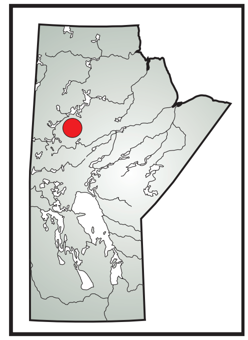

GS-8 Geometry and history of the Notigi Lake structure (parts of NTS 63O14 and 63B3)

by H.V. Zwanzig and L.A. Murphy

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Summary

The recently completed program of structural mapping and aeromagnetic interpretation at Notigi Lake was combined with stereographic analysis and a down-plunge-projection technique to decipher the Notigi Lake structure, a 30 km long inlier of mainly arkosic gneiss (Sickle Group) surrounded by metagreywacke migmatite (Burntwood Group) on the north flank of the Kisseynew Domain. The results are applied to further elucidate the regional structure and its probable continuity at depth and below lakes and recent cover. An understanding of the architecture of the uppermost crust is particularly important for identifying areas of nickel potential underlain by the newly described heterogeneous paragneiss (Wuskwatim Lake sequence) that locally overlies Archean basement rocks in the Northeast Kisseynew subdomain, southeast of Notigi Lake. The paragneiss is similar to the Ospwagan Group, which hosts ultramafic intrusions and all the nickel deposits in the Thompson Nickel Belt.

En échelon domes of the relatively younger Sickle Group at Notigi Lake were formed by the interference of late upright antiforms (F_3) with complex midcrustal recumbent structures (F_2) that refold major early folds (F_1) and a thrust. Applying this history to the economically important rocks in the Northeast Kisseynew subdomain indicates that this area, although not widely underlain by thick Archean basement at depth, hosts narrow structural inliers many kilometres long of Ospwagan-like rocks with nickel potential.

Introduction

In 2006, the Manitoba Geological Survey (MGS) initiated a program of remapping parts of the northeastern part of the Kisseynew Domain (Zwanzig et al., 2006), partly triggered by the Geological Survey of Canada's discovery of supracrustal rocks (the Wuskwatim Lake sequence of Percival et al., 2005) that contain virtually only Archean detrital zircons, like the Ospwagan Group, which hosts the nickel deposits in the Thompson Nickel Belt (TNB). Remapping has been most detailed in the Notigi–Wapisu lakes area (Murphy and Zwanzig, 2007; Murphy, 2008; Murphy and Zwanzig, GS-7, this volume). This area features a north–south tectonostratigraphic section from the margin of the Leaf Rapids Domain across the north flank of the Kisseynew Domain and into its northeastern subdomain. The structure at Notigi Lake has a complex geometry typical of the Kisseynew Domain, elsewhere resulting from widespread polyphase deformation. The principal structure at Notigi Lake, which is defined by six mappable Paleoproterozoic metamorphic units with known relative ages, acts as a proxy for the geometry of economically important, but poorly exposed, Archean basement and cover rocks that are structurally intercalated with Kisseynew metasedimentary rocks in the Northeast Kisseynew subdomain (Murphy and Zwanzig, Figures GS-7-1 and -2, this volume). The units in the Notigi Lake structure are characterized by a similar outcrop pattern and competency as the Archean outliers in the Wuskwatim Lake area, and must have a similar structural history. During earlier mapping (Baldwin et al., 1979), Archean rocks and their cover were included with the Proterozoic units in the northeastern part of the Kisseynew Domain, and were not fully traced out. The more recent studies indicated two possibilities for the structural geometry analyzed at Wuskwatim Lake (Percival et al., 2006): basement domes or more complex structural interleaving. An understanding of this geometry may prove critical for future exploration for nickel in the Northeast Kisseynew subdomain.

Geological setting

Map units at Notigi Lake comprise the Burntwood and Sickle groups of synorogenic Paleoproterozoic sedimentary rocks, and a volcano-sedimentary assemblage that is herein interpreted to be correlative with the older Paleoproterozoic Granville Lake assemblage discussed by Zwanzig (2008). The Sickle Group consists of various units of meta-arenite (Murphy and Zwanzig, GS-7, this volume) that are interpreted to have been deposited in shallow water on alluvial planes. It lies unconformably on the Granville Lake assemblage, which is well preserved northwest of Notigi Lake and extends north into the Leaf Rapids Domain, where it is interpreted to have a Paleoproterozoic basement and intrusions of volcanic arc plutons. The Burntwood Group paragneiss and migmatite were derived from greywacke-mudstone turbidite. They are interpreted to be in fault contact with the Granville Lake assemblage units, but units south of Granville Lake are also known to coarsen upward into the Sickle Group (Zwanzig, 2008). The Burntwood Group extends southeast into the Northeast Kisseynew subdomain, from Wapisu Lake (directly south of Notigi Lake) to the Thompson Nickel Belt (TNB) in the east. At Wapisu Lake, the Burntwood Group is in presumed fault contact with a thin sequence of heterogeneous paragneiss that appears to be typical of the rocks overlying Archean basement gneiss, including Archean detrital zircons (Percival et al., 2007; Murphy and Zwanzig, GS-7, this volume). The paragneiss is interpreted to be older than the Burntwood Group and intruded by pre-Burntwood quartz monzonite (Whalen et al., 2008). For these reasons, it is considered to be part of the Wuskwatim Lake sequence and related to the Ospwagan Group, which hosts all the nickel deposits in the TNB (Percival et al., 2005; Zwanzig et al., 2006; Murphy and Zwanzig, 2007).

