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Igneous Rock Associations in Canada 3. Large Igneous Provinces (LIPs) in Canada and Adjacent Regions: 3 Ga to Present

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Article abstract

Earth history is punctuated by numerous periods during which large volumes of mafic magma were emplaced. Such magmas not generated by a 'normal' spreading ridge or by subduction are termed Large Igneous Provinces (LIPs), and consist of continental flood basalts, volcanic rifted margins, oceanic plateaus, ocean basin flood basalts, submarine ridges, and seamount chains. Associated felsic rocks may also be present. LIPs of Mesozoic and Cenozoic age are typically the best preserved. Those of Paleozoic and Proterozoic age are usually more deeply eroded, and consist of flood basalt remnants and a deep-level plumbing system (of giant dyke swarms, sill provinces and layered intrusions). In the Archean the most promising LIP candidates are greenstone belts containing komatiites. Many LIPs have been linked to regional-scale uplift, continental rifting and breakup, and climatic crises. They can be used as precisely dated time markers in the stratigraphic record, and are key targets for Ni-Cu-PGE exploration. LIPs have also become a focus in the debate on the existence and nature of mantle plumes.

Canada has a rich record of LIPs. At least 80 candidates are recognized in Canada and adjacent regions, with ages ranging from 3100 to 17 Ma. We review proposed links between the LIP record of Canada and mantle plumes, continental breakup, regional uplift, and ore deposits. However, given that many mafic units in Canada remain poorly characterized, a concerted geochronology campaign with integrated paleomagnetism and geochemistry would be invaluable in expanding the application of the Canadian LIP record to solving major geological problems.

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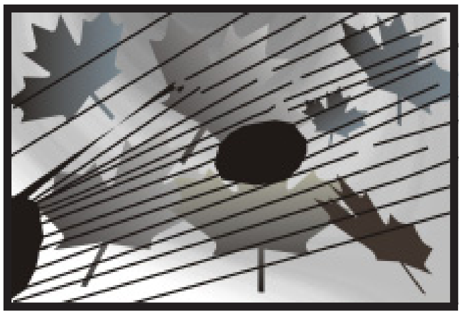

Igneous Rock Associations in Canada 3. Large Igneous Provinces (LIPs) in Canada and Adjacent Regions: 3 Ga to Present

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SUMMARY

Earth history is punctuated by numerous periods during which large volumes of mafic magma were emplaced. Such magmas not generated by a 'normal' spreading ridge or by subduction are termed Large Igneous Provinces (LIPs), and consist of continental flood basalts, volcanic rifted margins, oceanic plateaus, ocean basin flood basalts, submarine ridges, and seamount chains. Associated felsic rocks may also be present. LIPs of Mesozoic and Cenozoic age are typically the best preserved. Those of Paleozoic and Proterozoic age are usually more deeply eroded, and consist of flood basalt remnants and a deep-level plumbing system (of giant dyke swarms, sill provinces and layered intrusions). In the Archean the most promising LIP candidates are greenstone belts containing komatiites. Many LIPs have been linked to regional-scale uplift, continental rifting and breakup, and climatic crises. They can be used as precisely dated time markers in the stratigraphic record, and are key targets for Ni-Cu-PGE exploration. LIPs have also become a focus in the debate on the existence and nature of mantle plumes.

Canada has a rich record of LIPs. At least 80 candidates are recognized in Canada and adjacent regions, with ages ranging from 3100 to 17 Ma. We review proposed links between the LIP record of Canada and mantle plumes, continental breakup, regional uplift, and ore deposits. However, given that many mafic units in Canada remain poorly characterized, a concerted geochronology campaign with integrated paleomagnetism and geochemistry would be invaluable in expanding the application of the Canadian LIP record to solving major geological problems.

RÉSUMÉ

L'histoire de la Terre est ponctuée de nombreuses périodes de mise en place de forts volumes de magma mafiques. De tels magmas qui ne sont pas issus de zones d'expansion « normale » ou de subduction sont appelés Grandes provinces ignées (GPI), et celles-ci sont constituées de basaltes d'épanchements continentaux, de marges de fosse volcaniques, de plateaux océaniques, d'épanchements de basaltes de bassins océaniques, de crêtes sous-marines, et de chaînes de monts sous-marines. Peuvent également y être associées des suites de roches felsiques. Généralement, les GPI du Mésozoïque et du Cénozoïque sont les mieux préservées. Celles du Protérozoïque et du Paléozoïque sont généralement plus fortement érodées et sont constituées de vestiges de basaltes d'épanchement et des réseaux de conduits d'origine (réseaux géants de dykes, provinces de filons-couches et d'intrusifs stratifiées). Dans l'Archéen, les meilleurs candidats sont représentés par les bandes de roches vertes à komatiites. De nombreuses GPI ont été associées à des épisodes de soulèvement régionaux, de dérives ou de fragmentations continentales, ainsi qu'à des crises climatiques. Elles peuvent servir de marqueurs temporels stratigraphiques et sont des cibles de première importance dans l'exploration de gisements de Cu-Ni-ÉGP. Les GPI sont aussi devenues des arguments très considérés dans le débat sur l'existence et la nature des panaches mantelliques.

Le Canada possède de riches archives de GPI, et au moins 80 candidatures ont été isolées sur le territoire canadien et dans les régions adjacentes, leur âge délimitant une fourchette allant de 3 100 Ma à 17 Ma. Nous passons en revue les liens proposés entre la suite des GDI canadiennes d'une part, et celle des panaches mantelliques, des fragmentations continentales, des soulèvements régionaux, et des gisements minéraux, d'autre part. Toutefois, vu le piètre état de caractérisation des unités mafiques au Canada, une campagne de caractérisation géochronologique, paléomagnétique et géochimique serait d'une valeur inestimable pour favoriser l'utilisation des GDI canadiennes pour nous aider à solutionner de grands problèmes géologiques.

INTRODUCTION

Large Igneous Provinces (LIPs) represent voluminous magmatic events that were not generated by a 'normal' spreading ridge or by subduction (Coffin and Eldholm, 1994; 2001; Ernst et al., 2004). They may be emplaced as often as once every 10 Ma (e.g. Coffin and Eldholm, 2001), and time series analysis of the LIP record for the past 3.5 Ga suggests weak cyclicity (Isley and Abbott, 2002; Prokoph et al., 2004).

The most dramatic LIPs are emplaced rapidly (within <10 Ma and often within only a few Ma). These include continental flood basalts, seaward-dipping reflector sequences, oceanic plateaus, and ocean basin flood basalts. Continental flood basalts can be as large as several million cubic km (e.g. the Siberian Traps; Reichow et al., 2002). The largest LIP is the Ontong Java oceanic plateau, which has a volume of 44.4 million cubic km (Coffin and Eldholm, 2001) for combined extrusive (6 million cubic km) and intrusive components (Courtillot and Renne, 2003). The initial large-volume short-duration stage of magmatism of some LIPs has been linked to the arrival of a mantle plume (e.g. White and McKenzie, 1989; Campbell and Griffiths, 1990; Coffin and Eldholm, 1994; 2001; Campbell, 1998, 2001; Ernst and Buchan, 2001; Courtillot et al., 2003). Subsequent rifting/breakup is often associated with a second burst of volcanism (Campbell, 1998) by decompression melting (White and McKenzie, 1989). In addition, LIP magmatism can continue for prolonged periods after the initial outburst (or outbursts), in the form of seamount chains and ridges, which are usually explained as hotspot tracks associated with a plume tail. Other models invoke plate fracturing and 'edge convection' (upper mantle convection between thick and adjacent thin lithosphere), and have been suggested as an alternative to plume models for LIPs and hotspot chains (e.g. Anderson, 2001; Foulger and Natland, 2003).

The volcanic portion of older continental LIPs is largely removed by erosion and deformed during continental collision, whereas older oceanic LIPs are mostly lost during subduction and deformed during ocean closure. Therefore, in the Paleozoic and Proterozoic record, continental LIPs are typically recognized by their exposed plumbing system of giant dyke swarms, sill provinces, large layered intrusions, and remnants of flood basalts (Ernst and Buchan, 2001). The oceanic LIP record may be recognized in some accreted volcanic packages and ophiolite complexes (e.g., Coffin and Eldholm, 2001; Moores, 2002).

The extrapolation of the LIP record into the Archean is more speculative. There are erosional remnants of typical flood basalt provinces, namely the Fortescue sequence of the Pilbara craton of Australia and the Ventersdorp sequence of the Kaapvaal craton of southern Africa (Eriksson et al., 2002). However, most Archean volcanic rocks occur as deformed and fault-fragmented packages termed greenstone belts. Among these, the best candidates for LIPs are thick tholeiite sequences that contain komatiites. The nature of Archean LIPs is discussed in greater detail below.

LIPs are important 1) for testing plume and non-plume models for the generation of LIPs; 2) as precise time markers for stratigraphic correlations; 3) as an aid in reconstructing continents; and 4) as the hosts of major PGE deposits and as a potential tool in diamond exploration. In addition, they can be helpful in studying 5) climatic effects, and 6) regional uplift. We return to these topics after a review of the LIP record of Canada and adjacent regions.

PRELIMINARY LIP HISTORY OF CANADA AND ADJACENT REGIONS

Methodology

Our compilation is based on a recent summary of the global LIP distribution (Ernst and Buchan, 2001) and a newly published compilation of dyke swarms and related magmatic units in Canada and adjacent regions (Buchan and Ernst, 2004). We currently recognize at least 80 LIPs and possible LIP remnants in and adjacent to Canada. The Proterozoic and Phanerozoic mafic magmatic record is reviewed first since its links with LIPs are better defined (Table 1, Fig. 1). The more speculative Archean LIP history follows (Table 2, Fig. 1).

The Proterozoic record relies heavily on diabase dyke swarms and sills (Fig. 2). Dykes injected laterally into the interior of continents have a preservation potential that is much greater than that of associated lavas, and therefore provide a robust record of cratonic LIP events (e.g. Halls, 1982; Fahrig, 1987; Buchan and Halls, 1990).

The compilation includes information on tectonic setting. Our criteria for determining setting rely heavily on dyke swarm geometry and its relationship to cratonic margins (Fig. 3, Table 3). Events are inferred to have a mantle plume origin if a giant radiating dyke swarm is present. Giant linear dyke swarms that extend into a craton (i.e. trend perpendicular to a cratonic margin) are inferred to represent an aulacogen-type swarm ('failed-arm' type in Fahrig, 1987), and can also be used to infer a plume origin with the plume centre situated at the edge of a craton. By contrast, linear swarms that parallel the edge of a craton may simply be rift/breakup related (Ernst and Buchan, 1997) or may possibly represent a back arc rifting setting (e.g. Rivers and Corrigan, 2000), or overriding of a spreading ridge (Gower and Krogh, 2002).

In addition (Table 3), those Archean greenstone belts containing komatiites are inferred to be plume-related on the basis of the elevated temperatures required for generation of komatiites (e.g. Campbell, 1998, 2001; Arndt et al., 1998; Condie, 2001). Finally, small, intraplate events not obviously linked to a cratonic boundary are categorized as 'hotspots'.

Below (and in Tables 1 and 2) we summarize the main events, their age distribution and tectonic setting. It should be noted that referencing has been minimized in the text below because detailed referencing is available through Tables 1 and 2. Also note that we have included number-labels of the form [#14a] in order to facilitate easy cross-correlation with entries in Tables 1 and 2, and with the distribution of main units in Figure 1.

Proterozoic to Present

2.51–2.41 Ga: The earliest Proterozoic LIPs consist of dykes, layered intrusions and volcanic rocks and are mainly associated with the eastern and southern margin of Laurentia. Most notable are the ca. 2.5 Ga Mistassini [#1a] and 2.49–2.45 Ga Matachewan events [#1b] whose radiating diabase dyke swarms locate two plume centres about 800 km apart, and imply rifting of the southeast

Table 1 Large Igneous Provinces (LIPs) and potential LIPs in Canada and adjacent regions since 2.5 Ga. Names of the largest events are underlined. Obsolete names in square brackets. Pre-2.5 Ga record is discussed in Table 2. Anorthosites have not been included. Details and full referencing on most events are available in compilations [1] (=Ernst and Buchan, 2001) and [2] (=Buchan and Ernst, 2004), or in the additional cited references. Abbreviations: se. = southeast, ne. = northeast, c. = central, etc. Units in each entry are ordered in terms of decreasing size. "**REF.**:" = key reference(s). **SETTING** codes are explained in Table 3.

