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PHYSICAL MODELING OF THE FORMATION OF KOMATIITE-HOSTED NICKEL DEPOSITS AND A REVIEW OF THE THERMAL EROSION PARADIGM

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Abstract

Theoretical assessment of the physics of komatiites as resulting from open-channel flows indicates them to be turbulent and to have velocities ranging from meters/second to tens of meters per second, depending on slope and thickness (*i.e.*, depth) of the flow. These flows should also carry stratifications of suspended load (due to increasing content of crystals as the melt cools along its run) as do rivers transporting sediment. Depending on the distance from the source, the bed load may be rich in olivine crystals, the suspended load above it, rich in sulfides, and the upper portions of the flow may consist of more evolved material. Calculated thicknesses of these suspended loads and their vertical distributions correspond to field observations. Primocrysts (*e.g.*, chromian spinel) should accumulate at the boundaries separating each suspended load in the flow. The observed drop in temperature per kilometer of run of basalt lava flows provides a means to imply cooling rates for higher-temperature komatiite flows. Barring supersaturation, the implied rates of cooling indicate that sulfides should begin to precipitate from a komatiitic melt around 40 km from the source. Finite-element modeling of these flows indicates that eddies form on the upstream side of ledges or in hollows. These eddies provide an extremely efficient means for scavenging metals into sulfides, and their morphology corresponds to massive sulfide deposits associated with embayments. The vigor of the eddies is dependent on the Reynolds number *Re*, and indicates *Re* to be as important as the *R* factor for the formation of economic deposits. The sulfides must be well mixed with the melt in order to scavenge the greatest amount of nickel. Scavenging efficacy increases with *Re* to a maximum, then decreases. For example, a thick flow (large *R* factor) will be fast (large Reynolds number), in which case the melt may simply hurdle the embayment with little eddy formation and little catchment for massive sulfide formation. These numerical models support some of the physical models of Naldrett and coworkers. It is difficult to incorporate the results here into thermal erosion models, which is in line with recent critiques of such mechanisms. Thermal erosion is not seen in industrial practice, where continuous casting of melts of temperatures considerably higher than magmas yield only chilled margins between sluice and melt, which armors against any chemical communication between the two. Similarly, Hawaiian lavas do not thermally erode tar roads. A quenched crust is formed over the road, which armors it against the lava above it. The results herein seem to indicate the necessity of some topography to "trip" the flow and get it tumbling in order to secure thorough mixing.

Keywords: komatiite, nickel sulfide, mineralization, finite-element model, thermal erosion.

Sommaire

Une évaluation théorique des aspects physiques de la mise en place des coulées komatiitiques dans un chenal ouvert montre qu'elles étaient turbulentes et qu'elles avaient une vélocité allant de mètres par seconde jusqu'à des dizaines de mètres par seconde, selon la pente et l'épaisseur (c'est-à-dire, la profondeur) de la coulée. Ces coulées devraient aussi porter des traînées de particules en suspension, étant donné la formation de cristaux accompagnant le refroidissement du liquide à mesure qu'il s'épanche, tout comme une rivière peut transporter des sédiments. Dépendant de la distance de la source, ces traînées pourraient s'avérer être riches en olivine, et la suspension supérieure, riche en sulfures, tandis que les parties supérieures des coulées pourraient avoir une composition plus évoluée. Les épaisseurs calculées de ces traînées en suspension et leur distribution le long de l'axe vertical correspondent aux observations faites sur le terrain. Les cristaux primaires, par exemple les cristaux de spinelle chromifère, devraient s'accumuler le long d'interfaces séparant les accumulations de particules en suspension. La chute en température observée par kilomètre d'épanchement de lave basaltique nous permet d'estimer le taux de refroidissement des coulées de lave komatiitique, dont la température était plus élevée. A moins qu'il y ait sursaturation, et d'après les taux de refroidissement impliqués, les sulfures ont dû se déposer à partir d'un liquide komatiitique environ 40 km de la source. Une modélisation de ces coulées par éléments finis montre que les tourbillons apparaissent en amont des dalles en rebord ou bien dans

