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Komatiitic Sills and Multigenerational Peperite at Dundonald Beach, Abitibi Greenstone Belt, Ontario: Volcanic Architecture and Nickel Sulfide Distribution

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Abstract

The density and the tectonic stresses in the deep crust and the physical properties of komatiitic magmas determine the level to which they will rise, but once in the near-surface environment, the density and rheology of the near-surface rocks (consolidated and dense lava flows and sedimentary rocks versus unconsolidated sedimentary or volcaniclastic deposits) govern whether they will be emplaced as lava flows, invasive flows, or sills. Where near-surface strata are competent (i.e., flow-dominated or consolidated sedimentary and/or volcaniclastic successions), komatiitic magma erupts as flows that form extensive lava shields (e.g., Kambalda). However, where near-surface strata are not competent (i.e., unconsolidated volcaniclastic- and/or sediment-dominated successions), komatiitic magmas typically are emplaced as high-level sills that increase the bulk density of the volcano-sedimentary pile and eventually allow the eruption of lava and the construction of complex subvolcanic-volcanic lava shields (e.g., Dundonald and Shaw dome, Abitibi belt; Raglan, Cape Smith belt; Pechenga, Kola Peninsula; Thompson Ni belt, Manitoba). The latter environment is illustrated in the volcano-sedimentary succession in Dundonald Township, which is only weakly metamorphosed and deformed and superbly exposed in glacially polished outcrops.

The volcano-sedimentary succession in this area comprises (from base to top) (1) the McIntosh formation, composed of a succession of pillowed and massive intermediate volcanic flows; (2) the Dundonald formation, composed of a lower section of komatiite sills, argillites, and felsic volcaniclastic deposits and an upper section of komatiite flows, komatiitic sills, and pillowed intermediate volcanic flows; and (3) the Frederick House Lake formation, composed of massive and pillowed mafic flows. The distribution and thickness of argillites and felsic volcaniclastic rocks define a synvolcanic graben in which the Dundonald South and Alexo Ni-Cu-(PGE) deposits occur within the center and the margin, respectively. Sills and peperites in the lower komatiitic succession at Dundonald Beach exhibit a multigenerational emplacement history recording progressive lithification and increases in the bulk density and rheological strength of the unconsolidated argillites, which ultimately permitted the eruption of lavas at Alexo.

Importantly, the nature of the near-surface rocks also influences the localization of Ni-Cu-(PGE) deposits. In lava shields (e.g., Kambalda), the initial eruptions are typically most voluminous and, if erupted at sufficient flow rates, form channelized flows conducive to thermomechanical erosion of sulfur-rich footwall rocks. In subvolcanic-volcanic lava shields, however, channelized units may occur within the subvolcanic plumbing system and/or within overlying lavas. Where only sills are channelized (e.g., Thompson), mineralization will occur only

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within the subvolcanic environment; where only the flows are channelized (e.g., Damba-Silwane, Zimbabwe), mineralization will occur only within the volcanic environment. Where both sills and lava flows are channelized (e.g., Dundonald, Shaw dome, Raglan), the distribution of the mineralization is more diverse and may occur as subsea- or sea-floor Ni-Cu-(PGE) deposits.

Introduction

THE VOLCANIC setting (volcanic, invasive, or intrusive) of komatiite-associated Ni-Cu-(PGE) deposits remains controversial despite intensive research over the past 30 years. After Bowen (1927) cast doubt on an extrusive mode of emplacement for ultramafic rocks, most geologists considered them to be intrusive, until Viljoen and Viljoen (1969) described ultramafic lava flows along the Komati River in the Barberton Mountain Land. This discovery led to the recognition of komatiitic lava flows in most other Archean cratons. Although some were shown to be intrusive (e.g., Muir, 1979; Williams, 1979; Duke, 1986; Stone and Stone, 2000), virtually all massive and spinifex-textured ultramafic units within Archean greenstone belts were interpreted as lava flows, including the komatiite succession associated with the Dundonald South Fe-Ni-Cu sulfide deposit in Dundonald Township (Muir and Comba, 1979).

Although many concordant ultramafic units containing spinifex textures are extrusive (e.g., Pyke et al., 1973; Nisbet et al., 1977; Thomson, 1989; Dann, 2000), field work in several areas has shown that spinifex texture is not restricted to flows but also develops in komatiitic dikes (e.g., Davis, 1997; Dann, 2000) and in high-level komatiitic sills (e.g., Davis, 1999; Dann, 2000; Cas and Beresford, 2001; Houlé et al., 2002a-c; Arndt et al., 2004; Trofimovs et al., 2004). Spinifex is clearly not a "quench" texture, as it forms deep (decimeter to meter) within flows. Indeed, theoretical studies (Shore and Fowler, 1999) and experimental work (Faure et al., 2006) have demonstrated that spinifex forms in a thermal gradient, as occurs in both flows and high-level intrusions. Thus, the presence of spinifex texture cannot be used as the primary evidence for an extrusive origin for komatiitic rocks (e.g., Donaldson, 1974; Arndt et al., 2004; Houlé et al., 2004).

Komatiite-associated Ni-Cu-(PGE) deposits, which were originally thought to occur within intrusions, were subsequently reinterpreted as occurring in flows. For example, the ultramafic hosts of type I or Kambalda-type deposits (classification scheme of Lesher and Keays, 2002) in the Kambalda district of the Norseman-Wiluna greenstone belt were initially interpreted as intrusive (Woodall and Travis, 1969) but were subsequently reinterpreted as occurring within distal lava channels (Lesher et al., 1984; Cowden and Roberts, 1990). Type II or Mount Keith-type komatiite-associated deposits in the Perseverance-Mount Keith district of the Norseman-Wiluna greenstone belt were initially interpreted as occurring in subvolcanic intrusions (Naldrett and Turner, 1977) but were subsequently reinterpreted as occurring within proximal lava channels (e.g., Donaldson et al., 1986; Barnes et al., 1988; Hill et al., 1990) and, more recently, reinterpreted as occurring within a large sill (Trofimovs et al., 2003; Rosengren et al., 2005).

The intrusive or extrusive origin for komatiites hosting Ni-Cu-(PGE) mineralization, in part, reflects the different geodynamic environments into which komatiitic magmas have been emplaced. The purpose of this paper is to present a conceptual model of the emplacement of komatiitic magma within a volcaniclastic- and/or sediment-dominated environment and its role for the development of the komatiite volcanic architecture in Dundonald Township, Abitibi greenstone belt, Ontario.

In particular, we describe a spectacular and well exposed volcanic succession in Dundonald Township, including komatiitic sills and associated peperites, and use this description as a basis for defining the transition from intrusive and to extrusive komatiites. We interpret the mechanisms of komatiitic sill emplacement and the development of multigenerational peperite, and explore the role of komatiitic sills in changing the density and rheological characteristics of the sedimentary rocks and how this may affect the subsurface and surface architecture of komatiitic edifices and the location of komatiite-associated Ni-Cu-(PGE) deposits. Finally, we propose a new hypothesis for the evolution and architecture of komatiitic edifices where magma is emplaced into unconsolidated sedimentary and volcaniclastic strata in the near-surface environment.

Geologic Setting

The Dundonald Beach area occurs within the Kidd-Munro assemblage in Dundonald Township, which is located ~45 km northeast of Timmins in Ontario (Fig. 1, inset). The Kidd-Munro assemblage has been subdivided in Ontario into a lower stratigraphic succession (2719–2717 Ma) and an upper stratigraphic succession (2717–2711 Ma: Ayer et al., 2005; Thurston et al., 2008). Volcanic rocks of these ages extend for more than 400 km from west of the Kidd Creek deposit in Ontario to the Grenville Front in Québec, where the Kidd-Munro assemblage is referred to as the Kinojévis and Malartic Groups (Thurston et al., 2008).

In Dundonald Township, the volcano-sedimentary succession consists of folded units dominated by intermediate to mafic and ultramafic metavolcanic rocks with lesser felsic metavolcanic and metasedimentary rocks approximately 3,000 m in total thickness. The main structure in the area consists of a major subvertical, southwest-trending and -plunging fold axis offset by west-northwest– and north-northwest–trending faults (Fig. 1).

The Kidd-Munro assemblage in this area is tentatively subdivided into several informal mappable formations, members, submembers, and units summarized in Figure 2. Three informal formations are, from oldest to youngest, the McIntosh Lake, Dundonald, and Frederick House Lake formations.