Stratigraphic tops and the interpreted unconformity at the base of the Sickle Group on Notigi Lake are taken from regional relationships, the nearest reasonably well preserved primary structures being at Granville Lake, 75 km to the northwest (Zwanzig, 2008). Similarly, the fault contact between the Burntwood Group and the Granville Lake assemblage is evident at Granville Lake and other northwestern localities. The regional relationships, particularly near Lynn Lake (Gilbert et al., 1980; Zwanzig et al., 1999), indicate that the Granville Lake assemblage was thrust over the younger Kisseynew sedimentary rocks. This relationship was adopted as a working hypothesis for the Notigi Lake structure.

Structural geometry

The Notigi Lake structure is an irregular body 30 km long and up to 7.5 km wide, developed mainly in the Sickle Group and surrounded by the Burntwood Group rocks. It has an overall east–west trend with three contiguous northeast-trending segments (Murphy and Zwanzig, Figure GS-7-1, this volume). Each segment is an oval dome and is separated from its neighbour by a saddle structure. Two of these domes occur in the remapped area at Notigi Lake (Figure GS-8-1). The northeast ends of the domes plunge moderately to the northeast, whereas the southwest ends have a steep plunge, thus making the domes highly asymmetric. The downward facing of the unconformity in the outer mantle of the domes indicates that the outer contacts are structurally inverted. The older-over-younger relationship between the Granville Lake assemblage and the Burntwood Group indicates an early thrust. This relationship exists all along the Kisseynew Domain north flank (Zwanzig, 1990) and may explain the locally crosscutting nature of the outer fault. Based on its regional relationship, the outer contact fault is interpreted as a structurally inverted thrust.

The northeastern (Notigi) dome is the largest of the three and was analyzed in detail. Its asymmetric domal structure is illustrated in Figure GS-8-1, with β axes determined from girdles of poles to foliations in structural subareas. These axes show the local plunge of major folds pointing toward the margin of the dome, outward from its core at P and steeper at the margins. The Notigi dome, however, features not only the inverted outer contact with the Burntwood Group but also an inner, mainly upright core containing Burntwood Group gneiss also generally separated from the Sickle Group by the thin, apparently discontinuous Granville Lake assemblage. This geometry indicates that the Notigi dome represents a thick shell of Sickle Group gneiss overlain and underlain by the older units. Such structures can only be formed by nappe-like folding followed by doming. The outer and inner contacts have an identical fault relationship but face in opposite directions; the faults being referred to as the inner contact fault and the outer contact fault, respectively. The Sickle Group overlying the Granville Lake assemblage contains only biotite and magnetite as mafic minerals at the base (unit Kbt); then biotite-magnetite-hornblende (unit Khb); biotite and magnetite (also designated as unit Kbt); and at the stratigraphic top, biotite-magnetite-sillimanite (unit Ksm). The interlayering of units Kbt and Ksm may be the result of sedimentary facies changes or early folding. Between and inner and the outer contact faults, at Timew Island, the order of units is reversed, thus defining a syncline with its axial surfaces extending northwest across Timew Island (Figure GS-8-1). This structure is interpreted as an F_1 fold because it is affected by all other structures (*see* below). On the southeast side of the Notigi dome, the contact of the Burntwood Group (outer contact fault) cuts up the section from the Granville Lake assemblage to the upper unit (Ksm) in the Sickle Group. This may represent an imbrication or ramp in a décollement that originally lay below the earliest folds during D_1.

To analyze the complex refolding of the large F_1 syncline, a perspective diagram of the Notigi dome (Figure GS-8-2) was constructed from composite downplunge structure sections drawn from subareas with relatively uniform plunge (Figure GS-8-3). The panels in Figure GS-8-2 (viewed downward and to the north) show a major fold, about which the F_1 syncline and the contact faults are refolded. This is interpreted as an F_2 structure, a tight antiform shown in cross section in Figure GS-8-3a. It apparently had a gently north-dipping upper limb and a steeper overturned lower limb. Because of subsequent upright folding on the dominant northeasterly trend, the F_2 geometry is preserved as the east–west curvature of the dome and the abrupt change in plunge across the F_2 axial surface as well as the repetition of the main F_1 syncline on the northeast and southwest sides of the dome. The presence of the smaller contiguous dome to the east (D in Figure GS-8-1) suggests that adjacent F_2 folds formed large S-shaped structures with a southerly vergence. North of Timew Island, where there is little effect by later deformation, the main F_2 antiform plunges moderately northwest. The upright refolding has produced a major northeast-trending antiform interpreted as F_3 (viewed in panel C in Figure GS-8-2 and in Figure GS-8-3c. Several F_1 isoclines refolded in the F_3 antiform are apparent in Figure GS-8-3c, but their connection with F_1 on the south side of the dome is lost in a large area of unit Khb. The F_3 structure is developed mainly in the upper limb of the F_2 antiform; the F_2 hinge zone would have been