Event name (Age) *(Location)* [Size]	**Magmatic components** (Age)
1 2.51–2.41 Ga	
1a Mistassini (~2.5 Ga) *(e. Superior Prov.)* [100,000 sq. km]	**DYKES: Mistassini** (~2.5 Ga) **REF.:** #204 in [1]; #43 in [2] **COMMENT:** ?Link with **Ptarmigan** swarm (2.51 Ga [#35 in [2]] of ne Superior Prov. ?Link with **Du Chef** swarm (2.41 Ga) [#45 in [2]] along Grenville Front **SETTING:** Plume (P1); Breakup (B1; se. Superior Craton)
1b <u>Matachewan</u> (2.49–2.45 Ga) *(s.& c. Superior Prov.)* [360,000 sq. km]	**DYKES: Matachewan [Hearst]** (2.47 and 2.45 Ga) **LAYERED INTRUSIONS: East Bull Lake** (2.48 Ga); **Agnew** (2.49 Ga); **River Valley** (2.475 Ga); **Falconbridge Twp** (2.44 Ga) **VOLCANIC ROCKS: Dollyberry; Ellise Mountain**; **Copper Cliff** rhyolites (~2.45 Ga); **Thessalon**. **REF.:** #206 in [1]; #42 in [2] **COMMENT:** ? Link with **Ptarmigan** swarm (2.51 Ga [#35 in [2]] of ne. Superior Craton) **SETTING:** Plume (P1); Breakup (B1; s. Superior Craton)
1c Kaminak (ca. 2.45 Ga (Hearne Prov.) [18,000 sq. km]	**DYKES: Kaminak** (~2.45 Ga) **REF.:** #203 in [1]; #44 in [2] **SETTING:** Plume (?P1); ?Breakup (Hearne Craton) **COMMENT:** Linked with **Matachewan** event [#1b] by Bleeker (2004)
1d Mirond Lake (2.49 Ga) (*Trans Hudson*) [two 'windows' into Archean basement about 120 km apart]	**DYKES: Mirond Lake** (2.49 Ga) **REF.:** #41 in [2] **SETTING:** ?Breakup (Sask Craton)
2 2.24–2.21 Ga	
2a Kikkertavak (2.235 Ga) *(Makkovik Prov.)* [6500 sq. km]	**DYKES: Kikkertavak** (2.235 Ga) **REF.:** #47 in [2] **COMMENT:** Linked with **Lower Aillik Group** (2.18 Ga) rift magmatism [Ketchum et al., 2001] **SETTING:** ?Breakup (s. North Atlantic [Nain] Craton)
2b BN-1 (2.21 Ga) *(s. Greenland)* [54,000 sq. km]	**DYKES: BN-1** (norite) (2.21 Ga); **MD-1** undated but possibly similar in age **REF.:** #193 in [1]; #40 in [2] **SETTING:** ?Breakup (? North Atlantic [Nain] Craton)
2c <u>Ungava</u> (2.22–2.21 Ga) *(ne. and e. Superior Prov.)* [500,000 sq. km]	**DYKES: Ungava** radiating swarm = **Senneterre** (2.22 Ga), **Maguire** and **Klotz** (2.21 Ga) **SILLS: Nipissing** (2.22 Ga) **REF.:** #191 in [1]; #50-52 in [2] **SETTING:** Plume (P1); Breakup (B1, e. Superior Craton)
2d Malley–MacKay (2.23 and 2.21 Ga) *(Slave Prov.)* [35,000 sq. km]	**DYKES: Malley** NE trend (~2.23 Ga)]; **MacKay** ENE-E trend (~2.21 Ga) **REF.:** #192 and #197 in [1]; #48 and #57 in [2] **SETTING:** Breakup (Slave Craton)
3 2.19–2.17 Ga	
3a Dogrib (2.19 Ga) *(Slave Prov.)* [11,000 sq. km]	**DYKES: Dogrib** (2.19 Ga) **SILLS: Duck Lake** (2.18) **REF.:** #185 in [1]; #60 in [2]; Bleeker & Kamo, 2003 **SETTING:** Breakup (Slave Craton)
3b Tulemalu-MacQuoid (2.19 Ga) *(Hearne Prov.)* [15,000 sq. km]	**DYKES: Tulemalu-MacQuoid** (2.19 Ga) **REF.:** #186 in [1]; #61 in [2] **SETTING:** Breakup (Hearne Craton)
3c <u>Biscotasing</u> (2.17 Ga) *(Superior Prov)* [350,000 sq. km]	**DYKES: Biscotasing** (2.17 Ga) **REF.:** #184 in [1]; #64 in [2]; Halls and Davis, 2004 **SETTING:** Plume (P3)
3d Cramolet Lake–Payne River (2.17 Ga) (New Quebec Orogen) [30,000 sq. km]	**MAGMATISM: 'Cycle 1'**, including **Cramolet Lake** sill of basal **Seward Subgroup** (2.17 Ga) **DYKES: Payne River** ~2.17 Ga [S. Pehrsson, pers. comm., 2000] **REF.:** #63 in [2] **SETTING:** Breakup (B2, e. Superior Craton)

Table 1 Continued

4 2.12–2.07 Ga	
4a Marathon (2.12–2.10 Ga) *(c. Superior Prov.)* [60,000 sq. km]	**DYKES: Marathon-N** (2.12 Ga); **Marathon-R** (2.10 Ga) **REF.:** #180 & 181 in [1]; #69 in [2] **SETTING:** Plume (P2); Breakup (B1, either nc. or sc. Superior Craton)
4b Cauchon Lake (2.09–2.07 Ga) (*nw. Superior Prov.*)	**DYKES: Cauchon Lake** (includes **Birthday Rapids**) (2.09 and 2.07 Ga) **REF.:** #175 in [1]; #72 in [2] **SETTING:** ?Breakup (B2, nw. Superior Craton)
4c Fort Frances (2.075 Ga) *(sw. Superior Prov.)* [75,000 sq. km]	**DYKES: Fort Frances** (2.08 Ga) **REF.:** #174 in [1]; #73 in [2] **SETTING:** Plume (P2); Breakup (B1, sc. Superior Craton)
4d Lac Esprit (2.07 Ga) *(ne. Superior Prov.)*	**DYKES: Lac Esprit** (2.07 Ga) **REF.:** #74-75 in [2], Buchan et al., 2004 **SETTING:** Plume (P2); ?Breakup (B1, nc. Superior Craton)
4e Griffin (2.11 Ga) *(Hearne Prov.)* [80,000 sq. km]	**SILLS: Griffin [Hurwitz]** (2.11 Ga) **REF.:** #179 in [1]; #70 in [2] **SETTING:** Plume (P3); ?Breakup (Hearne Craton)
4f Napaktok (?2.12 Ga) *(Labrador Coast)*	**DYKES: Napaktok** (<2.13 Ga); **Tikkigatsiagak** (2.12 Ga); ?**Domes** **REF.:** #182 in [1]; #68 in [2] **SETTING:** ?
5 2.05–2.02 Ga	
5a Kangâmuit (2.05–2.04 Ga) *(wc. Greenland; Nain Prov.)* [20,000 sq. km]	**DYKES: Kangâmuit** (of Greenland) (2.04–2.05 Ga); **Iglusuataliksuak** (2.05 Ga) **REF.:** #170 in [1]; #80 in [2]; [#78 in [2] **SETTING:** Breakup (?B2, n. North Atlantic [Nain] Craton)
5b Lower Povungnituk (2.04 or 1.96 Ga) *(Cape Smith Belt, ne. Superior Prov.)*	**VOLCANIC ROCKS: Lower Povungnituk** **SILLS: Korak** [2.04 Ga) **REF.**: #169 in [1]; Modeland et al., 2003 **SETTING:** Breakup (B3, n. Superior Craton)
5c Hearne (2.04 Ga) *(Slave Prov.)* [15,000 sq. km]	**DYKES: Hearne** (2.04 Ga) **REF.:** #168 in [1]; #81 in [2] **SETTING:** Breakup (B2, s. Slave Craton)
5d Lac de Gras (ca 2.025 Ga) *(Slave Prov.)* [30,000 sq. km]	**DYKES: Lac de Gras** (2.02–2.03 Ga) **LAYERED INTRUSION: Booth River Complex** (2.02 Ga) **REF.:** #167 in [1], #82 in [2] **SETTING:** ?Plume (P3)
6 2.00–1.95 Ga	
6a Minto–Eskimo (2.00 Ga) *(e. Hudson Bay, ne. Superior Prov.)* [10,000 sq. km for dykes only]	**DYKES: Minto** (2.00 Ga); **Inukjuak** **VOLCANIC ROCKS: Eskimo; Persillon (Pachi); Nastapoka Group** **OPHIOLITE: Watts Group** (2.00 Ga) **REF.:** #162 in [1]; #88 and #92 in [2]; Scott et al., 1999 **COMMENT:** geochemically linked with western **Povungnituk** (2.04 Ga) by Legault et al. (1994) **SETTING:** Plume (P3);?Breakup (nc. Superior Craton)
6b Flaherty–Haig (?1.96 Ga) *(e. Hudson Bay)*	**VOLCANIC ROCKS: Flaherty** (? ~1.96 Ga) **SILLS: Haig**; **Sutton Inlier; Sleeper Island** **REF.:** #161 in [1]; Chandler and Schwarz, 1980; Schwarz and Fujiwara, 1981 **COMMENT:** linked with eastern **Povungituk** (1.96 Ma) by Legault et al. (1994) **SETTING:** ?Breakup (B3, nc. Superior Craton)
6c Upper Povungnituk (ca. 1.96 Ga) *(Cape Smith Belt, ne. Superior Prov.)*	**VOLCANIC ROCKS: Upper Povungnituk** (1.96 Ga) **REF.:** #169 in [1]; Pehrsson per. comm., 2000; Legault et al., 1994; Modeland et al., 2003 **SETTING:** Breakup (B3, n. Superior Prov. at 2.04 Ga)
6d Mugford (1.95 Ga) *(Nain Prov.)* 400 sq. km 1.2 km thick	**VOLCANIC ROCKS: Mugford** (~1.95 Ga); **?Ramah; ?Snyder** **REF.:** #159 in [1]; Hamilton pers. comm., 2000 **SETTING:** ? Rifting

Table 1 Continued

7 1.90–1.88 Ga (in Trans Hudson and adjacent Rae-Hearne Craton)	
7a Sandy Bay (1.90 Ga) *(Flin Flon belt) (Trans Hudson Belt)*	**VOLCANIC ROCKS:** oceanic plateau (**Sandy Bay**), oceanic island basalts and ocean floor assemblages **REF.:** #154 in [1]; Syme et al., 1999; Stern et al., 1999 **SETTING:** ? Plume (P6)
7b Josland (1.88 Ga) *(Amisk collage, Trans Hudson)*	**SILLS: Josland Lake** including **Mikanagan** (1.89–1.88 Ga) **REF.:** Stern et al. 1999; Zwanzig et al., 2001; Turek et al. 2000 **SETTING:** Back-arc (A2)
7c Bravo Lake (1.90–1.88 Ga) *(Piling-Penhryn Group, Rae Prov.)*	**VOLCANIC ROCKS AND SILLS: Bravo Lake** (1.90–1.88 Ga) **REF.:** Jackson and Taylor, 1972; Scott et al., 2002 **SETTING:** Rift
7d Lake Harbour (~1.87 Ga) *(Lake Harbour Group, Rae Prov.)*	**VOLCANIC ROCKS AND SILLS: Lake Harbour Group** (~1.87 Ga) **REF.:** St-Onge et al., 2000 **SETTING:** Rifting and breakup of the "Meta Incognita microcontinent" from the northern Superior Craton [St-Onge et al., 2000]
8 1.88-1.86 Ga (Circum-Superior events)	
8a New Quebec-Cycle 2 (1.88 Ga) *(New Quebec orogen)* [30,000 sq. km]	**VOLCANIC ROCKS AND SILLS: 'Cycle 2'** **SILLS: Montagnais** (1.88–1.87 Ga) **REF.:** #151 in [1] **SETTING:** Back Arc (A1)
8b Chukotat (1.89–1.87 Ga) *(Cape Smith Belt, ne. Superior Prov.)*	**VOLCANIC ROCKS: Chukotat** (lower portion are komatiitic basalts) (1.87 Ga) **SILLS**: Katniq sills (1.92 or ~1.89 Ga) **REF.:** #153 in [1]; N. Wodicka, pers. comm., 2004 **SETTING:** Plume (P4)
8c Molson–Thompson (1.88–1.86 Ga) *(Thompson Belt; nw. Superior Prov.)* [>30,000 sq. km]	**DYKES: Molson** (1.88 Ga); **Pickle Crow** (1.88 Ga) **SILLS: Fox River** (1.88 Ga); **Thompson Nickel Belt** magmatism **KOMATIITES**: **Winnipegosis** (1.86 Ga) **REF.:** #150 in [1]; #85 and #98 in [2]; Hulbert et al., 1994; Buchan et al., 2003; Hulbert et al., 2004 **SETTING:** Plume (?P1, P4); Back-arc (A1)
8d Hemlock (1.88 Ga) *(Animikie Basin - Marquette Range, Southern Prov.)*	**VOLCANIC ROCKS: Hemlock Fm** (1.87 Ga); **Gunflint Fm**. (1.88 Ga); **Badwater Greenstone** **SILLS: Kiernan** **REF.:** Ueng et al., 1988; Schneider et al., 2002; Fralick et al., 2002 **SETTING:** Rifting or Foredeep
9 1.83–1.82 Ga	
9a Sparrow (1.83 Ga) *(Rae Prov.)* [100,000 sq. km]	**DYKES: Sparrow** (1.83 Ga) **GABBRO BODIES:** In Wollaston-Mudjatik Transition zone (1.83–1.82 Ga) **REF.:** #146 in [1] & #101 [2]; Annesley et al., 2003 **COMMENT:** Is there a link with **Christopher Island Fm** (Baker Lake basin) (Cousens et al., 2001; Peterson et al., 2002)? **SETTING:** ? Breakup (Rae Craton)
10 1.75–1.71 Ga	
10a Cleaver (1.75–1.74 Ga) *(Bear and Rae Prov.)* [three locations spanning an area of 300,000 sq. km]	**DYKES: Cleaver** (1.74 Ga); **Hadley Bay** (~1.75 Ga) and **MacRae Lake** (~1.75 Ga) **REF.:** #105–107 in [2]; Irving et al., 2004. **COMMENT:** Is this event a precursor to **Bonnet River** dykes and stocks, and **Slab** volcanics (1.71 Ga), which have been linked with Wernecke Supergroup (Thorkelson et al., 2001)? Is there a link to **Pitz Fm** and **Nueltin Intrusive Suite** of Baker Lake area (Turner et al., 2003; Peterson et al., 2002)? **SETTING:** ? Plume (P3) Breakup (preceeding breakup of nw. Laurentia)
10b Winagami (?1.89–1.76 Ga) *(Western Canada Basin)* [120,000 sq. km]	**SUBSURFACE SHEETS: Winagami** (1.89–1.76 Ga). **REF.:** #149 in [1] **COMMENT:** Imaged seismically; possible link with **Cleaver** dykes suggested by Ross and Eaton (1997) **SETTING:** ? Plume (P3)
11 1.64 Ga	
11a Melville Bugt (ca. 1.64 Ga) *(w. Greenland)* [220,000 sq. km]	**DYKES: Melville Bugt** (~1.64 Ga) **REF.:** #132 in [1]; Hamilton et al., 2004 **SETTING:** ?