The McIntosh Lake formation ranges in thickness from 50 to 400 m and is composed of mafic to intermediate massive and pillowed flows, intermediate to mafic volcaniclastic rocks, and komatiitic volcanic rocks (Davis, 1997). The 200- to 2,000-m-thick komatiitic succession occurs in the upper part of the formation (Fig. 2), and it is composed of individual flows that range in thickness from less than 1 to greater than 10 m, with compositions from komatiitic basalt to komatiite and with well-developed spinifex textures (Davis, 1997). The

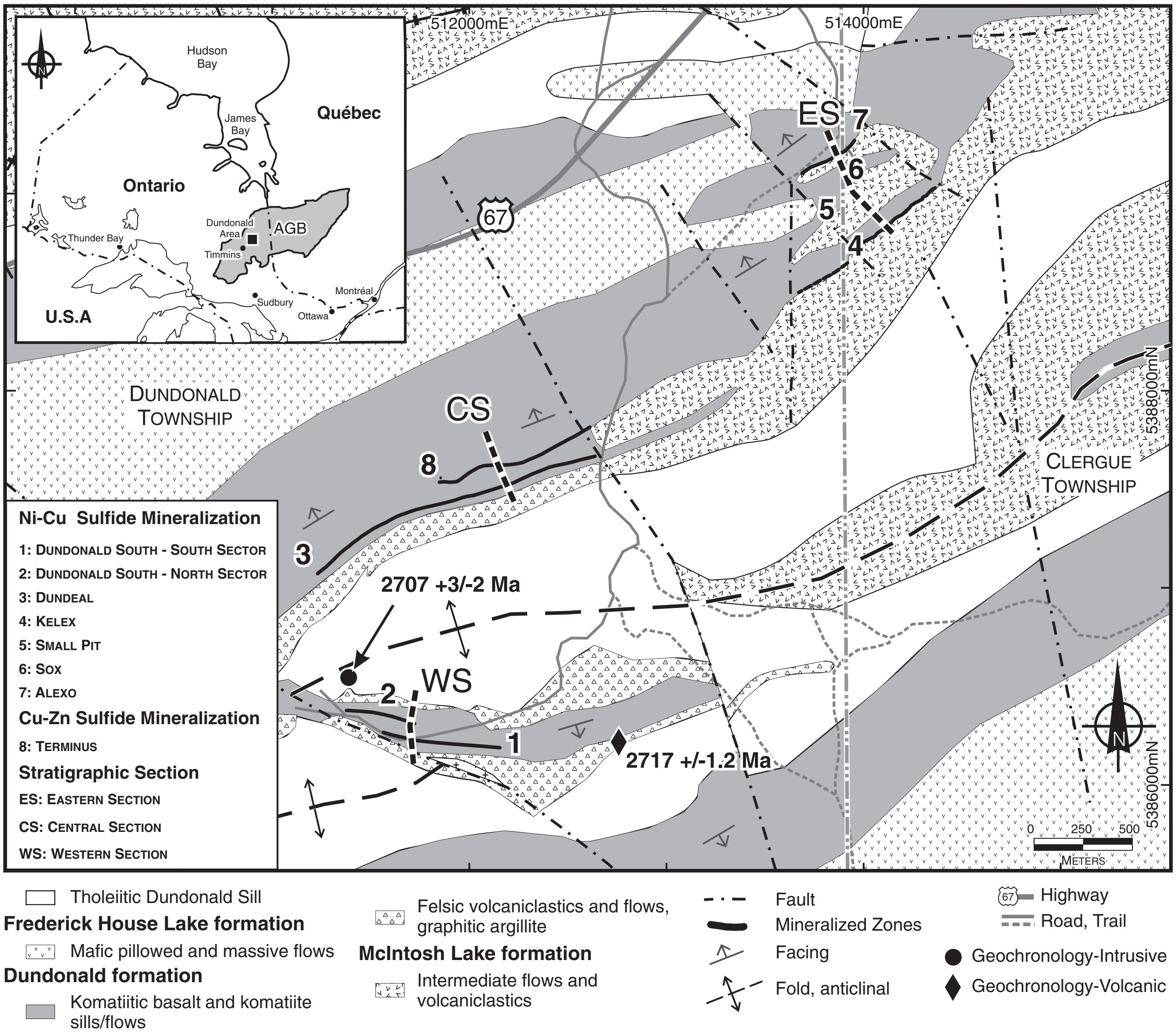

FIG. 1. Simplified geologic map of the Dundonald Township area, showing major geologic units and locations of komatiite-associated Ni-Cu-(PGE) deposits (modified from MPH Consulting Ltd., 2004). U-Pb ages are from Barrie et al. (1999). Sections WS, CS, and ES show the locations of stratigraphic columns in Figure 3.

komatiite unit is poorly exposed and the description and interpretations are based entirely on drill core data. It is not known to contain any komatiite-associated Ni-Cu-(PGE) mineralization.

The Dundonald formation consists of five informal mappable members, a lowermost felsic member, and four komatiitic members (Fig. 2). The felsic member is ~300 m thick and consists of felsic volcanic flows, volcaniclastic units, and minor komatiitic and mafic dikes. Zircons in a sample collected from the felsic member yielded an age of 2717 ± 1.2 Ma (Barrie et al., 1999). Graphitic, argillaceous metasedimentary rocks also occur within this member. The komatiitic members range in thickness from 1,000 to 2,000 m and are composed of komatiite and komatiitic basalt flows or sills, intercalated with lesser massive mafic flows and sparse felsic volcaniclastic rocks.

The Frederic House Lake formation is poorly constrained but is interpreted from drill core by Davis (1997) as a ~250-m sequence of massive and pillowed mafic flows. No komatiitic rocks have been reported in this formation.

The supracrustal rocks in Dundonald Township are intruded by the ~1,750-m-thick, layered, tholeiitic mafic-ultramafic, near-concordant, Dundonald sill. Zircons from a sample collected from the mafic part of the sill yielded an age of 2707.1^{+3}_{-2} Ma (Barrie et al., 1999).

The volcanic succession has been metamorphosed to lower greenschist facies and is locally faulted and/or sheared, but most of the deformation is nonpenetrative, and primary structures

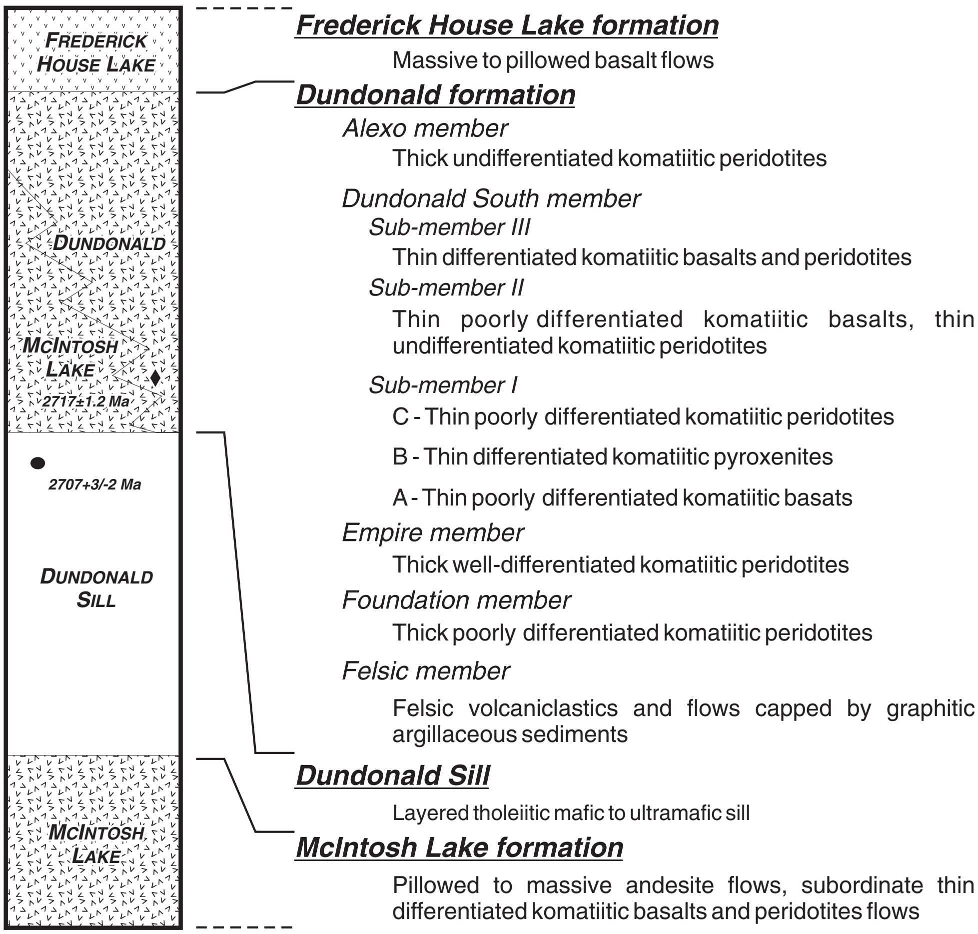

FIG. 2. Dundonald Township tentative schematic stratigraphic columns, showing the generalized components of each informal stratigraphic unit. U-Pb ages are from Barrie et al. (1999).

and textures are well preserved. We therefore describe the rocks using premetamorphic igneous and volcanic nomenclature.

Dundonald formation

The komatiitic units in the Dundonald formation have been subdivided based on this study and previous work conducted by Falconbridge Ltd., from lowermost to uppermost, as the Foundation, Empire, Dundonald South, and Alexo members. All members contain Ni-Cu-(PGE) occurrences and deposits (e.g., Kelex in the Foundation member, Dundeal in the Empire member, Dundonald South in the Dundonald South member, and Alexo in the Alexo member; Figs. 1–3).