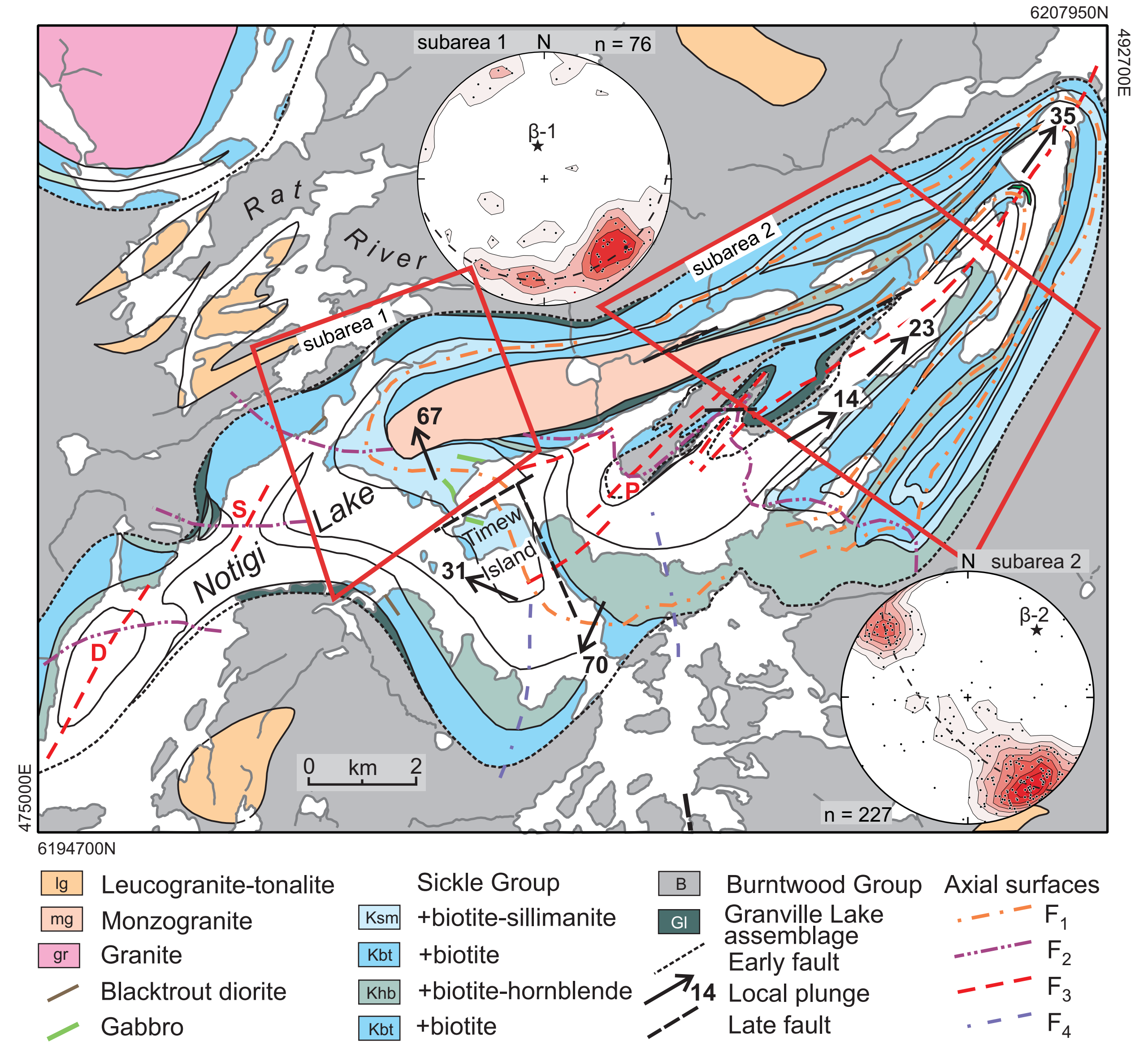

Figure GS-8-1: *Geological map of the Notigi Lake area showing the approximate locations of the main axial surfaces as interpreted by structural analysis from the interference pattern of units, stereographic projection of fabric data and the age relationships of fabrics and migmatitic veining (see text). The cores of two adjacent domes occur at D and P and their intervening saddle structure at S. The local plunge of major folds was determined in structural subareas; subareas 1 and 2 are shown with stereograms of foliation poles, their girdle distribution and β axis. Other selected β axes, similarly determined, also show the local plunge.*

more resistant to refolding than the long limb. The F_3 antiform appears to die out in the core zone of the older folds and is replaced by a late synform on the south side of the dome (F_4 in Figure GS-8-1). Such geometry is expected for superposed flexure folds formed in a relatively plastic state (Skjernaa, 1975).

