Report of Activities 2003

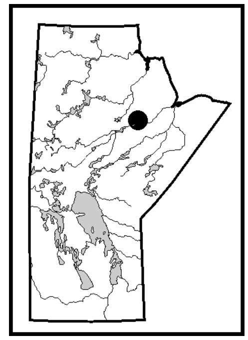
Published by:
Manitoba Industry, Economic Development and Mines
Manitoba Geological Survey, 2003.

ERRATA:

The publisher/department name in the bibliographic reference cited immediately below the title of each GS report should read **Manitoba Industry, Economic Development and Mines** instead of **Manitoba Industry, Trade and Mines**.

GS-13 **Bedrock mapping in the Gull Rapids area, northern Manitoba (NTS 54D6)**

by C.O. Böhm, M.S. Bowerman[1] and M.W. Downey[2]



Böhm, C.O., Bowerman, M.S and Downey, M.W. 2003: Bedrock mapping in the Gull Rapids area, northern Manitoba (NTS 54D6); *in* Report of Activities 2003, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 92–104.

Summary

Bedrock mapping at Gull Rapids forms an integral part of the new Superior margin program introduced in Böhm et al. (GS-12, this volume). Located at the northeastern margin of the Superior Province in Manitoba, Gull Rapids hosts a spectacularly exposed sequence of dominantly Archean supracrustal and intrusive rocks that have not yet been studied, and a planned hydroelectric project could make most of this exposure inaccessible to future investigation.

In the summer of 2003, the Manitoba Geological Survey, in collaboration with the Universities of Alberta and Waterloo, started a three-year integrated bedrock-mapping program with the aim of documenting the geology in great detail, to unravel the nature and age of the rocks and to resolve the timing and kinematics of structures at Gull Rapids. Mapping at 1:1000 scale, undertaken this summer, identified an Archean amphibolite-facies supracrustal assemblage consisting of amphibolite (metabasalt) and Fe-rich metagreywacke, with interlayered banded oxide-, sulphide- and silicate-facies iron formation. These supracrustal rocks are exotic compared to the dominantly meta-igneous granulite rocks of the Split Lake Block to the west and the Kisseynew-type metasedimentary rocks on Stephens Lake to the east. Comparable Mesoarchean supracrustal rocks are, however, exposed at Assean Lake.

The Gull Rapids supracrustal assemblage is in structural contact with Archean granodiorite and derived gneiss of currently unknown origin and age. Leucocratic felsic injection invaded both the supracrustal and granodiorite rocks, and major east-trending Paleoproterozoic mafic dikes cut all of the above rock types. Preliminary structural investigations using crosscutting relationships and orientations and styles of deformation revealed at least four generations of structures at Gull Rapids.

Background

Previous field investigations (Haugh and Elphick, 1968; Corkery, 1985) and regional magnetic surveys suggest that Gull Rapids is located at the boundary between two geological terranes: 1) the dominantly intrusive, Archean rocks of the Split Lake Block, belonging to the Superior Province; and 2) the Kisseynew-type metasedimentary rocks of assumed Paleoproterozoic age, belonging to the Trans-Hudson Orogen (*see* Fig. GS-12-1, this volume). Based on observations made on field trips over the past eight years, however, it became obvious that Gull Rapids hosts a package of supracrustal rocks that appear exotic compared to the Split Lake Block to the west and the Kisseynew-type paragneiss at Stephens Lake to the east. There is a noticeable change in the nature of the metasedimentary assemblages across the proposed Superior Province boundary at Gull Rapids, from typical 'Burntwood Group' Paleoproterozoic metagreywacke in the Stephens Lake area to a mixed assemblage at Gull Rapids that includes metagreywacke, amphibolite (metabasalt), iron formation and minor calcsilicate rocks (*see* below). Nevertheless, the supracrustal sequence at Gull Rapids shares similarities with the Mesoarchean supracrustal assemblage at Assean Lake (Böhm et al., 2000, 2003a), located in a similar tectonic position approximately 100 km west along the Superior margin (*see* Fig. GS-12-1, this volume). Such supracrustal rocks are not known from the Split Lake Block (Corkery, 1985; Böhm et al., 1999; *see also* GS-15, this volume).

Although the age of the assemblage at Gull Rapids is unknown, it is noteworthy that an undeformed east-trending mafic dike at Gull Rapids that crosscuts the supracrustal rocks yielded U-Pb zircon dates in the 2050 to 2070 Ma range (Heaman and Corkery, 1996). This swarm of dikes is the youngest geological unit at Gull Rapids and provides a minimum age constraint for the protoliths, their amphibolite-grade metamorphism and their deformation. In other words, the supracrustal rocks at Gull Rapids cannot be coeval with Paleoproterozoic supracrustal rocks of the nearby Trans-Hudson Orogen. Most likely, the supracrustal rocks in the Thompson Nickel Belt (Ospwagan Group) are also younger (e.g., Bleeker, 1990). This is consistent with a preliminary Nd model age of ca. 3.5 Ga for a sample of Gull Rapids metagreywacke, which is in stark contrast to a ca. 2.0 Ga Nd model age obtained for a 'Burntwood Group'

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greywacke sample collected in northwestern Stephens Lake (Böhm et al., unpublished data, 2000), and Nd model ages of 2.8 to 3.0 Ga for the Ospwagan Group (Zwanzig and Böhm, 2002).

Approach

Over the next three years, the Manitoba Geological Survey, in collaboration with the Universities of Alberta and Waterloo, is undertaking a detailed and integrated geological study of the Gull Rapids area. The nature and age of the rocks at Gull Rapids will be determined, based on 1:1000-scale and more detailed petrographic and structural mapping, partly undertaken in the summer of 2003 (M.Sc. thesis of M. Bowerman, University of Alberta). This will involve whole-rock geochemistry and reconnaissance Nd isotopic studies to constrain the nature and age of protoliths, and to identify potential ancient crust. In addition, U-Pb geochronology of accessory minerals (isotope dilution and laser-ablation multicollector ICP-MS techniques at the University of Alberta Radiogenic Isotope Facility) will be used to constrain the age and geological history of the rocks. A second line of research (M.Sc. thesis of M. Downey, University of Waterloo) focuses on detailed studies of the structure, kinematics and critical crosscutting relationships, which will provide a thorough understanding of the kinematics and timing of deformation zones at Gull Rapids and the tectonic evolution of the Superior margin in general.

Bedrock mapping in the Gull Rapids area

The initial phase of the Gull Rapids studies during the summer of 2003 focused on 1:1000-scale bedrock mapping by the authors of the entire area, measuring approximately 5 by 3 km. Based on this mapping, the geology of the Gull Rapids area is summarized in Figures GS-13-1 and -2, and is depicted in more detail (1:5000 scale) on a new preliminary geological map of the Gull Rapids area (Böhm et al., 2003b). The main lithological units shown in Figure GS-13-1 are summarized in Table GS-13-1. Figure GS-13-2 shows a representative selection of structural orientations in the Archean rocks at Gull Rapids.

