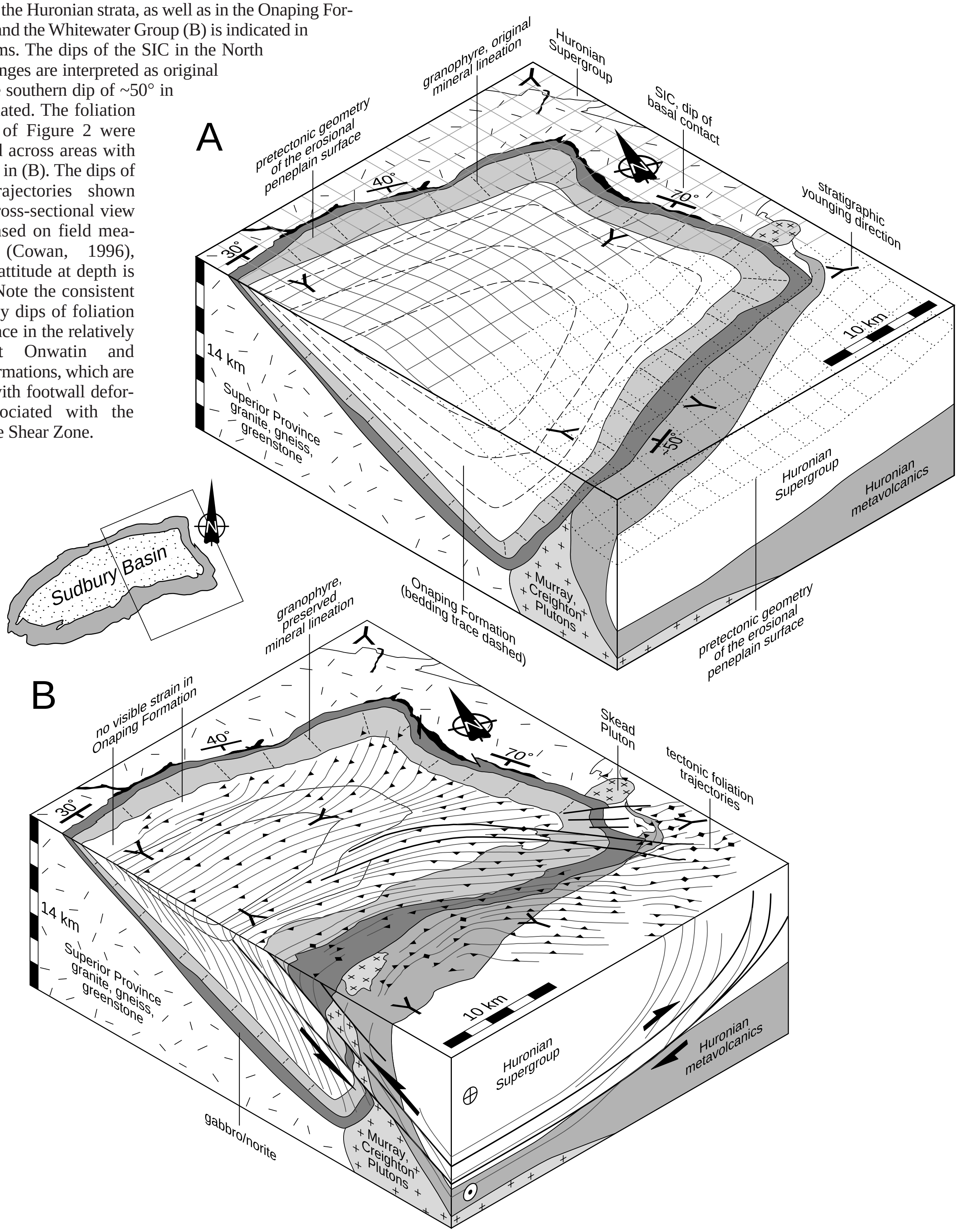


Figure 9. A and B, Map showing the direction of principal paleostress axes ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) derived from analysis of late orogenic, brittle shear fractures in rocks from the Sudbury area and the Grenville Front. Legend explained in Figure 8. B, Lower hemisphere equal-area projection showing orientation of principal paleostress axes in the SIC and Huronian rocks.

