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KOMATIITIC INVASIVE LAVA FLOWS, KAMBALDA, WESTERN AUSTRALIA

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ABSTRACT

Komatiite–substrate contacts have been reassessed at Kambalda, Western Australia, the type locality of komatiite-hosted Ni-sulfide ore deposits. The majority of the lower contacts between komatiite lava and sedimentary substrate are planar and rarely show evidence of erosion, marginal autoclasis and peperite formation. Rarely, komatiites have irregular and peperitic upper margins, with apophyses into the surrounding sedimentary rocks that are locally soft-sediment-deformed, indicating a shallow, synsedimentary intrusive origin. The restriction of these synsedimentary intrusive bodies to domains of thicker sedimentary substrate, the lack of komatiitic dykes, and the abundance of komatiite lava flows in the Kambalda region suggest that the synsedimentary intrusive bodies are of invasive flow origin, *i.e.*, due to burrowing of lava flows into the underlying wet, unconsolidated to semiconsolidated sedimentary substrate. Invasive flows can be explained by the much higher density of komatiitic lava (up to 2.75 g/cm^3) compared to unconsolidated water-saturated pelitic sediments (1.5–2.0 g/cm^3). The higher density and resultant negative buoyancy caused komatiites to load and burrow into the unconsolidated sediments.

Keywords: invasive flow, Kambalda, komatiite, peperite, thermal erosion, Australia.

SOMMAIRE

Nous avons ré-évalué les contacts intrusifs entre komatiite et roches sous-jacentes à Kambalda, en Australie occidentale, la localité-type de gisements de sulfures de nickel dans un hôte komatiitique. Dans la plupart des cas, les contacts inférieurs entre lave komatiitique et roche hôte sédimentaire sont planaires et ne montrent pas d'évidence d'érosion, d'auto-bréchification marginale et de formation de pépérite. Aussi est-il rare de voir des contacts supérieurs irréguliers et à allure de pépérite entre komatiite et roches hôtes; les apophyses recoupant les roches sédimentaires avoisinantes indiquent une déformation typique des roches non consolidées, et font penser que la mise en place s'est faite à faible profondeur et était synsédimentaire. Dans la région de Kambalda, l'intrusion de komatiites synsédimentaires dans les seuls domaines d'épais substrats sédimentaires, l'absence de filons de komatiite, et la profusion de coulées komatiitiques font penser que les massifs intrusifs ont été mis en place sous forme de coulée invasive. Les coulées auraient donc déplacé les boues non consolidées ou faiblement consolidées et saturées en eau. On peut expliquer de telles coulées invasives par la densité beaucoup plus élevée de la lave komatiitique (jusqu'à 2.75 g/cm^3) par rapport au sédiment pélitique non consolidé saturé en eau (1.5–2.0 g/cm^3). La densité plus élevée et la flottabilité négative qui en résulte ont forcé ces komatiites à creuser dans les sédiments non consolidés.

(Traduit par la Rédaction)

Mots-clés: coulée invasive, Kambalda, komatiite, pépérite, érosion thermique, Australie.

INTRODUCTION

Komatiites have been depicted as resulting from high-temperature, high-density, low-viscosity turbulent lava flows capable of thermally eroding their substrate (*e.g.*, Huppert *et al.* 1984, Lesher & Campbell 1993, Williams *et al.* 1998). If komatiitic lavas were fast-flowing, low-viscosity, highly turbulent, dense flows in proximal environments, then they should have caused physical erosion of the substrate sediments before thermal erosion could have occurred (Cas & Beresford 2001, Squire *et al.* 1998). The high density of komatiite lavas (2.75 g/cm^3; Huppert *et al.* 1984), relative to that of water-saturated unconsolidated sediments (1.5–2.0 g/cm^3) over which komatiites flowed, creates a density inversion. This instability may in some cases lead to invasion of the sediment by downward and lateral syndepositional intrusion of komatiite.

In this paper, we document evidence of synsedimentary intrusive bodies of barren and ore-bearing komatiites at Kambalda, Western Australia (Fig. 1), the type locality of komatiite-hosted Ni-sulfide ore depos-

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its. We interpret these synsedimentary intrusive bodies as lava flows that have burrowed into their underlying wet, unconsolidated sedimentary substrate. The data provide insights into the style of interaction between dense komatiitic lava flows and their sedimentary substrate.

General Geology

Kambalda is in the south-central part of the Archean Norseman–Wiluna greenstone belt, in the Yilgarn Craton (Fig. 1). The volcanic–sedimentary sequence was emplaced at approximately 2.7 Ga (Claoue-Long *et al.* 1988) and has been intruded by multiple suites of felsic intrusive bodies, metamorphosed to the lower amphibolite facies, and complexly faulted and folded during at least four phases of deformation (*e.g.,* Cowden & Roberts 1990). The stratigraphy has been established from over 30 years of exploration, mining and research activities. At the base of the sequence, a metabasalt unit (Lunnon Basalt) is overlain by serpentinized and variably talc–carbonate-metasomatized komatiites (Kambalda Komatiite Formation). A variety of metasedimentary units are commonly on the contact or intercalated with the metakomatiites (or both). Nickel sulfide mineralization is commonly located in embayments or trough structures at the base of the thick basal komatiitic lava flow (*e.g.,* Gresham & Loftus-Hills 1981; Fig. 1). There is generally an absence of sedimentary units in the troughs or ore environments [*e.g.,* Bavinton (1981), although there are numerous exceptions], indicating that sediment has been eroded from the ore environment.

Despite regional metamorphism to the lower amphibolite facies, igneous textures are locally well preserved and can be confidently interpreted. The prefix “meta” is implied for all lithological terms, but omitted for simplicity.

Sedimentary Protolith

A key to understanding the nature of komatiite–substrate interaction requires knowledge of sediment type and degree of water saturation at the time of komatiite emplacement. The application of textural terms and assessment of sedimentary protolith and provenance are critically dependent on textural preservation. Sedimentary units at Kambalda are commonly structurally deformed, have been overprinted by lower-amphibolite-facies metamorphism and assemblages of metasomatic minerals, and pervasively albitized or silicified, resulting in destruction of the majority of fine-scale primary sedimentary textures. We undertook a petrographic reassessment of the sedimentary units at Kambalda, including Bavinton’s (1981) thesis collections, in order to gain a greater understanding of the protolith, inferred provenance, and any paleogeographic significance of sedimentary units intercalated with komatiites at Kambalda. The results are briefly summarized herein.