The Gull Rapids area can generally be subdivided into two Archean crustal sequences: 1) a supracrustal assemblage containing Fe-rich, siliciclastic metasedimentary rocks, interlayered banded iron formation, and mafic volcanic rocks in the eastern half, and 2) granodiorite and derived gneisses in the western half of the map area (Fig. GS-13-1 and Table GS-13-1). These main lithological sequences generally strike northwest to north, subparallel to the presumed Archean-Paleoproterozoic boundary to the east and the general strike of Archean rocks in the Split Lake Block to the west (see Fig. GS-12-1, this volume; GS-15, this volume).

The relationship between the Gull Rapids supracrustal assemblage and the granodiorite (gneiss) is unclear. Exposed contacts are sheared. The granodiorite is straight layered to mylonitic near the contact with the mafic volcanic rocks, suggesting tectonic juxtaposition of the two crustal sequences. The mafic volcanic rocks and metasedimentary rocks form several separate sequences that are repeated, most likely by folding or faulting or both (Fig. GS-13-3). Hence, age determinations are paramount for establishing the tectonic relationship between the granodiorite (gneiss) and the supracrustal rocks. Both crustal packages are heavily injected by several phases of mostly leucocratic granodiorite and granite veins, sheets and more equant bodies. Most of these felsic injection phases seem to predate or have been formed during the main deformation (gneissosity). Consequently, temporal constraints on felsic magmatism and possibly related tectonothermal activity are an integral part of this project (*see* below). It is unclear whether the felsic injection phases in the granodiorite (gneiss) and supracrustal assemblage can be directly correlated. Similar structural relationships and compositions of the main injection phases suggest that at least some phases may correlate across the granodiorite-supracrustal contact. Detailed geochemistry and geochronology of various injection phases are therefore critical in establishing a magmatic and tectonometamorphic framework.

Preliminary field observations indicate that at least one intrusive phase (grey tonalite; *see* below) can be traced across the granodiorite-supracrustal boundary, suggesting that the granodiorite and supracrustal rocks were in contact prior to intrusion of the grey tonalite. All of the above rock types, including late pegmatitic injection, are cut by abundant mafic and ultramafic dikes that form part of a major, generally east-trending swarm (Fig. GS-13-1).

Main lithological units of the Gull Rapids area

Gull Rapids Archean supracrustal assemblage

Mafic volcanic rocks

The majority of amphibolite (unit 1) has a distinct compositional banding (Fig. GS-13-4e) that is marked by black- and green-striped units, as well as abundant crosscutting felsic injection (*see* below). The mostly fine- to

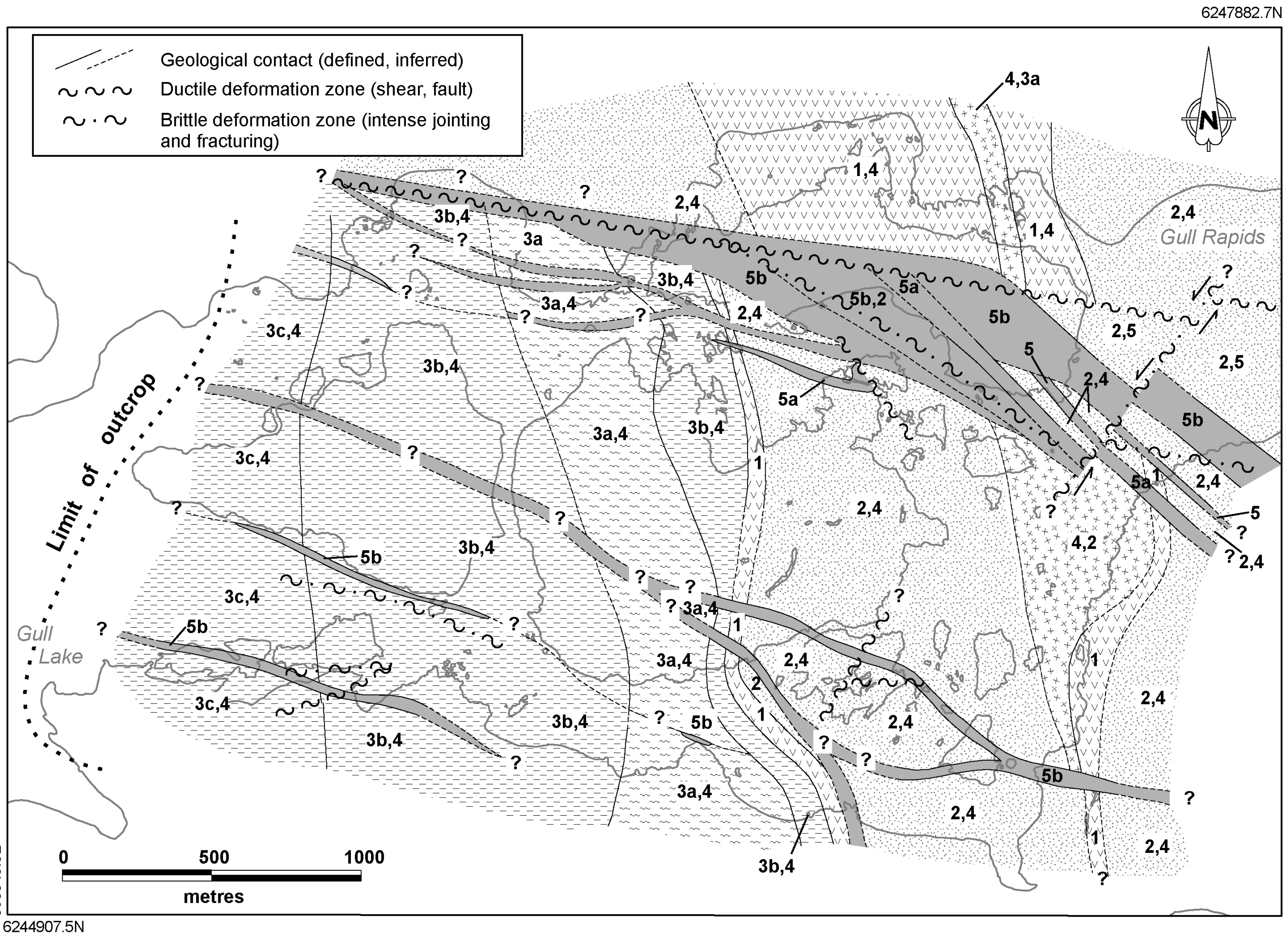

Figure GS-13-1: Simplified geology of the Gull Rapids area, showing the distribution and contact relationships of main lithological units. Unit numbers correspond to those in Table GS-13-1.