Table 1 Continued

12 1.47–1.44 Ga	
12a Moyie (1.47 Ga) *(Belt-Purcell basin, Cordillera)* [120,000 sq. km dykes only]	**SILLS: Moyie (Purcell)** (1.47 Ga) **VOLCANIC ROCKS: Purcell** **DYKES: Tobacco Root (Wyoming Block-1)** (1.46 Ga) **REF.:** #124 in [1]; #117 in [2] **SETTING:** Plume (P2); Breakup (w. or sc. Laurentia)
12b Michael–Shabagamo (ca. 1.47 Ga) *(ne. Grenville Prov.)* [two regions spanning 50,000 sq. km]	**SHEETS: Michael Gabbro** (~1.47 Ga); **Shabagamo** (~1.46, 1.45 Ga) **REF.:** Corrigan et al., 2000; Krogh, 1993 *in* Gower and Krogh, 2002; #122 in [1]; #119-120 in [2] **SETTING:** Back-arc (A1)
13 1.38 Ga	
13a Hart River–Salmon River Arch (1.38 Ga) *(n. Cordillera and s. Belt Basin)*	**VOLCANIC ROCKS and SILLS: Hart River** (1.38 Ga) of n. Cordillera; **Salmon River Arch** (1.38 Ga) of s. Belt Basin **REF.:** entry in Table 4 of [1]; #121 in [2] **SETTING:** ? Plume (P2) ? Breakup (nw. Laurentia)
14 1.28–1.27 Ga	
14a Mackenzie (1.27 Ga) (Canadian Shield) [2,700,000 sq. km]	**DYKES: Mackenzie** (radiating swarm) (1.27 Ga); **Bear River** (1.27 Ga); **'305'** **VOLCANIC ROCKS: Coppermine; Ekalulia**; **Nauyat**; **Hansen**; **Tweed Lake** **SILLS: Christie Bay**; **Tremblay**; **Goding Bay** **LAYERED INTRUSIONS: Muskox** (1.27 Ga) **REF.:** #107 in [1]; 140, 142, 143 in [2]; Sevigny et al., 1991; French et al., 2002; Schwab et al., 2004 **SETTING:** Plume (P1); Breakup (B1, n. Laurentia)
14b Harp–Nain–Nutak–middle Gardar 1.28 and 1.27 Ga (North Altantic Craton) *(Nain Prov. and s. Greenland)* [80,000 sq. km]	**DYKES: Nain-LP** (1.28 Ga); **Nutak** (1.27 Ga); **Nain-HP**; **Harp** (1.27 Ga) **Gardar-BD0** (~1.28 Ga) **Gardar-BD1** **REF.:** #108 in [1]; #132, #133, #137, #138, #139 and #141 in [2] **SETTING:** ?Breakup (se. Laurentia) **COMMENT:** The anorthosites, diorites, granites, and troctolites of the 1.35–1.29 Ga Nain Plutonic Suite [e.g. Ryan and James, 2004] which cover an area of 20,000 sq. km in Labrador, are unrelated
15 1.25–1.225 Ga (Grenville Province)	
15a Sudbury [dykes] (1.24 Ga) *(Superior and Grenville Prov.)* [90,000 sq. km]	**DYKES: Sudbury** (1.24 Ga) **REF.:** #104 in [1]; #146 in [2] **SETTING:** Plume (P2); Back-arc (A1)
15b Seal Lake–Mealy (1.25 Ga) *(Grenville Prov.)* [20,000 sq. km]	**VOLCANIC ROCKS: Seal Lake** **SILLS: Naskaupi** (1.25 and 1.22 Ga) **DYKES: Mealy** (1.25 Ga) **North West River**. **REF.:** #105 in [1]; #113, #144, & #144a in [2] **SETTING:** Back-arc (A1)
16 1.18–1.14 Ga	
16a Davy Group–Tshenukutish–Algonquin (1.18–1.16) *(Grenville Prov.)*	**SILLS AND DYKES: Davy Group** in Wakeham rift (1.18 Ga); **Lillian Suite** **CORONITIC GABBRO:** in Baie du Nord segment of Tshenukutish domain (1.17 Ga) **METAGABBROS: Algonquin** metagabbros in Central Gneiss Belt (~1.17 Ga) **DYKES: Kingston** (~1.16 Ga) **REF.:** #97 in [1]; #145, #147 & #149 in [2] **COMMENT:** Widely separated events in Grenville Prov. of the same age **SETTING:** Back-arc (A1)
16b Late Gardar (1.16 Ga) *(North Atlantic Craton, southern Greenland)*	**DYKES: Tugtutôq Giant Dykes** (1.18 and 1.16 Ga) **REF.:** Buchan et al., 2000; Upton et al., 2003 **SETTING:** Breakup (?)
16c Abitibi [dykes] (1.14 Ga) *(Superior Prov.)* [240,000 sq. km]	**DYKES: Abitibi** (1.14 Ga) **REF.:** #94 in [1]; #155 in [2] **SETTING:** Plume (P1); Breakup (? precursor to Keweenawan)
17 1.11-1.09 Ga	
17a Keweenawan (Mid-continent rift system) (1.11–1.09 Ga; main pulses: 1.11, 1.10 Ga) *(Southern Prov.)* [160,000 sq. km]	**VOLCANIC ROCKS, SILLS AND DYKES: Keweenawan** (1.11–1.09 Ga; main pulses, 1.107 and 1.097 Ga). **REF.:** #90 in [1]; #158-170 in [2] **COMMENT:** ?Relationship with **Southwestern USA Diabase Province** [#89 in [1]]; and **Moores Lake** sills (1.11 Ga) in Athabasca basin [French et al., 2002]. ?Link with **Umkondo** event of Africa [#91 in [1]; Hanson et al., 2004] **SETTING:** Plume (P3) Breakup (attempted breakup of Laurentia)

Table 1 Continued

18 0.78 Ga	
18a Gunbarrel (0.78 Ga) *(Slave Prov.; Mackenzie Mtns. of n. Cordillera; Wyoming Prov.)* [several areas spanning a distance of about 2500 km]	**SHEETS**: **Hottah** (sheets) (0.78 Ga) **VOLCANIC ROCKS: Huckleberry; Irene** (ca. 0.76 Ga) **SILLS**: **Faber Lake Gabbro** (0.78); **Wolf Creek** (0.78 Ga); **Mackenzie Mountains** **DYKES** (0.78 Ga)**: MacDonald**; **Mackenzie Mountains**; **Tobacco Root-Group B** **REF.:** #63 in [1]; #178-181 in [2]; Harlan et al., 2003b **COMMENT:** ?Link with Windermere rifting [#77 in [1]]; Both South China and Australia have been proposed as the rifted block(s) **SETTING:** Plume (P1); Breakup (B1, w. Laurentia)
19 0.72 Ga	
19a Franklin–Thule (0.72 Ga) *(Arctic Islands, mainly Baffin Island; also n. Superior Prov.)* [1,100,000 sq. km for Canadian portion]	**VOLCANIC ROCKS: Natkusiak** **DYKES**: **Franklin** (0.72 Ga); **Thule** (of Greenland) **SILLS:** (0.72 Ga) **Minto Inlier**; **Coronation**; **Dybbol**; **Banks Island**; **Steensby Land** (of Greenland) **REF.:** #58 in [1] and #185-186 in [2] **COMMENT:** Note 0.69 Ga **Gataga** and **Hyland Group** volcanics of northern Cordillera [Ferri et al., 1999; Colpron et al., 2002]. Do these represent subsequent rifting associated with the Franklin-Thule event? **SETTING:** Plume (P1); ?Breakup (B1, n. Laurentia)
20 0.615–0.56 Ga (Laurentian margin, Appalachians) Central Iapetus Event [Puffer 2002]	
20a Long Range (0.62 Ga) *(e. North America)* [105,000 sq. km]	**DYKES: Long Range** (0.62 Ga) **VOLCANIC ROCKS: Lighthouse Cove** **REF.:** #54 in [1]; #192 in [2] **SETTING:** ?Plume ?Breakup (B2, e. Laurentia from Baltica)
20b Grenville-Rideau (0.59 Ga) *(e. North America)* [140,000 sq. km]	**DYKES: Grenville** (0.59 Ga)-**Rideau-Adirondack** (fanning swarm) **REF.:** #53 in [1]; #194–196 in [2] **SETTING:** Plume (P1); ?Breakup (B1, e. Laurentia from ?Amazonia)
20c Sept-Îles–Catoctin (0.56 Ga) *(e. North America)*	**LAYERED INTRUSION: Sept-Îles** (0.56 Ga) **VOLCANIC ROCKS: Skinner Cove**; **Catoctin** (in US Appalachians) (0.56 Ga) **REF.:** #52 in [1] **SETTING:** ?Plume (P3); ?Breakup (e. Laurentia from Dashwoods Terrane)
21 0.62–0.55 Ga (Avalon terrane, Appalachians)	
21a Harbour Main (ca. 0.62 Ga) (*Avalon Zone, Appalachians*)	**VOLCANIC ROCKS:** part of **Harbour Main Group** (0.63–0.59 Ga) **INTRUSIONS: Holyrood** granite suite (0.62 Ga); **Connaigre Bay Group** (0.63 Ga); **Simmons Brook suite** (0.62 Ga); **Cap au Miquelon Group** (ca. ≥6.2 Ga); **East Bay Hills Belt** (ca. 0.62 Ga); **Coxheath Hills Belt** (ca. 0.62 Ga) **REF.:** Rabu et al., 1996; Bevier et al., 1993 **SETTING: ?**
21b Marystown (0.59–0.55 Ga) (*Avalon Zone, Appalachians*)	**VOLCANIC ROCKS: Marystown Group** (0.59–0.575 Ga); **Long Harbour Group** (0.57–0.55 Ga); **St. Pierre Group** (0.58 Ga); **Belle Riviere Group** (0. 57 Ga); part of **Harbour Main Group** (0.63-0.59 Ga); **Coastal Belt** (0.58 Ga) **REF.:** p. 15, O'Brien et al., 1996; Rabu et al., 1996; Bevier et al., 1993; Fig. 3 in McNamara et al., 2001 **SETTING:** Arc/ back-arc
22 0.57–0.52 Ga (Cordillera)	
22a Hamill–Gog (0.57 Ga) *(SE Canadian Cordillera)*	**VOLCANIC ROCKS: Hamill–Gog Group** (0.57 Ga) **REF.:** Colpron et al., 2002 **SETTING:** ?Breakup
22b Selwyn Basin (0.54–0.45 Ga) *(Cordillera, n. of and within Selwyn Basin)*	**SILLS: Post-Hyland Group** (0.52 Ga) **VOLCANIC ROCKS:** Alkali and potassic mafic volcanism **REF.:** #218 in [2]; Goodfellow et al., 1995; Abbott, 1997 **SETTING:** Selwyn Basin rifting
23 0.47- 0.42 Ga (Appalachians)	
23a Middle Ordovician 'Overstep' Sequence (0.47–0.45 Ga) *(Gander Zone–Dunnage Zone)*	**VOLCANIC ROCKS: Middle Ordovican 'Overstep Sequence'** includes bimodal magmatism (in Exploits subzone of Newfoundland, Bathurst area of New Brunswick, Maine, and United Kingdom) (0.47–0.45 Ga) **REF.:** van Staal et al., 1996 **COMMENT:** Coeval **Dunn Point** bimodal volc. (0.46 Ga) occur in the Avalon terrane, Nova Scotia (Hamilton and Murphy, 2004) **SETTING:** Back-arc