Bavinton (1981) defined three sedimentary rock types at Kambalda: (1) pale siliceous sedimentary rocks (so-called “albitic” cherts), (2) carbonaceous siliceous sedimentary rocks, and (3) chlorite-rich sedimentary rocks. This subdivision is continued in this study. Pale siliceous sedimentary rocks are the most common and

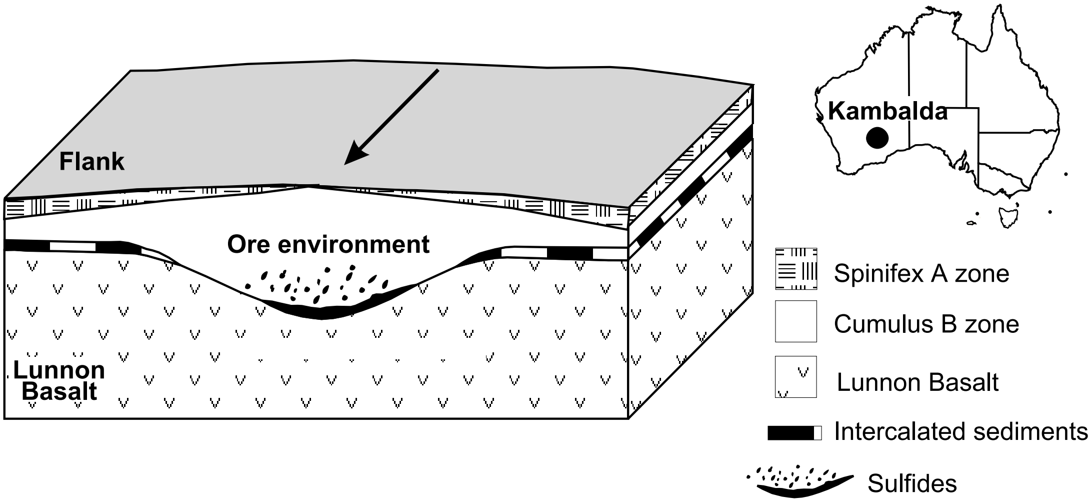

FIG. 1. Schematic block diagram of relationships of channel-confined komatiite-hosted Ni-sulfide ore deposits at Kambalda to their substrate and associated facies (adapted from Frost 1992). The ore environment contains thick high-Mg komatiites, associated ore and a marked sediment-ore antithetism. Flank environments contain thinner komatiites and intercalated sediments. The location of Kambalda in Western Australia is shown in the inset.

are dominated by granoblastic aggregates of albite and quartz with subordinate sulfides, chlorite, talc, carbonate, amphibole, biotite, clinozoisite, tourmaline, zircon, rutile, apatite and oxides. Carbonaceous sedimentary units exhibit similar mineral assemblages and textures to those in the pale siliceous sedimentary units, but with additional carbonaceous material. The chlorite-rich sedimentary units are dominated by chlorite with subordinate biotite, sulfides, feldspar, and oxides. The three sedimentary rock-types are commonly intercalated, and largely reflect varying proportions of graphite and chlorite. A spatial variation in sedimentary rock-types is suggested by the absence of carbonaceous sediments from the eastern part of the Kambalda Dome.

Sedimentary horizons range in thickness from a few cm to 12 m, but are commonly 2–5 meters thick and largely restricted to flanking environments (Bavinton 1981, Gresham & Loftus-Hills 1981; Fig. 1). Sedimentary rocks are locally traceable in outcrop along strike for several hundreds of meters, but the poor degree of lateral correlation in drill holes is inferred to reflect post-emplacement deformation or primary irregularities in the depositional environment, such as an irregular upper-flow surface or a lensoid geometry of the komatiite flows.

The sediments are planar-laminated to bedded (2 mm – 5 cm thick), consisting of very fine to fine silt-sized grains of albite and quartz. Rare massive units up to 30 cm thick are intercalated with the well-laminated and bedded units. Laminae are defined by variation in grain size and graphite content, or by the presence of massive sulfide layers (pyrite and pyrrhotite). The sediments are complexly deformed and are commonly pervasively foliated, folded, with localized domains of hydraulic breccia. Textures are commonly overprinted by decussate porphyroblasts of amphibole adjacent to intrusive porphyries or lithological contacts.

Bavinton (1981) interpreted the Kambalda sediments as having a chemical origin, with mafic or ultramafic detrital input. The fine-grained texture of the sediments, which resembles a cherty texture, was inferred to indicate a chemical origin. Groves *et al.* (1978) also favored an exhalative origin, arguing that the restriction of the sedimentary rocks to the lower part of the Kambalda Komatiite Formation, as well as the similarity to sedimentary rocks within the basaltic footwall, indicate a genetic link with waning basaltic volcanism rather than with komatiitic volcanism. Our initial results suggest that the fine-grained texture is a metamorphic granoblastic texture, and in no way reflects the original primary texture.

It is now known that cherts and siliceous rocks of cherty appearance can represent a wide variety of lithologies, including silicified volcaniclastic rocks, biogenic, and orthochemical deposits (*e.g.,* Lowe 1999). Many of the "cherty" rocks documented in Archean belts have formed by alteration of fine-grained volcaniclastic rocks (*e.g.,* Lowe 1999, Wilson & Versfeld 1994). Alteration may be related to synemplacement hydrothermal fluids or late-stage metasomatism accompanying the polyphase deformation, intrusion and metamorphic history of the Kambalda komatiites. The rare presence of graded bedding and cross lamination (Fig. 2) and clastic textures (Hudson 1972) in weakly deformed sedimentary rocks at Kambalda indicates a detrital component. A felsic volcanic provenance is suggested by rare clastic textures, the population of heavy minerals (Bavinton 1981), and in particular the presence of euhedral, non-abraded crystals of zircon (Claoue-Long *et al.* 1988). Anomalous levels of Pb and S(?) in the Kambalda sedimentary units may suggest a possible exhalative component (Bavinton 1981).