The Foundation member (Fig. 3) consists of a 45-m-thick, poorly differentiated komatiitic peridotite sill or flow in the eastern section and a 100-m-thick, massive, discontinuous komatiitic peridotite sill or flow in the central section (Davis, 1997; Montgomery, unpub. report for First Nickel Inc., 2004, 50 p.). It has not been identified in the western section.

The Empire member (Fig. 3) comprises a 100-m-thick, massive komatiitic peridotite sill or flow in the eastern section and a 180-m-thick, well-differentiated komatiitic basalt sill or flow in the central section (Vicker, 1991; Davis, 1997; Barrie et al., 1999). It has not been identified in the western section.

The Dundonald South member extends over the entire strike length of the Dundonald formation. Its thickness ranges from 100 m in the eastern section (Barnes et al., 1983; Arndt, 1986) to 80 m in the central section (Davis, 1997; Barrie et al., 1999), and 175 m in the western section (Fig. 3; Muir and Comba, 1979; Schofield, 1982; Davis, 1999; this study). The Dundonald South member is further subdivided into three submembers (Fig. 2). Submember I consists of komatiitic basalts, submember II consists of komatiitic basalts with well-developed spinifex textures, and submember III consists of komatiites with locally well-developed spinifex texture (Davis, 1999). The vertical compositional trend from komatiitic basalt upward to komatiite is the reverse of that normally found within komatiitic sequences (Figs. 3, 4; Gresham and Loftus-Hills, 1981; Lesher et al., 1984; Lesher and Arndt, 1995; Lesher, 2007). This member is composed of complexly intercalated komatiitic basalt and komatiite sills, argillite, and peperite in the western section and thin komatiitic basalt and komatiite sills intercalated with graphitic and locally sulfidic argillite with minor peperite in the central section (Fig. 3). In the eastern section, it exhibits a transition between intrusive and extrusive komatiites: the lower part of the member consists of thin differentiated komatiite and komatiitic basalt sills with minor peperite, whereas the upper part of the member is composed of thin, well-differentiated komatiitic flows with

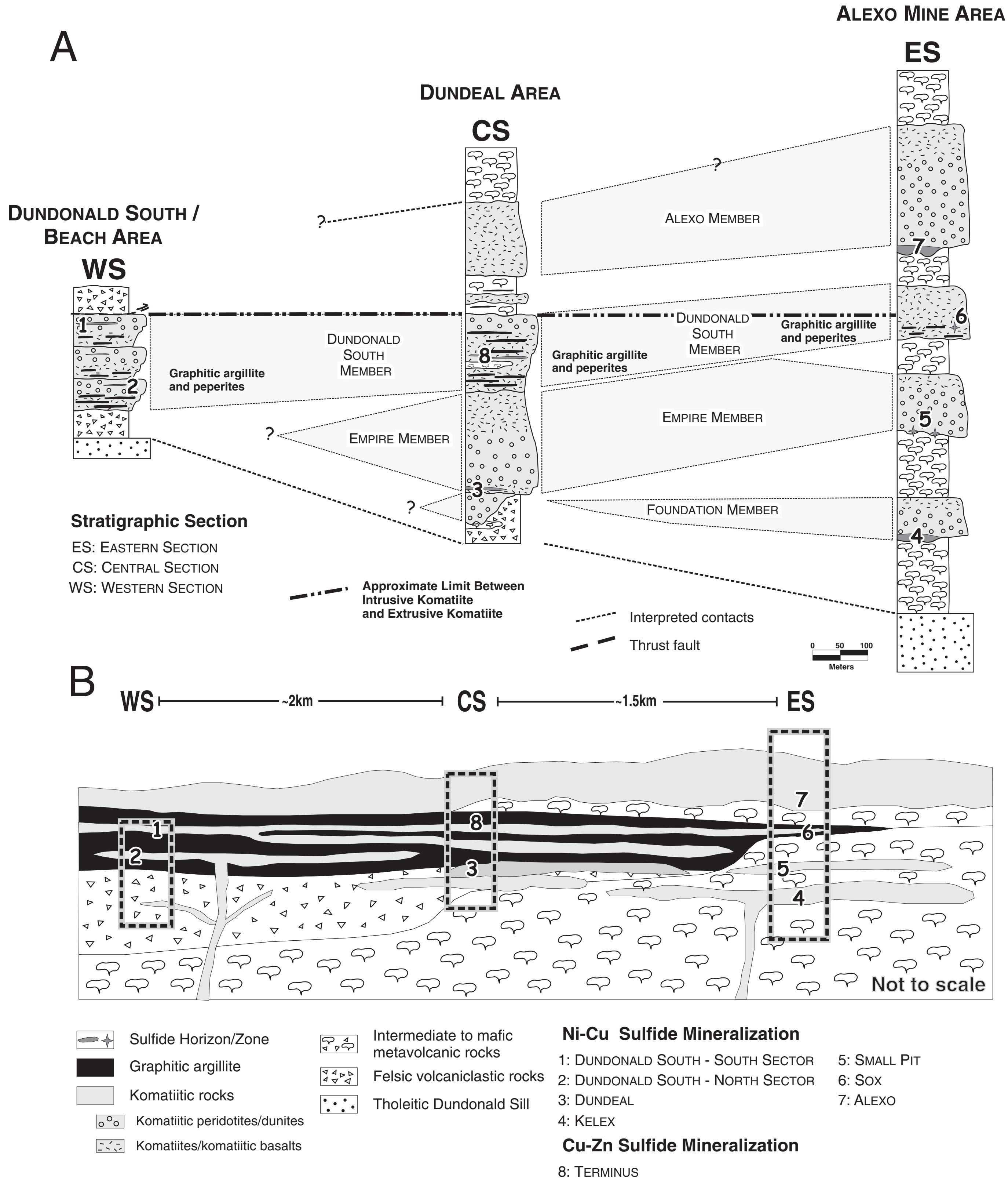

FIG. 3. Schematic stratigraphic columns (A) and paleotopographic reconstruction (B) of the komatiite succession of the Dundonald formation, showing the subvolcanic and/or volcanic architecture and locations of komatiite-associated Ni-Cu-(PGE) deposits in the western section (WS; this study), central section (CS; modified from Davis, 1997; Barrie et al., 1999), and eastern section (ES; P.C. Davis and Canadian Arrow Mines, unpub. data, 1999–2005; M.G. Houlé, unpub. data). Section locations in Figure 1.