The Notigi dome is thus an F_2-F_3 interference structure refolding an F_1 syncline. Because the F_3 hinge is superimposed on the F_2 antiform, it plunges gently northeast in the main part of the dome and steepens abruptly in the south. The F_2 antiform was least rotated in the F_3 hinge zone; therefore, the F_2 fold is suggested to have had a shallow to moderate northerly dipping axial surface and to represent a nearly recumbent antiform closing to the southwest.

The core of the Notigi dome features complex tubular (sheath) folds that show F_2-F_3 interference (at and above point P in Figure GS-8-3c). This was an area of strong constriction during F_3 folding, whereas the outer shells of the antiform show pinch-and-swell attenuation structures of the competent unit Ksm. This fold style is the result of flexural folding with a neutral surface between the core and the outer shells before it was tightened. Sheath folding has affected the inner contact fault and may have

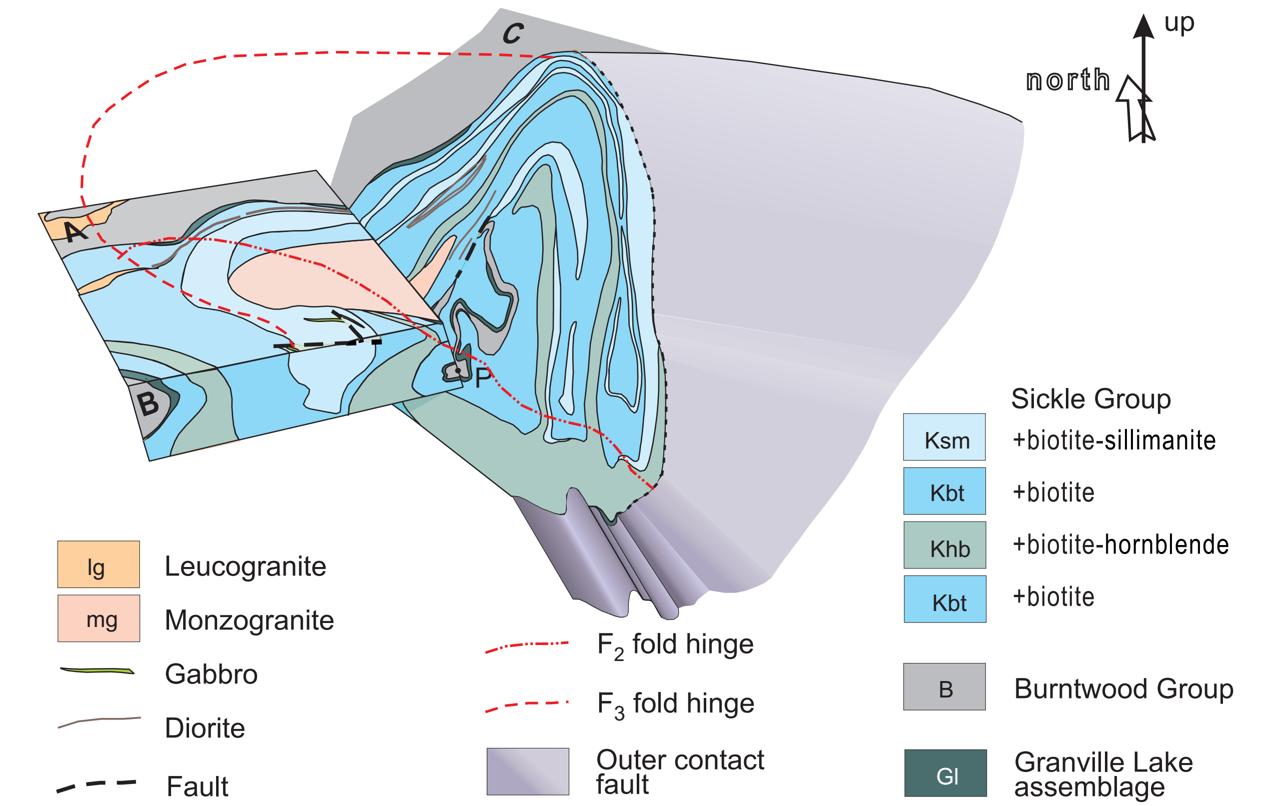

***Figure GS-8-2:** Perspective diagram representing the three-dimensional (3-D) geometry of the Notigi dome, viewed to the north and slightly downward. It was constructed from downplunge structure sections (a–c* in *Figure GS-8-3), each showing a different plunge as calculated using stereographic analysis. The three corresponding sectional cuts (panels A–C) are perpendicular to the mean local plunge. The panels are joined at point P. Panels A and B (on the left) are cut more or less parallel to the mean F_3 fold axis in the northeast and perpendicular to parts of the curved F_2 fold hinge. They also show the main F_1 syncline, which closes in panel B. Panel C is perpendicular to the mean F_3 fold axis, where it is only slightly curved in the northeast. The hairpin curve of the F_3 fold axis produced by the main F_2 fold is shown above panel A. The folded surface on the right front represents the D_1 outer contact fault.*