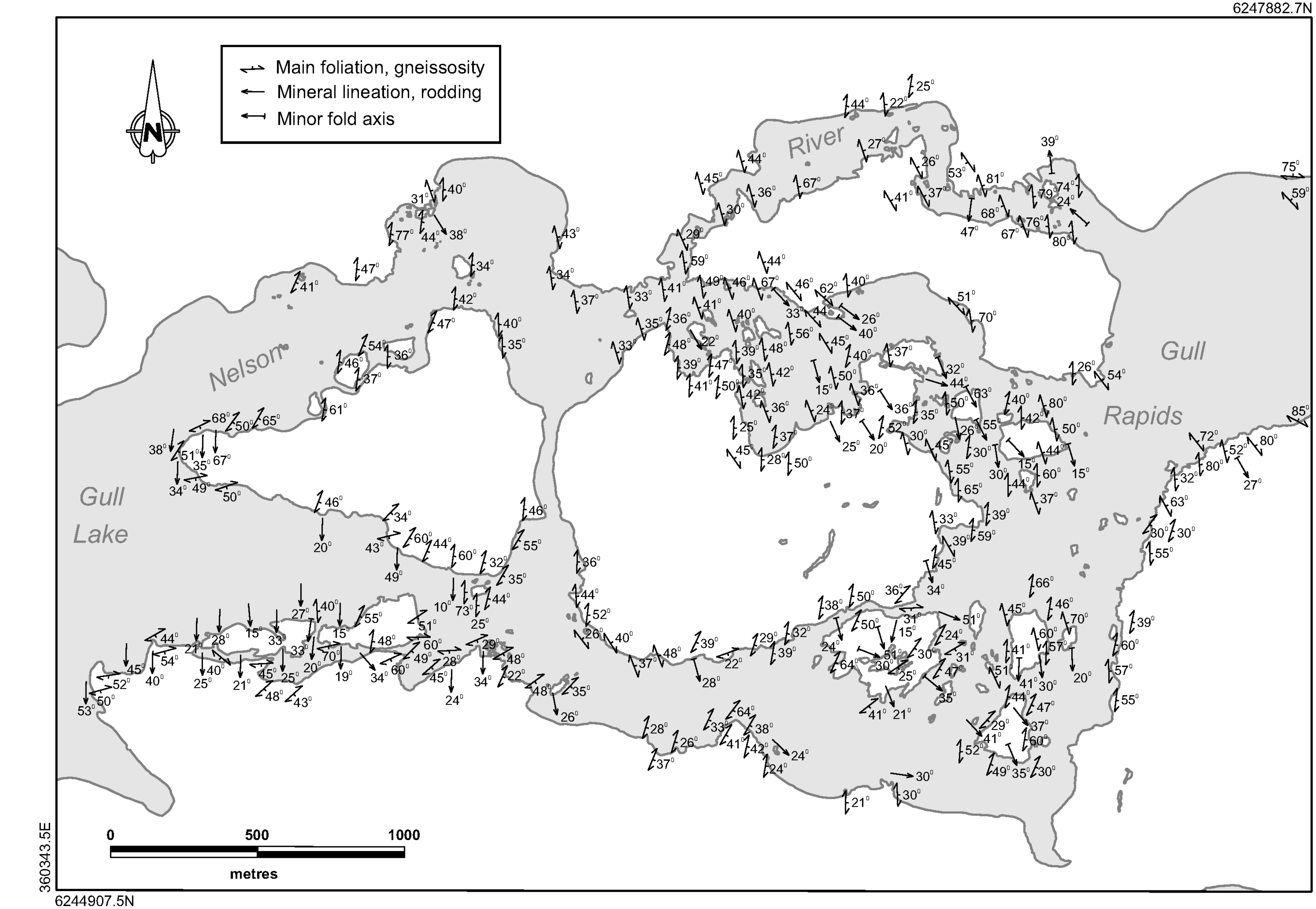

Figure GS-13-2: Orientations of main foliation, minor fold axes and lineations in the Archean supracrustal and intrusive units of the Gull Rapids area.

Table GS-13-1: Main lithological units of the Gull Rapids area. Unit numbers correspond to those in Figure GS-13-1.

Paleoproterozoic rocks		
5	**Mafic and ultramafic dikes**	
	5A	Diabase, up to a few metres wide, aphanitic to fine grained
	5B	Gabbro, up to 50 m wide, medium to coarse grained, massive to weakly foliated
Archean felsic intrusive rocks		
4	**Granitoid injections and pegmatite (form intrusive veins and bodies in units 1 to 3)**	
	4A	Granitic injection veins, sheets and bodies, leucocratic, locally chlorite clotted; pre-, syn- and post-D2 phases can be distinguished
	4B	Grey tonalite, fine to medium grained, massive to weakly foliated
	4C	Granitoid pegmatite, schlieric layered to massive, forms dikes in units 1–3, 4a and 4b
3	**Granodiorite and derived gneissic rocks (contain zones, up to 10 m wide, of dominantly mafic [amphibolite] rafts)**	
	3A	Granodiorite augen gneiss, locally up to 25% biotite±hornblende
	3B	Leucogranodiorite and derived gneiss, containing biotite±hornblende, locally straight layered to mylonitic
	3C	Granodiorite L-tectonite, strongly rodded and lineated, containing biotite ± hornblende
Archean Gull Rapids supracrustal rocks		
2	**Metasedimentary rocks**	
	Metagreywacke, interlayered pelite and psammite, medium to dark grey, Fe-rich, composed of quartz+biotite±feldspar, garnet, amphibole and cordierite; locally arkosic with calcsilicate layers; contains up to 80% unit 4 granitoid injection and discontinous layers of banded oxide-, sulphide- and silicate-facies iron formation	
1	**Mafic volcanic rocks**	
	Amphibolite interpreted as metabasalt, massive to laminated (hornblende+plagioclase±epidote±chlorite), interlayered with and intruded by medium- to coarse-grained amphibolite interpreted as metagabbro; contains unit 4 granitoid injection and (orthopyroxene-bearing) in-situ melt	

medium-grained amphibolite contains dominantly hornblende and plagioclase. Based on composition, texture and the presence of epidote-coated fractures, the amphibolite is interpreted to represent mafic volcanic rocks of dominantly basaltic composition. Interestingly, very similar looking mafic volcanic rocks of presumably Mesoarchean age are exposed at Assean Lake (Böhm et al., 2003a). More massive, coarse-grained amphibolite, interpreted as metagabbro, shows intrusive relationships with the finer grained amphibolite (mafic volcanic rocks). Thin, recessively weathering horizons of carbonate (with sulphides) are locally apparent. The amphibolite shows evidence of multiple episodes of deformation. Folding as well as boudinage is found in many exposures. Pegmatitic partial melts in boudin necks are interpreted to be syndeformational (Fig. GS-13-5d).

Metasedimentary rocks

A substantial portion of the eastern part of the map area is dominated by metagreywacke (unit 2) with felsic injection (unit 4). The composition of these generally Fe-rich metasediments ranges from psammitic to pelitic, as well as being mafic (mudstone) in some localities (biotite–quartz–plagioclase±K-feldspar±garnet±staurolite±Fe-amphibole±graphite±sulphides; Fig. GS-13-4a, f). It is common for the metagreywacke to display distinct mineralogical banding that is most likely the product of original, psammitic and pelitic compositional layering. The metagreywacke is typically medium grey and well layered to almost massive, and locally preserves graded bedding. Rare calcsilicate layers, no more than 20 cm in thickness, and rare mafic to ultramafic metaconglomerate are more resistant to weathering than the metagreywacke.

The metagreywacke shows evidence of deformation in a number of ways. Open to tight folding of the compositional layering is locally preserved. More generally, the felsic injection within the metagreywacke is intensely folded (Fig. GS-13-5a, -6f), and boudinage in relatively competent layers of iron formation is widespread (*see* below).

