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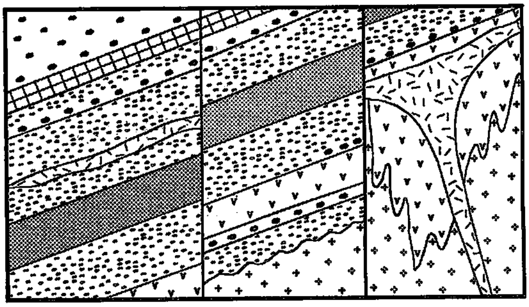
THE NORTHERN MARGIN OF THE SOUTHERN PROVINCE OF THE CANADIAN SHIELD



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PROGRAM AND ABSTRACTS

September 29 to October 1, 1995
Auditorium
Willet Green Miller Centre
Ontario Geological Survey
933 Ramsey Lake Road
Sudbury, Ontario, Canada

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Mineralogical Association of Canada
Sudbury Geological Discussion Group
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The Ontario Ministry of Northern Development and Mines

PROGRAM

Friday morning, September 29

0830-0840	**A.J. Naldrett** Welcome and Introduction
0840-0920	**G. Young** The Huronian Supergroup in the context of a Paleoproterozoic Wilson cycle in the Great Lakes region
0920-1000	**D. Long** Huronian sandstone thickness and paleocurrent trends as a clue to the tectonic evolution of the Southern Province
1000-1030	COFFEE AND POSTER VIEWING
1030-1110	**G.B. Bennett and W. Meyer** Stratigraphic relationships in the Lower Huronian of the Sault Ste. Marie – Elliot Lake areas and possible implications regarding Early Huronian tectonics
1110-1150	**S.L. Jackson** Metamorphic and structural history of the western Huronian Supergroup
1150-1230	**B. Milkereit** Geophysical constraints – seismic studies across the Southern Province
1230-1330	LUNCH

Friday afternoon, September 29

1330-1410	**W.A. Morris and E.L. Mueller** A 3-D geophysical model of the Sudbury Igneous Complex
1410-1450	**W.T. Jolly** Huronian volcanism in central Ontario: an Early Proterozoic example of passive continental margin plate tectonics
1450-1530	**D.C. Vogel, R.S. James, R.R. Keays, S.A. Prevec and D.C. Peck** The Agnew (Shakespeare–Dunlop) intrusion: an example of early mafic plutonism associated with the Huronian Rift Zone
1530-1600	COFFEE AND POSTER VIEWING
1600-1640	**S.A. Prevec, R.S. James, R.R. Keays and D.C. Vogel** Constraints on the genesis of Huronian magmatism in the Sudbury area from radiogenic isotopic and geochemical evidence
1640-1720	**R.R. Keays, D.C. Vogel, R.S. James, D.C. Peck, P.C. Lightfoot and S.A. Prevec** Metallogenic potential of the Huronian – Nipissing magmatic province

Saturday morning, September 30

0830-0910	**P.C. Lightfoot** Geochemistry of the Nipissing Gabbro: source and mineral potential
0910-0950	**H.C. Halls** Variation in paleomagnetic direction and feldspar clouding intensity across the Matachewan dyke swarm, and their relevance to the Huronian

0950-1030	COFFEE AND POSTER VIEWING
1030-1100	**D.L. Southwick** The nature of the foreland margin of the Penokean Orogen in the Great Lakes region of the U.S.A.
1100-1140	**H. Papunen** Proterozoic reactivation of the margin of the Fennoscandian Archean craton
1140-1320	LUNCH

Saturday afternoon, September 30

1320-1400	**J.A. Fyon, G.B. Bennett, J. Ireland, S.L.Jackson, M.J. Lavigne, P.C. Lightfoot and W. Meyer** Metallogeny of the Proterozoic Eon, Southern Province, Ontario
1400-1440	**M.-C. Williamson and C.E. Keen** How active are passive margins? Modern analogues of magmatism at rifts
1440-1510	COFFEE AND POSTER VIEWING
1510-1710	QUESTION AND ANSWER SESSION

ABSTRACTS

Friday Morning, September 29

THE HURONIAN SUPERGROUP IN THE CONTEXT OF A PALEOPROTEROZOIC WILSON CYCLE IN THE GREAT LAKES REGION

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The Huronian Supergroup comprises up to about 12 km of mainly sedimentary rocks. The basal part of the Huronian includes volcanic rocks, fluvial quartzites and a succession of turbidites (McKim Formation). These rocks are succeeded by a series of tripartite megacycles, involving diamictites, followed by mudstones and coarse cross-bedded sandstones. The formations comprising the upper Huronian include diamictites (Gowganda Formation), supermature orthoquartzites (Lorrain and Gordon Lake formations) and mudstones (Gordon Lake Formation). The lower Huronian rocks are relatively restricted in their distribution, whereas the upper Huronian formations are widespread and, in northern parts of the Huronian outcrop belt, commonly lie directly on the Archean basement.

Some authors have suggested that the tripartite cycles are mainly the result of tectonic control; in this model, the diamictites are interpreted as nonglacial mass-flow deposits, related to episodes of down-to-basin fault activity that stepped progressively craton-ward. Others have interpreted diamictites and associated rocks of the Ramsay Lake, Bruce and Gowganda formations as glacial deposits. According to this model, the tripartite cycles are related to repeated glacial advance and retreat. It has also been suggested that uplift (with concomitant basinal subsidence) may have induced glaciation. The lower Huronian sandstones are probably mostly fluvial. The depositional environments of the underlying mudstones are largely unknown, although stable isotope studies of carbonates of the Espanola Formation in the Elliot Lake area have been interpreted to indicate lacustrine (as opposed to marine) conditions. Significant regional subsidence during deposition of the Gowganda Formation brought about much wider distribution of the upper Huronian formations. This regional subsidence has been interpreted to coincide with the rift-drift transition and inception of an Atlantic-style continental margin. Parts of the upper Huronian have been interpreted as marine deposits.

The tectonic setting of the Huronian Supergroup has been the subject of considerable debate. Since the development of plate tectonic concepts, the Huronian has been regarded by many as having formed in an extensional regime, leading to formation of an ocean to the south. Interpretations are frustrated by the dearth of information on areas to the south (covered by Paleozoic rocks and the waters of Lake Huron) and to the east, where the Huronian fold belt is truncated by the Grenville Front, which juxtaposes high- grade rocks of the Gneiss Belt of the Grenville Province. Some authors have suggested that breakup of an Archean "supercontinent" took place at the time of deposition of the Gowganda Formation, and that the widespread upper Huronian succession represents a passive margin sequence. Large-scale folds in the southern part of the Huronian fold belt appear to have formed prior to intrusion of the Nipissing Gabbro (2.2 Ga). These large-scale early folds may have formed as a result of gravity-controlled mass movements from a marginal plateau or "continental ribbon" formed during continuing extensional tectonics.

Strong stratigraphic similarities have long been recognized between the Snowy Pass Supergroup in south-eastern Wyoming and the Huronian Supergroup. Similar but less complete Paleoproterozoic successions also are present in Michigan, in Quebec at Chibougamau, in the Hurwitz Group of the Northwest Territories, and in Finland. The striking stratigraphic similarities between the Huronian and Snowy Pass supergroups have been attributed to juxtaposition of the Wyoming and Superior provinces, so that the succesions could have been deposited on opposite sides of the same extensional basin. A more conservative interpretation places the Snowy Pass Supergroup depocenter along the same continental margin as the Huronian. In this model, the similarities between the two supergroups are attributed to similar tectonic and climatic influences at the time of deposition. Active rifting, involving transfer of thermal energy from the asthenosphere into the lithosphere, is normally associated with a strong expression of volcanism (*e.g.*, East African rift system); it seems unlikely that the Huronian rifting was of this kind. Evidence of widespread synsedimentary faulting, together with local development of bimodal volcanism in the lower Huronian, is probably more compatible with passive rifting.

The lowest part of the Paleoproterozoic succession in Michigan may correlate with the upper part of the Huronian (Gowganda and succeeding units). These rocks (Chocolay Group), like the Huronian, are thought to represent a rift - to - passive margin sequence. The overlying succession (Menominee, Baraga and Paint River groups) includes the Superior-type iron-formations, which have been interpreted as foreland basin deposits or as having formed in a secondary (back arc?) environment prior to the docking of the Wisconsin magmatic terrane to the south. Recent isotopic studies show that there is little or no Archean detritus in the flyschoid succession in the Lake Superior region (Menominee, *etc.*). The presence of a back-arc basin was invoked to explain the lack of Archean detritus. The Penokean orogeny produced major deformation in the Lake Superior region. In the Huronian fold belt, the second folding (major flattening event) may have formed at the same time. This deformation postdates intrusion of the Nipissing Gabbro and formation of the Sudbury-type breccias, which are related by some to the putative extra-terrestrial impact at Sudbury (*ca.* 1.85 Ga). The Penokean orogeny is attributed to events (~ 1.9 – 1.7 Ga) that culminated in the docking of the Wisconsin magmatic terrane.

Stratigraphic relationships among the Huronian, Marquette Range and Whitewater sediments remain contentious. The Onwatin and Chelmsford Formations in the Sudbury Basin, however, like their western counterparts in the Lake Superior region, comprise a coarsening-upward sequence of turbiditic or "flyschoid" character. Paleocurrent data from the sandstones of the Chelmsford Formation indicate consistent WSW transport across the Sudbury Basin. These rocks are probably a small remnant of a formerly much more extensive flysch apron, possibly correlative with the Rove and equivalents to the west. Recent isotopic investigations of detrital grains in the Chelmsford Formation, however, suggest an Archean provenance. If these turbiditic sandstones represent a synorogenic flysch, it must have been derived from an uplifted Archean block.

Nd and Pb isotopic characteristics of rocks in the Grenville Province to the east of the Huronian fold belt suggest that Archean basement extends for several tens of km into the younger province. Younger rocks to the southeast of this "Archean" region have an isotopic signature, considered by some to indicate derivation from juvenile crust, comparable to the Wisconsin magmatic terrane.

In summary, the Huronian is envisaged as a small remnant of a continental margin that developed during the breakup of a late Archean craton (Kenorland). The breakup appears to be related to passive rifting. The lower Huronian formed in rift environments, and the upper Huronian may represent a passive margin. The first (major) folds, which are best developed in the southern part of the Huronian outcrop belt, appear to predate intrusion of the Nipissing Gabbro (2.2 Ga) and may have formed as a result of gravity- controlled mass movements. The thick Neoproterozoic Dalradian Supergroup of Scotland may provide an analogue for similar early deformation and granite emplacement in an extensional setting. Subsequent history, which is best preserved in the Lake Superior region, may have involved development of a back-arc basin prior to closure and collision between the Wisconsin magmatic arc terrane and the Archean craton to the north. This closure involved significant northward-directed thrust tectonics. These events could correspond to the major flattening event in the Huronian, which tightened the first major folds in the south, without producing new major structures, but may have been responsible for some major structures in more cratonic settings to the north. This orogenic episode (1.9–1.7 Ga) could also have caused the folding observed in the Sudbury Basin, which represents a locally preserved remnant of a widespread flysch succession formed during compressive events that culminated in the Penokean orogeny.