made the Burntwood Group in the core rootless, but the dismembered or contiguous root lies at depth to the northeast. The hairpin shape of typical sheath-fold hinge lines (F_3, shown in Figure GS-8-2) is also expected for the F_1 hinges, which are interpreted to have been transposed from any early trends into the direction of northeast bulk stretching and flow. Strong planar and linear fabrics and northeast-trending cliff faces represent D_3 shear zones that appear to truncate units in the core of the Notigi dome. The overall shape of the northeast half of the dome is a roughly triangular sheath that plunges toward the northeast at 14–35°. High stretching in that direction would have further modified the shape of the Notigi dome and may explain the narrow core of Burntwood Group gneiss deep in its interior and the completely encircling F_1 folds in its mantle.

On the south side of the Notigi dome, a pair of open folds that warp the F_3 axial surface are interpreted as F_4 structures. These consist of an open north-northwest–plunging synform south of Timew Island and a very open northerly plunging antiform to its east, as well as late faults (Figure GS-8-1).

Minor structures

Small-scale F_1 folds are generally absent or too attenuated to be prominent. In the Wapisu Lake area, directly south of Notigi Lake, where bedding is preserved in the Burntwood Group, isoclinal folds in competent greywacke beds appear to pinch and swell due to high subsequent strain (Figure GS-8-4a). Such isoclines are more apparent in the hinge zones of major F_1 folds at a higher crustal level such as in the Granville Lake area to the northwest. The F_2 folds were formed during the development of leucosomal veins that are commonly folded in F_2 but have apophyses in the axial surface (Figure GS-8-4a, -4b). The flexural style of the F_3 folds (in which the hinge zone is not thickened) is apparent in simple minor structures of that age (Murphy and Zwanzig, Figure GS-7-4a, this volume). Minor F_2-F_3 interference structures occur only locally but some have the same style and shape as the major Notigi Lake structure (Figure GS-8-4c).

Fabric development

Foliation occurs in three styles and generations. An early composite foliation (S_0-S_1), generally expressed as

