Economic Geology
Vol. 96, 2001, pp. 1695–1700

SCIENTIFIC COMMUNICATIONS

PALEOSEA-FLOOR VOLCANIC-ASSOCIATED MASSIVE SULFIDE MINERALIZATION RELATED TO A COOLING KOMATIITE FLOW, ABITIBI SUBPROVINCE, CANADA

C. TUCKER BARRIE,†

C. T. Barrie and Associates, Inc., 23 Euclid Avenue, Ottawa, Ontario, Canada K1S 2W2

ALEX ERENDI, AND LAWRENCE CATHLES, III

Department of Geological Sciences, Snee Hall, Cornell University, Ithaca, New York 15823

Abstract

Paleosea-floor, volcanic-associated massive sulfide mineralization has been discovered 50 to 150 m upsection from a Late Archean peridotitic komatiite flow, where the flow is thickest in a thermal erosion channel. The Terminus massive sulfide occurrence is within carbonaceous argillites that are intercalated with basaltic komatiite flows and flow breccias. It contains appreciable Zn and Cu contents and is associated with silicification and chlorite-epidote alteration.

Ultramafic magmas are ideal heat sources for hydrothermal convective systems because of their extremely high liquidus temperatures and their tendency to become less permeable during serpentinization, which impedes advective cooling. Heuristic calculations indicate that there is sufficient enthalpy in the peridotitic komatiite flow to drive the hydrothermal system responsible for the Terminus mineralization. This hypothesis is tested using two-dimensional, finite element heat and fluid-flow simulations. The results suggest that, under the right circumstances (1) relatively thick komatiite flows may take hundreds of years to cool; (2) komatiite flow-driven hydrothermal systems can form sea-floor or subsea-floor deposits comparable in mass to those along the mid-Atlantic Ridge; (3) much of the metal leaching by hydrothermal fluids occurs below, and adjacent to, the flow; and (4) the shape of heat source komatiite flows, or subsea-floor magma chambers, affects the locus and distribution of hydrothermal upwelling. Similar, base metal-precipitating paleohydrothermal systems are present above ponded komatiite flows broadly along strike at the Potter Zn-Cu deposit in Munro township, Ontario. These paleohydrothermal systems, and the calculations presented here, suggest that thick, ponded basaltic flows on the modern sea floor have sufficient enthalpy to form significant hydrothermal sulfide accumulations.

Introduction

The majority of sea-floor and paleosea-floor sulfide deposits in volcanic settings are a product of magma chamber-driven hydrothermal convection, where metals are leached from surrounding rocks and precipitated at or near the sea floor when the hydrothermal fluids mix with cool seawater (Franklin et al., 1981; Hannington et al., 1995; Barrie and Hannington, 1999). However, many volcanic-associated massive sulfide deposits are not associated with observable synvolcanic intrusions, and their ultimate heat source is unclear. This study documents a paleosea-floor sulfide occurrence that is clearly linked to a cooling komatiite flow rather than a mafic or felsic magma chamber at depth. Ultramafic magmas are ideal heat sources for hydrothermal convective systems, principally because they have extremely high liquidus temperatures of >1,350° to 1,650°C (Bickle, 1982; Nisbet, 1982). They also may crystallize olivine in abundance, which adds to the enthalpy of the system as olivine has a high latent heat of crystallization (Sparks, 1986). Furthermore, they remain less permeable than other magmas and/or rock types during cooling because of serpentinization, which occludes fluid flow and prevents their convective cooling (Lister, 1974; MacDonald and Fyfe, 1985; O'Hanley, 1996). Despite these attributes, komatiite flows have not been considered as heat sources for volcanic-associated massive sulfide deposits. There are few volcanic-associated massive sulfide deposits or occurrences known to be associated with komatiites, and komatiites are generally considered to be relatively thin flows that cool in weeks to months in subaqueous settings (Bickle, 1982; Huppert et al., 1984), too quickly to generate significant sea-floor hydrothermal deposits (Cathles, 1983).

In this study, the geology of the Terminus Zn-Cu sulfide occurrence is described in relationship to the proposed heat source Empire peridotitic komatiite flow. A geologically realistic physical model of this setting is then simulated using a two-dimensional, finite element heat and fluid-flow model. The results are quantified in terms of the mass and temperatures of hydrothermal fluid vented on the paleosea floor and compared to the Terminus mineralization. The results presented here support the geologic evidence that enthalpy from the cooling Empire flow was responsible for hydrothermal circulation that led to the sulfide mineralization at Terminus. More generally, the results also support the contention that thick, ponded basaltic flows on the sea floor can, under the right circumstances, generate significant sea-floor sulfide accumulations today.