HURONIAN SANDSTONE THICKNESS AND PALEOCURRENT TRENDS AS A CLUE TO THE TECTONIC EVOLUTION OF THE SOUTHERN PROVINCE

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A variety of models have been proposed for the tectonic evolution of the southern part of the Superior Structural Province during deposition of the Paleoproterozoic Huronian Supergroup. These include deposition on a passive margin, within a fault- bounded basin representing a rift or aulacogen, or within a strike- slip belt. Thickness and paleocurrent trends within four thick sequences of fluvial sandstone in the supergroup (Fig. 1) can be used to provide constraints on tectonic models, as fluvial systems respond rapidly to tectonic change.

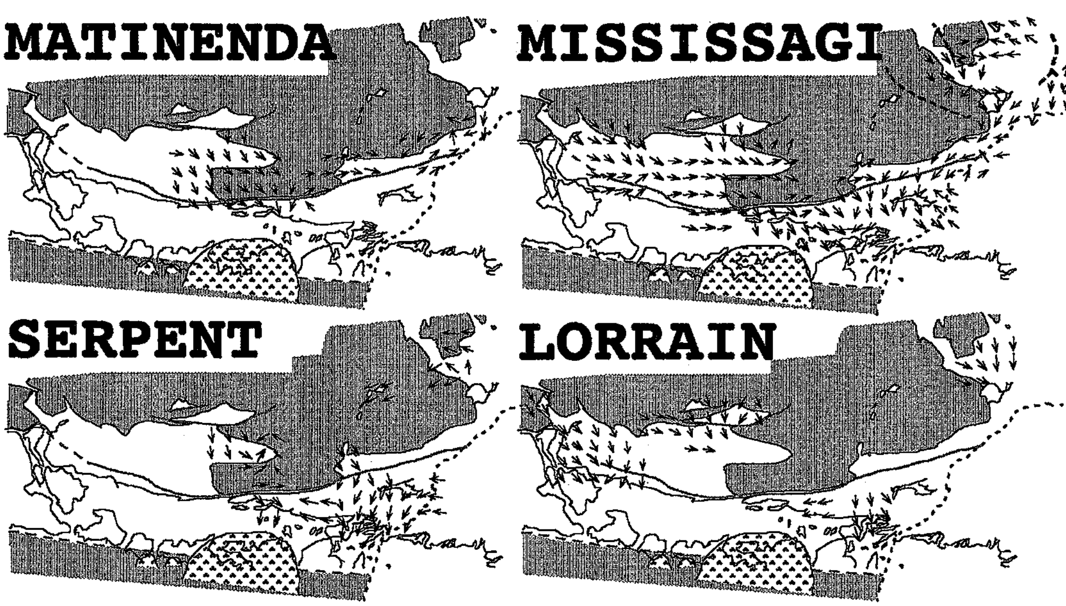

FIG. 1. Paleocurrent trends in the Matinenda, Mississagi, Serpent, and Lorrain formations.

Sandstones in the basal part of the Supergroup, including the Matinenda Formation and its equivalents, are largely absent south of the Murray Fault, where they are replaced by thick mudstones of lacustrine or restricted marine origin. The latter are intercalated with rift-related volcanic rocks, which are thickest in the area between Agnew Lake and Sudbury. Whereas paleoflow directions are toward the southeast in the Elliot Lake area, the distribution further east is more irregular, suggesting infill of a rapidly subsiding basin generated by left-lateral strike slip. Rapid subsidence is confirmed by the abundance of sandstones of grainflow origin in the Elliot Lake Group in the Agnew Lake area.

Rapid subsidence along the axis continued during deposition of the Hough Lake Group, as is indicated by marked thickening of the Matinenda Formation south of the Murray Fault. Paleocurrent flow in the Elliot Lake area was toward the southeast and then parallel to the Murray Fault, suggesting that faults to the south, under Manitoulin Island may have influenced flow. In the Cobalt Plain, irregular patterns of distribution are consistent with development of locally irregular topography, which may have been influenced by NNW-directed faults. East of Sudbury, there is evidence that flow was confined by highlands in the area now occupied by the Grenville Province and the Sudbury Structure. Thickening south of Sudbury supports continued subsidence within a pull-apart basin. A similar pattern is apparent in the overlying Quirk Lake Group, although there is evidence that fault-controlled basins north of Sudbury may have diverted flows into paleovalleys north of Agnew Lake.

Major changes in the geometry of the Southern Province may have occurred during deposition of the lower part of the Cobalt Group. Unfortunately, sandstones in the Gowganda Formation are non-fluvial and provide a less sensitive record of basin geometry. A transformation from strike slip to passive margin geometry may be indicated by a break-up discontinuity in the middle of the Gowganda Formation. Sandstones within the Lorrain Formation show less direct influence of the Murray Fault. The up-section increase in maturity of the Lorrain Formation, along with a marked onlap onto the shield, are consistent with a passive margin evolution for the upper part of the Huronian Supergroup. Tidal marine sandstones are seen for the first time at the top of the Formation. The presence of tidally influenced quartz arenites in the Flack Lake Group indicates reduced rates of subsidence as the pre-Penokean ocean broadened.

The style of the sediments in the Huronian Supergroup is consistent with the origin of the Southern Province as a strike-slip segment of a passive continental margin during formation of a pre-Penokean ocean. Closure of this ocean during the Penokean led to mountain building and deposition of unconfined axial turbidites of the Chelmsford Formation in a foreland basin setting.

STRATIGRAPHIC RELATIONSHIPS IN THE LOWER HURONIAN OF THE SAULT STE. MARIE – ELLIOT LAKE AREAS, AND POSSIBLE IMPLICATIONS REGARDING EARLY HURONIAN TECTONICS

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The lowermost Huronian rocks between Sault Ste. Marie and the Quirke Lake Syncline are those of the Livingstone Creek Formation. They were recognized in the Thessalon, Aberdeen Lake and Sault Ste. Marie areas by Frarey (1977) and, more recently, in the Quirke Lake Syncline (Bennett *et al.* 1991, Jensen 1994). The recognition of the Livingstone Creek Formation in the field is facilitated by its stratigraphic position below the Huronian volcanic rocks of the Thessalon Formation, and its uniform and relatively simple lithological composition. Drill holes in the Sault Ste. Marie area indicate a preserved thickness of at least 250 meters in that area.

The predominant lithology of the Livingstone Creek Formation is fine- to medium-grained grey arkose and subarkose that rarely contain clasts coarser than medium sand. Mudstones are rare. Trough cross-bedding is commonly defined by the differential weathering of carbonate-rich laminae along the foresets. A lower clast-supported, polymictic conglomerate member is generally present, although locally the sandstone member lies directly on the Archean basement rocks. The conglomerate clasts range in size up to a meter or more across and closely match the lithologies of the adjacent basement. Coarse, poorly sorted arkose is locally intercalated with the conglomerate units. Although foliated Archean volcanic rocks are common as clasts in the conglomerate units, clasts of Huronian volcanic rocks have yet to be identified.

The close association of fine sandstone and clast-supported conglomerate in the Livingstone Creek Formation suggests related but contrasting environments of deposition. The conglomerates indicate relative uplift of the Archean basement, leading to rapid erosion and development of alluvial fans along graben(?) walls, whereas the sandstone member may represent deposition of braided streams flowing longitudinally along the gently sloping valley floor.

There is, however, no evidence of contemporaneous or older volcanic activity. If the Livingstone Creek Formation represents rift-related sedimentation, it may be distant from the center of rift activity and volcanism. It may represent deposition in a passive rift, perhaps influenced by major Archean structures or zones of weakness such as the Great Lakes Tectonic Zone.

In the Thessalon area, the sandstone of the Livingstone Creek Formation is capped by a thin unit of locally pyritic and radioactive quartz-pebble – cobble conglomerate. The conglomerate is, in turn, overlain by a few meters of coarse arkose or grit, lithologically distinct from the underlying sandstone of the Livingstone Creek Formation. Locally thin beds of identical quartz-pebble conglomerate and grit are intercalated with the flows of the overlying Thessalon Formation. This quartz-pebble conglomerate – arkose has yet to be found interbedded with the Livingstone Creek Formation, although it has been recognized by its lithology and stratigraphic position in more than 15 outcrops and several drill holes over an area of approximately 5000 km^2. Although thin and discontinuous, its widespread aerial distribution indicates that the conglomerate represent a regional event or (much less likely) a number of local contemporaneous events. The fact that the quartz-pebble conglomerate unit is found directly upon, but never intercalated with, rocks of the Livingstone Creek Formation suggests that Livingstone Creek sedimentation had ceased prior to the deposition of the quartz-pebble conglomerate and that the Livingstone Creek sands had some degree of cementation (perhaps now reflected by the carbonate content of the rocks). The above relationships, as well as the resistant nature of the minerals in the quartz-pebble conglomerate (given a low ambient partial pressure of oxygen), suggest a disconformable relationship between the Livingstone Creek Formation and the surrounding rocks. The apparent lack of a paleosol directly below the quartz-pebble conglomerate may simply reflect the modest lithification of sandstone, which had already undergone one cycle of weathering.

There appears to be a regional variation in the thin quartz- pebble conglomerate unit from the Elliot Lake area in the east to the Sault Ste. Marie area in the west. In the Stanleigh mine at Elliot Lake, and in surface exposures near the Quirke mine, a very thin unit of sedimentary quartz breccia or "sharpstone conglomerate" lies at the base of the Huronian volcanic sequence. In the Sault Ste. Marie area, a medium-sand quartz arenite marks the base of the Thessalon volcanic sequence (or the top of the Livingstone Creek Formation). Since these rocks share the high quartz content and stratigraphic position of the quartz-pebble conglomerate described earlier, the increasing textural maturity of these rocks toward the west suggests a more proximal source-area in the Elliot Lake area.

The probable erosional upper surface of the Livingstone Creek Formation makes any comments regarding the distribution of thickness of the original basin highly speculative. The preserved thickness of the Livingstone Creek rocks suggests thinning toward the east. The most easterly exposures were those found by Jensen (1994), who recognized a thin basal polymictic conglomerate unit in the Pecors Lake area. Clastic dykes of grey sandstone in the nearby Archean basement indicate that the grey arkose unit may have been removed by erosion prior to the eruption of the Thessalon Formation.

The volcanic rocks of the Thessalon Formation interrupted the sedimentation of the uraniferous quartz-pebble conglomerate and signals the development of active rifting. Diamond drilling from the ice of Lake Huron south of Thessalon indicates the presence of a trough filled with volcanic rocks and covered with lower Huronian rocks of uncertain stratigraphic position.

The well-developed paleosol on the volcanic rocks in the Elliot Lake area indicates a period of stability and weathering prior to the deposition of the uranium-bearing gravels of the Matinenda Formation. This Matinenda sedimentation may simply involve a resumption of deposition of the uranium-bearing quartz-pebble conglomerate, which was interrupted by the Thessalon volcanic events. The Matinenda Formation can be recognized in the Thessalon and Sault Ste. Marie areas, although in these western parts of the Huronian belt, it is present as relatively fine-grained sericitic sandstone and pebbly sandstone lying directly upon the volcanic rocks of the Thessalon Formation.