The presence of siliceous sedimentary units of the same composition within both the Lunnon Basalt and Kambalda Komatiite Formation indicates that these sediments represent background sedimentation during mafic and ultramafic volcanism, largely from a felsic volcanic source, probably extra-basinal rather than directly related to intra-basinal volcanism. An intra-basinal source cannot be ruled out for the chloritic component in the sediments.

The very fine grain-size, thin laminae, rare cross-lamination, and rock association indicate that the sediments were deposited in a low-energy subaqueous environment, below wave base, probably in deep-water conditions, by pelagic and hemipelagic fallout (Squire *et al.* 1998).

KOMATIITE – SEDIMENTARY SUBSTRATE CONTACTS

Relations between komatiite and sedimentary substrate are difficult to assess in polyphase-deformed Archean terrains, as the vast majority of contacts are commonly modified or overprinted by shear zones or overprinted by assemblages of metasomatic minerals. Primary contacts are rare, but are defined as contacts with at least partial evidence of demonstrable depositional or intrusive relations. Modified contacts are marked by minor shearing or assemblages of secondary minerals (commonly assemblages of decussate secondary minerals *e.g.,* amphibole–chlorite ± biotite). The original nature of the contact can be in places confidently inferred. The vast majority of contacts at Kambalda are deformed, with prominent development of protomylonitic, mylonitic, or schistose fabrics.

Four types of primary contacts between komatiite and sedimentary substrate have been inferred at Kambalda: (i) passive, (ii) loading, (iii) erosive and (iv) invasive or peperitic (associated with synsedimentary intrusive bodies). The following is a synopsis of contact relations, with interpretation of contact genesis. Details of invasive contacts are expanded in later sections. Peperite is defined as a rock generated by mixing of coherent lava or magma with unconsolidated wet sediment.

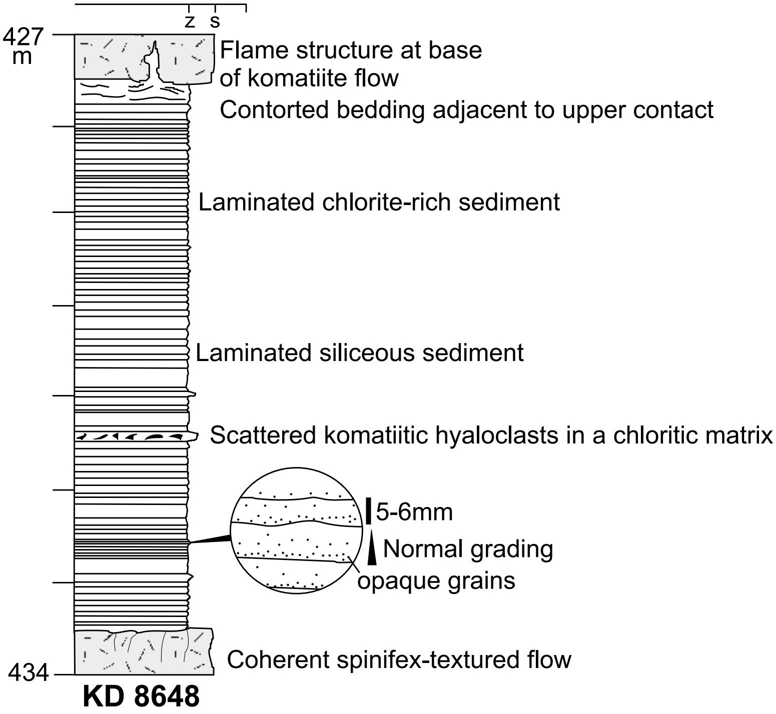

FIG. 2. Graphic log of typical sedimentary units intercalated with komatiites at Kambalda (*e.g.*, KD 8648, Coronet flank). Z: silt, s: sand.

Passive contacts

Conformable contacts between the komatiites and sedimentary units predominate, especially in flanking environments, and are interpreted as passive contacts, *i.e.*, no interaction between komatiite and underlying substrate, implying gentle emplacement by laminar flow. The presence of planar contacts between coherent komatiite and underlying delicate hyaloclastite flow-top breccias (Thomson 1989) also suggests passive emplacement.

Loading contacts

Basal contacts with either flame structures or lobate lower margins are interpreted as being due to gravitational loading of lava into the underlying water-saturated unconsolidated substrate, owing to density inversion, with minor contortion and fluidization of the underlying sediment.

Flame structures of massive chloritic or siliceous sediments are rarely present at the base of demonstrable komatiitic lava flows (*e.g.*, Coronet ore shoot, drill hole KD 8648, 428 m, Fig. 2; Dordie North, base of third flow, Fig. 3a). Sedimentary structures are usually destroyed adjacent to the komatiite lava.

Lobes or apophyses of komatiite at the base of units are present and extend from the komatiites. The surrounding sedimentary units show minor contortion and disturbance of bedding and little or no mixing with the komatiite, suggesting emplacement under gravitational loading. Similar loading phenomena have been observed at the base of flood basalts (Thordarson & Self 1998).

Erosive contacts

Erosional contacts are defined as the thermal, thermo-mechanical or physical removal of substrate. Thermal erosion is defined as the *in situ* anatexis of the substrate. Thermomechanical erosion is defined as the process by which preflow material is removed by mechanical incorporation, with subsequent melting or partial melting in the lava flow. Physical erosion is defined as density-induced scouring, or physical remobilization of the sediments due to turbulence or film boiling (Cas & Beresford 2001, Squire *et al.* 1998), without the necessary connotation of assimilation of the remobilized sediment into the komatiite flow, although some may occur.