† Corresponding author: e-mail, barriect@sympatico.ca

Geologic Setting: Along Strike with the Giant Kidd Creek Volcanic-Associated Massive Sulfide Deposit

The Terminus Zn-Cu sulfide occurrence is within the 2.71 to 2.72 Ga Kidd-Munro assemblage, a 180- × 2- to 12-km belt of ultramafic, mafic, and felsic rocks, extending from the giant Kidd Creek volcanic-associated massive sulfide deposit area north of Timmins to the Ontario-Quebec border (Jackson and Fyon, 1991; Fig. 1). The most prominent feature in the host stratigraphic succession is the Dundonald sill, a relatively unaltered, 20- × 0.8-km mafic-ultramafic intrusion. The Dundonald sill cuts the adjacent volcanic strata. Upsection from the Dundonald sill are dacite-andesite, komatiite, argillite, and basalt units, including the Empire peridotitic komatiite flow (Fig. 1). A dacite in this stratigraphic succession has a U-Pb zircon age of 2717.3 ± 1.2 Ma, and the Dundonald Sill has a U-Pb age of 2707^{3+}_{2-} Ma (Barrie et al., 1999a). Thus the sill is younger by ~10 m.y. than the strata that are host to the Terminus occurrence. The dacite U-Pb age is in agreement with an average galena Pb isotope model age of 2717.6 ± 4 Ma for the Terminus occurrence, using the Abitibi Pb isotope model of Thorpe (1999; App. 1).

The Terminus area stratigraphic succession is coeval with footwall rocks of the giant Kidd Creek volcanic-associated massive sulfide deposit (>150 Mt Cu-Zn-Ag sulfide ore; Hannington and Barrie, 1999), 40 km along strike to the west (Fig. 1). Komatiites are the most abundant rock type in the footwall section at Kidd Creek. The komatiites are intercalated with massive and epiclastic rhyolite, beneath the ore and the ore-hosting mine rhyolite unit. Outside the immediate mine area and at approximately the same stratigraphic level as the orebodies are chemically distinctive, low Ti basalt units, which are also present immediately upsection from the Terminus occurrence (Barrie, 1999; Barrie et al., 1999a; Wyman, 1999). The Kidd Creek footwall rocks are 2717 ± 2 to 2714.4 ± 1.0 Ma (Barrie and Davis, 1990; Bleeker et al., 1999).

The rocks in the vicinity of the Terminus occurrence have been subjected to two Late Archean folding events responsible for near-upright isoclinal folds, and then a transpressional event that produced the major gold-bearing east-west structures to the south. The stratigraphic succession has been folded into a west-facing west fold, with an open northern syncline and a tight southern syncline that is complicated by axial planar and other faults (Fig. 1b).

The Empire peridotitic komatiite flow

The Empire flow, 70 to 180 m thick, is a peridotitic komatiite flow or series of flows that contain the Dundeal Ni deposit and probably the Dundonald South and Alexo deposits as well (Figs. 1b, 2). The Empire flow has a lower, medium-grained, meso- to adcumulate peridotite-dunite section 40 to 85 m thick, an upper, medium- to fine-grained and locally aphanitic section of peridotite and pyroxenite with minor gabbroic sections of approximately equal thickness, and spinifex-bearing flow-top breccias from 0 to 10 m in thickness. Flow-top breccias and olivine spinifex at the top of the Empire flow commonly form multiple layers, and these are intercalated with graphitic and locally sulfidic argillite. The flow top is absent locally, and textures are consistent with erosion during emplacement of the overlying flow prior to crystallization. Olivine spinifex is locally bent or broken, an indication of burial by overlying flows prior to complete cooling (Gole et al., 1990). The meso- to adcumulate peridotite-dunite base of the flow is thickest in the vicinity of the Dundeal Ni deposit and the Terminus hydrothermal mineralization, and the flow geometry suggests a thermal erosion channel in this area (Fig. 2; Barrie et al., 1999a). The paleovertical wall in Figure 2b may thus represent a thermal erosion cut bank. The basal 1 to 3 m of the Empire flow is fine grained to aphanitic and commonly has moderate to strong chlorite and magnesite alteration. The base and 1 to 20 m of the adjacent host rock are cut by quartz-chlorite– or quartz-epidote–filled veinlets and hairline fractures. These veinlets and fractures are believed to reflect hydrothermal circulation at the margins of the flow during cooling.

Above the Empire flow are thinner basaltic komatiite and basaltic flows that are intercalated with graphitic and locally sulfidic argillite. The basaltic komatiite flows are generally well-preserved, with cumulus bases and spinifex-textured flow-top breccias, although in places flow tops are absent, with alternating peridotite and pyroxenite cumulate subunits on a scale of meters to tens of meters. The interflow sediments commonly exhibit peperite textures in contact with the komatiite flows that indicate the flow was emplaced into wet sediments (Busby-Spera and White, 1987). In places the peperite textures are preserved as delicate eggshell breccias, where shattered spherical glass rinds are mixed with graphitic argillite.