Table 1 Continued

23b Late Ordovician–Silurian magmatism of Atlantic Canada (0.44–0.41 Ga) (*c. Newfoundland and Maritimes*)	***GANDER ZONE–DUNNAGE ZONE (of New Brunswick, Quebec and Maine) (0.43–0.41 Ga)*** **VOLCANIC ROCKS: Tobique** and **Piscataquis** volcanic belts **REF.:** Keppie and Dostal, 1994 ***AVALON ZONE (of Nfld. and New Brunswick) (0.44–0.43 Ga)*** **SILLS: Cape St. Mary's** (0.44 Ga) **VOLCANIC ROCKS: Bayswater Group** (0.44 Ga); **Coastal Volcanic Belt** (0.43–0.42 Ga) **DYKES: Kingston Terrane** dyke complex (0.44–0.41 Ga); **Passamaquoddy Bay** **REF.:** Van Wagoner et al., 2001; Barr et al., 1999; Hodych and Buchan, 1998 ***MEGUMA ZONE (of Nova Scotia) (0.44 Ga)*** **VOLCANIC ROCKS: White Rock Fm** (0.44 Ga) **INTRUSION**: **Brenton** monzogranite (0.44 Ga) **REF.:** MacDonald et al., 2002; Keppie and Krogh, 2000 ***OVERSTEP SEQUENCE OF NEWFOUNDLAND (0.43–0.42 Ga)*** **VOLCANIC ROCKS**: bimodal volc. such as **King George IV** (0.43 Ga); **Springdale** (0.42 Ga), and **Botwood** groups; and mainly felsic volc. such as **Sops Arm** and **La Poile** groups **INTRUSION: Taylor Brook** (0.43 Ga); **Main Gut** (0.43 Ga) **REF.:** Chandler et al., 1987; Heaman et al., 2002 **SETTING**: ?
24 0.36–0.32 Ga	
24a Magdalen (Maritimes) Basin (0.36–0.32 Ga) *(Maritimes)*	**INTRUSIONS:** magmatic underplate underlying entire Magdalen (Maritimes) Basin, interpreted from gravity; **Wentworth** and **Wyvern** gabbros **VOLCANIC ROCKS: Cape au Diable; Fountain Lake** (mafic to felsic) **DYKES**: widespread **REF.:** Pe-Piper and Piper, 1998; Murphy et al., 1999 **SETTING:** Plume
25 0.27–0.20 Ga (Cordillera)	
25a Cache Creek (Late Triassic and mid-Permian) *(Cordillera)* [~1500 km long, 50–100 km wide]	**VOLCANIC ROCKS:** Late Triassic volcanics interpreted to represent oceanic plateau (Tardy et al., 2001). Overlies mid-Permian magmatism interpreted to represent underlying Permian Crust Alternative, more complex model suggested by Struik et al. (2001) **REF.:** #38 in [1] **SETTING:** ?Plume (?P6)
25b <u>Wrangellia</u> (0.23 Ga) *(Cordillera)* [1,000,000 cu. km]	**VOLCANIC ROCKS: Karmutsen; Nikolai** **INTRUSIONS: Kluane** **SILLS: Maple Creek** (0.23 Ga) **REF.:** #34 in [1]; #303-304 in [2] **SETTING:** Plume (P6)
25c <u>Ramparts Group</u> (0.21 Ga) *(Alaska)* [100,000 sq. km]	**SILLS AND VOLCANIC ROCKS: Ramparts Group** (0.21 Ga) **REF.:** #306 in [2] **SETTING:** ?
26 0.20 Ga	
26a <u>ENA</u> (Eastern North America) portion of **CAMP** (Central Atlantic Magmatic Province) (0.20 Ga) *(Atlantic Canada)* [7,000,000 sq. km for entire event]	**VOLCANIC ROCKS: North Mountain Basalt; Grand Manan** **DYKES: ENA** (0.20 Ga) **COMMENT:** Rest of CAMP event is located along east coast of US and also in Europe, NW Africa and South America **REF.:** #32 in [1]; #307 in [2] **SETTING:** Plume (P1); Breakup (B1, forming Atlantic Ocean)
27 0.14–0.09 Ga	
27a New England–Québec (NEQ); Monteregian) (0.14–0.11 Ga) [60,000 sq. km]	**INTRUSIONS AND PLUTONS: Monteregian Hills** intrusions of Quebec and related plutons of New England) (0.14–0.11 Ga) **REF.:** #323 in [2] **SETTING:** Hotspot
27b Trap *(sw. Greenland)* [20,000 sq. km]	**DYKES: Trap** (0.14 Ga) **REF.:** #30 in [1]; #322 in [2] **SETTING:** ? Breakup (B2, Linked to subsequent breakup of Greenland from Laurentia to form Labrador Sea)

Table 1 Continued

27c **Sverdrup Basin Magmatic Province** (part of High Arctic Large Igneous Province; HALIP) *(0.13–0.09 Ga) (Arctic Islands)* [550,000 sq. km]	**VOLCANIC ROCKS AND SILLS:** including **Strand Fiord Fm** (0.13–0.09 Ga; major pulse at 0.095 Ga); **Alpha Ridge** **DYKES: Queen Elizabeth Islands** (inludes **Hazen Strait**); **Lightfoot River** **INTRUSIONS: Wootton** (0.092 Ga) **REF.:** #12 in [1]; #325 in [2]; Tarduno et al., 1998; Trettin and Parrish, 1987 **COMMENT**: Part of Large Igneous Province that includes Svalbard and Franz Josef Land (Maher, 2001) **SETTING:** Plume (P1); Breakup
28 0.07–0.05 Ga	
28a Carmacks *(n. Cordillera)* [63,000 sq. km]	**VOLCANIC ROCKS: Carmacks** (0.07 Ga) **REF.:** #9 in [1] **SETTING:** Plume (? P6)
28b Crescent (0.06–0.05 Ga) (*western margin of North America*)	**VOLCANIC ROCKS**: **Crescent Terrane** (“**Coast Range Basalt Province**”) (0.06–0.05 Ga) **REF.:** #339 in [2]; Murphy et al., 2003 **SETTING:** Plume (? P6)
28c **North Atlantic Igneous Province (NAIP)** (0.06 Ga) *(Baffin Island, w. Greenland)* [1,300,000 sq. km for entire NAIP event]	**VOLCANIC ROCKS: Cape Dyer**; **West Greenland** **DYKES: Cape Searle**; **West Greenland** **REF.:** #334 and 335 in [2]; #5 in [1] **COMMENT:** Part of North Atlantic Igneous Province of Greenland, United Kingdom (0.062–0.052 Ga), and linked to present-day Iceland hotspot **SETTING:** Plume Breakup (Europe from Greenland)
29 0.025–0.015 Ga	
29a Behm Canal (Tertiary ‘Lamprophyre’ Province) (ca. 0.023–0.005 Ga) (*c. British Columbia*) [25,000 sq. km]	**DYKES: Behm Canal** (0.023-005 Ga) **REF.:** #348 in [2] **COMMENT**: alkalic lamprophyres **SETTING:** Hotspot (H1)
29b **Columbia River Basalt Group** (mainly 0.017–0.0150 Ga) *(nw. US)* [165,000 sq. km]	**VOLCANIC ROCKS, DYKES AND SILLS: Columbia River Basalt Group** (CRBG) **REF.:** #1 in [1] **SETTING:** Plume (P1, P7)
29c Chilcotin (Neogene-Paleogene; mainly Miocene) *(c. and sc. British Columbia)* [25,000 sq. km]	**VOLCANIC ROCKS: Chilcotin Group** basalts; **Anahim** volcanic belt; **Cheslatta Lake** suite; **Masset Fm** **REF.:** Anderson et al., 2001 **COMMENT:** Nearby to and potentially linked to **Columbia River Basalt Group** **SETTING:** Hotspot (H1) Back-arc (partial melting)

margin of Laurentia at this time. The conjugate margin may have been Baltica, which has a remarkably similar age range of magmatism (e.g. Heaman, 1997; Buchan et al., 2000), or the Hearne craton (Bleeker, 2004). Additional units in eastern and southwestern Laurentia, the 2.505 Ga Ptarmigan dykes [#1a, unit not displayed in Fig. 1] and the 2.408 Ga Du Chef dykes [#1a, unit not displayed in Fig. 1] have uncertain relationship with the events in the southeastern and southern parts of the Superior Province.

Elsewhere in Canada, there are additional events falling in this age range. These include the Kaminak dykes [#1c] in the Hearne Province, and the Mirond Lake dykes [#1d] in the Sask craton of the Trans Hudson orogen.

2.24–2.21 Ga: The next burst of activity in Laurentia was widespread in the North Atlantic (Nain), Superior, and Slave cratons [#2a-d]. The 2.235 Ga Kikkertavak swarm [#2a] has been linked with breakup along the southern margin of the North Atlantic Craton (lower Aillik Group) at 2.178 Ga (Ketchum et al., 2001) although the long interval between emplacement of the swarm and breakup 57 Ma later is problematic. The 2.21 Ga BN1 (and possibly correlative MD1) dykes [#2b] of western Greenland are also likely linked with North Atlantic Craton breakup.

Superior Province elements of this age include the 2.217–2.210 Ga Ungava giant radiating swarm [#2c] that spans the entire eastern half of the Superior Province (Buchan et al. 1998). The convergence point marks a plume centre and possible breakup of a continental fragment from the eastern margin of the Superior Province. Buchan et al. (1998) proposed that the Nipissing sills [#2c] of the Southern Province were fed laterally via the Ungava radiating swarm from the plume centre region >1000 km to the northeast.

The Slave Province is another node of activity in this age interval. The 2.23 Ga Malley and 2.21 Ga MacKay dyke swarms [#2d] are both roughly linear, and crosscut at a shallow angle. If they represent rift-parallel swarms (Fig. 3c) then they could be linked to breakup along the southeastern margin of the Slave Province (LeCheminant et al., 1996). However, if they represent an aulacogen (failed-arm) type swarm (Fig. 3b), then the plume centre and locus of breakup would have to lie at one end of the swarms; i.e., either on the east or southwest margins of the Slave Province.

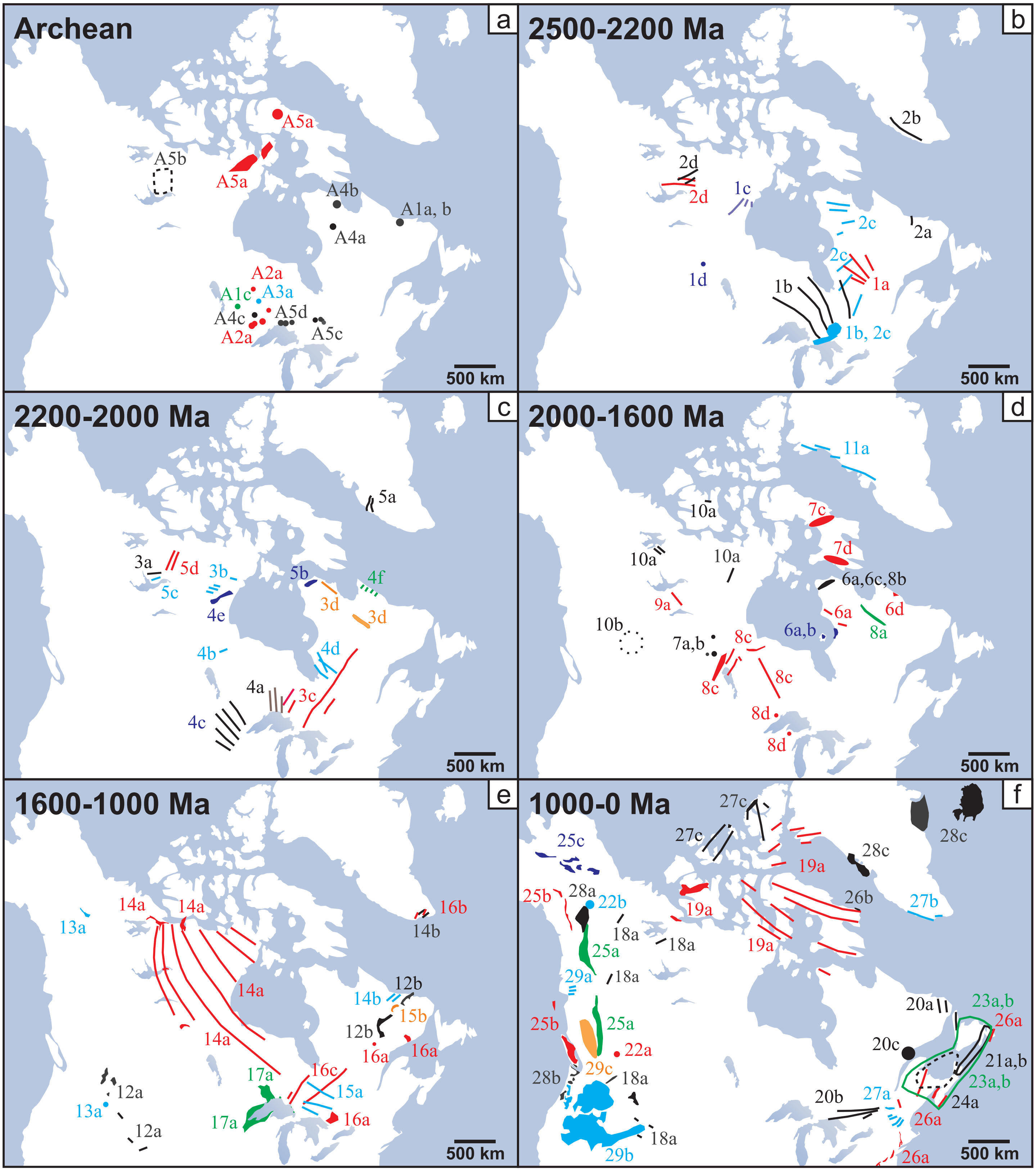

Figure 1 Distribution of mafic units discussed in the text. Numbers correspond to entries in Tables 1 and 2. Colours have no age significance; they are simply used to allow different magmatic events to be distinguished.