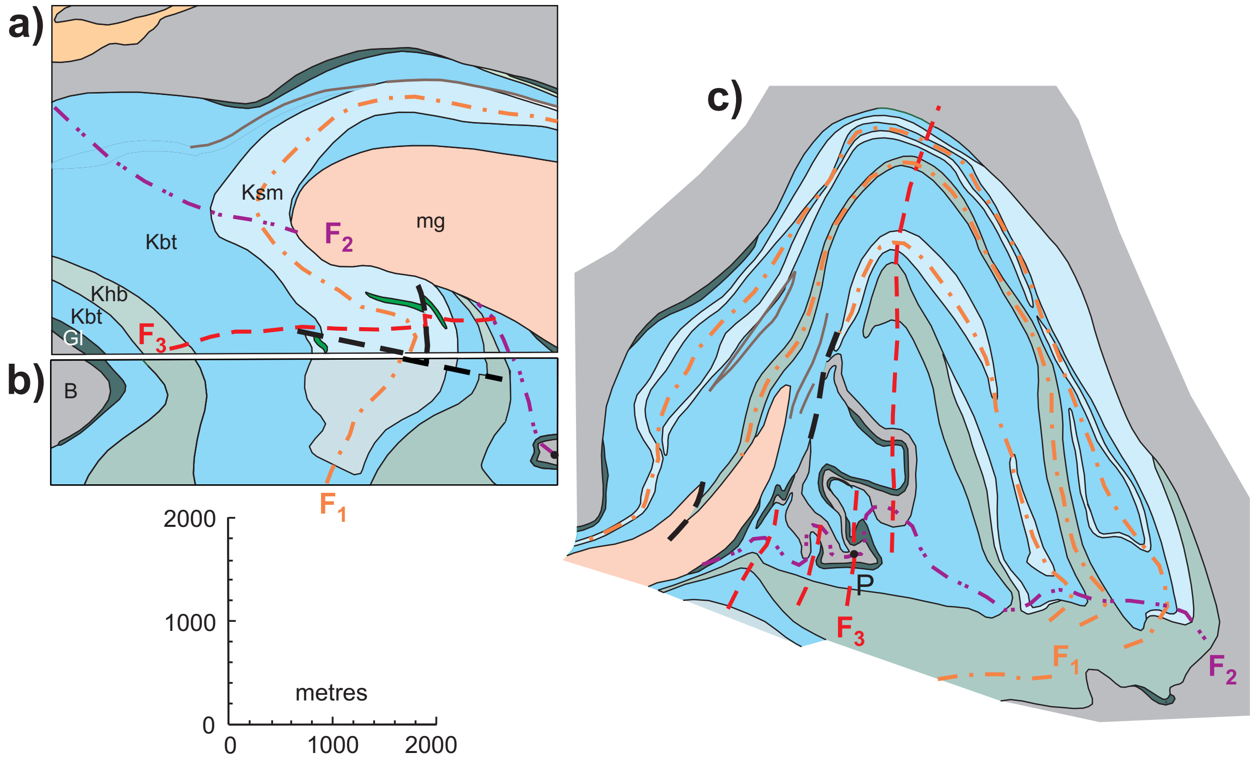

***Figure GS-8-3:** Downplunge structure sections (a–c) corresponding to panels A–C in Figure GS-8-2 that give their orientation and relative location in 3-D space. The margins of the sections are from the boundaries of the three structural subareas from which they were constructed and are necessarily distorted due to progressively changing plunge. Also shown are the approximate locations of the main axial surfaces: **a)** and **b)** the true F_2 fold cross sections and the somewhat distorted F_1 fold cross section; **c)** the true F_3 fold cross section with the refolded earlier structures.*

layering and parallel platy mineral alignment, occurs in the hinge zone and the steeper part of the lower limb of the main F_2 antiform, where it is at a high angle with the F_2 axial surface, evident in the central part of Notigi Lake. Shallowly dipping schistosity, also generally parallel to migmatite layering or primary bedding, commonly strikes into the northwest quadrant and dips to the north-northeast. Schistosity occurs locally parallel to the axial plane of F_2 recumbent minor folds and is therefore designated as S_2 (Figure GS-8-4d). Many areas have an anastomosing, northeast-trending, steeply dipping composite or transposition foliation (S_2-S_3) that acquired its final fabric and orientation during D_3. This foliation can express an extreme degree of flattening (Figure GS-8-4e). The transposition and external rotation also occurred under high-grade metamorphic conditions during development or injection of late leucosome and cannot generally be distinguished from S_2. Local excellent preservation of S_2 parallel to S_0-S_1 suggests that there was a flexural component to F_2 folding that allowed continued flattening of primary layering outside an F_2 neutral surface such as north of Timew Island and the pressure shadow of the Notigi granite.

The intersection of S_1 and S_2 produced local strong rodding (Figure GS-8-4f); most mineral and stretching lineations, however, plunge northeast or follow a hairpin bend along the crest of the Notigi dome (in the plane of the axial surface of the main F_3 antiform). Stretching is the result of the bulk internal strain and thus follows the intersection of the S_2 and S_3 planes of flattening. In the core of the dome and probably elsewhere, this is transposed into the direction of D_2 or D_3 flow. The similar fold styles, fabrics and participation of migmatitic leucosomes in the D_2 and D_3 phases suggest continuous deformation that started as midcrustal recumbent folding and continued as upright folding during the slow exhumation of the Kisseynew Domain.

Structural history

The progressive development of the Notigi Lake structure is best deciphered in the light of the regional structural history (Table GS-8-1).

The earliest recognized structures formed during D_1, possibly before complete lithification, presumably in a southeast-directed fold-and-thrust belt, as proposed for Granville Lake (Zwanzig, 2008). Early folding, coeval faulting and local fault imbrication at Notigi Lake are thus consistent with the interpretation of the early structural history at Granville Lake. Leucosomes folded by F_2 structures (Figure GS-8-4a, -4b) require at least 10 km of structural burial of the Sickle Group, which must have occurred during D_1 crustal thickening.