Terminus Zn-Cu occurrence

The Terminus Zn-Cu (+ minor Pb and Ag) sulfide occurrence is within graphitic and sulfidic argillite and basaltic komatiite-komatiitic basalt flow-top breccias, upsection 50 to 100 m from the top of the Empire flow, and ~350 to 400 m upsection of the Dundonald sill (Fig. 2). It is present only within 250 m of the thick peridotite-dunite core of the Empire flow, although minor pyrite occurrences occur along strike for several kilometers. The mineralization is discontinuous along strike and updip. It is characterized by semimassive and locally massive sulfide mineralization, with laminar and nodular pyrite-pyrrhotite concentrations, and bedded and veined sphalerite, chalcopyrite, and galena. The textures in the sulfide and at contacts with adjacent flows are well-preserved (e.g., preservation of delicate eggshell breccia textures), and centimeter- to millimeter-scale layering in sulfide is interpreted to represent primary bedding. The best intersection has semimassive sulfide in graphitic argillite, with 7.53 percent Zn, 1.37 percent Cu, 0.13 percent Co, 46 ppm Ni, 0.1 percent Pb, 1.1 ppm Au, 29.1 ppm Ag, Pt <20 ppb, and Pd <20 ppb, over an estimated true thickness of 7.5 m. Most of the other mineralized intersections have Zn/Cu = 3 to 100. Although a geologic resource has not been calculated to industry standards, the occurrence is estimated to have at least 5,000 to 15,000 t of ore-grade or near ore-grade material above a 500-m depth. The encompassing komatiite and komatiitic basalt flows exhibit weak to moderate serpentinization, overprinted by weak to moderate chlorite alteration and minor silicification. The silicification is confined to within ~10 m of the mineralization and to the margins of the Empire flow.

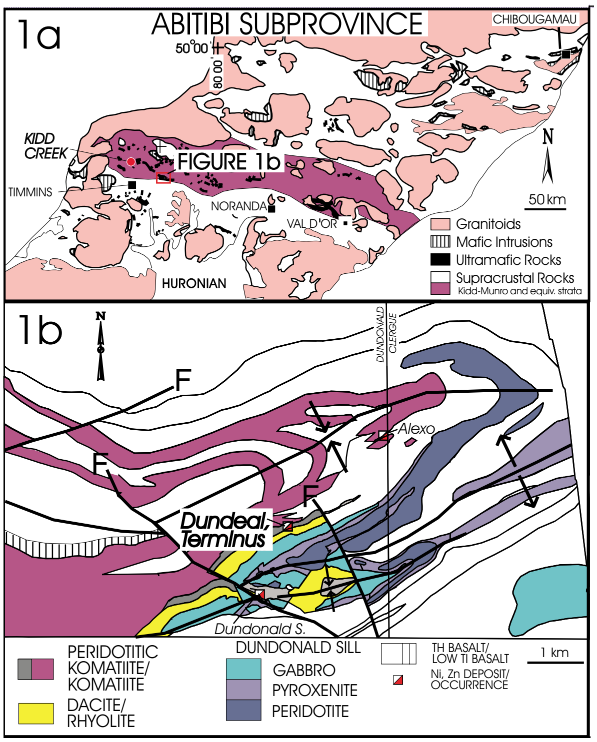

FIG. 1. a. Location map of the Terminus area within the Abitibi subprovince of Ontario and Quebec, Canada. b. Geology of the Dundeal-Terminus area. Modified after Barrie et al. (1999a).

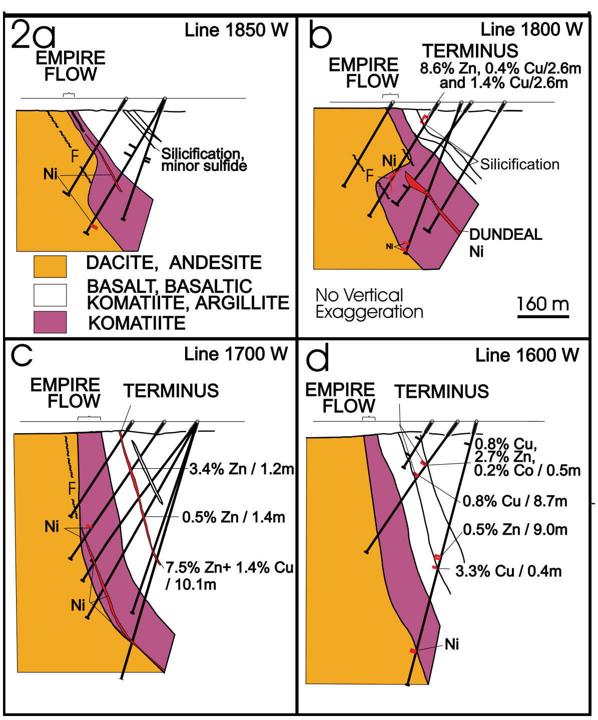

FIG. 2. West-southwest-facing cross sections based on drilling. a. Line 1850 (m) west. The Empire flow basal peridotite-dunite is core ~100 m thick. b. Line 1800 west. The basal cumulates are ~225 m thick, adjacent to a paleoovertical wall. The geometry suggests a thermal erosion channel. The core of the Dundeal Ni deposit is in this section. c. Line 1700 west. The Empire flow is overlain by significant Zn-Cu mineralization. d. Line 1600 west. The Empire flow flattens but is still ~150 m thick with an ~80-m-thick cumulate base. Modified after Barrie et al. (1999a).