The Aweres Formation is a thick assemblage of clast-supported polymictic conglomerate and intercalated coarse arkose in Aweres Township, northeast of Sault Ste. Marie. Clasts of Livingstone Creek Formation sandstone and Huronian volcanic rocks are prominent in the lower units. The lithologies indicate deposition as alluvial fans forming against scarps of volcanic rocks of the Thessalon Formation and sediments of the Livingstone Creek Formation. This faulting may be a response to the collapse of a rift shoulder to form a passive continental margin or uplift of the basement due to tectonic events to the north.

It should not be assumed that all tectonic events originated within or south of the Huronian basin. The resetting of lead and K/Ar dates in the rocks of the Kapuskasing Structure overlaps with the period of Huronian sedimentation. The major tectonic events of the Kapuskasing Uplift may have played an important role in providing a source for Huronian sediments, as well as influencing climate and tectonic events along the northern margin of the Huronian basin.

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METAMORPHIC AND STRUCTURAL HISTORY OF THE WESTERN HURONIAN SUPERGROUP

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The western Huronian Supergroup exhibits metamorphic and structural patterns consistent with at least two regional thermotectonic events (*D*1, *D*2). An early high-grade metamorphism and associated *D*1 deformation are recorded in rocks immediately south of the Murray Fault. In this area, porphyroblasts in greenschist- and amphibolite-facies rocks grew synchronously with development of a penetrative mica foliation that is oriented at a low angle to bedding and is locally axial planar to recumbent mesoscale folds. High extensional strains appear to be associated with this foliation. Bedding and foliation are folded and faulted by regional *D*2, WNW- to ENE-striking folds and faults that are associated with a well-developed, moderate to steeply dipping crenulation cleavage. The *D*2 folds and faults control and disrupt the distribution of metamorphic zones; textural evidence indicates that the *D*2 cleavage postdates both crystallization of peak metamorphic assemblages and some retrogression of the porphyroblasts. The *D*2 regional folds and faults are typical of structures commonly portrayed on regional maps and are interpreted as postdating peak metamorphism and D1 deformation.

North of the Murray Fault, but south of the Flack Lake Fault, rocks of low metamorphic grade are folded and reverse-faulted about WNW-striking upright folds and NE-directed reverse–thrust faults. In the Gordon Lake and the Ten Mile Lake areas, the folds are associated with weakly to moderately developed, steeply dipping, axial planar foliation. The regional structures resemble the *D*2 structures south of the Murray Fault. An earlier deformation and associated regional metamorphism, however, have not been established for this area. North of the Flack Lake Fault, rocks of the Cobalt Group are gently folded but generally gently south-dipping. Penetrative foliation in this area is restricted to proximity to the major faults.

The upright folds and reverse faults typical of the Huronian Supergroup are consistent with approximate north–south compression. Earlier deformation and high-grade metamorphism remain poorly understood, but may represent a distinct event recorded only south of, or near to, the Murray Fault zone.

SEISMIC STUDIES ACROSS THE SOUTHERN PROVINCE

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The success of preliminary Lithoprobe – GLIMPCE seismic surveys in northern Lake Huron laid the foundation for the acquisition of reconnaissance seismic reflection profiles across key geological structures of the northern margin of the Southern Province. In the study area north of Lake Huron, the tectonic history of the Southern Province begins (between 2.65 and 2.48 Ga) with extension along pre-existing zones of weakness in the Archean crust, followed by rifting and the formation of a passive margin (Bennett *et al.* 1991). At the base of the Huronian Supergroup, the Elliot Lake Group contains mafic volcanic rocks, gabbro – anorthosite and turbidites. The overlying Hough Lake, Quirke Lake and Cobalt groups form three sedimentary cycles, each consisting of conglomerate overlain by either mudstone, siltstone or carbonate units, capped by coarse sandstone. Rocks of the Huronian Supergroup are intruded by 2.2 Ga Nipissing Gabbro (Bennett *et al.* 1991). Since 1986, a series of seismic reflection profiles have been acquired across the Sudbury Structure, the Grenville Front Tectonic Zone (GFTZ), the Murray Fault system south of Sudbury, and the Proterozoic basement of the Michigan Basin beneath northwestern Lake Huron. In addition, several high resolution seismic profiles were collected across one of Canada's most prominent and enigmatic potential field anomalies, the Temagami Lake Magnetic Anomaly in the southern Cobalt Embayment area. This small but unique seismic database provides important insight into the deposition of the Huronian Supergroup, the relationship between the Sudbury Igneous Complex and the Southern Province, the deformation during the Penokean Orogeny, the lack of evidence for major deformation of the Huronian Supergroup north of the GFTZ during the Grenvillian Orogeny, and the reactivation of Proterozoic basement structures during the formation of the Phanerozoic Michigan Basin. The interpretation of the seismic data is constrained by boreholes-of-opportunity and complemented by down-hole geophysical, potential field and electromagnetic studies.

Early Proterozoic Rifting

Three high-resolution vibroseis reflection profiles were acquired across the undeformed Paleoproterozoic Huronian Supergroup (2.5–2.2 Ga) of the Canadian Shield, in the vicinity of the Temagami Lake magnetic anomaly (Milkereit & Wu 1995). The Supergroup, formed as a passive margin sequence and composed of volcanic and sedimentary rocks, unconformably overlies Archean rocks of the Superior Province. High-quality seismic images, obtained through innovative pseudo-3D seismic processing and constrained by lithological data from deep boreholes, reveal a 20-km wide early Proterozoic rift basin beneath the thick cover of the metasediments, the oldest preserved rift basin on Earth.

Sudbury Event and Penokean Deformation

Rocks of the Superior craton and overlying continental marin strata of the Southern Province were severely brecciated and melted by the proposed 1.85 Ga impact event (*e.g.*, Grieve *et al.* 1991). Reflection seismic images not only reveal that the Sudbury Structure is remarkably asymmetrical at depth (Milkereit *et al.* 1992), but also establish that brittle thrust-faulting played an important role in NW–SE shortening of the Sudbury Structure by clearly defining a major imbricated thrust-zone. During the early stages of the Penokean orogeny, northwest-directed compression deformed the original Sudbury Structure into a tight fold. Subsequent deformation, characterized by discrete thrusting, caused second-order shortening of the Sudbury Structure and adjacent Southern Province.

Grenvillian Orogeny

In Georgian Bay, the Grenville Front Tectonic Zone marks the junction of Southern Province rocks with uplifted lower crustal rocks of the Middle Proterozoic Grenvile Orogen (1.3–1.0 Ga). The GFTZ is characterized by prominent southeast-dipping reflectivity (Green *et al.* 1988), representing shear and mylonite zones created under ductile conditions. Seismic data from the Sudbury and the Cobalt Embayment survey areas, located about 20 to 30 km northwest of the GFTZ, provide little evidence for major tectonic deformation caused by the Grenvillian orogeny.

Phanerozoic Basin Formation

A dense network of seismic profiles in northwestern Lake Huron delineates important Proterozoic crustal structures, such the Grenville Front and the Manitoulin terrane beneath Phanerozoic sediments of the Michigan Basin (Green *et al.* 1988, Roberts & Milkereit 1994). These data provide a unique opportunity to study the defomed Huronian continental margin and the structural relationship of the Huronian metasediments with Archean basement. In addition, the seismic data reveal significant basement topography and indicate that movement along presumed Proterozoic structures controlled early deposition of Phanerozoic sedimentary deposits.

Acknowledgements

Proprietary seismic data from the Cobalt Embayment were made available by Falconbridge Ltd. Seismic surveys across the Sudbury Structure were funded by Inco Exploration and Technical Services Inc, Falconbridge Ltd. and the Ontario Geological Survey. The GLIMPCE program was funded jointly by the Geological Survey of Canada and the U.S. Geological Survey.

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Friday afternoon, September 29

A 3-D GEOPHYSICAL MODEL OF THE SUDBURY IGNEOUS COMPLEX

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Whereas the elliptical form of the periphery of the Sudbury Structure can be readily discerned from field mapping, the geometry of the Sudbury Igneous Complex (SIC) at depth under the center of the basin is somewhat speculative. Recent seismic surveys across the Sudbury Structure (SS) indicate that the North Range of the SIC continues under the center of the basin without any displacement. The same seismic data show that the South Range of the SIC is probably composed of a series of thrust slices. Recent structural geological mapping has also led to the concept of a south-dipping shear zone along which the South Range of the SIC has been significantly displaced to the north. The difference between the two models is the northerly limit of the thrust zone. An assumption of both models is that the south-dipping faults do not intersect the underlying continuation of the North Range of the SIC.

To investigate these models, we have constructed a 3-D model of the SS using an array of right vertical cubes having a 1-km unit dimension. Each cube represents a different geological unit with its own physical properties of magnetic suceptibility, natural magnetic remanence, and rock density. The majority of the magnetic signal from the SS is closely related to the surficial outline of the SIC. Local variations are intimately associated with lithological variations in the SIC. For example, magnetic highs are found associated with the altered granophyre and quartz-rich gabbro of the South Range. A feature not explained by the geometry of the SIC is a sharp linear magnetic high located on the border of the South Range Onaping and Onwatin formations. Preliminary modeling of this feature invoking upward displacement of the highly magnetic norite "floor" of the SIC on the south-dipping faults results in a similar linear anomaly, but it is much broader than the observed anomaly. A localized gravity high located within the South Range of the SIC appears to be more related to the presence of the dense quartz-rich gabbro unit than the uplift of the norite. Further revisions of this model are in progress.

Most of the deformation of the basin appears to have resulted from Penokean-age displacements. Magnetic anomalies associated with the Sudbury olivine diabase dykes provide ideal markers for locating the extent of Grenvillian deformation. Ductile deformation of Grenvillian age is limited to a small zone within 2 km of the Grenville Front. Between the Grenville Front and the SS, Grenvillian displacement is restricted to major fault zones, such as the Murray and Long Lake faults. Within the basin, significant displacement is restricted to the Cameron Creek Fault.

HURONIAN VOLCANISM IN CENTRAL ONTARIO: AN EARLY PROTEROZOIC EXAMPLE OF PASSIVE CONTINENTAL MARGIN PLATE TECTONICS

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The three-kilometer-thick sequence of Huronian volcanic extrusive rocks along the north shore of Lake Huron is dominated by originally horizontal basaltic lava flows, but it also contains abundant rhyolitic and lesser intermediate lavas. The oldest flows are interlayered with basal quartz conglomerate of the Huronian Supergroup; fragmental rocks of pyroclastic origin are scarce within basaltic strata, and comprise only a minor proportion of felsic accumulations, consistent with a passive tectonic setting. However, many of the lavas display geochemical features associated with island-arc volcanism, including enriched chondrite-normalized concentrations of large-ion lithophile (LILE) and light rare-earth (LREE) elements and Th, high Sr/Nd ratios, pronounced Pb spikes, strong normalized negative anomalies for high-field-strength elements (HFSE), and high Nd isotope ratios.