Rare primary contacts in the ore environment are marked by massive sulfides overlying massive or pillowed basalts (*e.g.*, Fig. 8 of Squire *et al.* 1998), indi-

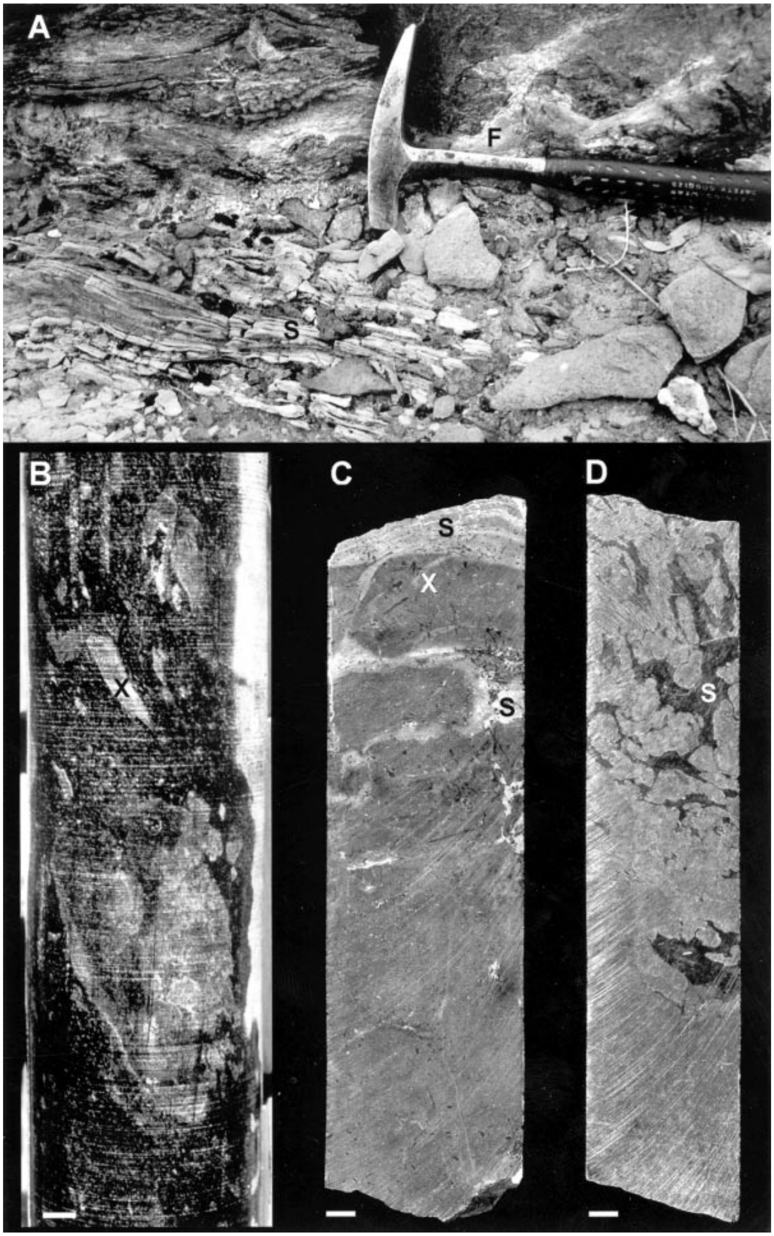

FIG. 3. A. Chloritic-sediment-infilled flame structure (F) at the base of a thin komatiite unit, Dordie North. Underlying sedimentary units (S) are intercalated chloritic and siliceous sediments. Hammer is 30 cm long; B. Metasedimentary xenolith (X) or intraclast-rich komatiites at the base of a komatiite unit (Victor, drill hole KD 6068AW1; 684 m). White scale-bar is 1 cm long in B, C and D. C. Elongate xenoliths of sediment (X) and fluidal peperite at the top of shallow intrusive body (Victor, drillhole KD 6071A; 487 m). Elongate xenoliths (X) are “ripped off” the overlying sedimentary unit (S). Fluidal peperite contains irregular clasts of komatiite in a siliceous sedimentary matrix (S). D. Fluidal peperite at the top of a shallow intrusive body. Small irregular apophyses of komatiite and associated fluidal clasts in a chloritic sediment host (S) (Coronet, KD 8683; 461 m).

cating no erosion of basalt but complete removal of sediment.

No tangible field-based evidence of thermal erosion has been observed at Kambalda, but the presence of scoured basal contacts and of pale siliceous sedimentary xenoliths or intraclasts has been observed at the base of some komatiite units (*e.g.,* Victor East, drill hole KD 6068AW1, 684 m; Fig. 3b). The intraclasts or xenoliths are interpreted as rip-up clasts of semicohesive siliceous sedimentary material incorporated by scouring by the overriding flow, *i.e.,* physical erosion. Xenoliths are either angular or irregular. Angular xenoliths are commonly elongate and represent an entire bed, or packages of laminated sediment. These clasts were clearly partially cohesive at the time of incorporation. Irregular xenoliths or sedimentary domains contain either contorted laminae or are massive, and are interpreted to represent variably fluidized semiconsolidated sediments. The variation between domains of fluidized sediment and angular xenoliths of sediment suggests a variation in sediment consolidation at the time of incorporation.

A single komatiite unit from the Victor region (*e.g.,* Victor South, drill hole KD 6071A, 487 m; Fig. 3c) has pale siliceous sedimentary xenoliths along the upper contact. The xenoliths are locally attached or partially attached to the overlying sedimentary horizon (indicating a synsedimentary intrusive origin; see below). This contact is remarkable as it records the process of clast incorporation into the komatiite, and indicates that the sediments were at least locally semicohesive.

TYPICAL KOMATIITIC LAVA FLOWS AT KAMBALDA

Komatiite lavas at Kambalda vary between 50 and 150 m in thickness, and exhibit the classical two-tiered A–B textural zonation typical of many komatiites (*e.g.,* Pyke *et al.* 1973). The A zone consists of an upper chilled margin (now replaced by fine-grained chlorite, amphibole and oxides), which grades downward into a spinifex zone. In rare cases, the upper margin of the komatiite is internally fractured and grades upward into jigsaw-fit monolithologic breccias, with localized domains of matrix-support and clast-rotation. The jigsaw-fit texture of the breccias, clast morphologies, and abundance of sand-size matrix are indicative of hyaloclastites resulting from quench-induced fragmentation *i.e.,* cooling and contraction due to supercooling by seawater (Cas & Beresford 2001). The B zone consists of multiple cumulate and vesicle horizons (Beresford *et al.* 2000).

SYNSEDIMENTARY INTRUSIVE BODIES

Rare and unusual komatiites within the basal komatiite units at Kambalda have irregular and peperitic margins, with apophyses into the locally soft-sediment-deformed surrounding sedimentary rocks.