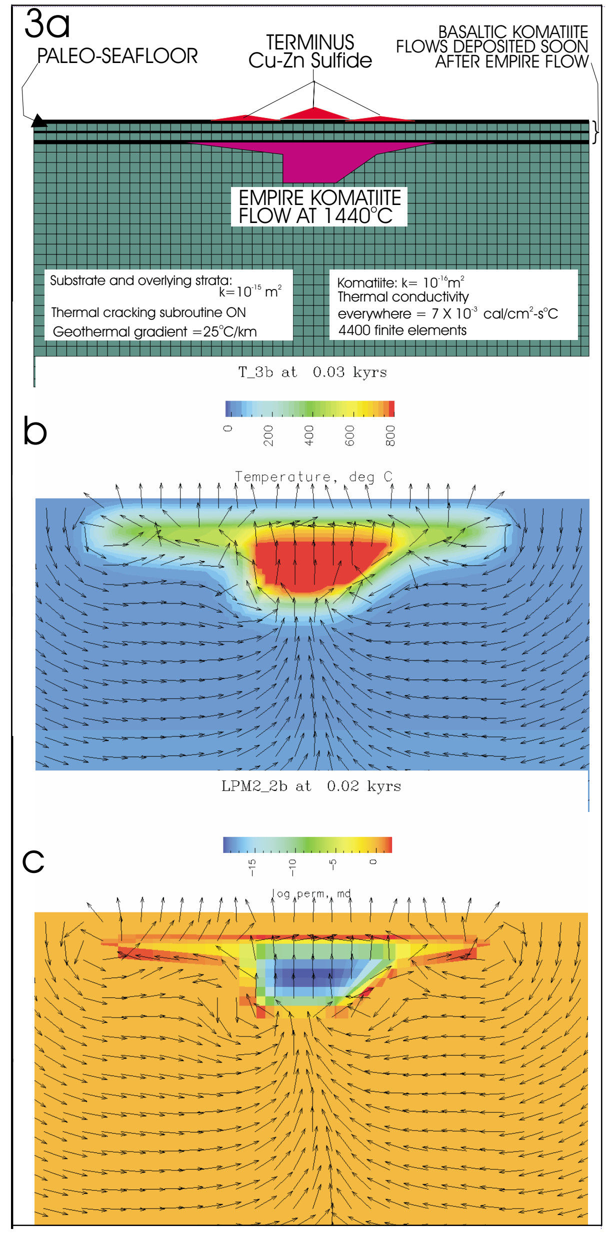

FIG. 3. a. Physical model for the Empire flow, based on section 1850 west in Figure 2. b. Temperature in finite element grid 25 yr after simulation starts. Vectors represent average direction of fluid flow for an area. c. Permeability at 25 yr, in millidarcy log units. The hot komatiite flow remains impermeable until it cools to <~500°C when thermal cracking begins.

Heat and Fluid-Flow Modeling for a Cooling Komatiite Flow

It is instructive to estimate the maximum mass of hydrothermal fluid venting at an average temperature of 200°C that can be produced by an intrusion. This can be calculated simply by balancing the heat lost from a cooling mass against heat gained by heating seawater from its ambient temperature on the sea floor to 200°C and considering the heat capacity of rock and water, as follows:

$$(\text{magma temperature} - 200°\text{C}) \times \text{mass of intrusion} \times 1/3 \text{ cal/g°C} = (200° - 0°\text{C}) \times \text{mass of hydrothermal fluid} \times 1 \text{ cal/g°C}. \quad (1)$$

The volume of the Empire flow in the flow channel beneath the Terminus occurrence (Fig. 3) is 200 m thick × (375) m in average width × 200 m along strike = 1.5 × 10^7 m^3. At 2.7 g/cc, this corresponds to a mass of 4.05 × 10^7 t. The liquidus temperature is 1,440°C, based on the anhydrous chill composition of the flow (Barrie et al., 1999a) and the MgO geothermometer for komatiites of Bickle (1982). Using these values and the equation above, this corresponds to 8.37 × 10^7 t of hydrothermal fluid at an average temperature of 200°C. If a hydrothermal fluid can transport ~10 ppm Zn + Cu at this temperature (Large et al., 1989), this corresponds to 8.37 × 10^2 t of metal or 8.37 × 10^3 t of sulfide with 10 percent combined Zn and Cu content. This is a reasonable estimate for the mass of the known base metal-bearing sulfide at Terminus.