Table 2 Archean greenstone belts in Canada interpreted to have a plume origin (i.e. tholeiitic sequences containing komatiites and/ or those interpreted as oceanic plateaus). Details and full referencing on most events is available in compilations [1] (=Ernst and Buchan 2001) and [2] (=Buchan and Ernst 2004), and Tomlinson and Condie (2001), or in the additional cited references. "**REF.**:" = key reference(s). **SETTING** codes are explained in Table 3.

Event name (Age) *(Location)*	**Magmatic components** (Age)
A1 3.11–2.98 Ga	
A1a Hunt River (3.11 Ga) (*Hopedale block, North Atlantic Craton)*	**GREENSTONE BELTS: Hunt River** (3.11 Ga) **REF.:** James et al., 2002 **COMMENT:** Includes komatiites **SETTING:** ?Plume (P4)
A1b Florence Lake (2.99–2.98 Ga) (*Hopedale block, North Atlantic Craton)*	**GREENSTONE BELTS: Florence Lake** (2.99–2.98 Ga) **REF.:** James et al., 2002 **COMMENT:** Includes komatiites **SETTING:** ?Plume (P4)
A1c North Caribou (2.99 Ga) *(n. Caribou Terrane, nw. Superior Prov.)*	**GREENSTONE BELTS: Balmer Assemblage** (**Red Lake** greenstone belt) (2.99 Ga) **REF.:** #256 in [2]; Tomlinson et al., 1998; Hollings et al., 1999 "plume related rifting" **COMMENT:** Includes komatiites **SETTING:** ?Plume (P4)
A2 2.93–2.92 Ga	
A2a Western Superior (2.93 Ga) *(Wabigoon subprov., w. Superior Prov.)*	**GREENSTONE BELTS: Steep Rock**; **Finlayson**; **North Rim Unit** of **McGruer Assemblage** (2.93 Ga) **Lumby Lake** 2963–2898 Ma, ? **Heaven Lake** [U 2954 Ma] **REF.:** #252 in [1] **COMMENT:** Includes komatiites. Rifting or impingement of plume in subduction setting (Hollings et al. 1999) **SETTING:** ?Plume (P4) Back-arc (A2)
A3 2.86 Ga	
A3a Pickle Crow (2.86 Ga) (*Uchi subprov., nw. Superior Prov.)*	**GREENSTONE BELTS: Pickle Crow Assemblage** (~2.86 Ga) **REF.:** #244 in [1] **COMMENT:** Includes komatiites **SETTING:** ?Plume (P4)
A4 2.79–2.78 Ga	
A4a Vizien (2.79 Ga) (*Minto Block, ne. Superior Prov.)*	**GREENSTONE BELTS: Vizien** (2.79 Ga) **REF.:** #236 in [1] **COMMENT:** Includes komatiites **SETTING:** ?Plume (P4, P6)
A4b Faribault–Thury (ca. 2.88–2.71 Ga) *(Minto Block, ne. Superior Prov.)*	**GREENSTONE BELTS:** greenstone belt remnants in **Faribault–Thury Complex** (~2.88–2.71 Ga) **REF.:** Maurice et al., 2003 **SETTING:** ?Plume (P4)
A4c Fourbay (2.78 Ga) *(Wabigoon subprov, w. Superior Prov.)*	**GREENSTONE BELTS: Fourbay Sequence** in **Savant Lake** and **Sturgeon Lake** (2.78 Ga) **REF.:** Sanborn-Barrie and Skulski, 1999 **COMMENT**: Possible oceanic plateau setting **SETTING:** ?Plume (P6)
A5 2.75–2.70 Ga	
A5a Prince Albert–Woodburn (2.73 Ga) (*Rae Prov.*) [>1000 km. long belt]	**GREENSTONE BELTS:** (~2.73 Ga): **Prince Albert Group**; **Woodburn Group**; **Mary River Group, ?Murmac Bay Group** **REF.:** #220 in [1]; Schau, 1997; Aspler et al., 1999; Zaleski et al., 2001; Hartlaub et al., 2002**;** Skulski et al., 003a,b. **COMMENT:** Includes komatiites **SETTING:** ?Plume (P4) ?Breakup Rae Craton
A5b Kam (2.73–2.70 Ga) (*Slave Prov.*)	**VOLCANIC ROCKS and DYKES: Kam Group** and early dykes (2.73–2.70 Ga). **REF.:** #227 in [1] **COMMENT:** Widespread tholeiitic cover sequence **SETTING:** ?Plume (?P3)
A5c Abitibi (2.75–2.70 Ga) (*Abitibi belt, Superior Prov.*)	**GREENSTONE BELTS:** includes komatiites: **Pacaud** (2750–2735 Ma); **Stoughton-Roquemaure** (2725–2720 Ma); **Kidd-Munro** (2718–2710 Ma); **Tisdale** (2710–2703 Ma) **REF.:** #224 in [1]; Ayer et al., 2002; Sproule et al., 2002 **COMMENT:** Includes komatiites **SETTING:** ?Plume (P4); Back-arc (A2)
A5d Wawa (2.75–2.74 Ga) (*Wawa belt, Superior Prov*.)	**GREENSTONE BELTS: Schreiber-Hemlo-White River-Dayohessarah** (2.75–2.74 Ga) **REF.:** #230 in [1] **COMMENT:** Includes komatiites **SETTING:** ?Plume (P4)

Figure 2a Aerial photograph (centred approximately at 67°18'N, 112°26'W) of 1.27 Ga Mackenzie dykes cutting the Recluse Group and other units of the Tree River fold belt, Wopmay Orogen. The dykes are up to 50 m wide and are exposed as prominent ridges because of differential erosion.

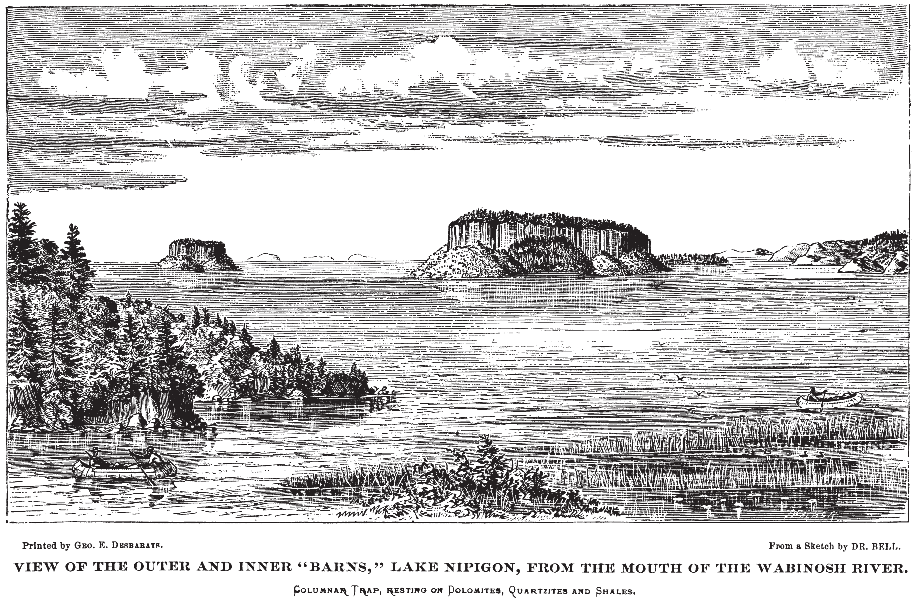

Figure 2b The 1.109 Ga Logan diabase sills of the Keweenawan magmatic event, shown here from an 1869 sketch by Robert Bell of the Geological Survey of Canada (Bell 1879), occur widely in the vicinity of Lake Superior and Lake Nipigon. Bell (1870) noted that "… the Inner Barn with its sides of columnar trap, rises like a great castle in the middle of the bay, to a height upwards of 600 feet, and appears to be the highest point around Lake Nipigon."

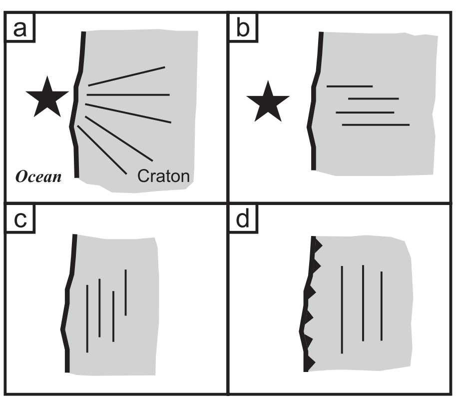

Figure 3 LIP setting determined from dyke swarm geometry and relationship to cratonic edge. These and other settings are described in Table 1. Star locates mantle plume center. **a.** Dyke swarm radiating from coeval cratonic margin (focus identifies plume centre) Type P1 and B1 of Table 3. **b.** Linear swarm perpendicular to nearby coeval cratonic margin (failed arm type of Fahrig, 1987). If a swarm extends across the craton to another margin, it is ambiguous as to which margin the dykes are related. Type P2 of Table 3. **c.** Linear swarm parallel to coeval breakup margin (passive margin type of Fahrig, 1987). Type B2 of Table 3. **d.** Linear swarm parallel to subducting margin. Type A1 of Table 3.

Table 3 Selected criteria for interpreting origin and setting of LIPs and smaller intraplate mafic events.

Label	Criteria
	MANTLE PLUME LINK
P1	Radiating dyke swarm
P2	Linear dyke swarm (or belt of mafic magmatism) perpendicular to cratonic margin (failed-arm type of Fahrig, 1987; could also be called aulacogen-type).
P3	Large event, distal from cratonic boundary
P4	Presence of high-Mg rocks, e.g. komatiites in Archean greenstone belts
P5	Geochemistry: OIB or FOZO signature
P6	Accreted oceanic plateaus
P7	Link to present-day hotspot
	BREAKUP LINK
B1	Radiating swarm or failed-arm type swarm (Fahrig, 1987) with convergence point near cratonic margin of similar age
B2	Linear dyke swarm, parallel to and nearby cratonic margin of similar age. This is termed passive margin type swarm by Fahrig (1987)
B3	LIP situated nearby cratonic margin of similar age
	ARC LINK
A1	Location in a back-arc setting relative to concurrent orogenic activity. However, this does not necessarily require back-arc extension processes. (See Note 1, below)
A2	Coexisting with arc magmatism
	HOTSPOT (OF UNSPECIFIED ORIGIN)
H1	Small (sub-LIP scale) region of anomalous intraplate mafic volcanism

Note 1: The Keweenawan rift activity is arguably in a back-arc setting with respect to the Grenville orogen, yet it is generally viewed that the Keweenawan magmatism is plume-related (see discussion in text).

2.19–2.17 Ga: Widespread activity occurred during this age interval. The oldest activity is represented by the 2.19 Ga Dogrib dyke swarm [#3a] in the Slave Province and the similar age Tulemalu-MacQuoid swarm [#3b] in the Hearne Province. While a connection would seem likely based on the age match, preliminary paleomagnetic data indicate that the Slave and Rae cratons were not in their present relative positions at this time (LeCheminant et al., 1997). Globally, a stage of Birimian magmatic activity in Western Africa has this age (event #187 in Ernst and Buchan, 2001). Magmatic activity in the Slave Craton continues to 2.18 Ga, the age of the Duck Lake sill [#3a, unit not displayed in Fig. 1].

The 2.17 Ga Biscotasing dyke swarm [#3c] is one of the most widespread in Canada, extending throughout much of the southern and central Superior Craton. Similar age activity [#3d] is present as the Payne River dykes in northern Ungava (Cape Smith Belt) and Cramolet Lake sills (part of “Cycle 1” magmatism) in the Labrador Trough. It seems unlikely that all these elements are part of a single event, but the association of Payne River dykes and “Cycle 1” magmatism in the Labrador Trough suggests a link to breakup along the eastern Superior Province. Globally, an identical age has also been obtained from a quartz diorite dyke in the Wyoming Province, although paleomagnetic data are inconclusive regarding the relative locations of the Wyoming and Superior provinces at this time (Harlan et al., 2003a).