These features are most enhanced in felsic end-members, and tend to decline in magnitude with height in the stratigraphic pile, becoming more MORB-like with time, such that the latest basalts in the sequence resemble modern N-MORB. The arc-like geochemical patterns of early flows are consistent with contamination of MORB-like tholeiite basalts by granitic upper continental crust, during which the basalts were enriched in LILE, LREE, and Th, but strongly depleted in HFSE. The crust was young (about 200 to 250 Ma) and relatively hot during Huronian volcanism (2450 Ma), and the parental magmas (about 49% SiO_2) were extensively contaminated by an unusual two-stage process of crustal assimilation. First, during their rise through the crust, the magmas incorporated up to 40% granitic material from the margins of the feeder system; the degree of such contamination decreased and was minimized in the late basalts, presumably owing to deposition of insulating layers along the channelways. A second period of contamination took place within systems of Nipissing-like subvolcanic sills, where up to 50% contamination and simultaneous fractionation of gabbroic assemblages produced intermediate to rhyolite lavas (about 70% SiO_2). Slightly elevated Sr/Nd ratios compared with N-MORB in the latest, least-contaminated basalts are consistent with equilibration of the lithospheric mantle source with arc magmas during the formation of the continental crust in Archean time.

THE AGNEW (SHAKESPEARE–DUNLOP) INTRUSION: AN EXAMPLE OF EARLY MAFIC PLUTONISM ASSOCIATED WITH THE HURONIAN RIFT ZONE

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The Agnew Intrusion (formerly the Shakespeare–Dunlop Intrusion) is one of several differentiated Early Proterozoic (2480–2490 Ma) gabbronoritic to leucogabbronoritic plutonic bodies that straddle the Superior Province – Southern Province boundary in the Sudbury region. They are collectively referred to as intrusions of East Bull Lake type, and form a sinuous ENE-trending belt a minimum of 170 km in length. These plutons were probably emplaced as "rift-shoulder" intrusive bodies during early stages in the development of the Huronian rift zone. The Agnew Intrusion, with a present exposure of 50 km^2, was an elongate body, from which its eastern half has been downfaulted and is no longer exposed. In cross-section, the Agnew Intrusion is interpreted as an asymmetrical boat-like structure with individual units of the stratigraphic sequence thickening along the synclinal axis of the intrusion and thinning out as they deflect upward along the walls of the magma chamber. A topological high in the footwall surface is predicted to occur along the length of the chamber, resulting in a northerly disposed step-and-riser configuration of the basal contact.

The intrusion has a maximum thickness of 3000 m and may be stratigraphically divided into three major series: the Marginal Series, predominantly leucogabbronorites composed of plagioclase (An_{60-80}), olivine and inverted pigeonite cumulates; the Lower Series, composed mainly of gabbronorites containing various proportions of cumulus plagioclase (An_{70-80}), olivine and inverted pigeonite, and the Upper Series, comprising plagioclase-phyric varieties (An_{60}) overlain by cumulus Fe–Ti-oxide-bearing rocks and ferrodiorite. Roof pendants have locally been recognized. The boundary between the Lower and Upper Series marks a shift from olivine-normative to quartz-normative rock types. Major lithological changes within the intrusion are interpreted in terms of (1) the sequential injection of three or four compositionally distinct magma-pulses that are nonetheless genetically related at depth, (2) fractional crystallization of plagioclase and, less importantly, inverted pigeonite and olivine, (3) ponding of fractionated residual liquids, and (4) the possible assimilation of granitic footwall and roof material.

The primary mafic mineralogy of the Agnew Intrusion has been pseudomorphically replaced by Ca-amphibole through greenschist- to lower-amphibolite-facies metamorphism associated with the *ca.* 1.9 Ga Penokean Orogeny. However, most plagioclase crystals, excepting those in the upper stratigraphic portion of the intrusion, have resisted metamorphic recrystallization and retained igneous compositions, suggesting that metamorphism was characterized by a finite amount of fluid. There is strong evidence to indicate that autometamorphic alteration occurred in the upper portions of the intrusion. This suggests that the magmatic fluid component was retained in the magma chamber and was not lost from the system. A further important implication of such an observation is that volcanic feeder conduits are unlikely to have emanated from the Agnew Intrusion, arguing against a direct genetic relationship between the intrusions of East Bull Lake type and the basal volcanic rocks in the Huronian rift zone.

Investigations of possible compositions of parental magma for the Agnew Intrusion have concentrated on suites of mafic dykes that immediately underlie and locally cross-cut the intrusion. These are subdivided into four groups based on variations in the field data, bulk-rock geochemistry and texture. Group 1 includes high-Al (>17 wt.% Al_2O_3) plagioclase-phyric diabases; group 2 is defined by low-Al (13–16 wt.% Al_2O_3) plagioclase-phyric diabases, and group 3 comprises high-LILE (K_2O between 1 and 3 wt.%, Ba between 200 and 800 ppm, Rb between 20 and 100 ppm) aphyric diabases. All these dykes are tholeiitic in character, with moderate concentrations of Ti (~1.3 wt.% TiO_2) and geochemically evolved compositions (Mg# < 56). Group 4 is represented by a single 50- to 300-m-wide gabbronoritic dyke, the Streich Dyke, that forms a prominent 4-km ridge linking the Agnew and East Bull Lake intrusions. It is characterized by a low concentration of Ti (<0.5 wt.% TiO_2), a higher Mg# of 64, and a markedly lower S tenor relative to group 1-3 dykes. The Streich Dyke appears to have acted as a feeder conduit to most of the Lower Series rocks.

The porphyritic plagioclase in groups 1 and 2 are glomerophenocrysts, 1–4 cm in diameter. It is as yet unclear whether these groups can be readily accounted for by an increase in glomerophenocryst population within group 1 relative to group 2. However, in favor of such a concept are element ratios. Those ratios not affected by variable concentrations of plagioclase are identical, *e.g.*, Ce_N/Yb_N between 1.3 and 2.8, Zr/Nb ≈ 18, whereas Eu/Eu* (1.1) and CaO/TiO_2 (11.3) are significantly enhanced in group 1 with respect to group 2. Group 3 is characterized by a greater range in chemical composition, with elevated REE ratios and LILE concentrations that may require the assimilation of a felsic contaminant at the source.

The incorporation of group-1 dyke fragments within Lower Series rocks suggests that group-1 magmas may have fed the underlying Marginal Series cumulates. In support of this hypothesis, it is noted that (1) both group-1 magmas and the majority of Marginal Series cumulates consist of leucogabbronorite with high levels of Al, and (2) both are olivine-normative. The observed petrological similarities and absence of cross-cutting relationships between group-2 dykes and the porphyritic Upper Series of the Agnew Intrusion make them candidates as feeder magmas also. The field occurrences and geochemical characteristics of group-3 dykes are not consistent with any magma compositions identified within the Agnew Intrusion and are believed to postdate its emplacement. Nevertheless, similar HFSE ratios recorded for all four suites of mafic dykes in proximity to the Agnew Intrusion may suggest a common parental source. In addition, data on PGE and chalcophile element ratios (Pd/Ir, Ni/Cu) imply that at least groups 1 to 3 exhibit values typical of flood basalt magmatic provinces.

CONSTRAINTS ON THE GENESIS OF HURONIAN MAGMATISM IN THE SUDBURY AREA FROM RADIOGENIC ISOTOPIC AND GEOCHEMICAL EVIDENCE

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The onset of *ca.* 2500 Ma magmatism associated with the basal Huronian Supergroup defines the initiation of the Proterozoic Era after a 170 Ma hiatus following the cessation of formation of granite–greenstone belts in the Abitibi Subprovince to the north. The "trans-Huronian" magmatism is almost exclusively mafic and is manifested in a variety of styles. These include dykes emplaced into the Archean craton (the Matachewan–Hearst dyke swarm), sills and sill-like plutonic bodies emplaced along the southern margin of the craton [bodies of the so-called "East Bull Lake (EBL) type", of which about six have been identified to date], and the mafic-member-dominant bimodal volcanic suite, which represents the base of the Huronian sequence proper. Associated felsic magmatism is limited to the rhyolitic upper member of the volcanic suite and the somewhat enigmatic felsic plutonism adjacent to the Sudbury Igneous Complex (SIC). This study will emphasize the relationships among the mafic intrusive components of the trans-Huronian suite, leaving the associated felsic rocks and the temporally distinct (younger) Nipissing Gabbro largely aside.

The EBL-type intrusions include, from west to east, the East Bull Lake and Shakespeare–Dunlop intrusions, smaller sills in May, Tennyson, Drury, Wisner and Falconbridge townships, and the River Valley Pluton in the Grenville Province, which is temporally and petrologically affiliated with this suite. In addition to a temporal correlation between these intrusions (*ca.* 2490 to 2450 Ma) and the Matachewan–Hearst dykes, and a broad tectonic association, petrographically similar dykes have been tentatively identified as basal feeders to the EBL and Shakespeare–Dunlop intrusions. All of these bodies can be broadly characterized as plagioclase-dominant, evident in the sills and plutons in their dominantly leucogabbro-noritic composition, bordering locally on anorthositic, and in the dykes by distinctive plagioclase-phyric textures. This is reflected, on average, by relatively high Al contents (18–20 wt.% Al_2O_3, as opposed to 14–16 wt.% in more typical basaltic compositions) in the larger intrusions and their potential basal feeders. It should be noted that the smaller sills and the Matachewan–Hearst dykes are *not* characterized by elevated Al contents, in common with the Huronian basalts.

The incompatible trace-element geochemical signatures of these intrusions are broadly similar. This is reflected by comparable absolute abundances and relative abundances, as plotted on diagrams normalized to more primitive compositions in the reservoir (*i.e.*, primitive mantle or chondrite), such as spidergrams and rare-earth-element profiles. Whereas local variations within a given unit may be attributed to contributions from local granites of crustal derivation, on the whole the trace-element geochemistry shows distributions consistent with control largely through the effects of fractionation and accumulation of calcic plagioclase, orthopyroxene and clinopyroxene, plus or minus olivine. The influence of accessory phases such as apatite and ilmenite is also apparent. Preliminary geochemical modeling (Prevec 1993) of fractionating phases and trapped evolved liquids suggests that these compositions can be derived from a parent liquid comparable to least-contaminated, moderately evolved Huronian basalts. More detailed and better-constrained subsequent modeling of the EBL intrusion (Peck *et al.*, and Prevec *et al.*, both in prep.) is consistent with a relatively high-Al parental magma that initially has plagioclase as the only liquidus phase (*followed* by olivine). This is supported by petrographic evidence at East Bull Lake (although not evident elsewhere owing to the paucity of preserved primary olivine).