A two-dimensional physical model, based on the cross section in Figure 2b, has a komatiite flow with a maximum thickness of 200 m, a width of 500 m, and thinner overbank deposits that extend to either side (Fig. 3a). The substrate is given a bulk permeability of 1 mD (= 10^{-15} m^2), the overlying rocks a value of 10 mD, and the komatiite is given 0.1 mD initially, in keeping with permeability reduction during serpentinization. Volcanic rocks in the upper oceanic crust have similar permeabilities (e.g., DDH 504B, East Pacific Rise; Anderson et al., 1985). A thermal cracking subroutine is incorporated that increases permeability over a temperature range of 275° to 475°C and decreases permeability at higher temperatures (Lister, 1974; Cathles, 1983; Barrie et al., 1999b, c). The calculations do not take into account latent heat of crystallization, which, for olivine, would add ~15 to 20 percent enthalpy during crystallization (Sparks, 1986). The finite element grid is refined (e.g., has more finite elements) at the edges and above the flow. The walls and floor of the finite element grid are insulating and impermeable. The top boundary (paleosea floor) is insulating but allows the passage of fluid flow, following Cathles (1983). Deep-water conditions and nonboiling fluids are assumed. Time steps for the finite element simulation presented here are based on mathematical convergence for each step and range from 1 to 20 yr.

Results

The two-dimensional finite element case presented here ran until no hydrothermal venting >100°C occurred, for 430 yr, effectively simulating all of the base metal-transporting hydrothermal circulation (Fig. 4). At this stage the core of the komatiite has cooled to <250°C. At the onset of convection, fluid flow migrates along the komatiite flow base and vents vigorously above the wingtip edges but remains below ~150°C. The base of the right side of the komatiite slopes upward, and this side draws more hydrothermal fluid than the vertical wall on the left side. The central venting builds soon thereafter, with vent temperatures approaching 250°C but

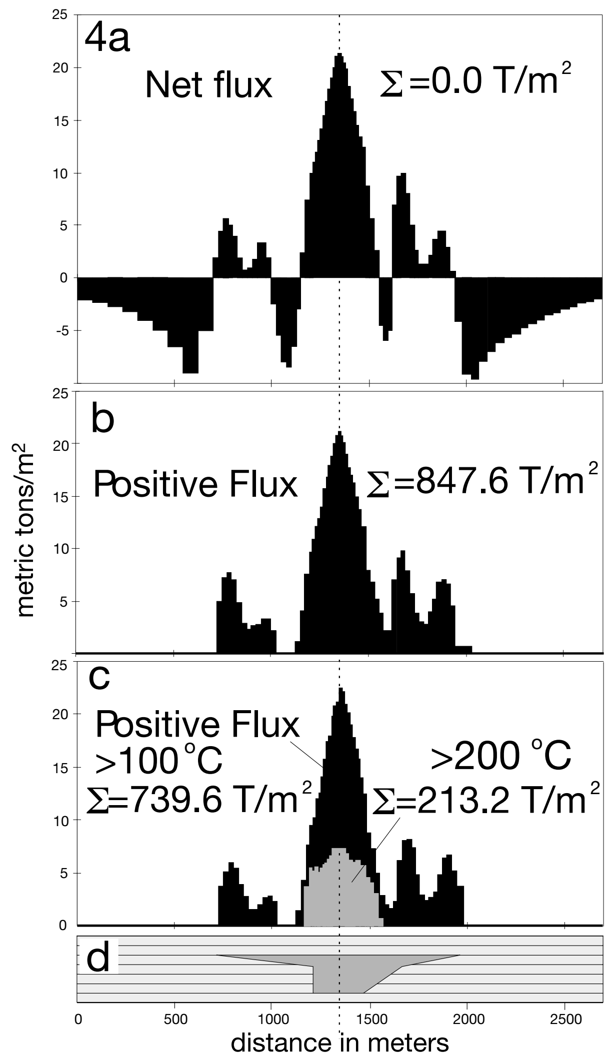

FIG. 4. a. Cumulative net flux at the sea floor. Mass is conserved across the sea-floor boundary. b. Cumulative, positive (e.g., upward vertical) flux. c. Cumulative positive flux for fluids >100° and >200°C. d. Physical model of komatiite flow in cross section, with same horizontal scale as panels above, for reference.

averaging ~170°C in this area. Most of the hydrothermal fluid venting occurs at 100° to 200°C (Fig. 4c) above the central core of the cooling komatiite flow. Downwelling occurs at the margins of the flow and, once the overbank deposits are cooled sufficiently, at the margin of the central flow core.

The cumulative mass of hydrothermal fluid vented over 430 yr is 847.6 t/m^2, whereas the cumulative masses at >100° and >200°C are 739.6 and 213.2 t/m^2, respectively. The total mass of vented hydrothermal fluids in three dimensions is calculated by multiplying these values by the width of venting in Figure 3b and c and by a 200-m strike length for the komatiite, perpendicular to the plane of the two-dimensional model. For the >100°C hydrothermal fluid (avg venting at ~170°C), which would transport most of the base metals, the cumulative mass is 1.78 × 10^8 t. This is 2.1× the estimate based on the heuristic calculations for 200°C above. This discrepancy is because the model komatiite channel is slightly larger than that in the heuristic calculations and the lower average venting temperature for the hydrothermal fluids in the finite element simulation.