Barren intrusive bodies

Contacts with the host sedimentary units are irregular and fluidal in form and mostly unbrecciated. The komatiite units are up to 7 m thick, and commonly aphyric or randomly spinifex-textured, but examples of komatiites with a classical A–B “Abitibi-type” textural zonation (Pyke *et al.* 1973) are not uncommon (*e.g.,* KD 6053A; Fig. 3). The host sedimentary units are up to 10 m thick, and are commonly silicified or pervasively replaced by biotite, but relict lamination and unaltered domains indicate a siliceous or chloritic sediment as a protolith.

The top contact of some komatiite units is highly irregular, with apophyses of komatiite and fluidal komatiite clasts (Figs. 3d, 4). The fluidal clasts are ovoid to amoeboid bodies separated by centimeters of host sediment. The clasts are typically less than 4 cm in diameter, but in places are up to 7 cm in diameter (*e.g.,* KD 6071A). Bulbous or elongate apophyses are at least 9 cm in length (limited information owing to drill-core width) and are commonly attached to the coherent komatiite by a narrow neck. Locally, fluidal clasts are observed detached from the apophysis margin, suggesting that fluidal clasts are derived by the fragmentation of the fluidal apophyses. These units are inferred to be fluidal peperites. Many of the irregular komatiite units resemble pillows with lobate margins (Kano 1991; Fig 4). The host sedimentary unit is commonly massive adjacent to the komatiite units, but localized domains of contorted or planar lamination are present up to the contacts. Structureless sedimentary rocks associated with peperites suggest fluidization of the fine-grained sediment (Kokelaar 1982). Locally, angular clasts of komatiite up to 4 cm in diameter form well-developed, poorly sorted, jigsaw-fit-textured domains grading into coherent komatiite (Fig. 4). Chaotic clast-rotated domains have not been observed. The host sedimentary unit is ubiquitously structureless. These jigsaw-fit-textured domains are restricted to areas with large fractures up to 30 cm long, which extend into the coherent komatiite. These fractures are inferred to be quench-related, associated with blocky peperite. The presence of peperitic contacts *indicates* that the sediments were unconsolidated to semicohesive at the time of komatiite emplacement.

Ore-bearing intrusive bodies

In the Coronet flank area, synsedimentary intrusive bodies contain 1–2 m of massive sulfide at their basal margins (Figs. 4, 5). Irregular apophyses and fluidal peperites are present at the upper margins, along with xenoliths or domains of structureless sedimentary rock. Host sedimentary units are commonly structureless or contorted, which suggests that fluidization and soft-sediment deformation of the sediments accompanied komatiite emplacement. The synsedimentary intrusive bodies are commonly overlain by a thick high-Mg flow with disseminated sulfides (Fig. 4). This association suggests that the thick high-Mg flow is genetically related to the underlying intrusive body (see below).

Origin of synsedimentary intrusive bodies and peperite

The presence of peperite at the upper contacts indicates that these units are shallow, synsedimentary intrusive bodies (Fig. 6). Synsedimentary intrusive bodies can be distinguished from lava flows by the irregular contact relations and the presence of peperite at their upper margins. We stress that synsedimentary intrusive bodies are distinct from spinifex-textured segregation dikes associated with komatiite B zones, and post-lithification intrusive bodies, as advocated by Grove *et al.* (1997) and Parman *et al.* (1997) for the komatiites in the Komati River Valley, Barberton Greenstone belt.

Any magma that rises through sediment will have a density greater than the wet unconsolidated sediment, *i.e.*, a negative buoyancy. The low tensile strength of the unconsolidated sediments will allow the komatiite to irregularly intrude the sediments. The komatiite is coherent over most of its extent because any fragmentation between hot magma and water or water-rich sediments is prevented by efficient film boiling (Mills 1984). The breakdown or collapse of this film results in direct contact between water and magma, accelerating supercooling, contraction, quench fragmentation and mixing with sediment, producing late-stage (quench?) fractures and associated jigsaw-fit breccias or blocky peperite. Peperites are thus useful, as they demonstrate that the sediment was unconsolidated, and therefore that the komatiite and sediment are contemporaneous.

Busby-Spera & White (1987) recognized two types of peperite, blocky and fluidal. The types of peperite are interpreted to represent end members relating to contrasting grain size and magma viscosity (Busby-Spera & White 1987, Goto & McPhie 1996). Goto & McPhie (1996) noted the two types of peperite associated with a single shallow intrusive body, which they