Banded iron formation

Iron formation, with centimetre-scale bands of oxide, sulphide and silicate facies (quartz–chert±magnetite±hematite±garnet±biotite±amphibole±sulphides; Fig. GS-13-4b), forms boudins along discontinuous layers within the metasediments. Exposures of iron formation are less than 2 m wide and no more than 4 m long. Tracing these

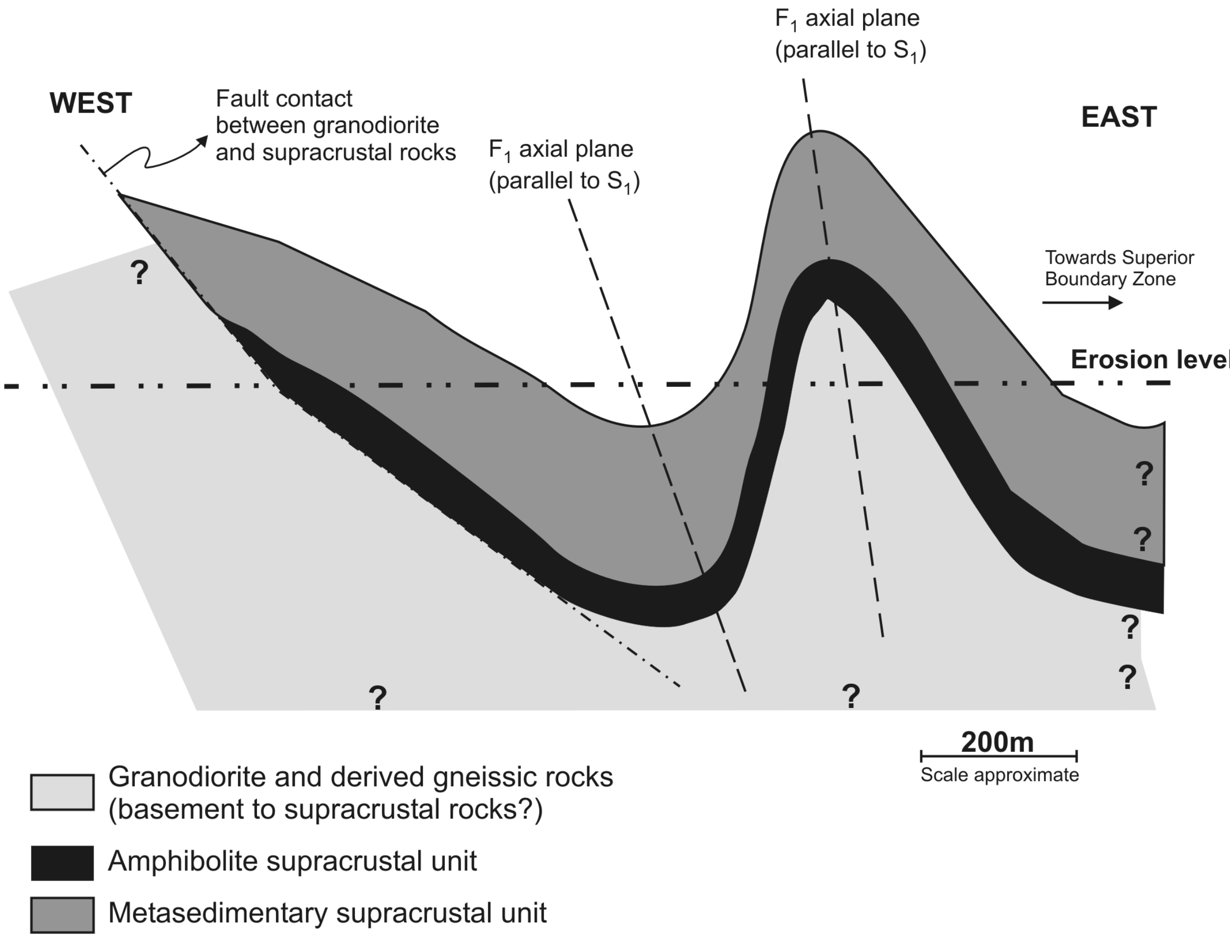

Figure GS-13-3: Schematic cross-section through the Gull Rapids area, showing macro-scale close to open, upright F_1 folding of amphibolite, metasedimentary rocks and granodiorite (gneiss). Based on preliminary mapping and structural studies, this simplified model explains the repetition of the main lithological units in the map area (Fig. GS-13-1, -2). The specific type of folding is unknown. The regional, main foliation S_1 is subparallel to F_1 axial planes. Granodiorite (gneiss) possibly forms the basement to the supracrustal units. Alternatively, the contact that is parallel to S_1 (approx. north-striking, dipping moderately to the east) is strictly tectonic.

iron-formation boudins as distinctive marker horizons within the metagreywacke has proven to be of limited use for mapping and unravelling the complex structures; the presence of many layers of iron formation suggests structural repetition of multiple iron-formation horizons within the complexly deformed metagreywacke stratigraphy.

Ultramafic conglomerate

Ultramafic conglomerate is present as rare boudins within the metagreywacke. A single discontinuous layer of five boudins can be traced in one locale, and single boudins occur elsewhere. The conglomerate is clast supported and features subangular, well-sorted metapyroxenite (Fig. GS-13-4c) within a mafic matrix. If additional occurrences of this layer are found, this may prove to be a useful marker unit that could help in understanding the structural complexities in the metagreywacke.

Archean felsic intrusive rocks

Granodiorite and derived gneissic rocks

Granitoid intrusive rocks of dominantly granodiorite composition and derived gneissic rocks form the western half of the map area (unit 3; Fig. GS-13-1). The granodiorite appears to have a uniform composition. Structural and textural rather than compositional changes provide distinctive features that allow its subdivision along generally north-trending zones (Fig. GS-13-1, Table GS-13-1). These zones comprise 1) porphyroclastic or augen gneiss (unit 3a;