Discussion

The Terminus mineralization is spatially associated with the thickest part of the most primitive komatiite flow in the area, and both heuristic and finite element calculations indicate that cooling of the komatiite flow was capable of driving a sufficient mass of hydrothermal fluid to account for the mineralization. Although there are dacite-rhyolite units downsection from the komatiite-basalt section that is host to the Terminus mineralization, these are not known to host any mineralization, and there are no known high-level felsic intrusions in the region that may be potential heat sources for paleosea-floor mineralization. The finite element simulation accurately predicts that ~three-quarters of the hydrothermal venting should take place over the thickest part of the komatiite flow, and the base and margins of the flow, particularly around the flow core, should be hydrothermally altered and thermally cracked.

The heat and flow model takes 430 yr until venting is at <100°C and the core of the komatiite is <250°C. Thus the model provides a first-order approximation for the cooling of a komatiite flow with these dimensions and where overlain (and partly insulated) by 100 m of more permeable material.

This relatively simple finite element model does not consider permeable fractures. There are no clear synvolcanic faults in the immediate Terminus area. In other magma sill-driven modeling exercises, we have found that the patterns of heat and fluid flow that develop without permeable fractures generally control the location of down- or upwelling. Adding permeable fractures can modify these patterns to a degree, but fractures may have only second-order controls on hydrothermal circulation patterns, particularly once the hydrothermal system is established.

Implications and Conclusions

As a volcanic-associated massive sulfide-style, paleohydrothermal system driven by a cooling komatiite flow, the Terminus occurrence is not unique. Other examples are found in the Kidd-Munro assemblage along strike to the east. The Potter Zn-Cu mine and the Potterdoal Zn-Cu deposit (Epp and Crocket, 1999) are above ponded peridotitic komatiites in Munro township, Ontario (Pyke et al., 1973; Arndt, 1986). The Potter mine has 1 to 2 Mt of Zn-Cu-bearing sulfide ore plus an equivalent amount of Zn-Cu-poor sulfide (Coad, 1976; and new discoveries), comparable to ~4 Mt at the TAG hydrothermal deposit, the largest of the deposits discovered along the mid-Atlantic Ridge (Hannington et al., 1995). Anomalous Zn has been documented in oxide minerals in komatiites and in interflow sedimentary rocks in the Kambalda Ni district (Groves et al., 1977; Bavinton, 1981), and hydrothermal alteration has been noted in the vicinity of Ni deposits (e.g., Shangani, Zimbabwe; Viljoen et al., 1976, Williams, 1979). Although volcanic-associated massive sulfide deposits within komatiite-basalt sequences outside of the Abitibi subprovince are undocumented, this study suggests that komatiite-bearing greenstone belts may be fertile ground for discovering occurrences and deposits similar to Terminus and those in Munro township.

This study raises the possibility that thick, ponded basalt flows or magma lakes on the sea floor may also have significant hydrothermal sulfide deposits. In comparison to komatiite magma, tholeiitic basaltic magma has one-half to two-thirds the enthalpy, so the ponded flows would have to be proportionally thicker. Thick ponded basalt flows may occur in active spreading centers adjacent to graben walls (e.g., CoAxial segment, Juan de Fuca Ridge; Chadwick et al., 1995) or in subaqueous, volcanically active ocean island settings (e.g., a submerged Kilauea Iki; Helz and Thornber, 1987).

The two-dimensional, finite element heat and fluid-flow model presented here predicts the pattern, relative strength, and temperatures of hydrothermal upwelling above the Empire peridotitic komatiite flow with reasonable accuracy. It demonstrates that heat and fluid-flow models can be used in a predictive fashion for magma-driven, paleosea-floor hydrothermal systems.

Acknowledgments

This work was supported by the Kidd-Munro extension project, a joint industry-government initiative sponsored by Teck Exploration Ltd., Outokumpu Mines and Exploration, Canada, Noranda Mining and Exploration, Falconbridge Exploration Ltd., Inco Exploration and Technical Services, Inc., the Ontario Geological Survey, and the Geological Survey of Canada; and CAMIRO (Canadian Mining Research Organization) project 96E01: "Heat and Fluid Flow Modeling of Giant Volcanic-Associated Massive Sulfide Systems," sponsored by seven mining companies and the Geological Survey of Canada. Paul Davis, Scott McLean, and Ray Band of Falconbridge are thanked for their help with, and support of, this project. We thank Paul Manhardt of GeoGroup, Inc. for help with the Access.basin™ finite element modeling computer code.