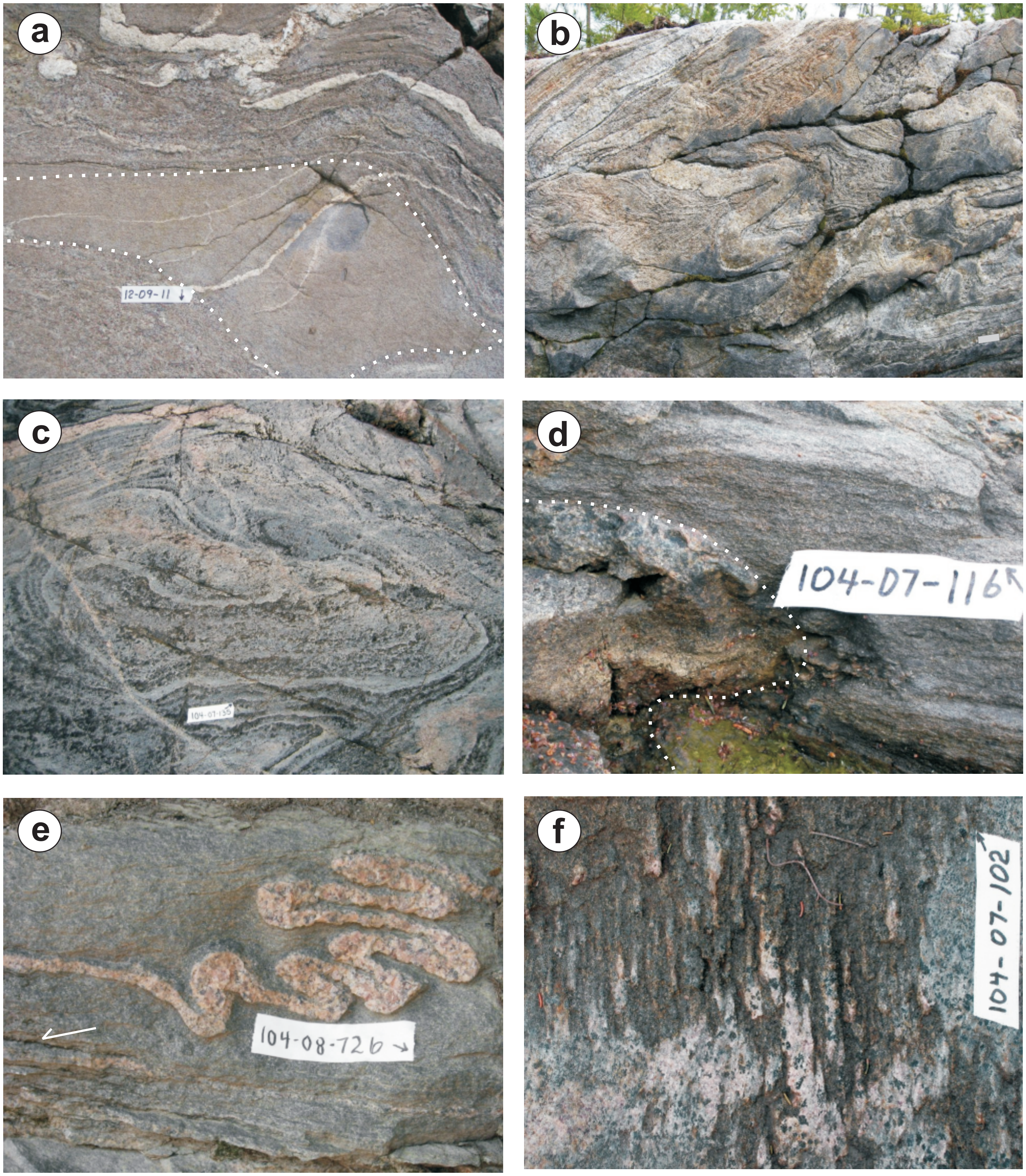

Figure GS-8-4: *Minor folds and fabrics. Tapes are 10 cm long with arrows pointing north:* ***a)*** *isoclinal fold in greywacke (lighter coloured outlined eye shape), interpreted as F_1 affected by later folding and pinch-and-swell; synkinematic granitoid veins show F_2 folding and injection into the axial plane;* ***b)*** *recumbent F_2 folds of bedding, early foliation and granitoid veins as seen on a steep rock face;* ***c)*** *F_2-F_3 interference structures near the hinge zone of a major F_2 anticline;* ***d)*** *S_2 schistosity parallel to the tape and the axial plane of an F_2 fold in bedding (outlined);* ***e)*** *ptygmatic fold showing extreme flattening in the plane of the composite S_2-S_3 schistosity (parallel to tape); note the immature fold pair (left of tape) inclined to the underlying sinistral shear zone (straight gneiss with C' fabric below arrow) and the overtightened mature folds (above the tape); such fold rotation and flattening is common in both D_2 and D_3 structures;* ***f)*** *rodding at the intersection of S_2 and early leucosome formed parallel to S_1 and bedding.*

Table GS-8-1: Local and regional structural history.

Kisseynew north flank				Kisseynew south flank[2]	
Notigi Lake		Granville Lake[1]			
D_1	F_1 folding (syncline closing at Timew Island) and thrusting (Granville Lake assemblage and Sickle Group over Burntwood Group)	D_1	Southeast-verging fold-and-thrust belt	D_1	Northeast-verging fold-and-thrust belt
	Development of S_1 schistosity				
D_2	Northerly overturning of Burntwood Group	D_2	North-verging F_2 backfolding	D_2	West-verging upright to recumbent folding with development of small nappes
	Recumbent southwest-verging refolding of D_1 structures (F_2 antiforms in core and mantle of Notigi dome); verical flattening, horizontal flow	D_3	Local southwest-verging folds in Sickle Group and common in migmatite south of Granville Lake[3]		
	Axial-planar S_2 schistosity; rodding at S_1xS_2			D_3	Recumbent refolding
D_3	Upright F_3 flexural flow folding forming the Notigi dome as F_2-F_3 interference with gently northeast-plunging sheath folds in the core	D_4	Northeast-trending upright folding	D_4	North-northeast–trending upright folding
	S_2-S_3 composite foliation transposing migmatite layering, S_1 and bedding				
D_4	Open F_4 folds with north to northeast plunge	D_5	Open northerly-trending folds	D_5	Northerly-trending, east-side-up faults
	Northerly trending faults				

[1] Zwanzig (1990); [2] Zwanzig (1999); [3] also northeast-dipping seismic reflectors in crust below Granville Lake.