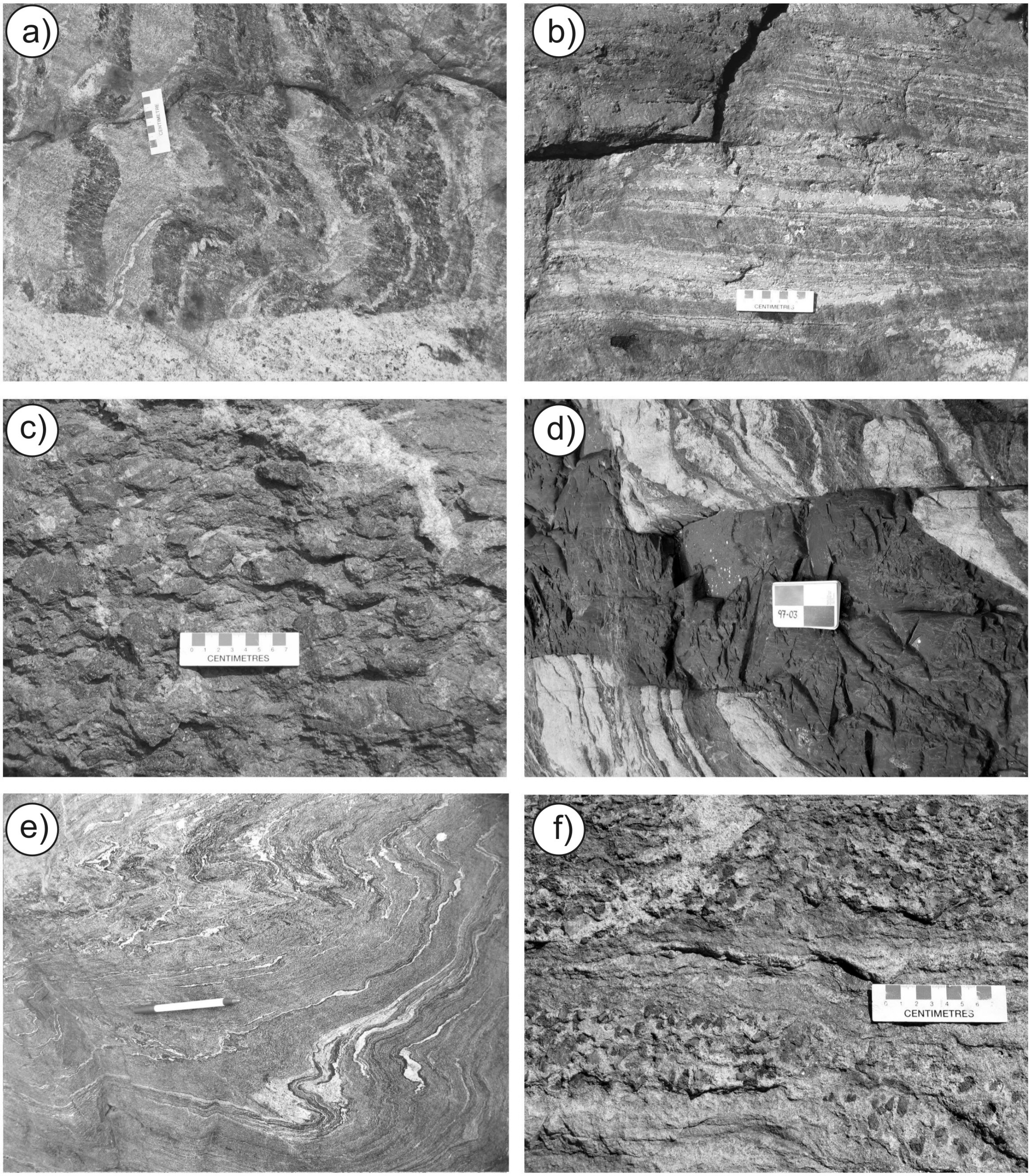

Figure GS-13-4: Outcrop photographs from exposures of units 1 and 2: a) folded, compositionally layered metagreywacke truncated by leucocratic injection (bottom of photo); dark pelitic layers show metamorphic mineral growth subparallel to axial-planar foliation; b) finely banded iron formation showing dark oxide layers with lighter coloured silicate facies; c) clast-supported ultramafic conglomerate, dominantly composed of metapyroxenite; d) mafic dike (field book for scale) crosscutting metagreywacke with abundant felsic injection along gneissosity; e) folded, compositionally banded amphibolite (mafic volcanic rocks); f) pelitic metagreywacke with abundant porphyroblasts of Fe-rich amphibole.

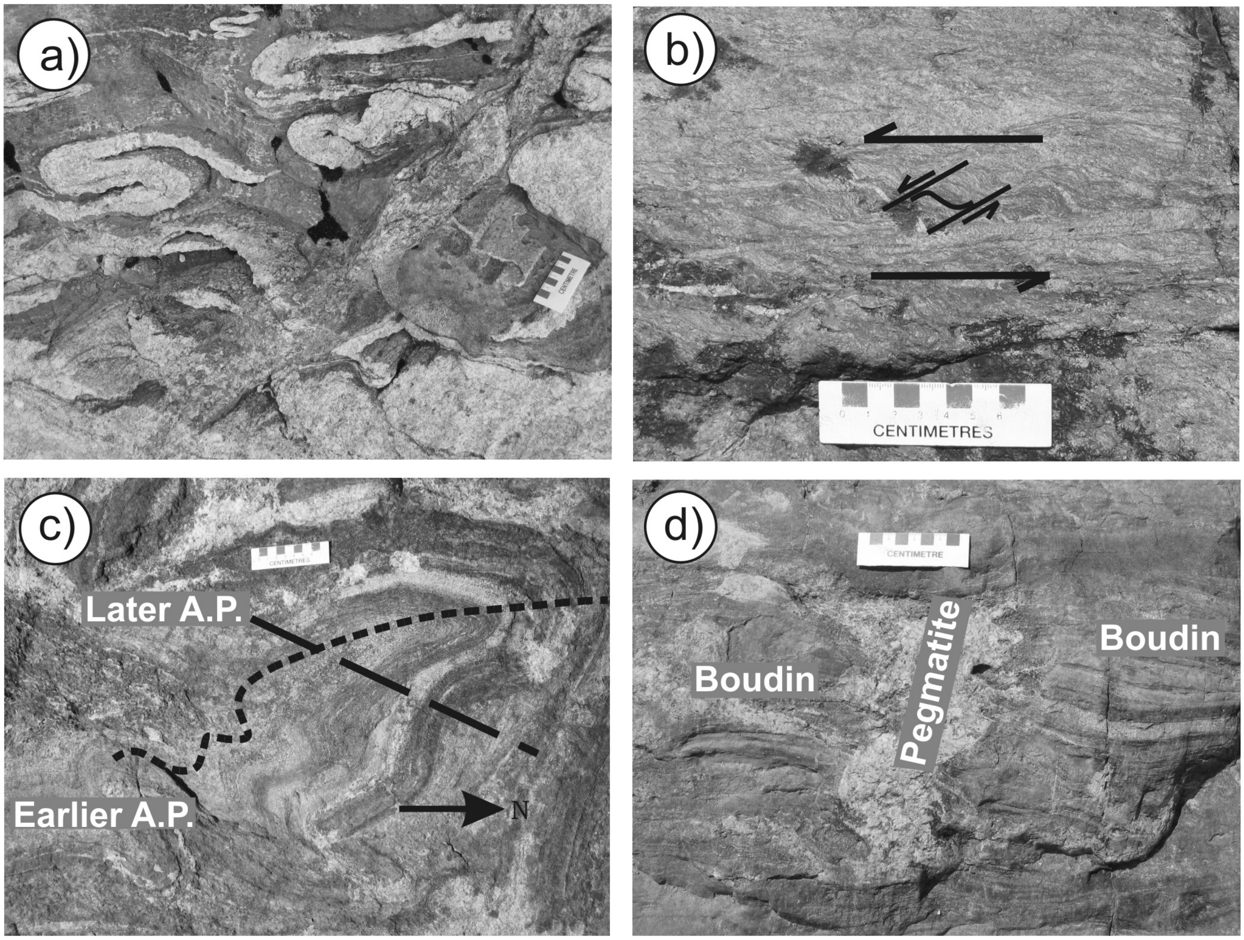

Figure GS-13-5: Outcrop photographs of example structures: a) tight to isoclinal, F_2, S-type minor folds of granitic veins and veinlets in metasedimentary rocks; b) sinistral shear bands in an early ductile shear zone in granodiorite gneiss; c) refolded fold in metasedimentary rocks containing Fe-rich layers; north-trending, earlier (F_1 or F_2?) isoclinal fold is refolded by an open, east-trending later (F_3?) folding event; black dashed lines represent axial planes of the F_1-F_2 and F_3 folds (see text for discussion); d) syn-D_2 pegmatitic injection in boudin necks in layered amphibolite.