February 5, June 13, 2001

REFERENCES

Anderson, R.N., Zoback, M.D., Hickman, S.H., and Newmark, R.L., 1985, Permeability versus depth in the upper oceanic crust: In situ measurements in DSDP hole 504B, eastern equatorial Pacific: Journal of Geophysical Research, v. 90, p. 3659–3669.

Arndt, T.N., 1986, Spinifex and swirling olivines in a komatiite lava lake, Munro township, Canada: Precambrian Research, v. 34, p. 139–156.

Barrie, C.T., 1999, Komatiite flows of the Kidd Creek footwall, Abitibi subprovince, Canada: ECONOMIC GEOLOGY MONOGRAPH 10, p. 143–162.

Barrie, C.T., and Davis, D.W., 1990, Timing of magmatism and deformation in the Kamiskotia-Kidd Creek area, western Abitibi subprovince, Ontario: Precambrian Research, v. 46, p. 217–240.

Barrie, C.T., and Hannington, M.D., 1999, Volcanic-associated massive sulfide deposits: Processes and examples in modern and ancient settings: Introduction: Reviews in Economic Geology, v. 8, p. 1–11.

Barrie, C.T., Corfu, F., Davis, P., Coutts, A.C., and MacEachern, D., 1999a, Geochemistry of the Dundonald komatiite-basalt suite and genesis of the Dundeal Ni deposit, Abitibi subprovince, Canada: ECONOMIC GEOLOGY, v. 94, p. 845–866.

Barrie, C.T., Cathles, L.M., Erendi, A., Schwaiger, H., and Murray, C. 1999b, Heat and fluid flow models and VMS systems: Reviews in Economic Geology, v. 8, p. 201–220.

Barrie, C.T., Cathles, L.M., and Erendi, A., 1999c, Finite element heat and fluid-flow computer simulations of a deep ultramafic sill model for the giant Kidd Creek volcanic-associated massive sulfide deposit, Abitibi subprovince: ECONOMIC GEOLOGY MONOGRAPH 10, p. 529–540.

Bavinton, O.A., 1981, The nature of sulfidic metasediments at Kambalda and their broad relationships with associated ultramafic rocks and nickel ores: ECONOMIC GEOLOGY, v. 76, p. 1606–1628.

Bickle, M.J., 1982, The magnesium contents of komatiite liquids, *in* Arndt, N.T., and Nisbet, E.G., eds., Komatiites: London, George Allen and Unwin, p. 479–494.

Bleeker, W., Parrish, R.R., and Sager-Kinsman, A., 1999, High-precision U-Pb geochronology of the Late Archean Kidd Creek deposit and Kidd Volcanic Complex: ECONOMIC GEOLOGY MONOGRAPH 10, p. 43–70.

Busby-Spera, C.J., and White, J.D.L., 1987, Variation in peperite textures associated with differing host-sediment properties: Bulletin of Volcanology, v. 49, p. 765–775.

Cathles, L.M., 1983, An analysis of the hydrothermal system responsible for massive sulfide deposition in the Hokuroku basin of Japan: ECONOMIC GEOLOGY MONOGRAPH 5, p. 439–487.

Chadwick, W.W., Embley, R.W., and Fox, C.G., 1995, SeaBeam depth changes associated with recent lava flows, CoAxial segment, Juan de Fuca Ridge: Evidence for multiple eruptions between 1981–1993: Geophysical Research Letters, v. 22, p. 167–170.

Coad, P.R., 1976, The Potter mine: Unpublished M.Sc. thesis, Toronto, Ontario, University of Toronto, 239 p.

Epp, M., and Crocket, J.H., 1999, Geology and geochemistry of the Potterdoal Cu-Zn deposit, Munro township, Ontario: ECONOMIC GEOLOGY MONOGRAPH 10, p. 593–612.

Franklin, J.M., Lydon, J.W., and Sangster, D.M., 1981, Volcanic-associated massive sulfide deposits: ECONOMIC GEOLOGY 75TH ANNIVERSARY VOLUME, p. 485–627.

Gole, M.J., Barnes, S.J., and Hill, R.E.T., 1990, Partial melting and recrystallization of Archean komatiites by residual heat from rapidly accumulated flows: Contributions to Mineralogy and Petrology, v. 105, p. 704–714.

Groves, D.I., Barrett, F.M., Binns, R.A., and McQueen, K.G., 1977, Spinel phases associated with metamorphosed volcanic-type iron-nickel sulfide ores from Western Australia: ECONOMIC GEOLOGY, v. 72, p. 1224–1244.

Hannington, M.D., and Barrie, C.T., 1999, eds., The giant Kidd Creek volcanogenic massive sulfide deposit, western Abitibi subprovince, Canada: ECONOMIC GEOLOGY MONOGRAPH 10, 672 p.

Hannington, M.D., Jonasson, I.R., Herzig, P.M., and Peterson, S., 1995, Physical and chemical processes of seafloor mineralization at mid-ocean ridges: American Geophysical Union Monograph 91, p. 115–157.