2.12–2.07 Ga: In the Superior Province there are several distinct stages of activity during this time interval. The 2.12–2.10 Ga Marathon dyke swarm [#4a] is a broadly linear swarm that cuts northward across the Superior Province from Lake Superior. This is an aulacogen-type swarm, and therefore could be associated with a breakup margin at the end of the swarm. Since the swarm may reach the cratonic margin on its north end as well as its south end (c.f. Fig. 3b), then the applicable breakup margin may also be at either end, either to the north in Hudson Bay or to the south in Lake Superior.

Slightly younger is the 2.09–2.07 Ga Cauchon swarm [#4b], which has been linked with breakup along the northwest margin of the Superior Province (e.g. Halls and Heaman, 2000). Two other events are also of this age: the 2.077 Ga Fort Frances (Kenora-Kabetogama) dykes [#4c] that are linked with breakup along the southern margin of the Superior Province, and the 2.069 Ga Lac Esprit swarm [#4d] located east of James Bay. There are no obvious connections between these widely separated but coeval 2.07 Ga events. However, future identification of additional dykes of this age in intervening areas could suggest a link.

In the Hearne Province, the widespread 2.111 Ga Griffin gabbros (formerly Hurwitz gabbros) [#4e] are presumably linked to breakup along the Trans-Hudson margin (Aspler et al., 2002).

Finally, the Napaktok swarm [#4f] trends perpendicular to and extends along the Labrador coast for at least 200 km. These dykes have an uncertain age between 2.50 and 2.10 Ga, and uncertain tectonic setting. Although more than one age of dykes may be present, at least part of this activity is dated by the 2.121 Ga age for the Tikkigatsiagak dyke.

2.05–2.02 Ga: In the Nain Province, the 2.045 Ga Iglusuataliksuak dyke [#5a, unit not displayed in Fig. 1] is coeval with the Kangâmuit swarm [#5a] of adjacent southern Greenland. The combined 2.04–2.05 Ga event would be areally significant, and may represent a breakup event associated with the northern margin of the North Atlantic Craton. Korak sills associated with the lower Povungnituk sequence [#5b] in the Cape Smith Belt of the northeastern Superior Province are of the same age as the Iglusuataliksuak dyke. However, given that the North Atlantic Craton had not yet docked at this time, two independent events are probable. The younger Upper Povungnituk sequence [#6c] is discussed below in the next section.

The third locus of activity of this age is in the Slave Craton. The 2.038 Ga Hearne dykes [#5c] parallel the southern Slave margin, possibly representing breakup along that margin (c.f. with evidence discussed above for an earlier 2.23–2.21 Ga breakup along that margin associated with the Malley/MacKay swarms [#2d]). In contrast, the younger 2.030–2.023 Ga Lac de Gras swarm [#5d] is not easily linked to any margin. It is centred in the Slave province and slightly converges to the north toward the similar-aged Booth River Complex in the Kilohigok sedimentary basin. LeCheminant et al. (1996) suggest that the Lac de Gras swarm is coeval with rifting on the western margin of the Slave Province.

2.00–1.95 Ga: Magmatism of this age range is distributed along the circum-Superior margin (e.g. Baragar and Scoates 1987).

In the Belcher Islands there are two main volcanic suites, the Eskimo [#6a] and overlying Flaherty [#6b] volcanics. Based on paleomagnetic correlations, the Eskimo volcanics may be linked with Richmond Gulf, Persillon, Pachi and Nastapoka Group volcanics (Chandler and Schwarz, 1980; Schwarz and Fujiwara, 1981), and with 1.998 Ga Minto dykes (Buchan et al., 1998). The Minto dykes and correlated suites are also coeval and perhaps cogenetic with the precisely dated Watts Group ophiolite. The Eskimo volcanics have been linked geochemically with the western Povungnituk [#6c] (Legault et al., 1994), but this link is now doubtful based on more extensive recent geochemical study (Modeland et al., 2003).

The overlying Flaherty Group [#6b] is essentially undated except for a very uncertain Pb-Pb age of 1960+/-80 Ma. However, paleomagnetic data suggest a link with the Haig and Sutton Inlier sills (Schwarz and Fujiwara, 1981). Geochemical correlations indicate that the Flaherty Group may be linked with the upper (eastern) Povungnituk [#6c] (Legault et al., 1994).

The Cape Smith Belt includes the tectonically juxtaposed 1.998 Ga Watts Group, 2.04–1.96 Ga Povungnituk suites [#5b & #6c], and ca. 1.87 Ga Chukotat Group volcanics [#8b]. (Note that the older 2.04 Ga portion of the Povungituk sequence [#5b] was discussed in the previous section.)

Additional magmatism in this age interval is present in the Nain Province. A 1.95 Ga plateau basalt sequence in the Mugford Mountains of Labrador [#6d] represents a rifting event (Wardle et al., 2002) that may be more widespread in the North Atlantic Craton based on possible correlations with the Ramah and Snyder groups.

1.90–1.88 Ga (Trans Hudson Orogen and Rae-Hearne Craton): Several non-arc packages are associated with the Trans Hudson during this age interval. These include the Sandy Bay assemblage of the Flin Flon Belt [#7a], which contains accreted oceanic crust of various affinities, including an oceanic plateau. In addition there are the Josland and related sills [#7b] in the Lynn Lake Belt of the Amisk collage, and the mafic magmatism in the Piling-Penhryn [#7c], and Lake Harbour [#7d] groups on Baffin Island.

1.88–1.86 Ga (Circum-Superior Province): 1.88–1.87 Ga mafic magmatism surrounds the Superior Province on all sides except the south-east where, if originally present, it has been obscured by the Grenville allochthon. This magmatism is present in the Labrador Trough (Montagnais sills belonging to New Quebec Orogen Cycle 2 [#8a]), Cape Smith Belt (Chukotat Group [#8b]), northwest Superior province (Fox River sill, Molson dykes, Thompson Nickel Belt, and Winnipegosis komatiites [#8c]), and the Animikie Basin and Marquette Range Supergroup of the southern Province (Hemlock and Gunflint formations and associated Kiernan sills [#8d]). The 1.88 Ga event or events are of particular importance because they represent a metallotect; the major Ni-Cu-PGE sulphide ores of both the Thompson Nickel Belt and the Raglan deposits of the Cape Smith Belt appear to be associated with this age of magmatism (e.g. Hulbert et al., 2004 for TNB; Wodicka, pers. comm. 2004 for Raglan).

1.88 Ga magmatism in the Cape Smith belt and Labrador Trough has been linked to rifting and possible separation of a microcontinent (St-Onge et al., 2000). However, the magmatism in both the Thompson belt and Animikie basin occurs within a broad period of ocean closure, and therefore may represent back-arc rifting. The recent discovery of a major ca. 1.88 Ga dyke, the NW-trending Pickle Crow dyke [#8c] crossing the interior of western Superior Province provides a link between the Animikie Basin and Thompson Belt magmatic activity, and may suggest a mantle plume model for the western part of the 1.88 Ga event (Buchan et al., 2003).

1.83–1.82 Ga: The Sparrow dyke swarm [#9a] of the western Rae Province is as yet uncorrelated with any volcanic sequences. Other units of similar age but uncertain relationship are 1) a meta-gabbro and two monzogabbros with U-Pb ages of 1.83–1.82 Ga in the Close Lake, Wollaston-Mudjatik Transition zone [#9a, unit not displayed in Fig. 1], and 2) the wide-spread Christopher Island formation volcanics of the Baker Basin region [#9a, unit not displayed in Fig. 1].

1.75–1.71 Ga: The Cleaver dykes in the Great Bear Magmatic Zone, the Hadley Bay sills on Victoria Island and MacRae Lake dykes in the northern Rae Province are coeval in age [#10a], suggesting a widespread event in northwestern Canada. This large region of 1.75 Ga activity could be associated with the generation of Wernecke sediments in the northwestern Cordillera, and the approximately 40 Ma younger 1.71 Ga Bonnet Plume River mafic magmatism [#10a; unit not displayed in Fig. 1]. The Wernecke sediments are inferred to represent the earliest rift stage of activity associated with the Cordilleran margin (Cook et al. *in* Percival et al., 2004). The Pitz formation felsic volcanics and Nueltin felsic intrusive suite [#10a, units not displayed in Fig. 1] of the Baker Basin region are similar in age.

Subhorizontal seismic reflectors interpreted as sills are present over a huge region (about 120,000 sq. km) in the basement underlying the Western Canada Basin. These Winagami sills [#10b] are roughly bracketed in age between 1.89 and 1.76 Ga, and have been tentatively linked with the Cleaver dykes by Ross and Eaton (1997).

1.64 Ga: The 1000 km long Melville Bugt swarm [#11a] is located in western Greenland. Although close to Baffin Island and other Canadian Arctic islands in a reconstructed Greeenland – North America configuration, Melville Bugt dykes have not yet been recognized in Canada.

1.47–1.44 Ga: There are two nodes of activity with this age. The Belt Basin of the western Cordillera contains extensive Moyie-Purcell sills and associated Purcell volcanics [#12a]. These may have been generated when a continent (perhaps Australia) was rifted from the western margin of Laurentia. It is also interesting that in the Wyo-ming Province there is an extensive linear dyke swarm (Tobacco Root – Group B; [#12a]) of the same age. Assuming that the dykes fed the volcanics and sills, we can infer that the magma source area was either on the western margin of Laurentia in the vicinity of the Belt Basin, or far to the southeast on the southern margin of Laurentia with magma being trans-ported laterally via the dykes to the Belt Basin. Long distance feeding of a sill province has been described above for the 2.22 Ga Ungava event, and may be a not uncommon consequence of the lateral flow pattern in giant dyke swarms (e.g. Ernst and Buchan, 1997).

A second node of this age is located in southeastern Laurentia. The Michael and Shabagamo gabbros [#12b] have an approximate age of 1.47–1.46 Ga and represent a significant event in the southeastern Laurentia. They are located in a back-arc setting to the evolving Grenville Orogen (Rivers et al. *in* Percival et al., 2004).

1.38 Ga: Hart River volcanic rocks and sills, and coeval sills from the Belt Basin region [#13a], may represent rift sequences (Abbott, 1997; Thorkelson et al., 2003).

1.28–1.27 Ga: One of the largest magmatic events in Canada occurred at 1.267 Ga [#14a]. Most prominently this event consists of the Mackenzie giant radiating dyke swarm. Mackenzie dykes (Fig. 2a) fan over an arc of 100° and cover almost 3 million sq. km of the Canadian Shield. Coeval Coppermine volcanics and the Muskox Intrusion are situated near the plume center, but additional volcanic and sill packages are distributed throughout the swarm and are inferred to be fed via lateral flow along dykes originating from near the plume center (e.g. Ernst and Baragar, 1992; Baragar et al., 1996). This LIP is presumed to be linked with continental breakup and formation of a northern ocean, which has been termed the Poseidon Ocean (G. Jackson cited in Fahrig, 1987). However, the missing rift block(s) has not yet been identified, although Siberia has been a repeated suggestion (see summary in Ernst et al., 2000; cf. Sears et al., 2004).

The North Atlantic Craton of North America and Greenland is another locus of magmatic activity during this time period [#14b]. The 1.280–1.277 Ga Nain-LP dykes of Labrador are correlative with the BD0 dykes of Greenland (Buchan et al., 1996). Also the 1.273 Ga Harp dykes of Labrador may be linked with Gardar (BD1, BD2, BD3) dykes of Greenland (Baragar, 1977). The setting of this 1.28–1.27 Ga activity is unknown, but it is clearly distinct in location, dyke-trend, and probably in origin from the coeval Mackenzie event. Also wide-spread in Labrador are the anorthosites, granites, diorites and troctolites of the older and probably unrelated 1.35–1.29 Ga Nain plutonic suite (Ryan and James, 2004 and references therein).

Coeval activity of this age is represented globally by the Central Scandinavian Dolerite Complex (sills) of the Baltic Shield. Paleomagnetic data and geological evidence suggest a reconstructed location east of Greenland (Buchan et al., 2000, and references therein), which is supported by geological evidence (Bingen et al., 2002). Given its great spatial separation from Canada in this reconstruction, the Central Scandinavian Dolerite Complex of Baltica must represent a separate event from the coeval Mackenzie (and also possibly the Nain Province) activity. The occurrence of multiple independent LIPs has been considered evidence for plume cluster events (Ernst and Buchan, 2002).

1.25–1.22 Ga: The Grenville Province and adjacent Superior Province contain widely separated packages of similar-aged magmatism. From southwest to northeast, these include 1.235 Ga Sudbury dykes [#15a], 1.25–1.225 Ga Seal Lake volcanic rocks and Naskaupi sills [#15b], and the 1.250 Ga Mealy dykes [#15b]. These 1.25–1.22 Ga events along the Grenville Orogen have not been previously linked to each other and more work is required to assess whether they represent disparate elements of the same event. They are situated in a back-arc setting with respect to the evolving Grenville orogen (e.g. Rivers and Corrigan, 2000; Rivers et al. *in* Percival et al., 2004). However a plume origin should not be ruled out. The Seal Lake suite has previously been considered analogous to a flood basalt sequence (“plateau basalt” is the term used in Baragar, 1977), and the aulacogen type geometry of the Sudbury dykes suggests derivation from a spreading center located to the south-east of the swarm (Fahrig, 1987).