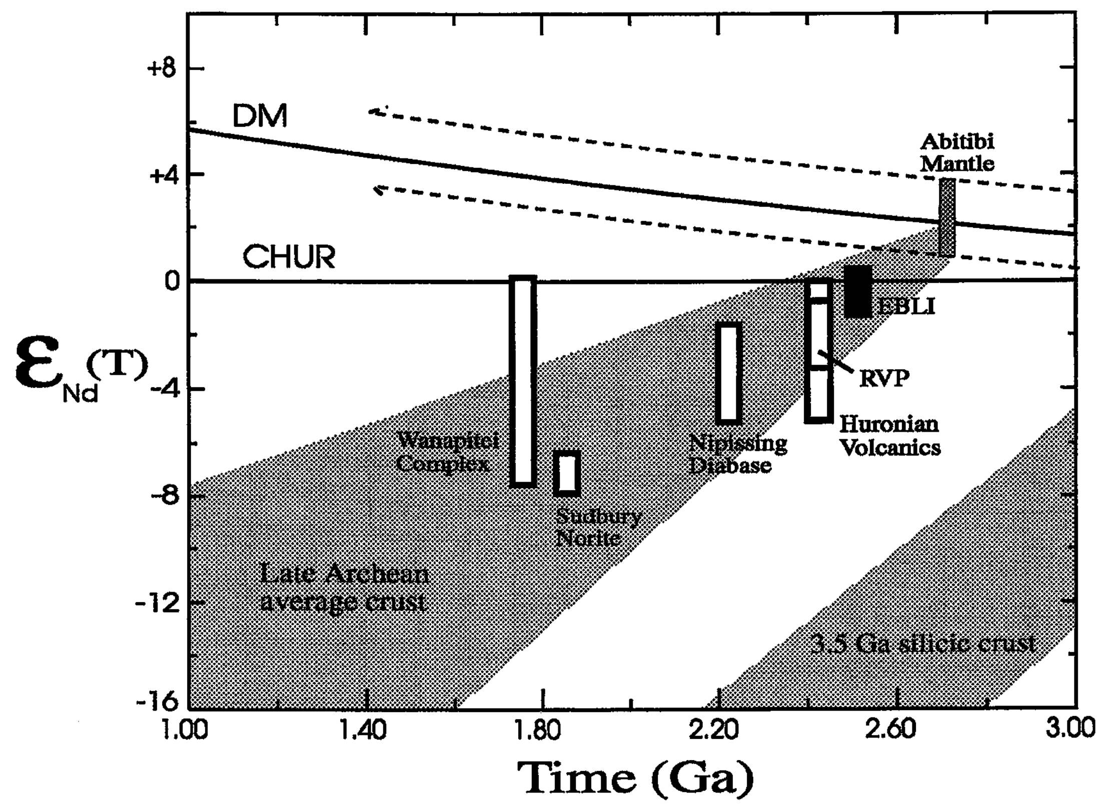

FIG. 2. Diagram showing $\varepsilon_{Nd}{}^{i}$ *versus* time and the variation in Sm–Nd isotopic compositions for selected Early Protorozoic mafic rocks. Symbols: EBLI: East Loon Lake Intrusion, RVP: River Valley pluton, DM: Depleting Mantle, CHUR: Chondritic Uniform Reservoir.

A relatively small amount of reliable geochronology is available for the trans-Huronian, constraining the pre-Nipissing magmatism to a span of about 50 Ma in the earliest Proterozoic, although some enigmatic results have been obtained from bodies nearer to the SIC (*e.g.*, Krogh *et al.* 1984, Prevec & Baadsgaard 1994). Studies of these rocks using radiogenic isotopic tracers to date consist of relatively preliminary Sm–Nd isotopic work on the larger units, including the Huronian basalts. However, all of the available data are consistent with derivation of a magma from a mantle source with $\varepsilon_{Nd}{}^{i} = 0$ at about 2.45 Ga, and subsequent variable amounts of contamination by older sial (Fig. 2). This suggests either the existence of a "chondritic" mantle reservoir beneath the southernmost Superior Province, or of a relatively uniformly enriched one (*i.e.*, a depleted mantle that has been relatively homogeneously enriched in the LREE). Geochemical modeling and isotopic evidence from the EBL intrusion and from younger but proximal intrusions (*i.e.*, the Wanapitei Complex) suggest that enrichment of the upper mantle in LREE occurred as a result of orogenic activity, followed (after *ca.* 200 Ma) by melting and synemplacement contamination of the enriched material.

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METALLOGENIC POTENTIAL OF THE HURONIAN–NIPISSING MAGMATIC PROVINCE

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Both direct as well as indirect evidence indicates that the Huronian–Nipissing Magmatic Province has considerable potential to host significant Cu–Ni–PGE sulfide mineralization. The magmatic components of this province were emplaced in two distinct episodes: (1) the first phase of magmatism generated early Huronian (*ca.* 2450 Ma) intrusive bodies and volcanic rocks during the initial rifting that led to the formation of the Southern Province, and (2) the second phase of magmatism at *ca.* 2220 Ma produced the Nipissing Gabbro intrusions, which were emplaced as sills within the Huronian sediments.

The type example of the early Huronian intrusions is the differentiated gabbronoritic to leucogabbroic East Bull Lake Intrusion (EBLI). The intrusions straddle the Superior Province – Southern Province boundary and are distributed throughout the Southern Province, extending from the EBLI and Agnew Intrusion in the west to possibly the Temagami Lake Intrusion in the east. A number of the intrusions (Joe Lake, Drury Township, and the Falconbridge Township intrusions) occur in the footwall rocks abutting the

Sudbury Igneous Complex (SIC). Some of the intrusions lie outside the Southern Province proper, these being the Fort Knox intrusion hosted by Archean rocks in the north and the River Valley Complex in the south, the latter straddling the Southern Province – Grenville Province boundary, with the bulk of complex occurring in the Grenville Province. There is compelling geochemical and field evidence to believe that the early Huronian intrusions are comagmatic with the Hearst–Matachewan Dyke Swarm and the earliest phase of Huronian volcanism, the Elsie Mountain Formation. Given the very wide spatial distribution of the early Huronian intrusions, dykes and volcanic rocks, it is probable that they were formed from a mantle plume.

A number of the EBL-type intrusions contain significant Cu–Ni–PGE mineralization. The East Bull Lake Intrusion contains a 16-km-long surface zone of contact sulfides along its base, the width of the zone being highly variable, ranging from a few meters to 150 meters (Peck *et al.* 1993). The zone hosts up to 10% disseminated sulfides (chalcopyrite, pyrrhotite and pentlandite); contact sulfide mineralization contains up to 1% Cu, 0.3% Ni, and 12 ppm combined Pd and Pt. Detailed mapping and extensive diamond drilling by BP Resources Canada Ltd. delineated an extensive zone of PGE–Cu–Ni mineralization in anorthositic cumulates from the margins of the Agnew Intrusion. Finally, the Fort Knox intrusion contains both massive and breccia-type mineralization in pod-shaped zones with maximum widths of 20–40 meters.

The Nipissing Gabbro is widespread throughout the Southern Province, accounting for *ca.* 25% of the outcrop area. As shown by Lightfoot *et al.* (1993), a number of the Nipissing Diabase sills contain significant Cu–Ni–PGE mineralization. For example, grab samples from the Rathbun Lake and Kukagami occurrences contain up to 0.7% Ni, 14.2% Cu, 3050 ppb Pt and 34,500 ppb Pd.

Although these occurrences of Cu–Ni–PGE mineralization are important guides for exploration, what is perhaps even more encouraging for explorationists is compelling evidence that the rocks of the Huronian–Nipissing Magmatic Province were formed from S-undersaturated magmas, a major requirement for the formation of significant Cu–Ni–PGE sulfide mineralization (Keays 1995). Most samples from the EBLI and the Agnew Intrusion, as well as a number of (feeder?) dykes in the footwall of the latter not only have high Pd/S and Pd/Se values, but also high absolute Pd and Pt contents. For example, analyses of samples from a 800-meter-long diamond drill hole in the EBLI showed that the entire intersection averaged 70 ppb Pd, with few samples containing less than 10 ppb Pd, and a 100-meter-wide zone toward the base averaging *ca.* 600 ppb Pd. The high Pd/S and high absolute PGE values of these rocks can only be a product of crystallization from S-undersaturated, PGE-rich magmas.

Hence, the early Huronian intrusive bodies were formed from S-undersaturated, PGE-rich magmas of the type that are required for the formation of major Cu–Ni–PGE sulfide deposits. Although background PGE data are only now in the process of being collected for the Nipissing Gabbro intrusions, the widespread occurrence of sub-economic Cu–Ni–PGE sulfides in these rocks suggests that they too were formed from S-undersaturated magmas. It would appear, then, that the Huronian–Nipissing Magmatic Province was formed by magmas that had the potential to form major Cu–Ni–PGE deposits. As also shown by Keays (1995), another requirement for the formation of such deposits is that the S-undersaturated, PGE-rich magmas encounter and react with a major crustal source of S. Exploration for Cu–Ni–PGE sulfides in the Southern Province should thus focus on areas where the favorable magmas that formed the rocks of the Huronian–Nipissing Magmatic Province interacted with crustal sulfides.

Finally, if the Cu–Ni–PGE ores of the SIC are a product of meteorite impact, it may be reasonable to assume that the metals were contained within protores rather than dispersed throughout the impacted crustal rocks. The only logical hosts for such protores are rocks of the Huronian–Nipissing Magmatic Province. If this were the case, then an additional line of reasoning would suggest that those components of the Province not impacted by the meteorite should have considerable potential to host significant Ni–Cu–PGE sulfide mineralization.

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Saturday morning, September 30

GEOCHEMISTRY OF THE NIPISSING GABBRO: SOURCE AND MINERAL POTENTIAL

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The 2.2 Ga Nipissing Gabbro intrusions consist of a suite of dominantly tholeiitic to calc-alkaline rocks ranging from chilled diabase through quartz diabase, gabbro, gabbronorite, vari-textured gabbro, and pegamatitic gabbro, to granodiorite, granophyric gabbro, and aplitic granitoids. The intrusions extend from Sault Ste. Marie through the Sudbury Region, to the Cobalt and Gowganda Regions, and outcrop as open ring structures, dykes, and undulatory sills (Card & Pattison 1973). U–Pb geochronology on magmatic baddeleyite from the Nipissing (Noble & Lightfoot 1992) for intrusions with at least two different directions of paleomagnetic remanence (Buchan *et al.* 1989) indicate that intrusions were emplaced within a period of less than 8 Ma. Many of the intrusions are elongate east–west, and it is possible that their emplacement was genetically linked to faulting accompanying the deposition of the Huronian sediments. The gabbros of the Sudbury Region are hosts to small bodies of massive sulfide, and the less differentiated gabbroic intrusions carry disseminated magmatic sulfides. The massive sulfides at Rathbun Lake, on the northern rim of the Wanapitei Intrusion, have up to 14 wt.% Cu, 1.5 wt.% Ni, 6 ppm Pt, 53 ppm Pd, and 6 ppm Au; these are overlain by a zone of blebby sulfide, and the blebs are fractionated into a pyrrhotite-rich base and a chalcopyrite-rich top. The disseminated sulfides (<5% sulfide) in the enstatite gabbros more than 200 m above the base of the Kukagami Lake intrusion have <3 wt.% S, but typically have 0.5–1.5 wt.% Cu, 0.1–0.4 wt.% Ni, 0.5–1.1 ppm Pt, and 1.5–3.3 ppm Pd. The observation that these mineralized intrusions are relatively mafic (10–30 modal % cumulus enstatite, 9.25 wt.% MgO, 0.41 wt.% TiO_2, and 51 ppm Zr), and carry significant amounts of disseminated sulfide, is important in the context of their setting. These intrusions lie on a southwest–northeast trend, which is a gravity and aeromagnetic high, and along which the mineralized early Proterozoic intrusions, the Sudbury Igneous Complex, and the Temagami copper deposits are located. At issue, therefore, is whether there are any unusual features to the gabbros in this region that might assist in exploration activities, and whether there is any regional variation in chemical composition that may have tectonomagmatic implications.