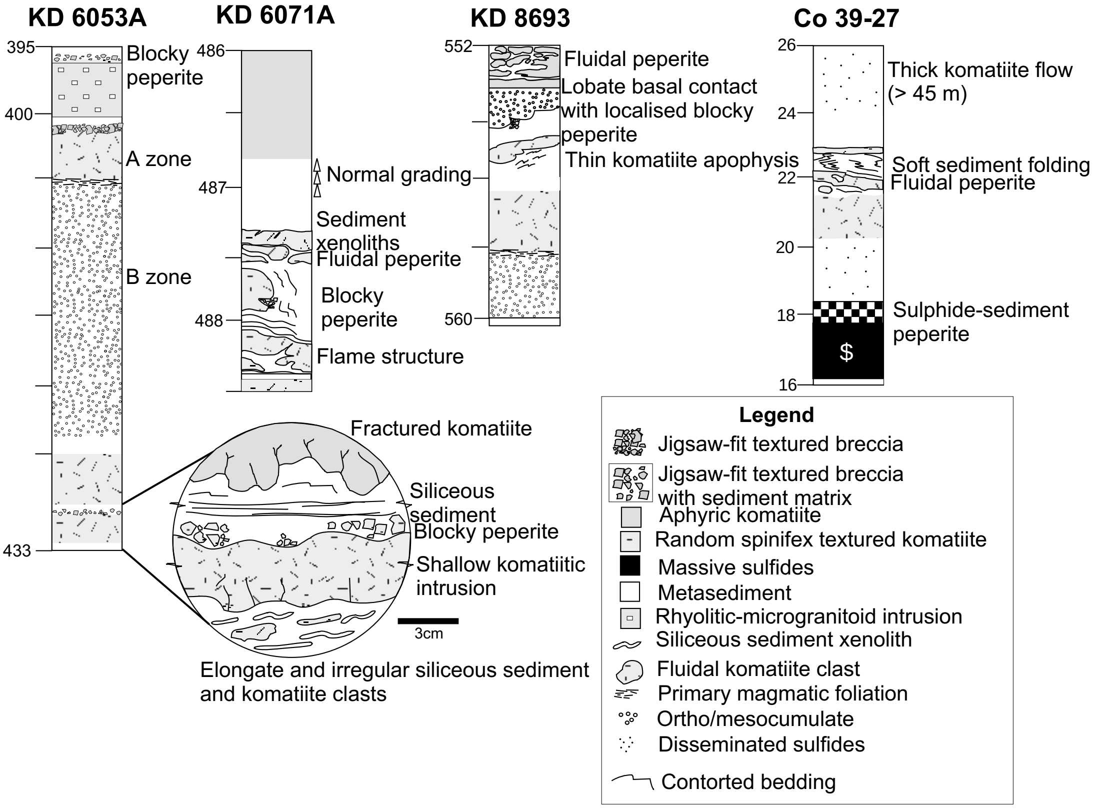

FIG. 4. Selected logs of shallow, synsedimentary intrusive bodies in the Coronet (KD 8693, Co 39–27) and Victor regions (KD 6053A, 6071A), illustrating irregular margins and localized peperitic contacts. Note the different scales.

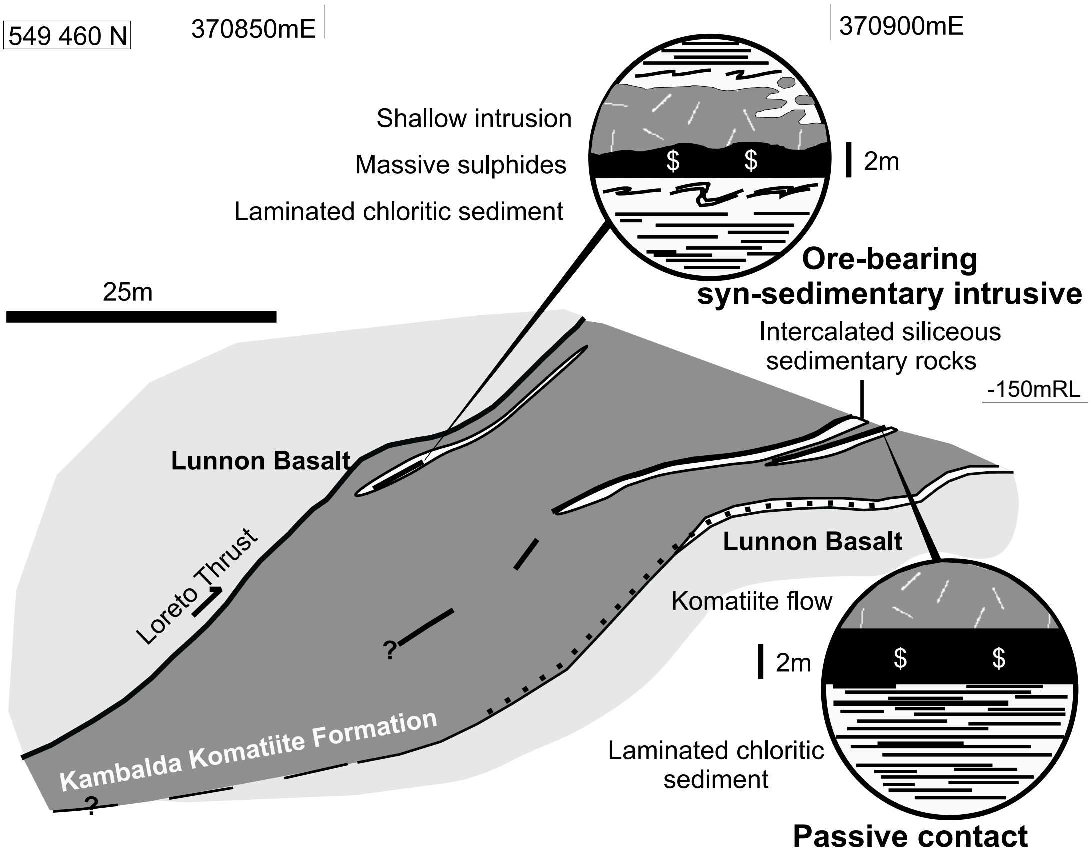

FIG. 5. Cross-section through the western flank of Coronet ore shoot (beneath the Loreto Thrust), illustrating massive-sulfide-bearing shallow intrusive bodies and four thin ore-bearing komatiite flows with passive lower contacts with underlying sediments (modified from Kambalda Nickel Operations, unpubl. data). Symbols as in Figure 4.

interpreted to result from two stages of peperite formation. There was an early fluidal stage, where the temperature contrast between magma and the sediments was greatest, and the magma had relatively low viscosity. Blocky peperite was inferred to relate to late stage *in situ* brittle fragmentation by cooling and contraction or quench fragmentation, possibly related to an increase in magma viscosity resulting from cooling.

An apophysis or intrusive body will advance until it terminates or is blocked by crystallization, quenching or brecciation, or a country rock with a strength that is greater than the magma's fluid pressure. Subsequent apophyses advance as breakouts from the main intrusive body as magma continues to be supplied to the intrusion front. Variations in magma supply to the intrusion front are likely to result in spatial variation in magma rheology, because domains will undergo crystallization or be quenched at varying times and places. This spatial variation in magma rheology during emplacement may result in autoclastic fragmentation, as in subaqueous lavas, and superimposition of quench fractures and domains of blocky peperite on original fluidal margins.

Fluidal textures should be commonly associated with komatiites because of the low viscosity of the magma. We have observed fluidal peperite associated with synsedimentary or shallow intrusive bodies of komatiite at Kambalda and Dundonald Beach (Abitibi Greenstone Belt). Blocky peperites are rarely associated with komatiites, but have been observed by one of us (SWB) associated with synsedimentary intrusive bodies of komatiitic basalt at Raglan, Cape Smith Belt.