Figure 10. A, Scaled isometric block diagram of the eastern Sudbury Structure at the time of consolidation of SIC, after the deposition of the Onwatin Formation (bedding trace in dashed lines); and B, diagram of the present structural configuration of the Sudbury Structure. The upper paleohorizontal plane of the block diagram in (A) is tangential to the present erosional peneplain surface (mesh surface) in the north, but does not represent the upper depositional surface of the Onaping Formation. The funnel-shaped SIC necessarily implies that the Onaping Formation filled a parabolic depression on impact. The lineated and contact-orthogonal mineral fabric of granophyre is schematically shown in both diagrams, but its delicate fabric is destroyed by the South Range Shear Zone in (B). The stratigraphic younging in the Huronian strata, as well as in the Onaping Formation (A) and the Whitewater Group (B) is indicated in both diagrams. The dips of the SIC in the North and East Ranges are interpreted as original dips, but the southern dip of ~50° in (A) is estimated. The foliation trajectories of Figure 2 were extrapolated across areas with no exposure in (B). The dips of foliation trajectories shown along the cross-sectional view in (B) is based on field measurements (Cowan, 1996), while their attitude at depth is estimated. Note the consistent southeasterly dips of foliation seen at surface in the relatively incompetent Onwatin and Onaping Formations, which are consistent with footwall deformation associated with the South Range Shear Zone.



of the tripartite main mass of the SIC. Thomson and Williams (1959, p. 61) stated that "Those who persist in believing that the eruptive is a folded sill must explain why much of its south side is overturned toward the north whereas the beds beyond are 'right side up' and facing south at high angles. They must also explain why most of the east side of the eruptive is very steep…," and, "In fact, gravitational magmatic segregation of the type generally visualized at Sudbury is *physically impossible* [their emphasis] in those places where the eruptive dips vertically or outward, when it is known that the eruptive was never extensively folded after its emplacement." While reverse shearing of the southern SIC may well have affected its attitude (Shanks and Schwerdtner, 1991a), the comments of Thomson and Williams (1959) still apply to the eastern SIC, which is characterized by dips of 70° (Fig. 2), in some places reported to be vertical (Dressler, 1982, p. 94). Similarly, Cooke (1948) explained the subvertical attitude of south-facing Huronian strata south of the SIC by folding prior to emplacement of the SIC, which is also corroborated by our structural results (for details, see Riller and Schwerdtner, 1997; Riller et al., 1998). Thus, the above observations, which have been part of the geologic literature for a long time, must be incorporated into models of the emplacement and primary geometry of the SIC.

Contrasting SIC petrofabrics

A common characteristic of terrestrial impact melts is that they cool as a single unit (Grieve, 1975; Floran et al., 1978). The pattern of mineral fabric in the norite and the gabbro differs from that of the granophyre and indicates that these units could not have shared the same crystallization history. Unlike the granophyre, which does not record a petrofabric modified by gravitationally induced flow, the gabbro and norite exhibit well-developed contact-parallel L-S mineral fabrics. This may indicate that the crystallization period of these phases relative to the granophyre was longer. The contrasting petrofabrics of the granophyre and the gabbro/norite may indicate, but do not necessarily prove, different origins for both units and appear to conflict with the hypothesis that the entire SIC was created by in situ differentiation of an impact melt. Chai and Eckstrand (1993a,b) suggested that two chemically distinct magmas contributed to the formation of the SIC. Their interpretation is corroborated by the phase equilibria calculations of Ariskin (1997), who could not account for the high volumetric proportion of granophyre by in situ differentiation of a single magmatic body. Unusually high volumetric proportion of the granophyre in relation to the mafic phase of the SIC suggests either, the presence of a large hidden parental source, regardless of whether the SIC is interpreted as an impact melt, mantle-derived body, or a mixture of the two; or it suggests that the granophyre phase represents an impact melt, whereas the gabbro, norite, Sublayer, and Offset Dikes were derived mainly from an impact-induced magmatic source (Dence, 1972; Shanks et al., 1990; Dressler et al., 1996). We cannot rule out either model on the basis of our structural data. However, both scenarios are consistent with the observed chemical discontinuity between the granophyre and norite/gabbro layers (Chai and Eckstrand, 1993a,b) and the contrasting petrofabric character of the granophyre and the norite/gabbro phases (Fig. 3).