Helz, R.T., and Thornber, C.R., 1987, Geothermometry of Kilauea Iki lava lake, Hawaii: Bulletin Volcanologique, v. 49, p. 6651–6668.

Huppert, H.E., Sparks, R.S.J., Turner, J.S., and Arndt, N.T., 1984, Emplacement and cooling of komatiite lavas: Nature, v. 309, p. 19–22.

Jackson, S.L., and Fyon, J.A., 1991, The western Abitibi subprovince in Ontario: Ontario Geological Survey Special Volume 4, p. 405–484.

Large, R.R., Huston, D.L., McGoldrick, P.J., Ruxton, P.A., and McArthur, G., 1989, Gold distribution and genesis in Australian volcanogenic massive sulfide deposits and their significance for gold transport models: ECONOMIC GEOLOGY MONOGRAPH 6, p. 520–536.

Lister, C.R.B., 1974, On the penetration of water into hot rock: Geophysical Journal of the Royal Astronomical Society, v. 39, p. 465–509.

MacDonald, A.H., and Fyfe, W.S., 1985, Rate of serpentinization in seafloor environments: Tectonophysics, v. 116, p. 123–135.

Nisbet, E.G., 1982, The tectonic setting and petrogenesis of komatiites, *in* Arndt, T.N., and Nisbet, E.W., eds., Komatiites: London, Allen and Unwin, p. 501–520.

O'Hanley, D.S., 1996, Serpentinites; Records of tectonic and petrological history: Oxford Monographs on Geology and Geophysics, v. 34, 277 p.

Pyke, D.R., Naldrett, A.J., and Eckstrand, O.R., 1973, Archean ultramafic flows in Munro township, Ontario: Geological Society of America Bulletin, v. 84, p. 955–978.

Sparks, R.S.J., 1986, The role of crustal contamination in magma evolution through geological time: Earth and Planetary Science Letters, v. 78, p. 211–223.

Thorpe, R.I., 1999, The Pb isotope linear array for volcanogenic massive sulfide deposits of the Abitibi and Wawa subprovinces, Canadian Shield: ECONOMIC GEOLOGY MONOGRAPH 10, p. 555–576.

Viljoen, M.J., Bernasconi, A., van Coller, N., Kinloch, E.D., and Viljoen, R.P., 1976, The geology of the Shangani nickel deposit, Rhodesia: ECONOMIC GEOLOGY, v. 71, p. 76–95.

Williams, D.A.C., 1979, The association of some nickel sulfide deposits with komatiitic volcanism in Rhodesia: Canadian Mineralogist, v. 17, p. 337–349.

Wyman, D.A., 1999, A 2.7 Ga komatiite, low Ti tholeiite, arc tholeiite transition, and inferred proto-arc geodynamic setting of the Kidd Creek deposit: Evidence from precise trace element data: ECONOMIC GEOLOGY MONOGRAPH 10, p. 511–528.

APPENDIX 1

Galena Lead Isotope Data for Terminus Zone Massive Sulfide

Galena from a sample of Terminus massive sulfide occurrence has been analyzed for its lead isotope geochemistry (Table 1A). The values are primitive, and they plot within the Abitibi linear array of Thorpe (1999). The values for grain II correspond to those of the Kidd Creek deposit (Barrie et al., 1999c), whereas grain I has a more evolved signature plotting in the field of values typical for Noranda. Model ages (Thorpe, 1999) for individual analyses range from 2713 to 2724 Ma (μ values from 8.36–8.47, κ values from 3.85–4.17), with a model age of 2717.6 Ma (μ = 8.40; κ = 4.51) for the average of all three analyses. The analyses show that the lead was derived from a primitive source at ~2.71 to 2.72 Ga, comparable to the U-Pb age for the underlying dacite, and that the lead isotope composition has not been disturbed since that time.

TABLE 1A. Pb Isotope Date for Terminus Zn-Cu Zone Galena

Galena	$^{206}Pb/^{204}Pb$	2σ (abs)	2σ (=% m; % r)	$^{207}Pb/^{204}Pb$	2σ (abs)	2σ (=% m; % r)	$^{208}Pb/^{204}Pb$	2σ (abs)	2σ (=% m; % r)
96TB0038-I	13.288	0.008	(0.018; 0.12)	14.485	0.012	(0.076; 0.18)	33.181	0.007	(.014; 0.24)
96TB0038-II-i	13.256	0.008	(0.016; 0.12)	14.442	0.012	(0.032; 0.18)	33.057	0.007	(0.07; 0.24)
96TB0038-II-ii	13.262	0.009	(0.038; 0.12)	14.449	0.012	(0.078; 0.18)	34.11	0.007	(0.1; 0.24)

Analyses by Fernando Corfu at the Royal Ontario Museum

Notes: All ratios corrected for 0.1%/amu fractionation; 2σ measurement error in absolute (= abs) and in percent (% m); (% r is reproducibility estimated from replicate measurement of standards); I,II = analyses of different grains from same sample; i, ii = replicate analysis of same grain