1.18–1.14 Ga: Widely separated but possibly linked nodes of mafic magmatism of 1.18 Ga are distributed along the Grenville Orogen. Specifically, toward the northeast end of the Grenville Province the Davy Group sills and dykes [#16a] in the Wakeham Group have an age of 1.177 Ga. Similar ages are found in coronitic gabbros [#16a] in the Baie du Nord segment of Tshenukutish domain. Finally, the same age but with larger uncertainties applies to Algonquin metagabbros [#16a] in the Central Gneiss Belt, southwestern Grenville Province.

Late Gardar magmatism in South Greenland ranges in age from 1.18–1.14 Ga [#16b], and includes the 1.18 and 1.163 Ga Giant Tugtutôq Dykes.

The sparsely distributed 1.141 Ga Abitibi dyke swarm [#16c] of the Central Superior Province has a width of 400 km and extends for nearly 700 km across the southern and eastern Superior Province. This event has long been considered as a precursor to the 1.109–1.085 Ga Keweenawan event [#17a] located at the southwest end of the swarm (next entry). However, the broadly linear pattern of the Abitibi swarm does not eliminate a possible source at the other (northeast end) of the swarm.

1.11–1.08 Ga: One of the most dramatic flood basalt events in Canada and the United States is arguably the Keweenawan magmatism [#17a] of the Mid-Continent Rift (e.g. Ojakangas et al., 2001). It comprises at least 2 x 10^6 cubic km of volcanic rocks and possibly an equal volume of intrusive rocks (Fig. 2b). The Mid-Continent Rift (and subsurface lavas) can be traced eastward through Michigan and southwestward into the central United States. A similar age of activity is found in the “South-western USA Diabase Province”, and in the Moores Lake sills of the Athabasca Basin (1000 km to the northwest). The Keweenawan activity consists of main pulses of activity at 1.109–1.105 Ga and 1.100–1.094 Ga, but activity is continuous to 1.085 Ga. Emplacement of the Keweenawan LIP is similar in age to that of terminal collision of the Grenville orogen (Rivers et al. *in* Percival et al., 2004). Although a back-arc rifting origin linked to the coeval Grenville orogeny has been suggested, the most widely accepted model links the event to a mantle plume on the basis of the great volume of tholeiitic magma generated in an intraplate setting (e.g. Ojakangas et al., 2001).

0.78 Ga: The Gunbarrel magmatic event [#18a] is distributed over a distance of 2400 km in western North America. Precise 0.780 Ga ages are found in the Hottah sheets of the Slave Province, the Mackenzie Mountains dykes and sills, the MacDonald dykes, and the Tobacco Root- Group B and Wolf Creek sills of the Wyoming Province (Harlan et al., 2003b). The Irene and Huckleberry volcanics of northwestern USA are also inferred to be of this age. The dykes define a radiating swarm with a convergence point in the southern Cordillera near Vancouver Island, indicating a mantle plume origin for this 0.78 Ga LIP (Park et al., 1995). The Windermere sedimentary/volcanic sequence starting at about 0.75 Ga may represent a passive margin associated with this 0.78 Ga plume. Both South China and Australia also contain magmatism dated at 0.78 Ga (events #67 and #64 *in* Ernst and Buchan, 2001, respectively) and both have been proposed as the rifted block(s).

0.72 Ga: Another major LIP event is represented by the Franklin dyke swarm [#19a] which extends throughout the southern Arctic Islands, but is most significant on Baffin Island, and also on reconstructed Greenland as the Thule swarm [#19a]. The convergence point marking the plume centre for this event is located north or northwest of Banks Island. Natkusiak volcanics, and Minto Inlier and Coronation sills [#19a] are also part of the Franklin event and are generally concentrated toward the plume centre region. The Franklin event may be linked with separation of an as yet unidentified continent.

Another possible locus of similar-aged activity is the Appalachians. A very approximate Rb-Sr age of 0.735 Ga has been suggested for coast-parallel dykes in basement inliers of the Appalachians of the United States (event #72 *in* Ernst and Buchan, 2001). This activity can been linked with additional magmatism and a stage of rifting along the Laurentian margin in the southern Appalachians (Aleinikoff et al., 1995).

0.62–0.56 Ga (Laurentian margin, Appalachians): The formation of the Iapetus Ocean was preceded by several distinct major magmatic events along the eastern margin of Laurentia. These include the 0.615 Ga Long Range dykes [#20a], the 0.590 Ga Grenville-Adirondack fanning swarm [#20b] and the 0.563 Ga Sept Îles layered intrusion [#20c]. The latter is roughly coeval with the Catoctin flood basalts [#20c, unit not displayed in Fig. 1] situated in the southern Appalachians of the United States. Other basaltic units and syenitic intrusions with ages 0.56 to 0.55 Ga are widely distributed (Puffer, 2002; Higgins and van Breemen, 1998).

The oldest event, the 0.615 Ga dykes [#20a] may have been linked to similar-aged magmatism in Baltica, which is represented by the aulacogen-type Egersund dykes (Bingen et al., 1998) and the coast-parallel Baltoscandian breakup swarm (event #55 in Ernst and Buchan, 2001). Two younger rifting events are also recorded in Laurentia: an early separation of Amazonia, and a later separation of the peri-Laurentian Dashwoods microcontinent (Waldron and van Staal, 2001; cf. Cawood et al., 2001). Within this context, the 0.590 Ga radiating swarm [#20b] (associated with the St. Lawrence rift system) may presage the separation of Amazonia from Laurentia at 0.57 Ga to form the Iapetus Ocean, and the magmatism at 0.563 Ga [#20c] may similarly be linked to the separation of the Dashwoods terrane at 0.550–0.540 Ga.

0.62–0.55 Ga (Avalon zone, Appalachians): The ca. 0.62 Ga Harbour Main [#21a] and the 0.585–0.555 Ga Marystown events [#21b] are recorded in the Avalon zone, which had an uncertain relationship with Laurentia during this period and subsequently drifted with Gondwana before closure of the Iapetus Ocean in the early Paleozoic.

0.57–0.52 Ga (Cordillera): The 0.57 Ga Hamill-Gog Group magmatism [#22a] in the southern Cordillera has been linked with a breakup along this Laurentian margin (Colpron et al., 2002).

In the northern Cordillera lower Paleozoic alkalic and potassic mafic magmatism [#22b] is linked with rifting of the Selwyn Basin (Goodfellow et al., 1995). This magmatism includes the Demster, Menzie Creek, Niddery volcanics, and younger Fossil Creek volcanics. The only precise age is a 0.518 Ga U-Pb age from a Post-Hyland Group sill, probably representing a widespread set of sills (Abbott, 1997). However, a range of volcanic ages from Lower Cambrian to Early Devonian is suggested on biostratrigraphic grounds (Goodfellow et al., 1995; Abbott, 1997).

0.47–0.41 Ga (Dunnage, Gander, Avalon and Meguma zones, Appalachians): In Atlantic Canada several important mafic (and bimodal) magmatic suites include the 0.46 Ga Dunn Point [#23a], and 0.44–0.43 Ga Bayswater and Cape St. Mary's suites of the Avalon zone [#23b], the Middle Ordovician Overstep Sequence of the Gander and Dunnage zones [#23a], the 0.44 Ga White Rock formation of the Meguma zone [#23b], and the early Silurian Overstep Sequence [#23b] of central Newfoundland (mainly in the Dunnage Zone). Much of this magmatism has been emplaced in a back-arc setting. During this period the Iapetus Ocean was closing, but the spatial relationship between these Iapetan terranes is still under debate.

0.36–0.32 Ga: The Carboniferous Magdalen (or Maritimes) Basin is thought to have been underplated by a layer of mafic magma with an average thickness of 13 km based on geophysical modelling [#24a] (Marillier and Verhoef, 1989). In addition, volcanic rocks and intrusions of this age are distributed widely around the western and southern perimeter of the basin. The Magdalen Basin magmatic event [#24a] has been inferred to represent the final breakthrough of a plume that had been trapped beneath a subducting slab (Murphy et al., 1999).

0.27–0.21 Ga (Cordillera): The mid-Permian to upper Jurassic (ca. 0.27–0.20 Ga) Cache Creek terrane of the Cordillera may include some oceanic plateau and hotspot material [#25a], but this remains controversial (cf. Tardy et al., 2001 and Struik et al., 2001).

Wrangellia is an important accreted terrane of the Cordilleran orogen [#25b], consisting of Karmutsen and Nikolai volcanics and associated 0.232 Ga Maple Creek sills. These units originated as an oceanic plateau possibly formed atop an island arc before being accreted onto the Cordilleran orogen (e.g. Richards et al., 1991).

Note that the Wrangell Lavas (0.065–0.002 Ga) (event #331 in Buchan and Ernst 2004), which extend from the Yukon into Alaska for a distance of ~430 km, are distinct from the much older Wrangellia flood basalts, despite the similar names. The extensive Wrangell lavas are not catalogued in Table 1 because they are linked to subduction along the Aleutian arc.

Ramparts Group magmatism [#25c] of Alaska is poorly dated (ca. 0.21 Ga). It is located in the Tozitna Belt of Alaska and is explained as a "parautochthonous rift assemblage" (p. 190, Dover, 1994).

0.20 Ga: The largest magmatic event on Earth in terms of areal distribution is the Central Atlantic Magmatic Province (CAMP) [#26a]. Found in North America, Europe, Africa and South America, it covers an area of nearly 7 million sq. km. It mainly consists of a giant radiating dyke swarm centred near Florida that was the precursor to the 0.175 Ga opening of the central Atlantic Ocean. Extensive sill provinces and volcanic packages are also found on all formerly adjacent blocks. In Atlantic Canada, this event is represented by several major dykes, as well as the North Mountain and Grand Manan volcanics [#26a].

A plume origin seems most likely based on the large scale and short duration of the event as well as presence of a giant radiating dyke swarm. However, a model involving "edge convection" has also been advocated mainly on the basis of 'non-plume' chemistry, and the suggestion that the dykes represent a superposition of distinct linear swarms rather than an overall single radiating swarm (e.g. several papers in Hames et al., 2003).

0.14–0.09 Ga: From 0.14 to 0.11 Ga there was extensive NEQ (New England-Quebec) magmatic activity [#27a] in the eastern United States and Quebec. The Monteregian Hills plutons and dykes of this magmatic event have been linked to a plume tail (the Great Meteor hotspot track) associated with the New England seamount chain (Heaman and Kjarsgaard, 2000). Problems with a plume origin for this magmatic province have been discussed by McHone (1996).

Another node of activity at this time is represented by the 400 km long Trap dyke swarm [#27b], which was emplaced along the southwestern coast of Greenland at 0.138 Ga. Given the proximity of Greenland to Labrador at this time, we would expect a continuation of this extensive magmatic event into eastern Canada. Globally, similar-aged magmatism is linked with two plume centres associated with the breakup of South America and Africa (Fig. 8 *in* Ernst and Buchan, 2002).

Magmatism on the Queen Elizabeth Islands [#27c] is part of the High Arctic Large Igneous Province (HALIP) [#27c]. This event is also present in northern Greenland, Svalbard and Franz Josef Land, as well as offshore (Tarduno et al., 1998; Maher, 2001). Precise dates of 0.095–0.092 Ga apply to both the Strand Fiord volcanics and the Wootton intrusion (Tarduno et al., 1998). However K-Ar and Rb-Sr dating as well as biostratigraphic control suggests that the magmatism may have begun at ca. 0.13 Ga. While a continuum of activity may be present, Maher (2001) interprets two pulses of activity, at ca. 0.13 and ca. 0.09 Ga. The identification of a radiating dyke swarm suggests a plume origin with a plume centre located near the Alpha Ridge (Embry and Osadetz, 1988; Ernst and Buchan, 1997; Maher, 2001).

0.07–0.05 Ga: The 0.070 Ga Carmacks volcanics [#28a] of the northern Cordillera have a slightly more potassic composition than most of the other events discussed in this paper, but they have a large areal extent (about 60,000 sq. km) and were apparently emplaced in a short duration. The slightly younger 0.06–0.05 Ga Crescent Terrane volcanics [#28b] consist of thick basaltic sequences distributed over a ca. 600 km distance along the Coast Ranges of western North America. They are inferred to represent accreted seamounts. Both the Carmacks volcanics [#28a] as well as the Crescent Terrane volcanics [#28b] have been interpreted as originating from earlier stages of the Yellowstone plume, prior to its main expression as the Columbia River LIP at 0.017 Ga (see next entry, [#29b]) (e.g. Johnston et al., 1996; Murphy et al., 2003).