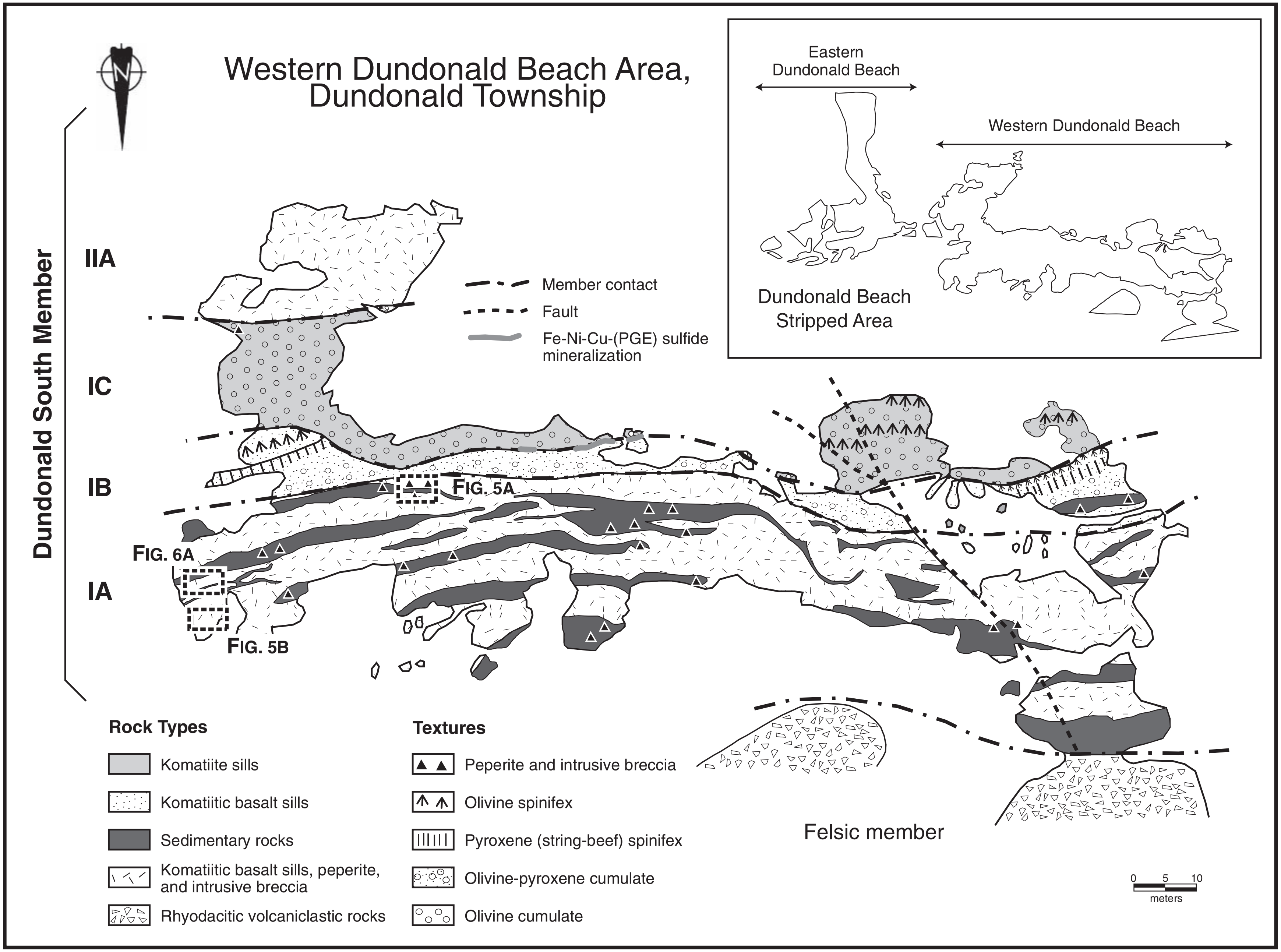

Fig 4. Simplified geologic map of the lower part of the Dundonald South formation at Dundonald Beach (modified from Davis, 1999, and Arndt et al., 2004). The map is drawn with north downward so that the volcanic stratigraphy youngs upward and corresponds to that of the geologic sections. The outcrops in this area expose units IA, IB, and IC and unit IIA of the Dundonald South formation.

hyaloclastite flow-top breccias. The extrusive nature of the komatiitic rocks in the upper part of this member is well documented from the detailed work of Barnes et al. (1983) and Arndt (1986), who focused on an excellent exposure in the upper part of the Dundonald South member underlying the Alexo deposit. In contrast, an intrusive nature of some of the komatiitic rocks in the lower part of this member is indicated by the presence of peperite at the upper margins of thin komatiitic basalts observed in drill core.

The Dundonald Beach outcrop provides an excellent exposure of a well-preserved section through the Dundonald South member (submember I) that was mechanically and hydraulically stripped of glacial overburden by Falconbridge Ltd. in 1989 and by Hucamp Mines in 2001, exposing ~9,000 m^2 of glacially polished outcrops. The felsic member, submember I, and the lowermost part of submember II of the Dundonald South member are exposed on this outcrop. Submember I is ~70 m thick and is subdivided into three units (Muir and Comba, 1979; Davis, 1999; Fig. 4), from stratigraphic base to stratigraphic top.

1. Unit IA comprises multiple, thin, undifferentiated to poorly differentiated, noncumulate sills of komatiitic basalt and porphyritic komatiitic basaltic sills intercalated with graphitic argillaceous metasedimentary rocks containing fluidal and blocky peperite.
2. Unit IB is a differentiated, noncumulate komatiitic basaltic sill with a lower olivine-clinopyroxene cumulate zone, a thick parallel acicular ("string-beef") pyroxene spinifex-textured zone, a thin random platy olivine spinifex-textured zone, and a thin fine-grained upper chilled margin.
3. Unit IC consists of multiple, differentiated komatiite sills (Arndt et al., 2004) with thick, lower olivine mesocumulate zones and thin, upper olivine spinifex-textured zones. Ni-rich sulfide mineralization occurs at the bases of several of these units.

The underlying felsic member consists of poorly bedded rhyodacitic volcaniclastic rocks (lapilli tuff to tuff breccia) and is cut by dacitic, mafic, and komatiitic dikes (Davis, 1997, 1999).

The Alexo member (Fig. 3) consists of a 225-m-thick sequence of massive komatiitic peridotite with local spinifex textures in the eastern section and a 100-m-thick sequence of thin differentiated komatiitic basaltic flows with well-developed parallel acicular pyroxene spinifex textures in the central section (Naldrett, 1966; Davis, 1999; M. Houlé, unpub. data). The Alexo member has not been identified in the western section.

A reconstruction of the Dundonald formation, based on detailed mapping and core logging, indicates that it represents a progression from a dominantly subvolcanic intrusive lower part to a dominantly extrusive volcanic upper part (Fig. 3). Eruption and emplacement of komatiites was preceded by subsidence, as indicated by the accumulation of felsic volcaniclastic and argillaceous sedimentary rocks, which contain clasts of the komatiitic basalts and underlying volcaniclastic rocks, within a downfaulted basin or a topographic low (Davis, 1999: western section and central section; Fig. 3). The Dundonald formation displays not only a vertical lithofacies variation from sills to flows (dashed line in Fig. 3) but also a lateral variation, wherein portions underlain by volcaniclastic and sedimentary lithofacies are dominated by komatiitic sill lithofacies (western section and central section; Fig. 3), and portions underlain by coherent andesitic flow lithofacies grade from a komatiitic sill to a flow-dominated lithofacies (eastern section; Fig. 3). The Dundonald Beach area (western section; Fig. 3), which contains a thicker argillite unit, is interpreted to occur in the central part of the basin. The Dundeal area (central section; Fig. 3), which contains thinner argillite units, is interpreted to occur closer to the basin margin, and the Alexo area, which contains lesser, thin units of argillite and no felsic volcanic lithofacies, is interpreted to occur at the basin margin (eastern section; Fig. 3).

Discrimination between Komatiitic Sills and Flows

Interpretation of the emplacement of komatiitic rocks in Dundonald Township has changed over the years. They were initially interpreted by Naldrett and Mason (1968) as ultramafic intrusions, although they recognized that the skeletal "chicken track" textures that we now refer to as random olivine spinifex indicated a near-surface setting. Following the work of Viljoen and Viljoen (1969) in the Barberton Mountain Land and Pyke et al. (1973) in Munro Township, ~65 km to the east, all of the komatiitic rocks in the area were subsequently reinterpreted as flows (Muir and Comba, 1979; Schofield, 1982; Barnes, 1983). Davis (1997, 1999) identified and described mixed volcanic-graphitic sediment peperites, which were subsequently described by Cas and Beresford (2001) and Houlé et al. (2002a-c).

Distinguishing between an extrusive versus intrusive origin for a komatiitic unit requires detailed examination of the contact relationships of the komatiite with its enclosing rocks. Some textures and structures that are typically associated with lava flows, such as spinifex textures, amgydules, peperites along lower margins, and transgressive lower contacts, can occur in both extrusive and intrusive komatiites. Other textures and structures such as flow-top breccias, hyaloclastites, and polyhedral jointing provide more reliable evidence for an extrusive mode of emplacement (Arndt et al., 2004). Development of peperite along upper margins and transgressive relationships with overlying units provide unequivocal evidence for an intrusive mode of emplacement (see discussions by Dann, 2000, and Arndt et al., 2004).

Intrusive contacts and transgressive relationships

The komatiitic rocks within units IA and IC in the western part of the outcrop area at Dundonald Beach (Fig. 4) have intrusive and transgressive contacts, suggesting an intrusive origin. For the komatiitic units IB the situation is less clear because of poor exposure and also because its upper contact is interpreted to have been eroded by the overlying unit (IC).

The 0.2- to 4-m-thick komatiitic basaltic sills in unit IA have thin (1–2 cm) symmetric, upper and lower chilled margins that clearly cut other komatiitic basalt sills and invade the graphitic argillaceous sediments, forming fluidal and blocky peperite (Davis 1997, 1999; Cas and Beresford, 2001; Houlé et al., 2002a-c). However, some of the komatiitic basalt sills also transgress previous generations of peperite (Fig. 5A).

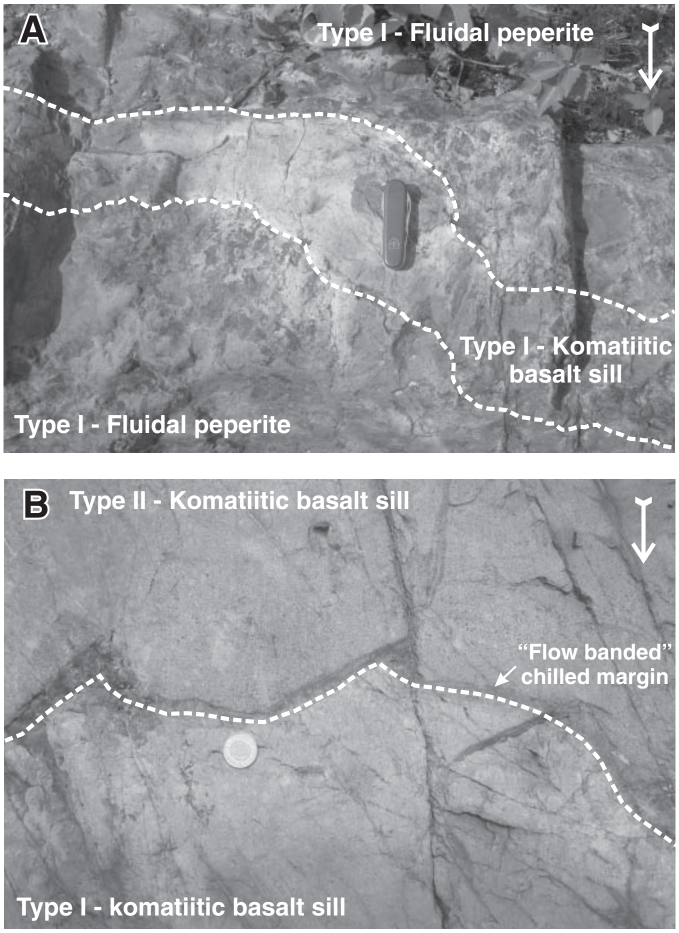

Fig. 5. A. Type I komatiitic basalt sill transgressing komatiitic basalt-graphitic argillite peperite. B. Type II komatiitic basalt sill transgressing an earlier komatiitic basalt sill. The locations of A and B are shown in Figure 4. Arrows indicate the facing directions.