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les dépressions. Ces tourbillons fournissent un mécanisme très efficace d'extraction et de répartition des métaux dans la fraction sulfurée, et leur morphologie correspond aux accumulations de sulfures massifs associés aux dépressions. La vigueur de ces tourbillons dépendrait de l'amplitude du facteur de Reynolds *Re*, ce qui montre que *Re* revêt une importance équivalente au facteur *R* pour la formation de gisements économiques. Les sulfures doivent être bien mélangés au liquide pour que l'extraction du maximum de nickel puisse se faire. L'efficacité de l'extraction augmente avec *Re* jusqu'à un maximum, pour ensuite diminuer. Comme exemple, une épaisse coulée (et donc un facteur *R* élevé) sera rapide (facteur *Re* élevé); dans ce cas, le liquide pourrait tout simplement enjamber la dépression sans qu'il puisse s'y développer un tourbillon, et donc il n'y aurait pas de mécanisme d'accumulation des sulfures. Ces modèles numériques étayent certains des modèles de Naldrett et de ses collègues. Il est difficile d'incorporer ces résultats dans un schéma d'érosion thermique, ce qui concorde avec les critiques récentes de tels mécanismes pour atteindre une saturation en sulfures. L'érosion thermique ne semble pas importante dans l'industrie, où l'écoulement continu de liquides ayant une température de beaucoup supérieure à celles des magmas ne mène qu'au développement d'une bordure figée entre substrat et liquide. Cette bordure figée empêche le transfert de matière d'un médium à l'autre. De façon semblable, les laves hawaiiennes ne causent pas d'erosion de routes pavées. Une croûte trempée se forme et empêche l'interaction avec la coulée sus-jacente. Les résultats présentés ici semblent indiquer la nécessité d'avoir un certain relief topographique pour faire qu'une coulée cascade, afin d'assurer un mélange intime avec les particules en suspension.

(Traduit par la Rédaction)

Mots-clés: komatiite, sulfures de nickel, minéralisation, modèle à éléments finis, érosion thermique.

Introduction

We report herein our preliminary efforts to model numerically flows of komatiitic lava with the objective of shedding light on the mechanisms by which massive metal sulfide deposits are formed. We assume that sulfides were in solution or in suspension in the flows at the outset.

The approach to the modeling has been in two steps: 1) we employ standard practice from the point of view of physics of sedimentation, and incorporate both empirical and mathematically derived relationships for simple configurations; 2) we employ more powerful finite-element numerical procedures to establish in greater detail the geometry of the flow and address complications that cannot be treated with the relationships derived for simpler situations. Both methods have reproduced features observed in the field and indicate that it might be useful to devote more attention to some earlier, qualitative proposals regarding the manner in which these massive sulfide deposits were formed. The results of the finite-element calculations, shown graphically, have many of the features of these deposits: the barren eye surrounded by sulfides has been reported (*e.g.*, J. Blaine, Falconbridge Ltd., personal commun, 1999). Particularly heartening is the recognition that many aspects of these processes can be quantified. Their further development should yield a welcome tool with which to assess exploration targets. Slope and thickness of run as well as *R* factor appear to dictate whether or not a deposit will form.

Physical Analyses of Open-Channel Flow

Although the power of finite-element numerical methods as a mathematical tool for modeling is renowned, use of these methods must be underpinned with a foundation arising from a well-developed body of empirical evidence. There is a wide body of experimentally derived relationships and mathematical formulae for simple systems whose use should be exhausted before attempting to bring to bear the more powerful techniques of finite-element analyses. We provide some results of both below. We have assumed in all our models that we are dealing with a continuous stream of lava and not the advancing flow front.