Fig. GS-13-6a), b) straight-layered and banded granodiorite and derived gneiss (unit 3b; Fig. GS-13-6c), and c) strongly rodded L-tectonite (unit 3c; Fig. GS-13-6d). The augen gneiss (unit 3a) appears to be slightly more mafic than the locally leucocratic granodiorite gneiss (unit 3b). A north-trending zone of L-tectonite (unit 3c) is preserved toward the western part of the map area (Fig. GS-13-1). These boundaries are not sharp; a wide transition zone usually borders them. Rafts of amphibolite are common in the granodiorite gneiss and locally form zones of agmatite (Fig. GS-13-6e). Amphibolite rafts occur as discontinuous trains or layers of angular to rounded, partially resorbed xenoliths. The composition of the amphibolite rafts ranges from hornblendite to diorite and rarely metapyroxenite. Foliation within these rafts is common, but compositional banding is rare and unlike the distinct lamination in the mafic volcanics to the east. The granodiorite appears to be more mafic (plagioclase, K-feldspar, quartz, >10% biotite±hornblende) compared to the generally leucocratic felsic injections that, in places, form up to 80% of the granodiorite outcrops (Fig. GS-13-6b).

Compositionally banded gneiss (unit 3b), which has very straight layers, is also present in a north-trending zone (Fig. GS-13-1, -6c). The layers range from tonalitic to granitic and are generally leucocratic. The straight-layered gneiss becomes locally mylonitic where it marks the transition zone between the supracrustal rocks (amphibolite) and the granodiorite (gneiss), suggesting that it may represent a structural contact (Fig. GS-13-3).

Felsic injection phases and pegmatites

Crosscutting felsic injections (unit 4) are common throughout the map area in all of the above rock types. The dominant composition of felsic injections is leucocratic granodiorite to granite (unit 4a; plagioclase–quartz–K-feldspar±biotite±amphibole±garnet±pyroxene). Aggregates of biotite±garnet±hornblende±pyroxene are retrogressed to

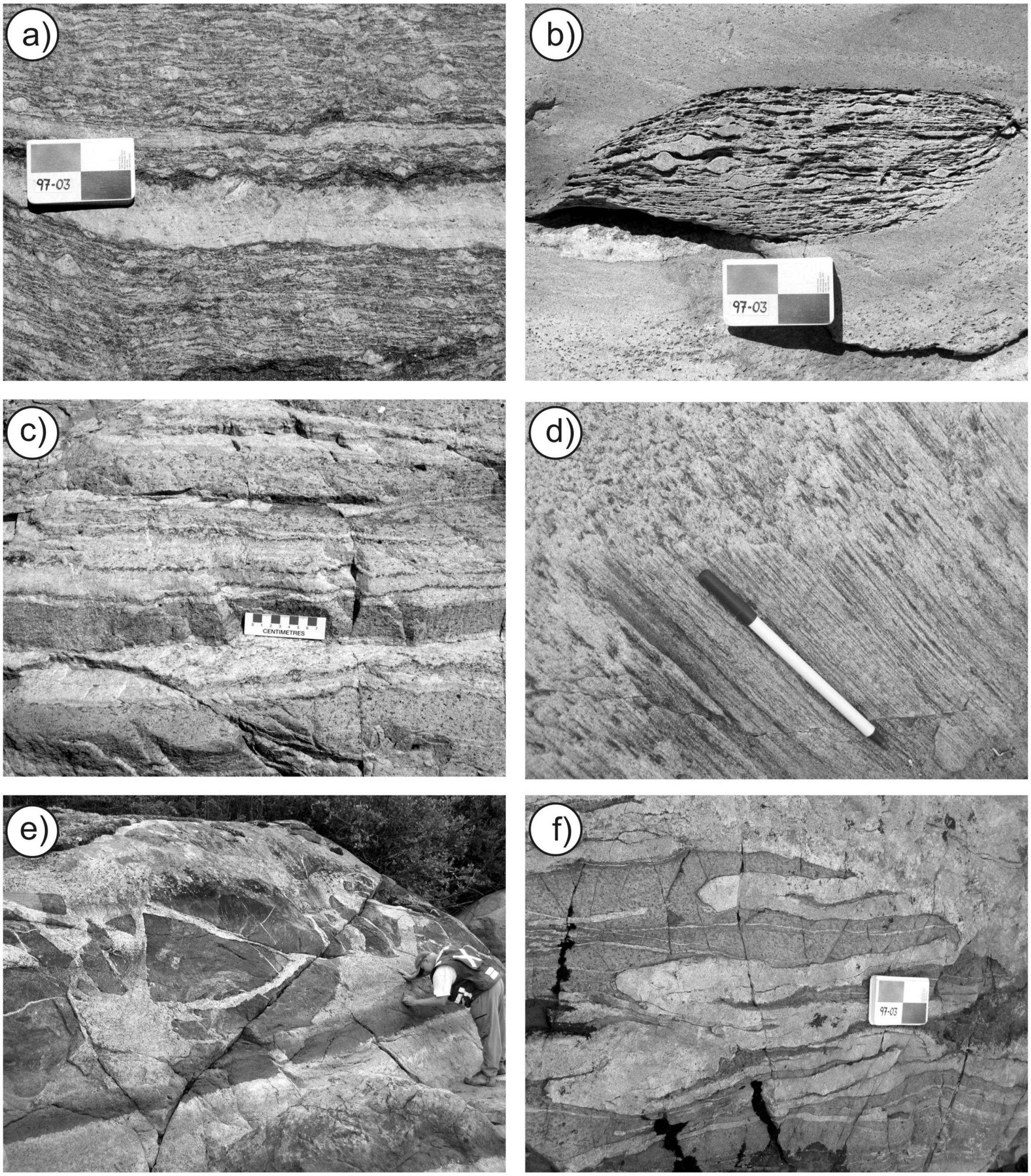

Figure GS-13-6: Photographs from outcrop exposures of units 3 and 4: a) granodiorite augen gneiss showing metamorphic segregation layering of alternating leucocratic and mesocratic bands (field book, for scale, is 18 cm long); b) raft of augen gneiss within leucogranitic injection (field book for scale); c) strong compositional layering in granodiorite gneiss; d) well-developed L-tectonite in granodiorite; pen is parallel to the stretching lineation, which trends southeast, subparallel to the predominant orientation of lineations in the Gull Rapids area (see also 'Structure and Kinematics' section below); e) agmatitic zone of amphibolite rafts in granodiorite gneiss; f) isoclinally folded felsic injection in metagreywacke.

mainly chlorite and give a spotted to clotted appearance in places. Locally, there appear to be several generations of injection phases within single exposures. Separation of the various injection phases, however, is challenging; it is even more difficult to extend these relationships across the entire map area. Some felsic injection phases crosscut an early fabric, whereas the majority seem to have formed during the main deformation phase and been folded and boudinaged along with the host rocks (Fig. GS-13-6f). Locally, felsic injections are massive and contain nebulitic biotite trails and xenoliths of host rock (Fig. GS-13-6b)

Grey tonalitic injection (unit 4b) is found in a few places crosscutting metagreywacke and granodiorite gneiss, providing evidence that felsic injection phases intruded both units. The tonalite is fine grained and contains dominantly plagioclase, quartz and less than 5% biotite±hornblende. These tonalitic injections are generally less than 5 m wide, weakly foliated to massive, and crosscut an early leucogranite injection phase.