The komatiitic basalt sills at Dundonald Beach can be subdivided into two types. Type I sills are thin (<50 cm) and composed of fine-grained komatiitic basalt with variolitic interiors and sparsely variolitic margins. Their contacts are wavy and irregular with very thin (<1–2 cm) upper and lower chilled margins that are flow banded parallel to contacts. Variolitic textures have been variously interpreted to reflect magma mingling, undercooling (i.e., spherulitic growths), devitrification, contamination, and alteration (see Fowler et al., 2002). The varioles in these sills appear to be related to localized alteration but may have resulted from original compositional and/or textural heterogeneities produced by contamination and/or undercooling. Type I sills appear to have interacted extensively with wall rocks and to have been injected at a stage before induration of the unconsolidated sedimentary strata (Fig. 5A). Type II sills are relatively thick (~4 m), composed of fine- to medium-grained komatiitic basalt, and have straight contacts with thin (~2–3 cm), fine-grained lower and upper chilled margins (Fig. 5B). They do not appear to have interacted extensively with their argillaceous wall rocks and are interpreted to have intruded later in the evolution of the sediment-sill succession.

Unit IC exhibits significant structural and textural variations over a strike length of ~150 m. In the southwestern part of the outcrop (Fig. 4), it comprises at least two cooling units. Only the lowermost is completely exposed, and it exhibits a ~1.5-m-thick upper olivine spinifex-textured zone and a ~4.5-m-thick lower olivine ortho-mesocumulate zone. To the east (Fig. 4), the same two sills have only very thin (0.5 m) upper olivine spinifex-textured zones. In the southeastern part (Fig. 4), unit 1C is a single ~20-m-thick sill composed almost entirely of olivine mesocumulate that clearly transgresses underlying komatiitic basalts (Fig. 4) and hosts small amounts of very high tenor Ni-Cu-PGE mineralization along its basal contact (Davis, 1999). Arndt et al. (2004) interpreted unit 1C as a sill based on the absence of a flow-top breccia (polyhedral fracturing) along its upper contact, grain sizes at the margin that are greater than those in typical komatiite flows, and the occurrence of vesicles within 1 cm of the upper contact of the unit.

Peperite

Peperite is a rock formed essentially in situ by disintegration of magma intruding and mingling with unconsolidated or poorly consolidated, typically wet sediments (White et al., 2000; Skilling et al., 2002). Peperite occurs at the contacts of most komatiitic units within the lower part of the Dundonald South member but is best exposed within unit IA at Dundonald Beach where it occurs along the upper and lower contacts of komatiitic sills with graphitic sedimentary rocks (Fig. 4). The formation of peperite during the emplacement of komatiitic magma into graphitic argillaceous sediments, not only along the lower but also along the upper contact, provides unequivocal evidence that the sedimentary strata were unconsolidated and wet at the time of intrusion and suggests that the intrusions are synvolcanic sills. Fluidal and blocky peperite, which differ in juvenile clast morphology, and intrusive breccia have developed in decimeter- to meter-thick zones adjacent to the intrusions.

Fluidal peperite is characterized by amoeboid fragments and irregular fingerlike projections of variolitic, highly vesicular, and inclusion-rich komatiitic basalt within a matrix of desiccated graphitic argillite and occurs as lobes within the argillite (Figs. 6A, C, 7). Blocky peperite is characterized by blocky fragments of variolitic, highly vesicular, but inclusion-free komatiitic basalt within a matrix of desiccated graphitic argillite, and occurs as sheets within argillite. Intrusive breccia occurs locally along the upper, and less commonly, lower contact of sills with argillites. This variety is characterized by angular, random, and jigsaw-fit clasts of desiccated graphitic argillite, in a white, silicified komatiitic basaltic matrix (Fig. 6A, B).

Fluidal and blocky peperite generally occur in close proximity and in many cases represent the products of two separate intrusive events. This relationship is well illustrated in Figure 7, which shows the distribution of blocky and fluidal peperite between two komatiite sills intersected in a drill core through unit 1C. The variolitic upper chilled margin of the lower sill is bordered by a zone of fluidal peperite containing dispersed, amoeboid fragments of komatiite with abundant fine-grained (1–3 mm) inclusions of graphitic argillite in a matrix of graphitic argillite. The chilled lower margin of the

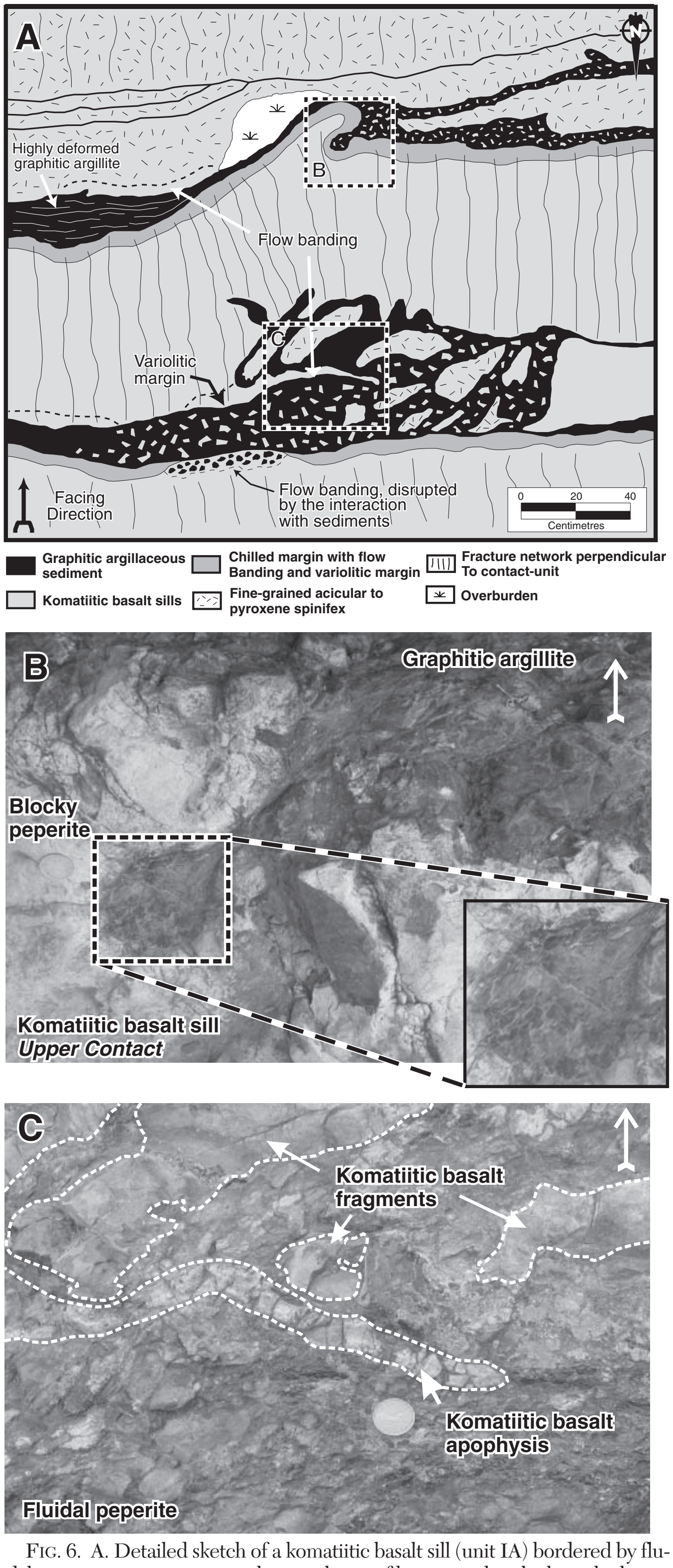

FIG. 6. A. Detailed sketch of a komatiitic basalt sill (unit IA) bordered by fluidal peperite containing irregular apophyses of komatiitic basalt along the lower, and to a lesser extent upper, contacts of the sill. The irregularity of the upper and lower contacts of the sill and the presence of necked apophyses in the basal zone suggest that the peperite along both margins is the product of quench fragmentation by the intruding sill and was not produced during an earlier event. B. Intrusive breccia developed along the upper contact of a komatiitic basalt sill. C. Lobes and fragments of komatiitic basalt in a fluidal-blocky peperite. The location of Figure 6 is shown in Figure 3. Arrows indicate the facing directions.

upper sill is bordered by a zone of blocky peperite containing angular jigsaw-textured fragments of inclusion-poor komatiitic basalt in a matrix of graphitic argillite (Fig. 7).