Inferences from the Literature on Open-Channel Flow

It is important to know whether the lava flow is laminar or turbulent. Laminar flow is characterized by the lack of mixing between any section of the flow. If the laminar flow follows a straight channel, a batch of fluid will move along in a straight line and never across the direction of the stream. Increasing the flow velocity can eventually lead to turbulence. Turbulent flow is characterized by eddies, roiling and even whirlpools. In turbulent flow, the fluid is continually banging from one side of the channel to the other and tumbling as it moves downstream. Turbulence is a far more effective mixer than laminar flow. Heat transfer and mass transfer are therefore much greater in turbulent flow than in laminar flow. The higher velocities also provide greater shear stress at the boundaries. The magnitude of the Reynolds number $Re = \rho Vh/\mu$ (where μ is viscosity, ρ is density, V is velocity and h is thickness or height of the surface of the flow above its bed) provides a quantitative criterion whether or not a flow will be turbulent. The Reynolds number is the ratio of inertial forces to viscous forces. Resorting to analogies to explain these forces, inertial forces are those experienced in turning a corner in a car (they throw the passenger to the side); viscous forces are those experienced by applying the brakes. Using the Reynolds number as a characterizing parameter also allows one to take advantage of dynamic similitude

(Kundu 1990). That is, any calculation for a given *Re* will apply to any other flow whose combination of physical parameters yields the same Reynolds number. Hence, another flow ten times as deep (or thick) but also ten times as viscous will also lead to the same outcome as the original case. In this paper, by depth or thickness, we will mean the distance in meters from the bottom of the flow to the top.

For open-channel flow, such as might apply to lava flows, the general rule is that for $Re < 600$, the flow is laminar. For $Re > 600$, the flow is turbulent (*e.g.*, Morisawa 1985). For flows with yield strength, the Reynolds number criterion is modified by the Bingham number or the Hampton number. Yield strengths of significant value are restricted to more silicic flows. The literature provides densities (2800 kg/m^3), viscosities (0.1 to 1 Pa s) and thicknesses (~10–100 m) for komatiitic flows (Williams *et al.* 1998) from which it may be inferred that a flow 100 m thick can be turbulent for average velocities as low as 0.02 m/s. It is safe to say that one might expect nearly all flows in nature to be turbulent (*e.g.,* rivers, lakes, pouring molten steel... as can be ascertained from sizes, velocities, viscosities). Rare exceptions might be very silicic, therefore very viscous, lava flows or candy extruded in a factory. Kauahikaua *et al.* (1998) provided a summary of observations of the velocities of Hawaiian lava flows: 1–6 m/s, depending on the slope. Extrapolation of observed velocities for Hawaiian lavas imply that komatiitic flows will be extremely turbulent.

Velocities of open-channel flows are easily calculated for laminar conditions. That is,

$$V = (\rho g/3\mu)h^2 (dh/dx)$$

where g is gravity and dh/dx is the slope of the run (Morisawa 1985). From this relationship, it may be inferred that thick silicic flows (*e.g.,* felsites) can reach considerable distances.

However, since it is likely that turbulence will invariably attend komatiitic lava flows, the use of the Chezy equation to estimate velocity V is required, *i.e.*,

$$V = R^{2/3}S^{1/2}/n$$

where R represents the hydraulic radius (cross-sectional area/perimeter), S is the gradient (or slope or grade), and n is the Manning coefficient (Morisawa 1985). For a very mild slope of 0.03% (practically flat), a viscosity of 1 Pa s, and a Manning coefficient of 0.03 (clean, straight channels), a velocity V of approximately 3 m/s can be expected for a flow ~100 m in thickness and ~100 m in width. It is emphasized that such a small slope requires a relatively thick flow to secure the above velocities. Lower viscosities can occur for komatiites which, for the same slope, would decrease the required thickness of the flow (by a concomitant amount) to secure the same velocity. Likewise, increasing the slope will secure an increase in the velocity.

Komatiitic flows are reported to be zoned in the vertical, each zone generally separated from each other by a sharp contact [*e.g.*, see Fig. 2 of Barnes *et al.* (1992) and Figs. 24.3 and 24.5 of Naldrett & Campbell (1982)]. Komar (1972, 1976) noted that such stratifications or zonings in the igneous setting are amenable to the quantitative interpretations applied to a suspended load of sediment in rivers and streams. Sedimentary material carried as a suspended load in rivers is subject to dispersive pressures (*i.e.*, the Bagnold effect), which cause segregation. Lowe (1982, Fig. 11) shows such stratifications arising in sedimentary deposits and in which Komar (1972, 1976) saw an analogue to differentiation and segregation in sills and dykes.