A late pegmatitic phase (unit 4c) crosscuts all of the above rock types, as well as the finer grained granitoid injections (unit 4a). Pegmatite veins range up to 1.5 m in width and locally feature large feldspar phenocrysts, up to 20 cm in length, along with dark grey-blue quartz. Zones of graphic texture are also found in some of these veins. These pegmatite bodies do not appear to be the product of partial melting of their host rocks, because vein margins are usually very straight and exhibit little mingling with the country rock.

Paleoproterozoic mafic and ultramafic dikes

Mafic and ultramafic dikes (unit 5) of various widths, grain sizes and orientations occur throughout the map area and form part of a generally east-trending major dike swarm, which can be traced for more than 50 km along the Nelson River to the west. They are the youngest lithological units in the Gull Rapids area. Grain size within these dikes ranges from aphanitic (diabase) to coarse grained (gabbroic; pyroxene–plagioclase±amphibole). Gabbroic dikes (unit 5b) tend to contain pegmatitic segregations in their cores and, on larger bodies, develop chilled margins. Aphanitic diabase dikes (unit 5a) intrude gabbroic dikes in places. Shear fabric occurs along numerous dike margins. The generally dark green to black colours become light green where chloritic alteration has occurred. Amygdules are found in some dikes and, in one place, the amygdules are filled by pyrrhotite. Fine-grained quartz diorite dikes, which cut the mafic dikes, could represent a late, related phase of the intrusions.

Geochemistry, geochronology, and tectonothermal history: proposed work

The lack of geochronological constraints for most of the rock types at Gull Rapids requires that a range of research topics, including geochemistry and isotope studies, be carried out to understand the nature, protolith history and provenance of intrusive and supracrustal rocks. A broad sampling program for thin section, geochemistry and isotope studies, undertaken in the summer of 2003, included samples of all rock types. Detailed petrographic studies will provide insight into the nature of the various lithological units, as well as their metamorphic grades. Whole-rock geochemistry will allow classification and subdivision of the main rock types into subunits, based on composition and comparison with similar lithologies elsewhere (e.g., felsic injections, granodiorite).

The application of radiogenic isotope techniques in this field area is useful for a number of purposes other than dating. Samarium-neodymium whole-rock isotope analysis will provide information on the nature and approximate age of protoliths of the granitoid injections and the granodiorite (gneiss). Furthermore, Nd isotopes may also prove useful for tracking possible incorporation of ancient crust and to determine whether and where a boundary between the Split Lake Block and the Gull Rapids crustal sequence exists. For example, a change in Nd isotopic composition between the Neoarchean Gull Lake granite (Split Lake Block; e.g. Böhm et al., 1999) and possibly older or ancient orthogneiss at Gull Rapids may reveal such a boundary.

Based on detailed field relationships, the authors propose to separate and date different phases of the ubiquitous felsic injections by using geochemical and geochronological methods. Unravelling the timing of felsic injection phases is critical for understanding the tectonothermal history, since the timing of at least some felsic injection phases is likely linked to deformation events. In addition, ages of injection phases will further constrain the depositional ages of the supracrustal units in the map area.

Investigation of the metamorphic history of the Gull Rapids area will include geothermobarometry on metamorphic mineral assemblages in pelitic metagreywacke. Detailed thin-section studies may confirm the gradual increase in metamorphic grade across Gull Rapids to the west that has been indicated by field observations. The timing of metamorphism will be ascertained by U-Pb geochronology on amphibolite. Zircons in amphibolite and their partial pegmatitic melts may provide insights into one or more episodes of metamorphism.

Structure and kinematics: preliminary results

The structural studies at Gull Rapids during the 2003 field season involved extensive collection of data on fabrics, folds, faults, shear zones and fractures (joints). From an engineering point of view, the fault, shear and late brittle fracture data are of most importance for Manitoba Hydro's Gull Rapids dam project. Micro-scale structural analysis will take place at the University of Waterloo during the winter months, using thin-sectioned samples collected during the 2003 field season. The timing of deformation in the map area is based on critical crosscutting relationships and structural interference patterns (e.g., Fig. GS-13-5c), and will be directly constrained by applying U-Pb dating techniques on selected samples. Preliminary investigations have identified at least four generations of structures (D_1 to D_4), based on overprinting relationships and styles of deformation. These are summarized below. Absolute dating may show if one specific generation of structures corresponds to one episode of deformation.

D_1

The most widespread deformation event in the Gull Rapids area is D_1, which is represented by large-scale F_1 folds and the main foliation S_1. The F_1 event is characterized by open to tight folds of the supracrustal rocks and the granodiorite (gneiss), with an amplitude of approximately 500 m (Fig. GS-13-3). These meso-scale F_1 folds are rarely recognized, due to deformational overprinting and granitic injection. The F_1 fold axes trend east-southeast and plunge moderately. The S_1 foliation throughout the map area strikes 345 to 030° and dips 40 to 50° to the east (main foliation in Fig. GS-13-2). Because S_1 is generally parallel to the F_1 axial planes, it is assumed that S_1 is an F_1 axial-planar foliation. In the metasediments, primary bedding S_0 is preserved in many outcrops, and is generally subparallel to S_1. In a few localities, S_0 is isoclinally folded by F_1. The L_1 lineation is not seen in the supracrustal units, but forms the main structural element in the westernmost zone of the granodiorite (gneiss) in the map area (Fig. GS-13-1, -2). Here, the strain has changed from a field of flattening to one of intense stretching (L-tectonite granodiorite; Fig. GS-13-6d). The S_1 foliation is weak to nonexistent in the L-tectonite granodiorite. The L_1 stretching direction generally trends southeast, subparallel to lineations elsewhere in the map area, and is parallel to the strike of S_1 where S_1 is weakly developed. In L-S tectonite elsewhere in the granodiorite, lineations developed on S_1 surfaces and are therefore L_2. Augen gneiss is predominant in a zone parallel to S_1, flanked by zones of layered granodiorite gneiss (Fig. GS-13-1). The augen most likely formed during D_1, but are rarely asymmetric and therefore formed mainly during coaxial strain with a low simple shear component.

Ductile, generally east-trending shear zones affected the granodiorite (gneiss), amphibolite and metasedimentary rocks. This shear event is best developed in the granodiorite (gneiss), where ductile shear zones with synshear pegmatitic injection have formed along the shear bands (Fig. GS-13-5b). Throughout the map area, the shears cut and deform S_1 fabrics but not folds, suggesting that shear zones are syn- or post-D_1. Shear zones are not present in felsic injection phases, which are interpreted to be post-D_1 and pre- or syn-D_2, consistent with the interpretation that shear zones developed during late D_1 or after D_1, but likely before D_2.