The development of either blocky or fluidal peperite has been interpreted by Busby-Spera and White (1987) to reflect the different rheological characteristics of the host sediment caused by differences in grain size, sorting, and water content. Both types of peperite develop in the same type of sediment at Dundonald Beach; formation of either blocky or fluidal peperite is interpreted to be strongly influenced by the degree of consolidation (rheology) of the sediment, which changed as a result of successive sill emplacement. Fluidal peperite is interpreted to have formed where sills were emplaced into wet unconsolidated sediment; this allowed the formation and maintenance of a vapor film at the magma-sediment interface, effectively insulating the ductile magma and allowing for irregular protrusion and mingling of magma and sediment to produce the irregular, amoeboid, globules typical of fluidal peperite (Squire and McPhie, 2002). Blocky peperite is interpreted to be a product of quenching and autobrecciation (mechanical fragmentation), which occurred where the komatiite intruded graphitic sediments (and peperite) that was partially dewatered and lithified by previous sill emplacement. The occurrence of peperite comprising a mixture of both blocky and fluidal clasts, which must have formed under different thermal and mechanical conditions, indicates that peperite formation at Dundonald Beach was a multistage process (see discussions by Squire and McPhie, 2002, and Skilling et al., 2002).

Discussion

The different geodynamic environments into which komatiitic magmas have been emplaced range from old continental crust overlain by thick sequences of basaltic strata (e.g., Kambalda), to continental margins containing a combination of basaltic and sedimentary strata (e.g., Bulawayan belt, Zimbabwe; Cape Smith belt, Canada) to island- and/or back-arc settings containing a combination of felsic and mafic volcanic, volcaniclastic, and sedimentary strata (e.g., Abitibi belt: Ayer et al., 2002). The bulk density of the crust and the density and rheology of the supracrustal rocks in these environments varies considerably, and it is the nature of the deep crustal rocks (cratonic or juvenile) and the tectonic environment (extensional versus convergent) that influences the rate of magma ascent and the location of magma emplacement (Lesher and Keays, 2002). However, in each of these environments the density and rheology of the near-surface rocks (lava flows and sedimentary rocks versus unconsolidated volcaniclastic rocks and sediments) governs the mode of emplacement (flows versus invasive flows versus sills and/or dikes). Thus, there is potential for a spectrum of komatiitic edifice types between those characterized by flow-dominated successions and those characterized by volcaniclastic- and/or sediment-dominated successions. Recognizing that Ni-Cu-(PGE) deposits occur within the most magnesium-rich, channelized units (Lesher, 1989; Lesher and Barnes, 2008), we believe that the nature of the near-surface rocks is crucial in determining the architecture of submarine komatiitic flow fields, their subvolcanic plumbing systems, and the location of Ni-Cu-(PGE) deposits.

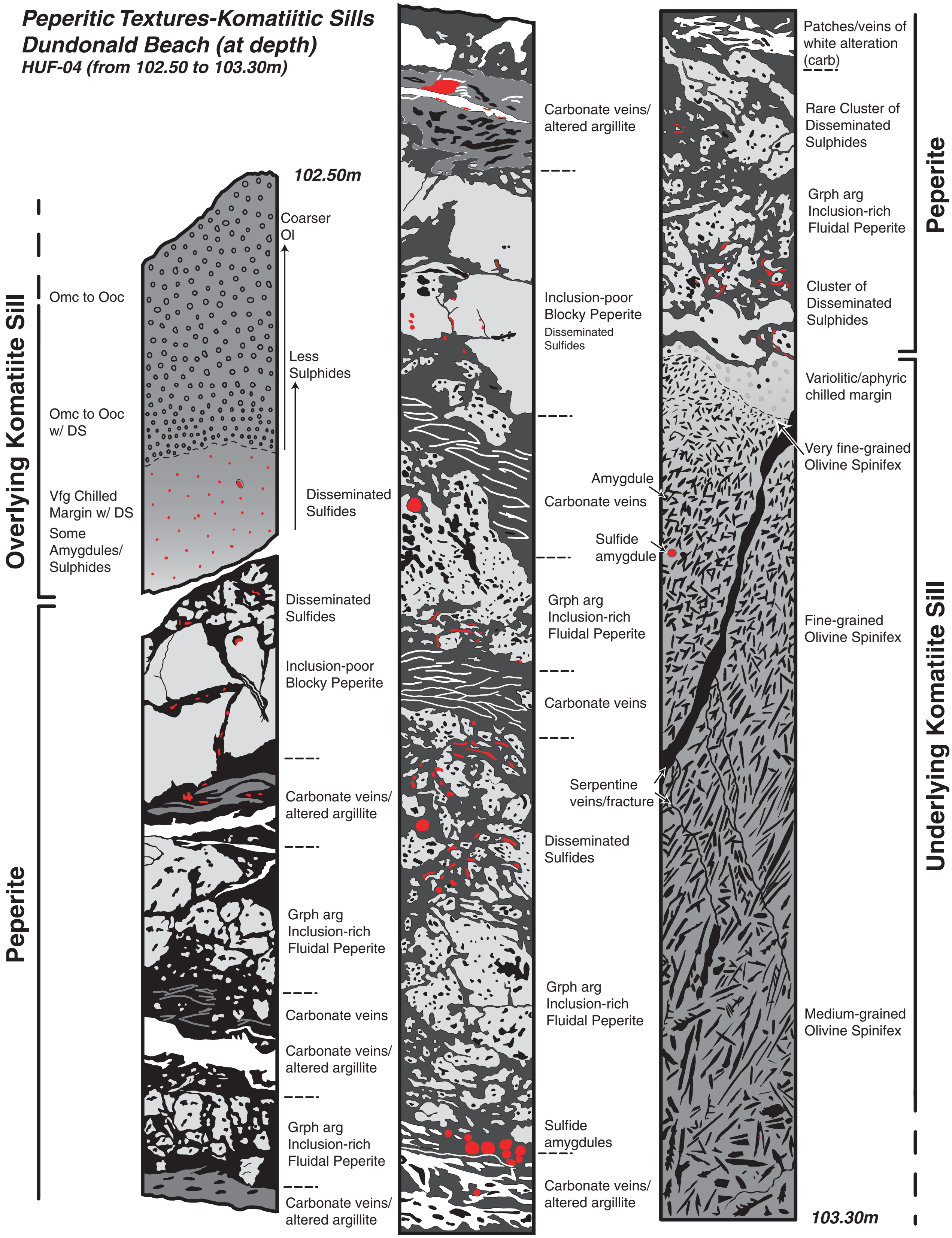

FIG. 7. Detailed sketch of diamond drill core (HUF-04) through subunit IC ~300 m east-southeast of the Dundonald Beach outcrop, illustrating multigenerational peperite development adjacent to two komatiite sills. Abbreviations: carb = carbonate, DS = disseminated sulfides, grph arg = graphitic argillite, Ooc = Olivine orthocumulate, Omc = olivine mesocumulate, Vfg = very fine grained. Core width is 45 mm (NQ).

Paleoenvironmental constraints

Komatiites, tholeiitic basalts, andesites, and high silica rhyolites of the Kidd-Munro assemblage have been interpreted as forming in a rifted arc (e.g., Jackson and Fyon, 1991; Wyman et al., 1999; Ayer et al., 2002). The presence of fine-grained, graphitic, sulfidic argillaceous sedimentary rocks and local exhalative Cu-Zn mineralization indicate a relatively deep water environment (Davis, 1997, 1999), most likely an extensional, fault-controlled basin (Fig. 3). The occurrence of peperite along the margins of komatiitic sills and dikes at Dundonald Beach provides unequivocal evidence of a shallow subvolcanic environment of emplacement for at least the lower part of the Dundonald South member in that area (Fig. 4).

Mechanisms of emplacement

Crosscutting relationships between sills and peperite indicate that the komatiitic basalts in unit IA were emplaced in at least five stages (Fig. 8).

Stage I: Type I peperite, consists of wispy, fluidal, and blocky, highly vesicular and variolitic komatiitic basalt fragments (1–5 cm) mixed with nonlaminated graphitic argillite. Type I peperite occurs as irregular lenses several decimeters to several meters in size within otherwise argillaceous sediments. It is not associated with coherent sills and is interpreted to be a product of the total disintegration of an initial komatiitic basalt magma emplaced into unconsolidated argillite. The absence of bedding or delicate lamination within the argillite suggests that it was fluidized or partly fluidized during early sill emplacement, disintegration, and peperite formation.

Stage II: Continued emplacement of komatiitic basalt sills into unconsolidated argillite and type I peperite produced type II peperite. Type II peperite consists of a complex mixture of argillite and highly vesicular komatiitic basalt that cuts and engulfs type I peperite and argillite.