Geochemical data for strongly differentiated Nipissing sills indicate that the intrusions underwent significant *in situ* differentiation coupled to the assimilation of the roof sediments. Lightfoot & Naldrett (1989) showed that much of the assimilation was linked to the fractionation of the magma in a coupled process, in which the latent heat of crystallization of the magma produced a commensurate amount of assimilation of country rocks. In some cases, irregular lenses of aplitic granitoids formed near the roof of the Nipissing intrusions, and these can be considered as anatectic melts of Huronian sediments. Some of the less differentiated intrusions of the Gowganda region show geochemical evidence for the emplacement of as many as four batches of magma into a single undulatory sheet (Conrod 1989).

The chilled quartz diabase margins, and the least- differentiated samples of quartz diabase and gabbro, have been analyzed to establish whether all of the Nipissing gabbros crystallized from a similar magma-type. The chilled margins from seven different sills are characterized by 8.8 wt.% MgO, 51.6 wt.% SiO_2, 0.7 wt.% TiO_2, 69 ppm Zr, La/Sm = 2.7, and Gd/Yb = 1.8. Samples of quartz diabase and gabbro from 22 different intrusions contain 8.1 wt.% MgO, 51.8 wt.% SiO_2, 0.65 wt.% TiO_2, 66 ppm Zr, La/Sm = 3.0, and Gd/Yb = 1.75. Systematic attempts to distinguish geochemically different sills have failed, and therefore only one magma type is proposed for the Nipissing event. Compositional differences in the more differentiated rocks can be attributed to fractionation and *in situ* assimilation of roof rock. A comparison of the magma type responsible for mineralized and unmineralized sills also has failed to detect a significant difference in composition of the parental magma, although many of the samples from the mineralized sills tend to be enriched in cumulus enstatite, and therefore have more mafic compositions. The parental Nipissing magma type is marked by moderate enrichment in the light rare-earth elements and large-ion lithophile elements, together with negative anomalies on mantle-normalized spidergrams at Ta + Nb, P, and Ti. These are features indicative of interaction with a crustal reservoir; the homogeneity of the magma throughout the magmatic province led Lightfoot *et al.* (1993) to propose that this was a feature inherited from the source region of these magmas, possibly the continental lithospheric mantle.

The sills found in large igneous provinces such as the Karoo and Siberian Trap are considered to be not only intrusive equivalents of the lavas, but also the conduits through which the magma travelled to the surface. In some cases, the lavas record evidence of strong contamination, and depletion in Ni, Cu, and platinum-group elements, such as that found at Noril'sk. Although there are no known extrusive equivalents of the Nipissing Gabbro, nor any large mineral deposits, the abundance of high-grade disseminated mineralization in many of the intrusions provides good reason to search for targets where these metals have been enriched by either gravitational or hydrothermal processes.

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VARIATIONS IN PALEOMAGNETIC DIRECTION AND FELDSPAR CLOUDING INTENSITY ACROSS THE MATACHEWAN DYKE SWARM, AND THEIR RELEVANCE TO THE HURONIAN

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The early Proterozoic Matachewan dyke swarm contains two approximately antipodal directions of remanent magnetization, designated normal (N) and reversed (R), which were produced by a single reversal of Earth's magnetic field during the time of igneous activity about 2.45 Ga ago. Field relations show that the N magnetization is the younger (Halls 1991). Across more than 90% of the swarm, R dykes dominate, with N ones forming about a fifth of the total dyke population. However, on the upthrown sides of major thrust faults associated with the Kapuskasing structural zone (KSZ), a major linear belt of Proterozoic crustal uplift, the dykes are exclusively of N polarity, but across the faults on their downthrown side, the dykes are dominantly reversed (Halls & Palmer 1990, Bates & Halls 1990, Halls & Zhang 1995a). The N polarity regions are considered to represent deeper levels in the crust where dykes, mostly emplaced during the R epoch, did not acquire their final magnetization owing to slow cooling until the following N epoch (Halls *et al.* 1994). Uplift along the faults has then brought these regions or domains of N dykes into juxtaposition with the R ones. The concept to use magnetic polarity domains as a method to infer major faults has been explored southwest of the KSZ, where two major faults have been discovered and another extended, on the basis of paleomagnetic work from a further 80 dykes (Halls & Zhang 1995a) (Fig. 3). The results demonstrate the utility of paleomagnetic data from Proterozoic dyke swarms in delineating major faults in shield areas, particularly in gneissic or other homogeneous terranes where visible lithological offsets are subtle or lacking.

The variation in regional paleomagnetic direction across the Matachewan swarm, within each polarity, also has been used to measure crustal deformation. For example, the Archean crust to the east of Lake Superior has been

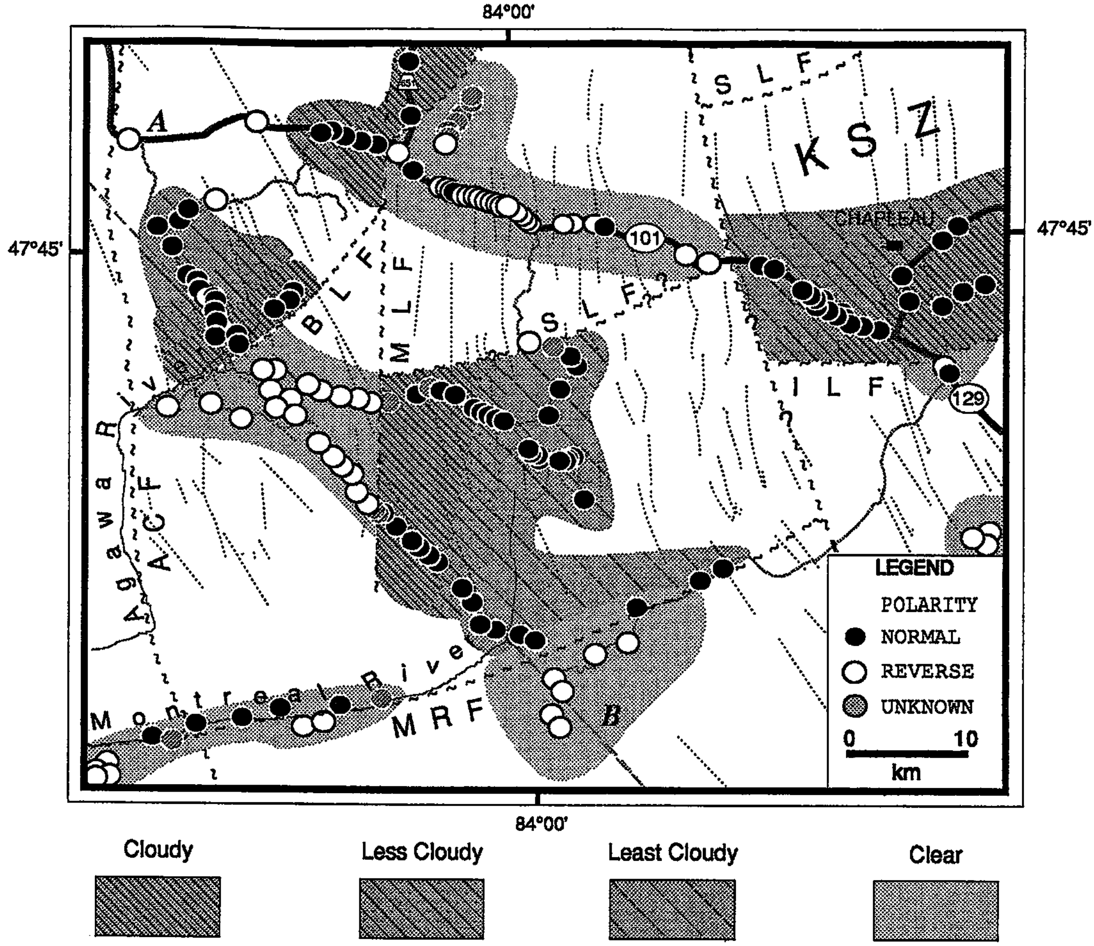

FIG. 3. Map of the southern end of the Kapuskasing Structural Zone (KSZ) showing the spatial relationship between paleomagnetic polarity and intensity of clouding of feldspar in Matachewan dykes (dotted lines). Note that the intensity of clouding, as determined by visual inspection of thin sections, increases toward major faults. Paleomagnetic sites are shown by circles, coded as to whether the polarity of the dyke is normal (black), reversed (white), or indeterminate (grey). ACF, BLF, ILF, SLF, MLF and MRF are the Agawa Canyon, Budd Lake, Ivanhoe Lake, Saganash Lake, McEwan Lake, and Montreal River faults, respectively. The bounding faults of the KSZ are the SLF and ILF. Figure from Zhang & Halls (1995b).

tilted more than 50° westward as a result of subsidence within the Keweenawan basin (Halls & Shaw 1988). The application of this method to Archean rocks adjoining the Huronian fold belt may help to throw light on the extent of basement involvement in the deformation of Huronian sequences.

On the upthrown sides of major faults associated with the Kapuskasing structure, Matachewan dykes exhibit, in addition to N polarity, a tea-colored clouding of their feldspars (Halls & Palmer 1990, Zhang & Halls 1995) (Fig. 3). This phenomenon characterizes many tholeiitic Proterozoic swarms throughout the world where the regional metamorphic grade of the host rock is amphibolite to granulite (Halls & Zhang 1995b). For the Matachewan swarm, the clouding was produced during the initial slow cooling of dykes at relatively deep crustal levels of about 10–20 km, where ambient temperatures were about 500–600°C (Halls *et al.* 1994). The intensity of clouding increases with the depth of dyke emplacement, as given by geobarometric evidence (Percival *et al.* 1994). Rock-magnetism experiments (Zhang & Halls 1995) show that submicroscopic magnetite contributes to the clouding and to the normal (N) polarity remanence of those Matachewan dykes that have been raised from deeper crustal levels. Since the N polarity epoch started during the latter part of the Matachewan igneous episode, the clouding seems to be virtually a primary feature, insofar as it formed, probably by exsolution, during cooling of the crust immediately following dyke emplacement (Zhang & Halls 1995).

Around the northern margin of the Sudbury Igneous Complex, the Matachewan dykes found within Levack gneisses commonly are disrupted or occur as clasts within the Sudbury Breccia. Their feldspars are cloudy, in sharp contrast to dykes of the same swarm farther north, in the Timmins–Gogama area. The interpretation of the clouding, in light of the KSZ experience, is that the dykes crystallized at deeper crustal levels before being raised, along with the Levack gneisses, probably during the same event that formed the Sudbury breccia.

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THE NATURE OF THE FORELAND MARGIN OF THE PENOKEAN OROGEN IN THE GREAT LAKES REGION OF THE U.S.A.

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The Early Proterozoic Penokean orogen, on the southern flank of the Late Archean Superior craton, contains rocks and structures that formed in the interval between 2.5 and 1.75 Ga. The Penokean belt is truncated on the east by the Grenville orogen (1.0 Ga) a short distance east of Sudbury, Ontario and on the west by the Central Plains orogen (~1.6 Ga) in the subsurface of east-central Nebraska, and it is transected by both arms of the Midcontinent Rift System (1.1 Ga) south of Lake Superior. Thus its preserved length of about 1,200 km is an unknown fraction of its original length.