D_2

The D_2 deformation affected the entire map area, and is best represented by large-scale folding of S_1 in the supracrustal rocks. The F_2 folding is open to tight, with variable amplitudes. It is best developed as open to tight, symmetric and asymmetric minor folds of S_1 in the metasedimentary rocks, with amplitudes on the scale of a few metres, as well as tight to isoclinal folding of pre- or syn-D_2 granitic injection parallel to S_1 (Fig. GS-13-5a, -6f). In many localities, granite veinlets are ptygmatically folded (disharmonic folds). The genesis of this type of folding is controversial, but ptygmatic folding is common in layers of high competence (granitic veinlets) in a less competent matrix (sedimentary rocks; Davis and Reynolds, 1996). The axes of the F_2 folds plunge moderately to the southeast; axial planes are subparallel to S_1. An L_2 mineral lineation is generally developed on foliation-plane surfaces in metasedimentary rocks, subparallel to the F_2 fold axes. Measurements of S_1 foliation were taken from long and short limbs in Z-asymmetric F_2 folds of metasedimentary layers. The D_2 axial plane, fold axis and lineation orientations were determined using stereographic projection (Fig. GS-13-7). The stereographic projections show that the F_2 fold axes and L_2 lineations are parallel to a fold axis calculated for a number of Z folds, providing evidence that both types of folds formed during F_2 folding.

Locally, an F_2 axial-planar foliation S_2 is developed subparallel to S_1, making it difficult to distinguish the foliations of D_1 and D_2. Alternatively, instead of two separate deformation events, there may have been a single prolonged

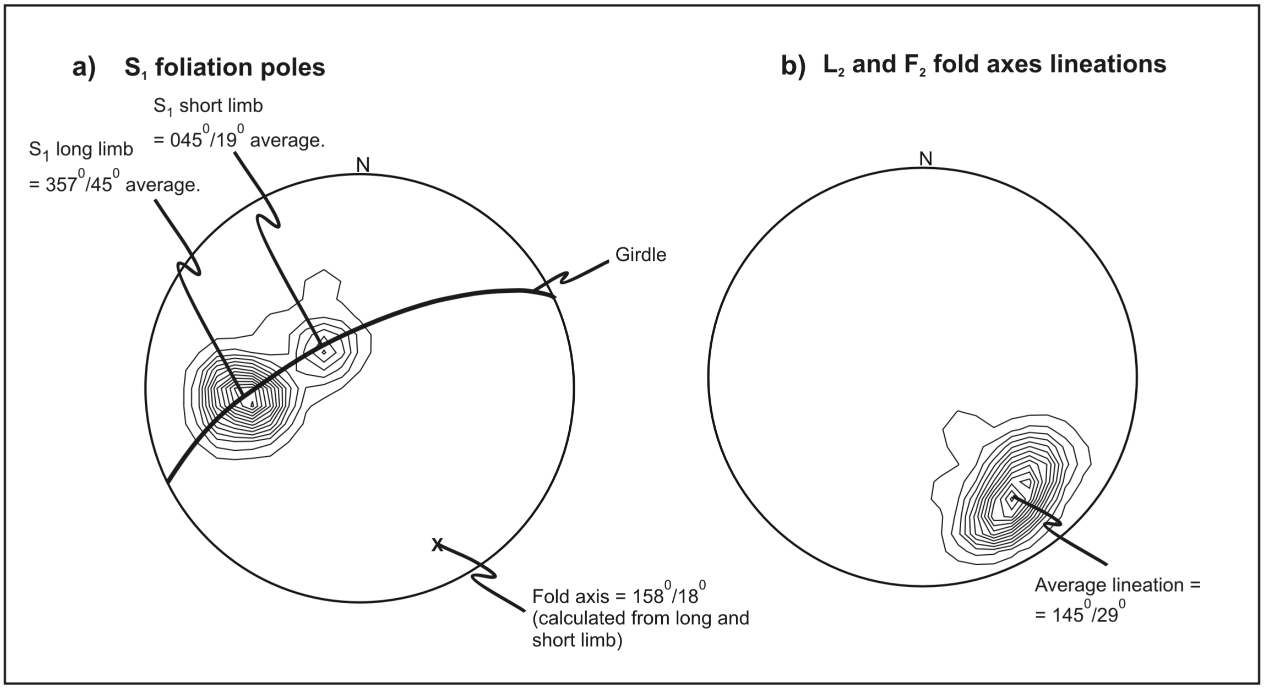

Figure GS-13-7: a) Equal-area lower-hemisphere projection of 50 S_1 foliation measurements from a subdomain within the metasedimentary package, comprising long limb and short limb measurements of Z folds within layers of metasediment (fold axis = 158°/18°). b) Equal-area lower-hemisphere projection of 60 L_2 lineation and F_2 fold-axis measurements from the same subdomain within the metasedimentary package. The average of these lineation measurements is 145°/29°, subparallel to the calculated fold axes of the Z folds in the metasedimentary layers (158°/18°).

deformation phase with multiple stages. In this case, F_1 would have formed the large-scale isoclinal fold structures, including parasitic Z, S, and M folds. Evidence in favour of two separate deformation events, however, is the abundant boudinage of folded and foliated metasedimentary layers, with boudin necks subparallel to L_1-L_2 and fold axes.

D_3

The D_3 deformation, which is only present in the supracrustal rocks and granitic injections, is an open-style F_3 fold event that changes S_1-S_2 strike orientations of 345 to 000° in the northern part of the map area to 030 to 050° in the southern part. The F_3 fold structure has an axial plane striking approximately 090° and an amplitude of approximately 1 km. Paleoproterozoic mafic dikes (Heaman and Corkery, 1996) cut D_3 structures (*see* below).

D_4

The D_4 deformation is expressed by brittle faulting. The D_4 structures are generally oriented 110 to 160°, subparallel to the presumed Superior Boundary Zone, and affected all rock types in the map area, including the ca. 2050 to 2070 Ma mafic dikes (Heaman and Corkery, 1996), suggesting that D_4 is Hudsonian. This faulting occurs in discrete zones, ranging in width from a decimetre to several metres, that consist mainly of fault gouge along the margin of mafic dikes. The abundant, generally east-trending mafic dikes at Gull Rapids are possibly transposed toward 140° close to the Archean-Proterozoic boundary east of the map area. In addition, zones of intense jointing and fracturing within the mafic dikes (*see* Fig. GS-13-1), as well as centimetre-scale kink bands in the supracrustal rocks and granite injection sheets, are oriented 110 to 140° and might therefore form part of D_4.

Economic impacts

This study will provide accurate bedrock maps and structural data of the Gull Rapids area for Manitoba Hydro and other land-use clients. Based on its location at the Superior margin between the exposed portions of the Thompson Nickel and Fox River belts, the study area will provide geological information from an economically important but insufficiently studied area. The results of the investigations at Gull Rapids provide a comparison or contrast to the supracrustal rocks that contain Thompson-type nickel deposits and Assean-type gold prospects, and therefore fundamental information that could guide exploration programs along the Superior Boundary Zone.

Acknowledgments

The authors are indebted to Manitoba Hydro for logistical and financial support of the program. They would also like to thank Trevor Allen, Tara Penner, Drew Heasman and Daniel Martin for their enthusiastic and capable assistance in the field. Neill Brandson once again provided thoughtful and professional logistical help. Larry Heaman and Shoufa Lin provided considerable inspiration. Bonnie Lenton did an excellent job on Figures GS-13-1 and -2, and Herman Zwanzig provided helpful comments on an earlier version of this report. This program would not have been possible without Tim Corkery's immense enthusiasm and support.

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