Stage III: Emplacement of komatiitic magma into type I and II peperite and associated partially lithified sediment produced type I sills, which are coherent and crosscut earlier peperite. The occurrence of type III blocky peperite along the upper and/or lower contact of these sills and angular, jigsaw-fit clasts of desiccated sediment in a silicified komatiitic basaltic matrix indicate that these sills were quenched and brecciated through interaction with the argillite.

Stage IV: Continued emplacement of komatiitic magma into earlier formed type I sills, type I through III peperite, and argillite produced type I sills that display only minimal development of peperite along their margins.

Stage V: Continued emplacement of komatiitic magma produced type II sills with straight contacts and thin (~2–3 cm), fine-grained, lower and upper chilled margins that exhibit flow-banding but no trace of variolitic textures within their borders. The absence of intrusive breccias or peperite along sill margins and their straight and regular contacts indicate that type II sills did not interact extensively with the argillaceous sediments and that the argillite was consolidated and dry. The end result of this intrusive history is the formation of a subvolcanic, sill-sediment complex characterized by multigenerational, crosscutting komatiitic basalts sills, peperite, and intercalated argillite (Fig. 8).

Volcanic and subvolcanic architecture

The changes in sill morphology, contact relationships, and sill-sediment interactions indicate a progressive change in the water content, density, and rheology of the host argillite in response to sill emplacement (e.g., Gibson et al., 2003). The disintegration of the initial komatiitic magma in stage I, and the presence of abundant peperite, indicates that the argillaceous sediments were initially unconsolidated and water saturated. The reduction in the abundance of peperite and the restriction of peperite to type I sill margins in stages II to IV reflect progressive dewatering and consolidation of the argillaceous sediments, involving expulsion of water and cementation via growth of authigenetic minerals produced during accelerated diagenetic reactions driven by the heat of successive sill emplacement (e.g., Gibson et al., 1999, 2003). Type II sills cut across earlier sills and, less commonly, argillite and peperite but did not generate irregular margins or peperite along their contacts. This indicates that the argillite was essentially lithified during the emplacement of type II sills and that at this stage there were no significant rheological differences between the host argillite and previously emplaced sills. The occurrence of localized peperite along the upper and lower contacts of the thick, differentiated komatiitic basalt sill (subunit IB; Fig. 4) indicates that it was emplaced into more consolidated sediments, after the emplacement of the thin undifferentiated komatiitic basalts sills in unit IA (Fig. 4). The thick, cumulate-textured komatiite sills of unit IC (Fig. 4) clearly transgress unit IB and an overlying argillite (not shown at the scale in Fig. 4), indicating that it postdates all of the underlying units.

The crosscutting relationships and variations in the mechanism of peperite and sill emplacement indicate that dewatering and lithification of the argillaceous sediments was progressive and resulted from the continuous emplacement of subvolcanic sills in a subsea-floor environment. Sill emplacement and accompanying dewatering and lithification increased the density and modified the rheology of the sedimentary strata, resulting in substantial increases in bulk density and competency (Lesher and Keays, 1996; Burnham et al., unpub. report for CAMIRO project 97E-02, 2003, 410 p.). A consequence is that successive komatiitic magmas would have reached progressively higher stratigraphic levels and eventually erupted at the surface (Fig. 9). The complex interactions between komatiitic sills and graphitic argillite at Dundonald Beach suggest a near-vent or proximal subvolcanic facies.

The sequence of events outlined above has undoubtedly occurred in other komatiite-hosted Ni-Cu-(PGE) districts where near-surface rocks are dominated by unconsolidated sediments or volcaniclastic rocks resulting in the location of Ni-Cu-(PGE) mineralization within subsea-floor sills (e.g., Mt. Keith, Western Australia: Rosengren et al., 2005; Raglan Belt, New Québec: Lévesque et al., 2003; Thompson Nickel belt: Burnham et al., unpub. report for CAMIRO project 97E-02, 2003, 410 p.; Pechenga belt, Russia: Melezhik et al., 1994). This mode of komatiitic magma emplacement is significantly different from that in the Kambalda district of Western Australia, where the near-surface rocks are dominated by competent lava flows that would have produced surface eruptions rather than sill emplacement.

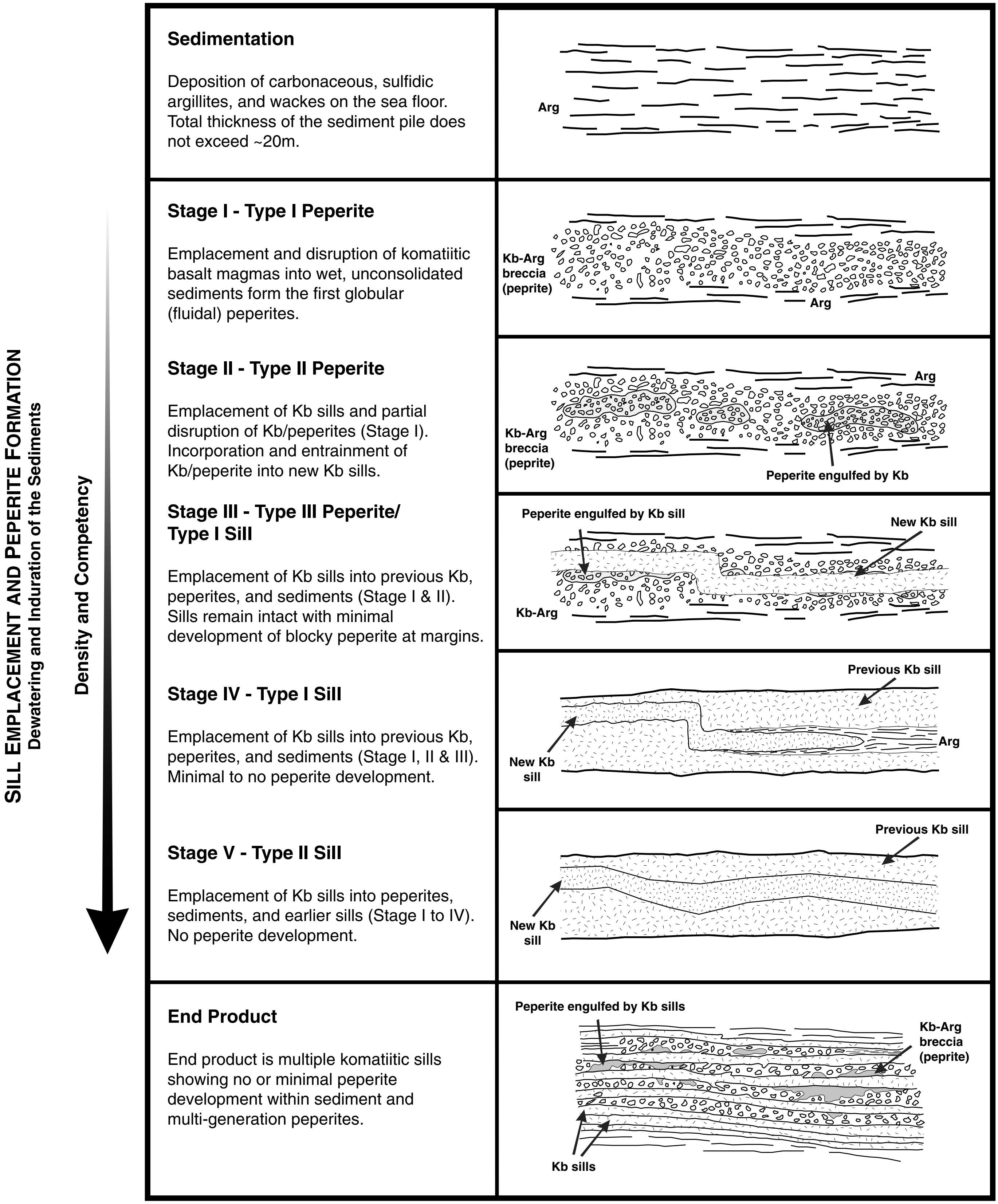

FIG. 8. Conceptual model showing the evolution of sill architecture and concomitant peperite development at Dundonald Beach resulting from the multiple emplacement of komatiitic basalt sills within argillaceous sediments. The sequence formed in five stages (stages I-V), produced by at least five generations of komatiitic basalt injections, three of which are manifested by sills and two, the earliest stages, manifested by peperites. Arg = argillite, Kb = komatiitic basalt.