The depth at which the komatiites intruded at Kambalda is limited to the thickness of the total pile of sediments (commonly <10–15 m) or of the host sediment (commonly <4 m). Synsedimentary intrusive bodies can form either as apophyses branching directly off upward-propagating dykes, or intruding from the base of lavas. The lack of dykes and the abundance of lava

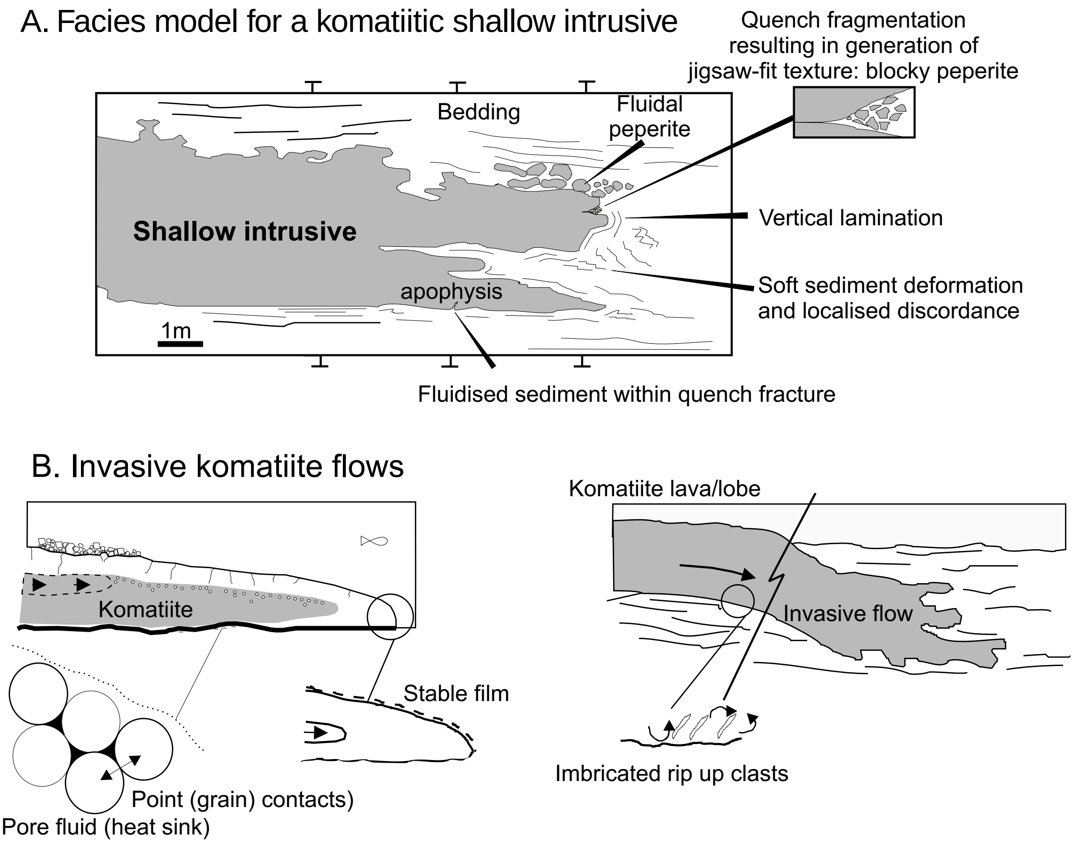

FIG. 6. A. Facies model of synsedimentary intrusive bodies in the Kambalda region. B. The shallow intrusive bodies are interpreted as lava flows that burrowed into wet unconsolidated sediments, producing invasive flows.

flows in the Kambalda region suggest that these apophyses may have intruded from the base of flows, *i.e.,* they are invasive flows.

INVASIVE FLOWS

The abundance of demonstrable lava flows in the Kambalda district and the restriction of shallow, synsedimentary intrusive bodies to domains of thicker sedimentary substrate suggest that the shallow intrusive bodies are of invasive flow origin, *i.e.,* due to burrowing of lava flows into the underlying wet, unconsolidated to semiconsolidated sedimentary substrate.

Invasive flows can be explained by the much greater density of komatiite lava (up to 2.75 g/cm^3) compared to unconsolidated water-saturated sediments (1.5–2.0 g/cm^3) over which they flow. The higher density and resultant negative buoyancy caused the komatiitic lava to load and burrow into the unconsolidated sediments. This process, in places, led to invasive flows or lobes (Fig. 6B) similar to those recorded in modern basalt lavas and flood basalts (*e.g.,* Byerly & Swanson 1978).

As no komatiitic units have been observed cutting other komatiitic units, we interpret each invasive flow or lobe to have formed prior to the next flow or invasive flow. The lava burrows into the sediment to a depth controlled largely by the depth to consolidated sediment or underlying coherent komatiite, *i.e.,* the law of superposition still applies. We infer that invasive flows are unlikely in sediment packages less than a few meters thick. If the sediment pile was only a few meters thick and unconsolidated, and the komatiitic lava was flowing in a turbulent state, then the sediment should have been removed by physical erosion (Cas & Beresford 2001), by scouring due to the density inversion; if the sediment was semicohesive, then the sediment pile may have been lifted over the approaching komatiitic lava. A similar phenomenon associated with flood basalts is referred to as "sediment lifting" (Reidel 1998).

The lateral extent of the invasive flows is difficult to ascertain from drill core, but invasive flows have been documented in basaltic terranes ranging from a few square meters (S. Self, pers. commun. 1999) to areas covering up to 10,000 km^2 (Rawlings 1998).

IMPLICATIONS FOR THE MODE OF EMPLACEMENT OF KOMATIITIC MAGMA

The majority of contacts between komatiitic lava and sedimentary substrate in flank environments are planar, and rarely show evidence of erosion (either thermal or physical), marginal autoclasis, or peperite formation. The presence of planar contacts, the lobate morphology of cross-sections, and the preservation of delicate *in situ* hyaloclasts in underlying flow-top breccias suggest that these flows of komatiitic magma were passively emplaced by laminar flow, which is consistent with recent theoretical reconsideration of the likely flow-front thickness and behavior of active komatiitic lavas (Cas *et al.* 1999), and the textural zonation and vesicle distribution in komatiites (Beresford *et al.* 2000).

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REFERENCES

BAVINTON, O.A. (1981): The nature of sulfidic metasediments at Kambalda and their broad relationships with associated ultramafic rocks and nickel ores. *Econ. Geol.* **76**, 1606-1628.