Initial geometry of the SIC

Seismic profiles show that the SIC is bound by two parallel contact surfaces (Milkereit et al., 1992). This excludes emplacement models in which the primary geometry of the SIC is characterized by a concave base and a horizontal top, i.e., a ponded impact sheet (e.g., Grieve et al., 1991, Fig. 8; Wu et al., 1994, Fig. 4A; Thompson and Spray, 1994, Fig. 8; Wood and Spray, 1998, Fig. 7). Such an initial configuration of nonparallel surfaces requires substantial tectonic strain to generate the observed parallelism of the base and top of the SIC. However, there is no field evidence for large strains in the SIC of the East and North Ranges (Rousell, 1984; Muir, 1984). Consequently, theoretical models that invoke large degrees of tectonic strains in the entire the SIC are implausible (e.g., Morrison, 1984, Fig. 23.3; Golightly, 1994, Fig. 10.3; Roest and Pikington, 1994, Fig. 3). We argue that the upper surface of the SIC was initially nonhorizontal and that the SIC consolidated as a parabolic body. Strain data suggests that the SIC was never circular along a horizontal plane (i.e., not the present erosion plane, since this plane was not originally horizontal: see Fig. 10A**)**. Thus, the North Lobe and the South Lobe are most likely primary features (Fig. 10A**)**.

Knowledge on the original dips of the gabbro/norite and granophyre sheets is most critical for discriminating between emplacement models. In situ differentiation of the SIC, characterized by primary contacts dipping between 30° and 90°, would likely lead to subhorizontal phase boundaries between the norite, gabbro, and the granophyre. Based on the seismic image, however, the phases boundaries are subparallel to the inclined base of the SIC (Milkereit et al., 1992). Phase boundaries that are parallel to steeply inclined contacts are known from large ultramafic intrusions (e.g., references in Cawthorn, 1996). While it is possible that the relatively thin norite and gabbro sheets may have formed by in situ differentiation along steep contacts, such origin appears to be implausible for the granophyre, given its large volume in relation to the total volume of the SIC (Ariskin, 1997).

Conflicts with theoretical impact models

Our structural results of the SIC and its host rocks are best explained in terms of a primary parabolic geometry of the SIC, but this conflicts with popular impact cratering models. Finite-element models of large impact structures predict a horizontal impact melt-sheet ponded in a complex crater (e.g., references in Melosh, 1989; Ivanov and Deutsch, 1997) and are consistent with the geometry of impact-melt rocks associated with some terrestrial impacts (Grieve, 1975; Floran et al., 1978). Assuming that our interpretation of structural relationships is correct and that geochemical data are consistent with at least the granophyre representing impact melt (Chai and Eckstrand, 1993b), numerical models predicting impact cratering dynamics, melt generation, and emplacement may not readily apply to the SIC. In particular, such models do not account for the inferred emplacement of the granophyre sheet in a parabolic geometry after deposition of the Onaping Formation. They are compatible with an origin of the granophyre only as a melt sheet ponded in the impact crater before emplacement of the suevite (assuming that the Onaping Formation represents a suevite [Ames and Gibson, 1995]). If the granophyre is regarded as an impact melt, a hitherto unknown physical process must have injected the granophyre magma after emplacement of the Onaping Formation. Any model explaining the origin of the SIC must account for its synformal geometry during consolidation.

Numerical models of impact cratering predict large differential displacements on faults at ultra-high strain rates and a pervasive disaggregation of target rocks by large amounts of rigid-body rotation and discontinuous deformation (e.g., O'Keefe and Ahrens, 1994; Ivanov and Deutsch, 1997). Such deformation has been explained by Melosh (1979) in terms of acoustic fluidization. It is inferred that the process of acoustic fluidization can be accomplished only by distributed fracturing of the crust, yet there is little field evidence for the presence of an extensive network of brittle faults separating rotated blocks in Archean or Huronian target rocks. Pseudotachylyte dikes in the Sudbury area have been recently interpreted as structures marking fault surfaces that formed during the latest stage of crater modification (Thompson and Spray, 1994; Spray and Thompson, 1995; Spray, 1997). The lateral continuity of these features, however, remains to be substantiated with detailed fieldwork away from road exposures (Spray and Thompson, 1995, Fig. 1A). Moreover, the continuity of pre-SIC structures in Huronian host rocks bordering on the southern SIC suggests little differential rotation within these rocks following the impact (Cowan and Schwerdtner, 1994; Riller, 1996). We contend that much of the geologic history of the Sudbury area can be explained without invoking impact-related deformation. The conspicuous lack of extensive translation and rotation of target rocks upon impact (cf. Melosh, 1979) must be included in impact cratering models.