A moving fluid carrying a suspended load can commonly become stratified, the upper section of the flow clear of any particulate matter, and the lower section turbid, *i.e.*, carrying the suspension. Quantitative rules are available for estimating the thickness of the suspended load. These are discussed in detail in Rice (1998a, b, c) and Rice & von Gruenewaldt (1995). One such relationship is

$$D = 4.4V^3/rgcv_s$$

where D is the thickness of the suspended load, r is equal to $(\rho_s - \rho_l)/\rho_l$, where the subscript "l" implies liquid and the subscript "s" implies solid, V is the shear velocity or average velocity of the flow, v_s is the settling velocity of the crystals, and c is the concentration of the particulate content of the suspended load. For the komatiitic flow modeled above as having a mean velocity of 3 m/s, this relationship predicts that a suspended load of about 30 m thickness will be carried at the bottom of this flow.

Following the reasoning of Rice (1998a, b, c) and Rice & von Gruenewaldt (1995), the suspended load would be composed of the first crystals to solidify from the melt. Since the upper section of the flow is free of this suspended load, it will be more evolved in composition. As the flow moves along, however, it will continue cooling. This movement will spawn a new population of crystals, which can again contribute to the development of a new suspended load riding on top of the first one, much like the layers shown in Lowe (1982, Fig. 11). Nearer the source of the lava, one would then expect the bottom load of the flow to be olivine-rich komatiite. Rice (1998a, b, c) has pointed out that these stratifications should start forming after the melt has gone through about 10% of crystallization. Another 10% of crystallization may place the second suspended load into sulfide supersaturation if sulfide solubility for komatiites qualitatively follows the inferences of Naldrett & von Gruenewaldt (1989). In this section of the flow, the majority of the sulfides would be carried in the upper layers. Naldrett & Campbell (1982, Fig.

24.3) indicated similar situations can be found in the field.

Cashman *et al.* (1999) observed that when lava leaves the vent, there is no crust on top of the lava for up to a kilometer or so of run. During this "open" stage, the surface of the lava will rapidly cool by 12–14°C owing to intense radiative heat-transfer. After this distance, a cold crust is carried on the surface that thickens with time. They noted that once the insulating crust is formed, "these very high cooling rates are not maintained". The same is to be expected for komatiites except that the crust will form sooner as the radiative transfer rates will be about seven times greater (owing to the fourth power dependency on temperature). They cited other workers (Lipman & Banks 1987, Crisp *et al.* 1994) who have secured values similar to theirs for cooling of "proximal to medial open channel Hawaiian flows": a "5–7°C drop in temperature over 10–11 km of transport". This is approximately the same as reported in Greeley *et al.* (1998), who observed that basaltic lavas, initially at around 1100°C, cool at a degree or less per kilometer of run. Komatiite flows, when initially at 1600°C, can be expected to cool about 55% faster, the cooling rate slowing as the temperature drops (the 55% is obtained by noting that the cooling rate is proportional to the temperature difference between flow and ambient conditions). Assuming that the initial temperature of lava is close to its liquidus, and the solidus is some 400°C below this, the melt will have seen about 20% crystallization (80°C temperature drop) by the time the flow has gone about 40 km (this includes losses at the vent). If this temperature drop carries the melt into sulfide supersaturation, it may be anticipated that sulfides will start dropping out of solution as early as some 40–50 km from the source. This prediction assumes that the sulfides come out of solution as soon as supersaturation is reached. Sulfides might be completely out of solution (but not necessarily out of the lava) some 150 km from the source. Rice & von Gruenewaldt (1995) have also pointed out that the dispersive pressure effect pushes primocrysts into zones of high shear, and they would be expected to collect there. To draw upon an analogy, there is no shear on a freeway if all the cars are moving at constant velocity. If, however, a car spins out, it will create a velocity differential across the highway, that is, a zone of high shear, and vehicles will aggregate. Rice & von Gruenewaldt (1995) have applied this concept to collect crystals into flow-boundary layers and have termed it "shear aggregation" (see also Komar 1972). Within komatiitic flows, a peak of primocrysts would accumulate in the boundary layers separating different layers of suspended flow, each layer of differing composition. If the primocrysts consist of chromian spinel, then a Cr high would be expected at the boundary layers. This appears to be the case (see Naldrett & Campbell 1982, Fig. 24.5).