The stratigraphic and structural attributes of the preserved supracrustal rocks are indicative of a predominantly extensional depositional regime in the Huronian segment of southern Ontario and of a predominantly convergent depositional regime in northwestern Wisconsin and east-central Minnesota. In general, the rock sequences interpreted to have been deposited on an extending continental margin (Huronian Supergroup and possible correlatives to the west) are older than those interpreted to have been deposited in intra-arc basins and migrating foredeeps (Baraga and Animikie groups and possibly the North Range Group in the Cuyana iron district of Minnesota). The rock record therefore is broadly consistent with a Wilson-cycle model in which (1) the Superior craton underwent extensional breakup, leading eventually to a Penokean ocean basin or seaway, and (2) the ocean basin subsequently closed by plate-subduction mechanisms. Though conceptually simple, this process clearly was complex in detail, and many aspects of it remain to be worked out.

The foreland margin of the Penokean orogen is marked by a major unconformity between Archean basement and superjacent sedimentary rocks of Early Proterozoic age. In the east, the basal unconformity is beneath the Huronian Supergroup and is interpreted tectonically as a break-up unconformity related to cratonic extension. In the area south and southwest of Lake Superior, the basal unconformity is beneath the Baraga and Animikie groups, both of which are now interpreted as sequences deposited in migrating foredeeps toward the close of tectonic convergence. The "basal" unconformity thus is not a time-equivalent surface along the length of the orogen; indeed, the sub-Huronian unconformity may predate the sub-Animikie unconformity by 100 m.y. or more. If the sub-Huronian unconformity exists anywhere in the Lake Superior region, it is likely to be on basement uplifts within the fold-and-thrust terrane of east-central Minnesota, northern Wisconsin, and adjacent parts of northern Michigan. Correlations between Huronian strata and rock units in Michigan and Wisconsin have been difficult to establish. The best candidates for correlation are glaciogenic sequences (Fern Creek, Reany Creek formations) that may be equivalents of the Gowganda Formation in Ontario.

The Penokean orogen trends more or less due west from the Sudbury area to east-central Minnesota, where it curves abruptly southward; it recurves to a west-southwest trend near the Minnesota–Iowa border and continues on that trend to its western terminus. The oroclinal bend in Minnesota may reflect a jog in the rifted continental margin that subsequently influenced the geometry of plate convergence and subduction. The postulated marginal jog occurs near the junction between the Wawa and Minnesota River Valley subprovinces of the Superior craton, and it may have been localized by mechanical contrasts between these subprovinces as the craton was initially extended. The exterior of the bend is the focus of a radiating dyke swarm (2.1 Ga) in the cratonic foreland that was emplaced before the filling of external foredeeps with Animikie-equivalent sedimentary rocks. Interior zones of the Penokean belt in the vicinity of the bend contain a large volume of late- to post-tectonic granitic plutons and a relative lack of supracrustal rocks.

Structures developed in rocks of the Huronian Supergroup in Canada indicate a compressional history of deformation, but no rock sequences are known that have unequivocal convergent-margin depositional attributes. The tectonic equivalent of the sub-Animikie unconformity may lie beneath the Paleozoic cover south of the Huronian outcrop belt, or it and the superjacent Animikie-equivalent foredeep strata may have been removed totally by erosion. Another possibility, first postulated by Young (1991) and best left to local experts for evaluation, is that the Onwatin and Chelmsford Formations of the Whitewater Group in the core of the Sudbury Structure are remnants of an Animikie-style foredeep sequence. Is the base of the Onwatin an unconformity? Could the "event" responsible for the Sudbury Structure have postdated Penokean extension but predated Penokean convergence?

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PROTEROZOIC REACTIVATION OF THE MARGIN OF THE FENNOSCANDIAN ARCHEAN CRATON

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THE ARCHEAN

The Archean Fennoscandian Shield comprises 2790–2750 Ma greenstone belts, and several phases of felsic plutonism. The first phase of plutonism is responsible for the tonalite–trondhjemite gneisses, and is older than the greenstones (>2843 Ma); the second phase of plutonism is responsible for the granodiorites, and is younger than the greenstones (2740–2690 Ma). The third and youngest phase of intrusive activity is represented by granodiorites (2676 Ma) and pegmatites (2642 Ma).

Paleoproterozoic Events at 2450–2440 Ma

The earliest Proterozoic tectonic reactivation at around 2450 Ma led to the formation of structurally controlled basins, which were filled with volcano-sedimentary sequences of granitoid breccias, arkoses, subaerial to subaqueous basalts, andesites, arenites and polymictic conglomerates (Sariola tectofacies). The reactivation was in part coeval with, but not geographically related to, the basic magmatism at 2440 Ma. This basic magmatism focussed along continental rift zones as a belt of layered mafic intrusive complexes. The magmas responsible for these mafic intrusions were boninitic in composition, and were injected as several pulses of magma, and formed cyclical units, one on top of the other. The intrusions contain economic deposits of chromite, platinum-group elements, Ni–Cu sulfides, and Fe–Ti–V oxides. Although faulting split the mafic complexes into separate segments, the intrusions of the Tornio–Narankavaara belt in Finland form a roughly east–west-trending array along strike of the major trend of the rifting event. Some east-west trending noritic dykes in the Kuhmo–Suomussalmi area, mostly to the south of the layered intrusion belt, are of the same age and boninitic in composition. A total of about 20 layered complexes of about 2440 Ma age exist in the Archean area of the Shield. The 2440 Ma reactivation and continental rifting in eastern Finland was also accompanied by potassic "rapakivi"-type granites, which were emplaced as separate intrusions not directly related to the mafic complexes (a cogenetic granite porphyry dyke gave an age of 2435 ±12 Ma). The mafic complexes were faulted, uplifted as separate blocks, and eroded to outcrop on the surface before the extrusion of the Perapohja and Lapponian volcanic rocks (the oldest phases of volcanism give an age of 2330 Ma).

Rifting and Magmatic Activity at 2200–2100 Ma

Conglomerates, arenites, turbiditic arenites, muddy sediments and metalavas were deposited in a narrow sea or inland sea; this setting suggests an extensional tectonic regime during the formation of a basin in Kainuu. The Kainuu tectofacies, as well as the Archean granitoid areas, were intersected by low-Al tholeiitic sills (2200 Ma), which commonly are fractionated into ultramafic clinopyroxenite and wehrlite in the lower portions, and magnetite gabbro and granophyre at the top. Mafic dyke swarms of Fe-tholeiitic composition are the most abundant in the Archean rocks. In southeastern Finland, these 2200 Ma dykes locally are feeder channels for the Jatulian mafic volcanic suite, thus giving the minimum ages for the epicontinental quartzites underlying the volcanic rocks and representing a period of extensive weathering of the Archean bedrock. The deposition of shelf sediments and the intrusion of mafic dykes along listric shear zones accompanied the opening of the pre-Svecofennian sea, and the development of this passive continental margin. The intracratonic Hoytiainen basin system developed at about 2100 Ma as a result of extensional tectonics of a passive margin in an asymmetrical rift or half graben above a major detachment fault extending deep into the lithosphere. The general northwesterly trend of the 2200 Ma mafic dykes thus indicates the initiation of extension of the craton in a southeast–northwest direction, with a displacement fault dipping toward the southwest.

In the sedimentary sequence, there is an abrupt change in facies from psammites and dolostones to carbonaceous rocks. The facies change is accompanied by a dramatic change in C isotope ratios of the carbonates, which is interpreted to reflect the change in concentration of atmospheric oxygen at 2200–2100 Ma.

Layered Mafic Complexes at 2040 Ma

A magmatic period at 2040 Ma gave rise to the Otanmaki layered mafic complex with Fe–Ti–V oxide deposits and the associated potassic and alkaline anorogenic granitoids not far from the Svecofennian Archean boundary in central Finland. The same age is reflected extensively in the magmatic activity of Lapland by the intrusion of the sulfide-bearing Keivitsa layered complex and the extrusion of the ultramafic Kummitsoiva – Sattasvaara – Karasjokk komatiitic volcanic belt.

Ultramafic Assemblage and Rifting at 1970 Ma

The ultramafic Outokumpu assemblage was formed during rifting of the ocean floor. It is about the same age as the 1970 Ma Jormua ophiolite complex in the Kainuu basin. These rocks, therefore, indicate a younger phase of extension at the margin of the craton than the 2100 Ma Hoytiainen basin.

Underplating of the Crust

The crust at the Svecofennian–Archean boundary is locally very thick, ranging from 46 to 65 km. The upper and middle crust amounts to about 30–35 km thick, and most of the variation in thickness is in the high-velocity lower crustal layer. The thick lower crust is anticipated to be the result of mafic underplating during the collision of the Svecofennian domain with the Archean continent. The lithosphere in the central part of the Fennoscandian Shield is inferred to be about 200 km thick.

Resetting of Archean Isotope Systematics

The marginal part of the Archean crust is characterized by fault-bounded structures with a metamorphic grade varying from one block to the other, indicating that different extents of uplift of the blocks occurred. A major thermal resetting of the K–Ar ages of biotite and hornblende to 1850–1800 Ma, and Rb–Sr systematics of granitoids to 1800–1760 Ma, has taken place in the Archean area. This is associated with fluid activity, regional metamorphism, and local metamorphism along shear zones. The resetting is considered to be related to the thickening and underplating of the crust.

Saturday afternoon, September 30

METALLOGENY OF THE PROTEROZOIC EON, SOUTHERN PROVINCE, ONTARIO

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Several tectonic episodes are recorded between 2.48 and 1.0 Ga in Paleoproterozoic and Mesoproterozoic rocks of the Southern Province that crop out along the southern margin of the Superior Province craton. During this protracted tectonic history, a spectrum of types of mineral deposit formed in diverse tectonic settings. The metallogeny of the Huronian Supergroup and Proterozoic rocks in the Lake Superior area is synthesized and interpreted in terms of a copper (nickel, platinum-group element) metallogenic province, that is punctuated with several metallogenic epochs.

In the Lake Superior region, Proterozoic tectonic episodes include: 1) deposition of the Paleoproterozoic Animikie continental-margin sedimentary prism, between 2.1 and 1.85 Ga, prior to, and during, the 1.86 Ga Penokean Orogeny and emplacement of carbonatite and alkaline complexes at about 1.9 Ga; 2) emplacement of *ca.* 1.54 Ga Mesoproterozoic anorogenic granites and the deposition of the rift-related Sibley Group, and 3) Mesoproterozoic rifting along the Midcontinent Rift System between *ca.* 1.11 to 1.09 Ga, during which the Keweenawan Supergroup was deposited. Metallic mineral deposits that formed during these Paleoproterozoic tectonic events include: 1) iron formation in the rifted, passive margin and synorogenic foredeep sedimentary rocks of the Animikie Basin, and 2) VMS mineralization in volcanic arc successions of the Wisconsin Magmatic Terrane.