BERESFORD, S.W., CAS, R.A.F., LAMBERT, D.D. & STONE, W.E. (2000): Vesicles in thick komatiite lava flows, Kambalda, Western Australia. *J. Geol. Soc.* (*London*). **157**, 11-14.

BUSBY-SPERA, C.J. & WHITE, J.D.L. (1987): Variation in peperite textures associated with differing host-sediment properties. *Bull. Volcanol.* **49**, 765-775.

BYERLY, G. & SWANSON, D.A. (1978): Invasive Columbia basalt flows along the northwestern margin of the Columbia Plateau, north-central Washington*. Geol. Soc. Am., Abstr. Programs* **10**, 98.

CAS, R.A.F. & BERESFORD, S.W. (2001): Field characteristics and erosional processes associated with komatiitic lavas: implications for flow behavior. *Can. Mineral.* **39**, 505-524.

________, SELF, S. & BERESFORD, S.W. (1999): The behaviour of the fronts of komatiite lavas in medial to distal settings. *Earth. Planet. Sci. Lett.* **172**, 127-139.

CLAOUE-LONG, J.C., COMPSTON, W. & COWDEN, A.C. (1988): The age of the Kambalda greenstones resolved by ion-microprobe: implications for Archaean dating methods (Australia). *Earth. Planet. Sci. Lett.* **89,** 239-259.

COWDEN, A.C. & ROBERTS, D.E. (1990): Komatiite hosted nickel sulphide deposits, Kambalda. *In* Geology of the Mineral Deposits of Australia and Papua New Guinea (F.E. Hughes, ed.). *Austral. Inst. Mining Metall., Monogr.* **14**, 567-581.

FROST, K.M. (1992): *The Role of Ground Melting in the Genesis of Komatiite-Associated Nickel Sulfide Deposits at Kambalda and Widgiemooltha, Western Australia*. Ph.D. thesis, Univ. of Western Australia, Perth, Australia.

GOTO, Y. & MCPHIE, J. (1996): A Miocene basanite peperitic dyke at Stanley, northwestern Tasmania, Australia. *J. Volcanol. Geotherm. Res*. **74**, 111-120.

GRESHAM, J.J. & LOFTUS-HILLS, G.D. (1981): The geology of the Kambalda nickel field. *Econ. Geol*. **76**, 1373-1416.

GROVE, T.L., DE WIT, M.J. & DANN, J.C. (1997): Komatiites from the Komati type section, Barberton, South Africa. *In* Greenstone Belts (M.J. de Wit & L.D. Ashwal, eds.). Oxford University Press, Oxford, U.K. (438-453).

GROVES, D.I., BARRETT, F.M. & MCQUEEN, K.G. (1978): Geochemistry and origin of cherty metasediments within ultramafic flow sequences and their relationships to nickel mineralization. *Geological Department and Extensional Services, University of Western Australia, Publ.* **2**, 57-69.

HUDSON, D.R. (1972): Sediment–ore relationships at Lunnon shoot. Unpubl. WMC Report.

HUPPERT, H.E., SPARKS, R.S.J., TURNER, J.S. & ARNDT, N.T. (1984): Emplacement and cooling of komatiite lavas. *Nature* **309**, 19-22.

KANO, K. (1991): Miocene pillowed sills in the Shimane Peninsula, SW Japan. *J. Volcanol. Geotherm. Res*. **48**, 359-366.

KOKELAAR, B.P. (1982): Fluidization of wet sediments during the emplacement and cooling of various igneous bodies. *J. Geol. Soc.* (*London*) **139**, 21-33.

LESHER, C.M. & CAMPBELL, I.H. (1993): Geochemical and fluid dynamic modelling of compositional variations in Archean komatiite-hosted nickel sulfide ores in Western Australia. *Econ. Geol*. **88**, 804- 816.

LOWE, D.R. (1999): Petrology and sedimentology of cherts and related silicified sedimentary rocks in the Swaziland Supergroup. *In* Geologic Evolution of the Barberton Greenstone Belt, South Africa (D.R. Lowe & G.R. Byerly, eds.). *Geol. Soc. Am., Spec. Pap.* **329**, 83-114.

MILLS, A.A. (1984): Pillow lavas and the Leidenfrost effect. *J. Geol. Soc.* (*London*) **141**, 183-186.

PARMAN, S., DANN, J., GROVE, T.L. & DE WIT, M.J. (1997): Emplacement conditions of komatiite magmas from the 3.49 Ga Komati Formation, Barberton Greenstone Belt, South Africa. *Earth Planet. Sci. Lett.* **150**, 303-323.

PYKE, D.R., NALDRETT, A.J. & ECKSTRAND, O.R. (1973): Archean ultramafic flows in Munro Township, Ontario. *Geol. Soc. Am., Bull.* **84**, 955-978.

RAWLINGS, D. (1998): Extensive basalt sheets with marginal peperite, Australia: shallow tabular sill analogy of tube-fed lava. *IAVCEI Int. Volcanological Congress* (*Cape Town*), *abstr.*, 48.

REIDEL, S.P. (1998): Emplacement of Columbia River flood basalt. *J. Geophys. Res.* **103**, 27393-27410.

SQUIRE, R.J., CAS, R.A.F., CLOUT, J.M.F. & BEHETS, R. (1998): Volcanology of the Archaean Lunnon Basalt and its relevance to nickel sulfide-bearing trough structures at Kambalda, Western Australia. *Aust. J. Earth Sci.* **45**, 695-715.

THOMSON, B. (1989): Petrology and stratigraphy of some texturally well preserved thin komatiites from Kambalda, Western Australia. *Geol. Mag.* **126**, 249-261.

THORDARSON, T. & SELF, S. (1998): The Roza Member, Columbia River Basalt Group: a gigantic pahoehoe lava flow field formed by endogenous processes? *J. Geophys. Res.* **103**, 27411-27445.

WILLIAMS, D.A., KERR, R.C. & LESHER, C.M. (1998): Emplacement and erosion by Archean komatiite lava flows at Kambalda: revisited. *J. Geophys. Res.* **103**, 27533-27549.

WILSON, A.H. & VERSFELD, J.A. (1994): The early Archaean Nondweni greenstone belt, southern Kaapvaal Craton, South Africa. I. Stratigraphy, sedimentology, mineralization and depositional environment. *Precamb. Res.* **67**, 243-276.

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