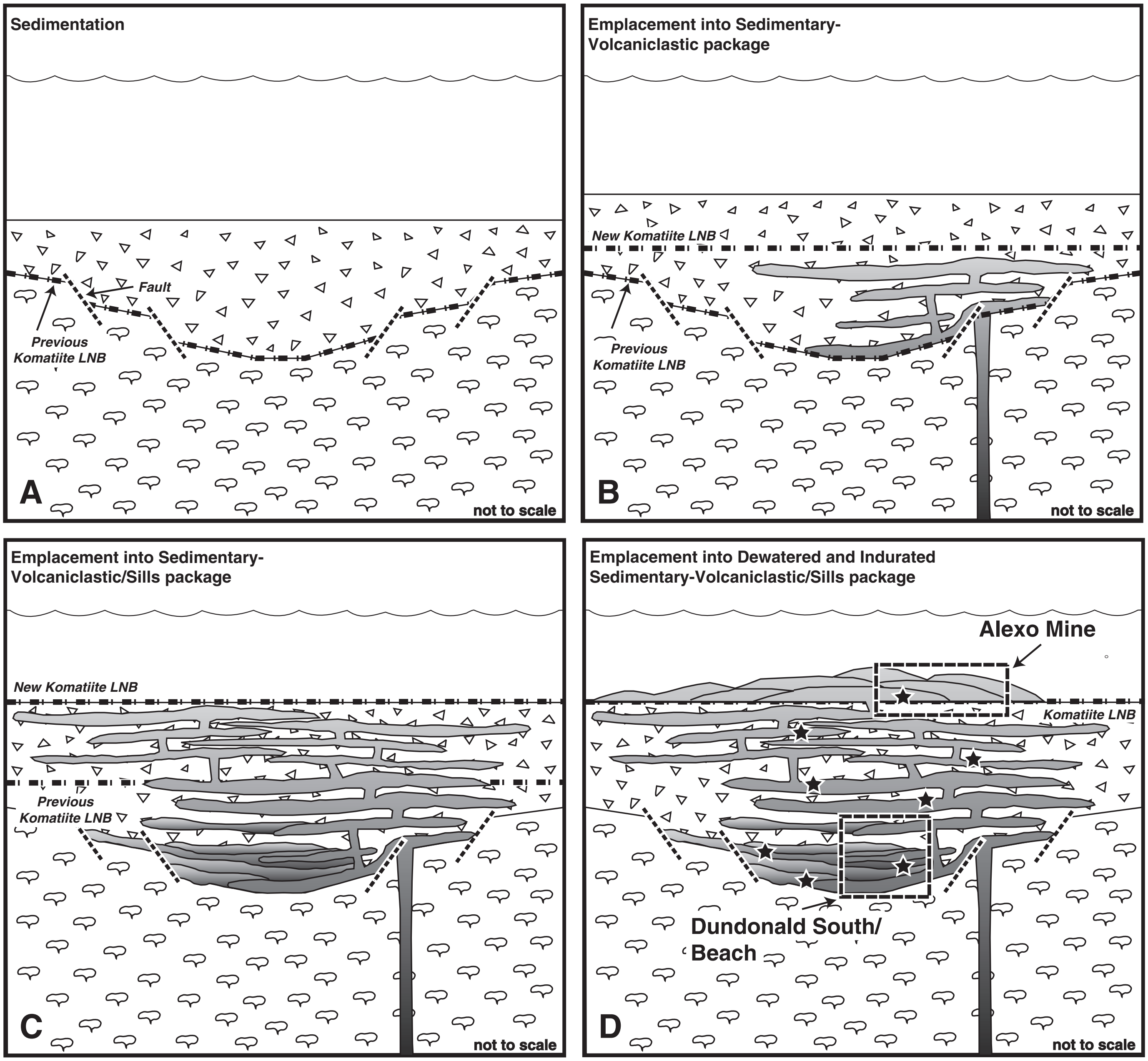

FIG. 9. Idealized model showing the evolution of komatiitic subvolcanic and/or volcanic architecture (A-D) within a volcaniclastic- and/or sediment-dominated komatiite volcanic environment (e.g., Dundonald Beach, Raglan). Dashed boxes in D represent the approximate location of Dundonald South/Beach and Alexo mine within the komatiite volcano. Stars represent the potential location of komatiite-associated Ni-Cu-(PGE) mineralization in sediment- and/or volcaniclastic-dominated succession. LNB = level of neutral buoyancy.

Because the physical characteristics of near-surface rocks play a critical role in the development of the architecture of subvolcanic and/or volcanic komatiite plumbing systems, the distribution of Ni-Cu-(PGE) mineralization associated with volcaniclastic- and/or sediment-dominated successions should be different and more stratigraphically diverse than mineralization associated with flow-dominated successions where sulfur saturation is achieved through thermomechanical erosion of footwall rocks and mineralization is concentrated in lava channels, typically at or near the bases of the flow successions. The distribution of Ni-Cu (PGE) deposits and occurrences in the Dundonald area, within both flows in the upper part (Alexo) and sills above the base of the lower intrusive part (Dundonald South, Dundeal), may reflect sulfur saturation during sill emplacement that allowed Ni-Cu (PGE) mineralization to be concentrated within the subvolcanic plumbing system and within the overlying komatiitic flows. Thus, knowing the architecture of the komatiitic succession, whether intrusion- or flow-dominated, allows one to predict the possible location and environments of Ni-Cu (PGE) mineralization.

Regardless of volcanic-subvolcanic architecture, Ni-Cu-(PGE) sulfide mineralization is almost always hosted within the most magnesian and channelized flows, invasive flows, or sills (Lesher and Keays, 2002). At Dundonald Beach the most magnesium-rich sills do not occur at the base of the succession but higher in stratigraphy, which may be interpreted to reflect density filtering of the more magnesian komatiite magmas prior to dewatering and lithification.

Importantly, the sequence of emplacement (and ore formation) may not necessarily be the same as the final stratigraphic sequence. Establishing the stratigraphy and understanding crosscutting relationships is crucial in terranes such as the Thompson nickel belt (Burnham et al., unpublished report for CAMIRO Project 97E-02, 2003, 410 p.), where more intense strain and higher grade metamorphism obscure the stratigraphic complexities. There is a great diversity in the architecture of komatiite volcanic-subvolcanic systems. Thus, when exploring for magmatic Ni-Cu-(PGE) deposits in volcaniclastic- or sediment-dominated successions one must consider the possibility of mineralization in locations other than at the base of a komatiitic succession.

Conclusions

The temperatures, viscosities, and densities of magmas, the density of the crust, and the tectonic setting into which magmas are emplaced influence the location and morphology of volcanic systems. Close to the surface, the rheology and competency of the rocks controls the volcanic architecture of submarine lava flow fields, either komatiitic or tholeiitic. Where the near-surface strata are competent, such as environments dominated by flows, komatiitic magma erupts as flows (e.g., Kambalda). Where the near-surface strata are not competent, such as environments dominated by unconsolidated volcaniclastic rocks and sediments, komatiitic magma is initially emplaced as high-level sills (e.g., Thompson, parts of Pechenga). Successive sill emplacement gradually lithifies and consolidates the volcaniclastic or sedimentary strata through the expulsion of water and cementation by secondary, diagenetic minerals. With time, the bulk density and competency of the sill-sediment and/or volcaniclastic package becomes sufficient to permit komatiitic magmas to reach the sea floor and erupt (e.g., Raglan, Dundonald, Shaw dome, parts of Pechenga). With construction of a surface edifice, later komatiitic magma may eventually be emplaced as high-level intrusions into a komatiitic volcanic pile (e.g., Shaw dome, Abitibi greenstone belt: Burnham et al., 2003).

Komatiites at Dundonald Beach erupted through juvenile crust and a thin sedimentary sequence. Low in the succession, they formed abundant thin subvolcanic sills; higher in the succession, they erupted as lava flows. The volcanic architecture and abundance of high-level subvolcanic komatiitic sills suggest a proximal to near-proximal volcanic environment.

Komatiite-associated Ni-Cu-(PGE) mineralization occurs in a wide variety of extrusive (e.g., Kambalda), invasive (e.g., Raglan), and intrusive (e.g., Thompson, Shangani, Dumont) environments (Lesher and Keays, 2002). Knowledge of the volcanic-sedimentary environment is required to predict the morphology and/or architecture of the komatiitic edifice and the location of Ni-Cu-(PGE) deposits in a komatiitic succession. In flow-dominated volcanic environments the highest potential for Ni-Cu-(PGE) deposits is where the komatiitic magma reached the surface and attained sulfur saturation through melting and/or assimilation of S-rich footwall rocks within large lava channels. In this environment Ni-Cu-(PGE) sulfides are more likely to form and be restricted to lava channels at the base of the komatiitic edifice. In volcaniclastic- or sediment-dominated environments, the komatiitic magma may attain sulfide saturation by assimilation of sulfide-bearing sediments or volcaniclastic rocks during ascent and/or during emplacement as sills, provided that they remain channelized. In this environment Ni-Cu-(PGE) deposits are more likely to form in subsurface sills and within the overlying komatiitic flow succession. Importantly, at Dundonald Beach, emplacement of thin basaltic komatiitic sills did not result in assimilation of sedimentary strata or achievement of sulfide saturation, probably because of an insufficient magma supply to melt and dissolve sulfur from the graphitic sediments. However, progressive lithification of the host sediments increased the bulk density and competency of the sill-sediment succession, permitting subsequently intruded thicker channelized pyroxenitic and peridotitic komatiitic sills to thermomechanically erode some komatiitic basalt sills and some of the graphitic, sulfidic argillaeous rocks, achieve sulfur saturation, and segregate Ni-Cu-(PGE) sulfide mineralization.

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