Although no mineral deposits are known, the Mesoproterozoic 1.53-Ga anorogenic granites of the Lake Nipigon area have potential to host copper mineralization of the Olympic Dam type or deposits of fluorite, yttrium, zirconium, rare-earth elements, and tin. Clastic sedimentary sequences that were deposited in the rift-related, 1.5- to 1.3-Ga Sibley Group, are host to unconformity-related uranium mineralization and red-bed-type copper mineralization. Mesoproterozoic Keweenawan rifting was accompanied by the formation of a diverse spectrum of deposit types: 1) magmatic nickel – copper – platinum-group element and chromite mineralization in Keweenawan gabbro intrusions (*e.g.*, Duluth and Crystal Lake) and the Coldwell alkaline complex; 2) disseminated, native copper that fills amygdules in Keweenawan basalt flows, copper impregnation in interflow conglomerates, and bornite – chalcocite – quartz – calcite veins; 3) amethyst and silver-bearing veins in, and adjacent to, faults that cut Archean granitoid plutons and Keweenawan sedimentary rocks; 4) copper sulfide mineralization in porphyry intrusion-related breccia pipes, and 5) uranium mineralization along unconformities. The clastic sedimentary sequence of the Oronto Group was deposited late during the Keweenawan rift event, in response to continued subsidence following volcanism, and hosts red-bed-type and shale-hosted copper deposits (*e.g.*, White Pine, Michigan).

The Paleo- and Mesoproterozoic history of Huronian Supergroup rocks is characterized by at least five tectonic episodes. Early tectonism began at about 2.45 Ga with rifting of the composite Archean craton and the emplacement of 2.48 Ga gabbro–anorthosite intrusions (*e.g.*, East Bull Lake) that are host to magmatic nickel – copper – platinum-group element mineralization. Rift development may also have been accompanied by the eruption of the 2.45 Ga metavolcanic rocks in the lower part of the Elliot Lake Group. Base-metal sulfide occurrences, some of which resemble VMS mineralization, occur spatially associated with these volcanic rocks. Continued extension and attendant erosion resulted in deposition of the northward-onlapping, shallow-water clastic prism of the Huronian Supergroup upon a south-facing continental margin. Paleoplacer uranium deposits at Elliot lake accumulated within quartz-pebble conglomerate units in the Matinenda Formation, within the lower part of the clastic prism. The Lorrain and lower part of the Gordon Lake formations, part of which may have been deposited in a hot and arid environment, are host to red-bed or sabkha copper mineralization. Shale-hosted copper mineralization occurs within the Gowganda Formation.

Between 2.39 and 2.33 Ga, the Murray and Creighton granitic plutons were intruded into lower Huronian sedimentary rocks near Sudbury. The tectonic significance of these intrusions is not clear. At about 2.22 Ga, sedimentary rocks of the Huronian Supergroup were cut by Nipissing gabbros that are host to magmatic nickel – copper – platinum-group mineralization. Some polymetallic skarn mineralization occurs in calcareous sedimentary rocks of the Espanola Formation, adjacent to Nipissing Gabbro. Silver-, cobalt-, sulfarsenide-bearing veins in the Cobalt embayment cut *ca.* 2.2 Ga Nipissing Gabbro, but a minimum age of this vein mineralization is unconstrained.

The Penokean Orogeny in the Huronian Supergroup is characterized, in part, by crustal thickening, metamorphism, and thrust faulting. The emplacement of the 1.85 Ga norite of the Sudbury Igneous Complex, host to magmatic nickel – copper – platinum-group mineralization, was coeval with the Penokean Orogeny. Broadly coeval with the Sudbury Igneous Complex and the Penokean Orogeny was the formation of sediment-hosted (SEDEX), massive, base-metal sulfide deposits at the top of the Onaping Formation, Whitewater Group, in sedimentary rocks that may be time-equivalent to the foredeep Animikie sedimentary rocks of the Lake Superior area. Several types of polymetallic hydrothermal veins occupy Penokean structures, indicating that the veins formed during, or after, the Penokean Orogeny, at least 0.3 billion years after the intrusion of the Nipissing Gabbro.

Following the Penokean Orogeny, 1.74-Ga anorogenic magmatism in the Killarney Magmatic Belt reflects an extensional phase of a *ca.* 1.7-Ga collisional orogeny that affected the northwestern part of the Grenville Province. Gold, copper–gold, and perhaps lead–zinc-bearing veins and 1.7-Ga sodium metasomatism, which cut rocks of the Huronian Supergroup and the Sudbury Igneous Complex, may have developed late during the 1.74-Ga Penokean Orogeny. A period of 1.45-Ga anorogenic magmatism within the Killarney Magmatic Belt is coeval with 1.55- to 1.4-Ga anorogenic magmatism in the Lake Nipigon and Wisconsin areas and may indicate a period of widespread crustal extension. These granitoid intrusions may be related to the Eastern Granite–Rhyolite Province.

Tectonic and magmatic activity along the Mesoproterozoic Midcontinent Rift System, at 1.11 to 1.09 Ga, was temporally associated with native copper and base-metal sulfide veins that formed in, and adjancent to, Keweenawan fault zones. At this time, the Tribag breccia- and Jogran felsic-intrusion-associated copper mineralization formed in the Sault Ste. Marie – Batchawana area.

The Huronian Supergroup may be defined as a metallogenic province for the metal assemblage nickel, copper, and platinum- group elements. Specific metallogenic epochs for magmatic nickel – copper – platinum-group-element mineralization occurred at: 2.48 Ga (*e.g.*, East Bull Lake), 2.22 Ga (Nipissing Gabbro), and 1.8 Ga (*e.g.*, Sudbury Igneous Complex). Hydrothermal copper metallogenic epochs occurred at: 2.48 to 2.40 Ga (*e.g.*, shale-hosted, sabkha, and red-bed copper mineralization), 2.22 Ga (copper-bearing skarn), <2.22 Ga (*e.g.*, silver-, cobalt-, arsenide-, copper-bearing veins), 1.85 Ga (*e.g.*, shale-hosted copper, SEDEX, and vein copper), 1.74 Ga (copper and copper–gold veins), and *ca.* 1.0 Ga (*e.g.*, vein, disseminated, and breccia-pipe copper). In addition, there is a zonal distribution of metal assemblages within the eastern part of this metallogenic province, consisting of copper-rich metal assemblages in the Sault Ste. Marie area, copper – nickel – platinum- group-element assemblages in the Sudbury area, and silver-, cobalt-, arsenic-, and copper-bearing metal assemblages in the Cobalt Embayment area. Whereas the development of mineral deposits in the Lake Superior region is telescoped into a shorter time-frame (*ca.* 1.9 to 1.0 Ga), copper is a common constituent of several types of deposit that formed at different times. These observations indicate that the whole of the Southern Province may be considered as a metallogenic province for copper (nickel + platinum-group elements). These metallogenic provinces are consistent with an endogenic, large-scale crustal or mantle influence, perhaps manifested by the Elliot Lake – Englehard gravity high, on the development of mineral deposits in the Southern Province.

HOW ACTIVE ARE PASSIVE MARGINS? MODERN ANALOGUES OF MAGMATISM IN RIFTS

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In little more than a decade, the concepts that underlie our knowledge of passive margin development have changed dramatically. Two important reasons for this change are (1) the large number of seismic surveys and the extensive drilling that accompanied petroleum-industry-related activity in many offshore rift basins, such as those of the eastern Canadian margins, the northwest Australian margin and the North Sea Rift, and (2) progress in understanding the observed variations in the composition and thickness of oceanic crust. The notion that rifting is either passive (*i.e.*, extension-driven) or active (*i.e.*, plume-induced) cannot adequately explain the variations in stratigraphic and structural style that are observed along modern rifted margins. Other processes may be important. Even in the oceanic domain, the classifications of active or passive may be oversimplified; recent results suggest that attributes of both are present (Anderson 1995).

Most modern rifted margins can be categorized as either nonvolcanic or volcanic, according to the thickness of igneous crust associated with the rifting and early drifting stages of development. Volcanic margins are characterized by large thicknesses of igneous rocks (*ca.* 10 to 25 km) below the margin, whereas nonvolcanic margins generally exhibit less than *ca.* 5 km of igneous material. In general, the region near the continent–ocean boundary (COB) of volcanic margins appears to have formed above sea level. A sequence of seaward-dipping basaltic lava flows, several kilometers to tens of kilometers long, forms the basement. The basement close to these margins is typically smooth, unlike that of nonvolcanic margins, which commonly is dissected by normal faults. Also, volcanic margins do not generally exhibit thick sequences of syn-rift marine sediments near the COB, whereas nonvolcanic margins commonly subside and accumulate syn-rift marine sediments. Both types of margin may show later post-rift subsidence.

The decompression melting model of McKenzie & Bickle (1988) can account for the production of basaltic melts at nonvolcanic margins and failed rifts by melting of H_2O-free asthenospheric mantle. In these models, the lithosphere is passively extended, and mantle material upwells below the thinning lithosphere. The temperature of asthenospheric mantle material and its final depth control the amount of melting. These properties are, in turn, dictated by the deformation history within the rifting system (Keen *et al.* 1994). Very slow rifting can delay and reduce melt production. The physical conditions in the rifted lithosphere and the details of the deformation history will determine the petrological sequence of magmas generated over time (Williamson *et al.*, in press).

Three end-member processes that can account for the large volume of magma emplaced at volcanic rifted margins are: (1) deep melting at the center of a large-scale plume characterized by high temperatures (>1550°C) of the asthenospheric mantle; (2) enhancement of melt delivery by small-scale convection near the lithosphere–asthenosphere boundary, requiring moderate temperatures in the mantle, and (3) melting of an already modified continental "lithospheric" source with lower-than-normal solidus temperatures (amphibole- or phlogopite-bearing peridotite).

Several new lines of evidence challenge the validity of the "plume" model. Some volcanic margins show no geological evidence for the passage of a plume (*e.g.*, the eastern U.S. margin). Seismic tomography suggests that anomalously high temperatures in the mantle at hot spots are confined to the upper mantle (less than *ca.* 400 km depth). Finally, basaltic rocks recovered during ODP Leg 152 to the southeast Greenland volcanic margin do not exhibit a clear "plume" signature, suggesting that the magmas were generated within the upper mantle. The plume model predicts that basaltic melts will inherit the enriched trace-element signature and distinct isotopic character of deep, primitive mantle. The location of the enriched mantle reservoir (EM) is still debated because old, subcontinental lithosphere shares many of the same geochemical characteristics as primitive, undifferentiated mantle originating at the core–mantle boundary. The possibility of a lithospheric source is attractive. However, the lower lithosphere at depths where temperatures exceed *ca.* 600°C is probably very mobile and "decoupled" from the overlying rigid plate, making it an unlikely reservoir for long-lived, isotopically distinct enriched mantle (Anderson 1995).

Small-scale convection confined to the upper mantle is driven by "passive" rifting of the overlying plate. At the same time, it is an "active" process that can lead to many of the features observed at volcanic margins. Although vigorous convection leading to widespread magmatism may depend on certain physical conditions, such as the geometry of the rift system or the presence of large-scale lithospheric faults, it can explain many of the physical characteristics of large igneous provinces (LIPs: Coffin & Eldholm 1993). Could this process also account for the "enriched" geochemical signature of some basaltic magmas (*e.g.*, continental flood basalts) generated at LIPs? The small-scale convection model implies that EM may lie within the upper mantle. We are presently testing this hypothesis by examining the causes for noble-metal enrichment in basaltic melts and upper-mantle rocks exposed in ancient continental rifts (*e.g.*, Lorand *et al.* 1993).

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