The F_2 folds formed under high-grade metamorphic conditions at a midcrustal level over an extended period of D_2 deformation (Zwanzig, 1999). They represent subhorizontal plastic flow of the basement, cover and early plutons during the formation of large recumbent folds with structurally inverted lower limbs. The structural inversion of the outer mantle of the Notigi dome is interpreted to have formed early during D_2. It is consistent with the regional overturning of early structures at Granville Lake (Zwanzig, 1990) and in the Leaf Rapids Domain north of Notigi Lake, where the Burntwood Group also commonly overlies the Sickle Group (Elphick, 1972; Schledewitz, 1972). The reconstructed F_2 hinge at Notigi Lake suggests tectonic transport toward the south-southwest. Other areas on the Kisseynew north flank (e.g., Lenton, 1981) and south flank (Zwanzig, 1999) indicate a westerly vergence for F_2 folds. Thus, the F_2 hinges at Notigi Lake may have been rotated during D_2 flow or formed during an advanced stage of D_2 (called D_3 in Zwanzig, 1999).

Upright F_3 flexure folds are typical of the Kisseynew Domain (e.g., Lenton, 1981; F_4 in Zwanzig, 1990, 1999). They also characterize the structural culminations containing Archean basement with cover rocks at Wuskwatim Lake in the Northeast Kisseynew subdomain (Percival et al., 2006). At Notigi Lake, the structures are more plastic than elsewhere and probably formed deeper in the crust. This is consistent with the abundance of metamorphic clinopyroxene in the local amphibolite units: the rocks are transitional to granulite. Northeast-trending D_3 shear zones occur in the core of the Notigi dome. Figure GS-8-2 suggests that displacement was northwest side up.

Regional and economic considerations

The structure of the Notigi dome is very similar to structures elsewhere in the Kisseynew Domain (e.g., Lenton, 1981; Zwanzig, 1990) and its margins (Zwanzig, 1999). The complete Notigi Lake structure of three en échelon domes closely resembles the map pattern of inliers of Archean basement gneiss, its cover rocks and pre-Burntwood quartz monzonite plutons in the Northeast Kisseynew subdomain (Murphy and Zwanzig, Figures GS-7-1 and -2, this volume). The Notigi Lake structure can therefore act as a proxy for the structure of the inliers in that subdomain and answer questions regarding their continuity at depth (Percival et al., 2006). Understanding the 3-D geometry of these inliers may aid nickel exploration in the area.

Four en échelon domes were developed in early gneissic syenite–granodiorite (Footprint Lake plutonic suite of Whalen et al., 2008) with local sidewalls of Ospwagan-like supracrustal rocks extending from Attic Lake to Footprint Lake in an east-trending belt directly south of and parallel to the Notigi Lake structure (Murphy and Zwanzig, GS-7-1, this volume). A second belt, in which Archean basement is also locally exposed, extends from Threepoint Lake to Wuskwatim Lake and southward from Opegano Lake along the TNB (Murphy and Zwanzig, GS-7-1, this volume). These belts are interpreted to have a similar structural geometry as the Notigi Lake structure because they too are surrounded by Burntwood Group migmatite and have a similar structural history as the Granville Lake assemblage and Sickle Group.

Detailed structural mapping of these belts is impossible due to insufficient exposures, but the structural regional model derived from local analyses suggests that the belts of the Northeast Kisseynew subdomain have undergone possible D_1 interleaving along thrusts over the Burntwood Group and F_2-F_3 fold interference as well as later open refolding. The belts are parallel to the F_2 trend in the Notigi dome and are interpreted to have been flattened into F_2 recumbent folds and then refolded by F_3 upright structures to produce the en échelon pattern. This indicates that the Archean rocks and their cover sequences represent relatively thin refolded structures and that their volume at depth is most likely no more than at surface. Consequently, the Northeast Kisseynew subdomain is not widely underlain by thick Archean basement at depth. The large amplitude of the folds, however, indicates the possibility of structural windows of Ospwagan-like rocks many kilometres long but mostly covered by glacial drift and clay. As demonstrated in the TNB, diamond drilling will be required to identify the favourable supracrustal succession (i.e., the Wuskwatim Lake sequence of Percival et al., 2005). The recently published magnetic maps (Kiss and Coyle, 2008) and MGS geological maps published and in preparation should be a considerable help in such an endeavour.

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