The North Atlantic Igneous Province (NAIP) [#28c] is most voluminous in eastern Greenland and the UK, and adjacent offshore regions. Minor activity at Cape Dyer and Cape Searle on Baffin Island, as well as more substantial magmatism in west Greenland are linked with the NAIP. The NAIP LIP is linked to the present-day Icelandic hotspot.

0.025–0.015 Ga: An important intraplate event is the widespread Behm Canal event [#29a] of the Cordillera, which is also known as the Tertiary Lamprophyre Province. It consists of alkaline lamprophyres that are considered volatile-enriched equivalents of alkali basalts (Rock, 1991, p. 11-12, 122).

The voluminous Columbia River Basalt Group (CRBG) LIP [#29b] of the northwestern United States was mainly erupted from 0.017 to 0.015 Ga. It has been linked to the Yellowstone plume. The coeval Chilcotin Group volcanics [#29c] are located a short distance to the north in Canada, and although they are areally extensive they are volumetrically minor.

Archean

Archean greenstone belts represent deformed and fragmented volcanic suites, and are of two main affinities: calc-alkaline and tholeiitic (e.g. de Wit and Ashwal, 1997; Condie, 2001; Bleeker, 2002). The calc-alkaline suites are considered to be of arc origin whereas the tholeiitic suites, particularly those containing komatiites, are not. The presence of komatiites satisfies one requirement for the identification of LIPs, i.e. that they not be produced by subduction. In addition, greenstone belts with komatiites are probably not produced by normal spreading ridge processes because komatiites indicate source region temperatures higher than those associated with normal spreading ridges. There is some controversy on this point since the Archean geotherm was hotter. The scale of Archean LIP candidates is also uncertain. In most cases deformation and faulting prevents the recognition of Archean tholeiite-komatiite greenstone belts over LIP-scale distances. So the Archean LIP history, discussed below and summarized in Table 2 and Figure 1, remains speculative. Events are included in Table 2 on the basis of either the presence of komatiites, and/or inferred oceanic plateau setting.

3.11–2.98 Ga: The oldest known period of potential LIP activity is represented by komatiite-bearing greenstone belts (3.105 Ga Hunt River [#A1a] and 2.99–2.98 Ga Florence Lake [#A1b] belts) located in the Hopedale block of the Nain Province of the North Atlantic Craton. Another important magmatic event is associated with the ca. 2.99 Ga rifting [#A1c] of the ancient Archean nucleus in the western Superior Province comprising the North Caribou, Central Wabigoon and Marmion blocks (Tomlinson et al., 1999; Tomlinson and Condie, 2001).

2.93–2.92 Ga: A subsequent stage of komatiite-bearing greenstone belts [#A2a] at about 2.93–2.92 Ga is also widespread in the western Superior Province, but the setting and link with associated arc-type greenstone belts is unclear.

2.86 Ga: The Pickle Crow greenstone belt [#A3a] in the Uchi subprovince is approximately dated at 2.86 Ga and contains komatiites.

2.79–2.77 Ga: The 2.786 Ga Vizien greenstone belt [#A4a] of northern Quebec contains komatiites and has been linked with formation of an oceanic plateau. Greenstone belt fragments (containing komatiites) within the Faribault-Thury Complex [#A4b] are also situated in northern Quebec, and are bracketed in age between 2.785 and 2.710 Ga. (Note that if future dating determines an age closer to the younger end of the age bracket, then the Faribault-Thury Complex event would be grouped in the next entry.)

The 2.775 Ga Fourbay sequence [#A4c] of the western Superior Province lacks komatiites, but is included in this LIP compilation because of its inferred oceanic plateau origin.

2.75–2.70 Ga: In various portions of the Canadian Shield there was widespread mafic magmatism falling in the age range 2.75–2.70 Ga. This is discussed in terms of three regional groupings.

It has been suggested that the Prince Albert Group [#A5a] can be correlated with the Woodburn and Mary River groups, thus defining a single event in the Rae Province of northern Canada, which is distributed over a lateral distance of nearly 1000 km. The magmatism which includes komatiites is interpreted to have initiated at 2.73 Ga and may be associated with plume-generated continental breakup.

The Kam Group [#A5b] has been traced across large parts of the Slave Province through a complicated deformation pattern (Bleeker, 2003, and references therein). The magmatism of the Kam Group ranges from 2.734–2.700 Ga, and was particularly voluminous from 2.72–2.70 Ga.

Magmatism in the Abitibi greenstone belt [#A5c] of the central Superior Province is widespread and consists of four distinct stages of komatiite-associated magmatism emplaced during the interval 2.75–2.70 Ga (e.g. Sproule et al., 2002). The interspersed calc-alkaline magmatism suggests a plume arc association (e.g. Wyman, 1999). The Schreiber-Hemlo-White River-Dayohessarah packages found in the Wawa greenstone belt [#A5d], also contain significant komatiite-bearing tholeiitic magmatism with ages between 2.75 and 2.73 Ga. The Wawa belt is on strike with and is probably the continuation of the Abitibi belt.

DISCUSSION

As described above, Canada has a rich LIP history consisting of at least 80 possible events (Fig. 1, Tables 1 and 2). They range from Archean greenstone belts (containing komatiites) such as the Prince Albert Group and probable correlatives, which may extend for >1000 km along the Rae Province, through Proterozoic giant radiating dyke swarms, such as the Mackenzie swarm that covers nearly 3,000,000 sq. km of the Canadian Shield, to young flood basalts, such as the rift-related Keweenawan Group and the accreted oceanic plateau, Wrangellia, in the Cordillera. LIPs are key to resolving a number of important geological issues and processes. Here we apply our database of Canadian LIPs to several frontier issues.

Plume vs. Non-plume Origins

As mentioned earlier, there is currently an intense debate about plume versus non-plume origins for LIPs. This debate is occurring both on the web (e.g. www.mantleplumes.org; www.largeigneousprovinces.org) and in the scientific literature (e.g. Anderson, 2001; Foulger and Natland, 2003; DePaolo and Manga, 2003; Ernst et al., 2004). The Canadian LIP database can contribute to this debate in various ways. Giant radiating dyke swarms are strongly indicative of mantle plumes (e.g. Ernst and Buchan, 1997). Using this criteria, plumes would be inferred at 2.45, 1.27, 0.78, 0.72, 0.20 Ga. Furthermore, many Canadian swarms have a failed-arm (aulacogen setting) (Fig. 3b, Table 3), which also suggests plume involvement. In addition, Archean greenstone belts, which contain komatiites, are arguably plume-related. Finally, recognition of additional mantle plumes may also derive from studies of regional uplift patterns (see below). On the other hand, some LIPs having a linear distribution, such as those in a back-arc setting, may be consistent with non-plume origins. Those along a breakup margin may be generated by decompression melting accompanying rifting. Some LIPs may consist of two pulses, an initial burst of magmatism associated with plume arrival and a second caused by the onset of decompression melting associated with breakup.

Precise Time Markers for Stratigraphic Correlation

The wide distribution (potentially over millions of sq. km) and the typically short duration of events makes them ideal as precise stratigraphic markers (e.g. LeCheminant and Heaman, 1989; Harlan et al., 2003b). For instance, recognition of the same magmatic event within widely separated sedimentary sequences represents an ideal marker for inter-basin correlation. In Canada, the 1.27 Ga Mackenzie, 0.78 Ga Gunbarrel, and 0.72 Ga Franklin LIPs represent particularly good markers.

Reconstruction of Continents

Globally there is a clear link between young LIPs and breakup margins (e.g. Courtillot et al., 1999). The Canadian landmass preserves a history of continental breakup, and subsequent reassembly marked by sutures. Therefore, the Canadian LIP record is fertile ground for exploring links with breakup events. Archean continental fragments each contain a particular age distribution of mafic events (mostly Proterozoic dyke swarms) that represent a distinct "bar code" (Bleeker, 2003, 2004). Comparison of the "bar code" from the approximately 35 different Archean continental fragments (at least eight of which are in Canada) represents a key tool for proposing reconstructions between these fragments. Reconstructions can be tested by comparing the paleomagnetism of coeval mafic units on the different continental fragments (Buchan et al., 2000). In addition, linear (Fig. 4a) and radiating (Fig. 4b) dyke swarms can be used to constrain the reconstruction geometry. Some suggested correlations are given in

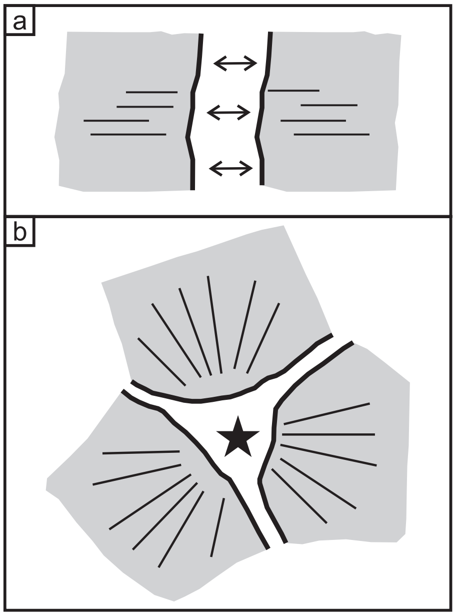

Figure 4 Use of giant dyke swarms for continental reconstruction **a.** Giant linear dyke swarms used as piercing points. **b.** Giant radiating swarms.

Tables 1 and 2, and in the accompanying text.

Exploration (Ni-Cu-PGEs and Diamonds)

Ni-Cu-PGE deposits are commonly associated with LIPs. Notable examples include the Siberian Traps and the Bushveld Complex (e.g. Naldrett, 1999; Pirajno, 2000; Diakov et al., 2002; Hulbert, 2002). Ernst and Hulbert (2003) carried out a preliminary analysis of background PGE levels in about 60 Canadian LIPs and other intraplate mafic events in order to assess which are more likely to host such deposits. Events with elevated background PGE levels (≥10 ppb Pt and Pd) are thought to have greater potential for enrichment during magmatic emplacement. Ernst and Hulbert (2003) found that events with high background levels include the 2.50–2.45 Ga Matachewan, 2.22–2.21 Ga Ungava-Nipissing, 1.27 Ga Mackenzie, 0.72 Ga Franklin, 0.59 Ga Grenville and portions of the 1.11–1.09 Ga Keweenawan and 0.13–0.09 Ga Sverdrup Basin events.

Some studies have proposed a direct link between kimberlites and underlying plumes (Haggerty, 1999; Heaman and Kjarsgaard, 2000; Schissel and Smail, 2001). Recently it has also been suggested that some kimberlites might be preferentially localized along particular dyke swarms such as the 2.023 Ga Lac de Gras swarm of the Slave Province (Wilkinson et al., 2001; Stubley, 2003) and the 2.50–2.45 Ga Matachewan dykes of the Attawapiskat region in the James Bay lowlands (Stott and Halls, 2002). Further work is required to test the potential of fractures and zones of weakness represented by major dyke swarms to localize kimberlite magmas during their ascent through the crust.

Climate Change

Numerous studies have explored the link between LIPs and climate change (e.g. Condie, 2001; Isley and Abbott, 2002; Courtillot and Renne, 2003; Ernst and Buchan, 2003, Prokoph et al., 2003). The correlation between extinction events and LIPs is compelling (Courtillot et al., 1996; Courtillot and Renne, 2003) and suggests that some LIPs, perhaps acting in concert with meteorite impact events, may be the trigger for extinction events. Evaluation of a robust Canadian LIP record can contribute to the global understanding of the effect of LIPs on climate. For instance, all other factors being equal, the largest LIP events should have the largest climatic effect. Some of the largest LIPs in Canada are the ca. 1.88 Ga Circum-Superior, 1.27 Ga Mackenzie, 0.72 Ga Franklin, 0.615–0.555 Ga Central Iapetus, and 0.20 Ga CAMP events. Only the climatic effect of the youngest of these events has been evaluated (Pálfy 2003).

Regional Domal Uplift

LIPs linked to mantle plumes should be associated with regional domal uplift. The scale of uplift corresponds to the size of the plume head (e.g. Cox, 1989; Rainbird and Ernst, 2001; Campbell, 2001; Şengör, 2001; He et al., 2003). The largest plumes are thought to generate uplifts with a radius 1000 km and a peak elevation 1 to 2 km. Such uplifts should exert a first-order control on concurrent regional sedimentation patterns. Plume head related uplift has only received preliminary investigation in Canada, where it has been associated with 1.27 Ga Mackenzie, 0.72 Ga Franklin, and 0.615–0.555 Ga Central Iapetus events (e.g. Rainbird and Ernst, 2001). It is hoped that the LIP database for Canada will stimulate further investigation of regional uplift patterns.

EXPANDING THE LIP DATABASE TO ADDRESS FRONTIER ISSUES

The frontier issues discussed above can only be fully addressed using a more robust LIP record. Although an extensive database is presented in this paper, many major mafic and ultramafic units remain undated and poorly characterized. Rapid improvement in the LIP database can be achieved only through a concerted campaign of geochronology integrated with other fields such as paleomagnetism and geochemistry, as is being proposed for Canada by Bleeker (2004) and internationally by Ernst et al. (2004).

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