CONCLUSIONS

Results of our structural analysis of the Sudbury Igneous Complex and its host rocks suggest that the complex had a parabolic geometry and was noncircular in plan view at the time of its consolidation (Fig. 10). Structural evidence for these conclusions include the following points:

1. The presence of radial igneous fabrics of the gabbro and norite dipping toward the center of the synformal SIC, interpreted to be a product of inwardly dipping initial SIC contacts.

2. The preservation of contact-orthogonal petrofabrics of the granophyre in the North Lobe, implying that folding was not responsible for the tight curvature after consolidation of the granophyre.

3. Steep attitudes of Huronian strata prior to the emplacement of the SIC, consistent with a formation of a structural dome prior to the Sudbury impact event, but inconsistent with impact-related overturning of strata.

4. The lack of evidence for large strains imparted to the SIC and its Huronian host rocks by noncylindrical buckle folding, which is required if the SIC was a horizontal sheet prior to deformation.

We concur with the original interpretation by Dietz (1964), in which the Sudbury region was the site of a hypervelocity impact. Our structural evidence appears, at least indirectly, to partly affirm Dietz's interpretation that the SIC is an impact-induced magmatic body (see also French, 1970), or more precisely, a mixture of impact melt and magmatic component generated by impact-induced decompression melting (cf. Dence, 1972; Dressler et al., 1996; Rousell et al., 1997). While recent geochemical evidence for the contribution of impact-induced crustal melt appears persuasive to some (e.g., Lightfoot et al., 1997), the geometric state of the SIC is inconsistent with presently accepted models of impact cratering. The chemical signature of crustal contamination of the SIC will remain a contentious issue until our structural data are incorporated into a unifying geologic model explaining the compositional and geometric peculiarities of the SIC.

There are many geologic features of the Sudbury Structure that cannot be explained with current models of impact cratering: (1) the primary basinal geometry of the SIC, (2) the inferred nontabular initial geometry of the Onaping Formation (Fig. 10A), (3) the paucity of large rotated blocks bound by pseudotachylyte dikes, and (4) the inferred late intrusion of the gabbro/norite (Dressler, 1987). In the light of our structural results, modes of impact melt formation and theoretical impact cratering models may have to be reassessed. Geologic features predicted from these models have led to a strongly biased interpretation of geologic relationships in the Sudbury area (e.g., Huronian outliers representing down-faulted blocks due to crater wall collapse) and to models that purport the existence of features that are not substantiated (e.g., interpretation of the SIC as a ponded melt, interpretation of pseudotachylytes delineating normal faults). Notwithstanding the fact that we may not immediately have satisfactory models to explain our observations, we view that careful description of field data is essential to interpreting and modeling observed features of the Sudbury Structure.

ACKNOWLEDGMENTS

We thank INCO, Ltd., and Falconbridge, Ltd., for permission to access their properties. Magnetic fabric statistics were computed using software AMS-PLOT written by John Dehls. Doreen Ames and Christina Wood are thanked for providing copies of their publications in press. The manuscript greatly benefited from comments by Stuart Brown, and from helpful reviews by Burkhard Dressler, Roy Kligfield, and Peter Schultz. This research was funded by an Ontario Geological Survey Special

Grant and Natural Enviroment Research Council operating grants (to W.M.S); by support from the Canadian Commonwealth Scholarship and Fellowship Plan (to E.J.C.); by Grant HSPII-AUFE from the German Academic Exchange Service and Grants Ri 916/1-1 and Ri 916/2-1 from the German Science Foundation (to U.R.). Computer support and funding during the preparation of the manuscript was provided by the Tectonics Special Research Centre, University of Western Australia. This is Lithoprobe publication 938.

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Manuscript Accepted by the Society December 16, 1998

Printed in U.S.A.