Variations on the above scenarios may be anticipated. The olivine may be left behind in the upstream section of the flow, in which case the sulfides would then be put down at the base of the flow in its further reaches. In addition, as discussed in the section below (entitled Finite-Element Models), embayments form traps for sulfides. In such a case, the sulfides would be expected to lie at the base of the embayment. In this context, it has been suggested (S.J. Barnes, pers. commun., 1999) that these mechanisms might apply to Group-A and Group-B ore types of komatiite flows (*e.g.,* Lesher 1989). The computational results discussed in the next section imply the possibility that massive sulfides accumulate only in regions of high shear, *i.e.*, thorough mixing, such as attend embayments. The subeconomic Group-B ore types may have been formed from flows that did not encounter the topography (*e.g.*, embayments) that generated eddies to secure effective mixing and accumulation of massive sulfides.

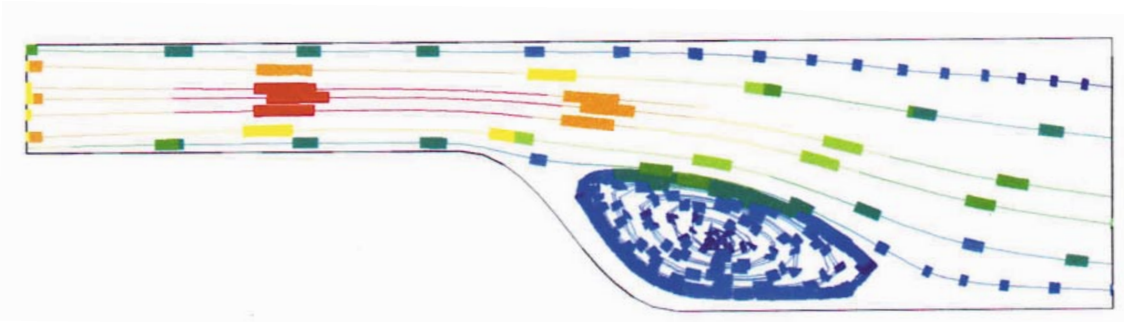

FIG. 1. Particle traces, *i.e.*, the paths that some particles would take in the flow, are depicted here. The views shown for all figures are side views, and the flow is from left to right for all cases given here. In this case, a Reynolds number of 450 typifies the flow. Note the back eddy, which has developed under the ledge or embayment. This eddy will assure mixing of sulfides and melt, to scavenge Ni from the melt.

Finite-Element Models

We present below a number of calculated situations of lava flow over ledges and hollows, which are taken to be embayments (Figs. 1–6). We know of no other similar work in this area. The full set of Navier–Stokes equations are employed in a commercial CFD (Computational Fluid Dynamics) software package: Flotran. Turbulent flow is handled through the "Standard K–E Model" (Launder & Spalding 1974). The flow is from left to right. Incompressible flow and no slip (zero velocity) on relevant boundaries are assumed. Particle traces are shown, *i.e.*, the paths that suspended particles would follow in the flow (red is high velocity, and blue is low velocity). For clarity, the paths of only a few particles are plotted. The views shown are side views. These calculations are given as functions of the Reynolds number, $Re = \rho Vh/\mu$. The Reynolds numbers we arbitrarily employed are 450 (laminar), 4500 (turbulent) and 45000 (turbulent). If the other physical parameters in the Reynolds number h (flow thickness), ρ (density), and μ (viscosity) are constant except for V, the average velocity, then increasing the Reynolds number ten-fold for each case implies that we are increasing the velocity ten-fold. The advantage of parameterizing the calculations against *Re* is apparent when we note that the same results will apply to a flow 10 times as thick if we drop the velocity by a factor of 10. The vertical scale in the figures is the same as the horizontal. The aspect ratio, *i.e.*, inlet height to length of channel, is 1:10 for the short channel and 1:40 for the long channel. Therefore taking the entrance depth to be 100 m implies the length of the short channel to be 1 km.

Note the back eddy, which develops behind the ledge in all cases (Figs. 1, 2). This eddy would be very effective in mixing sulfides with melt to scavenge Ni from

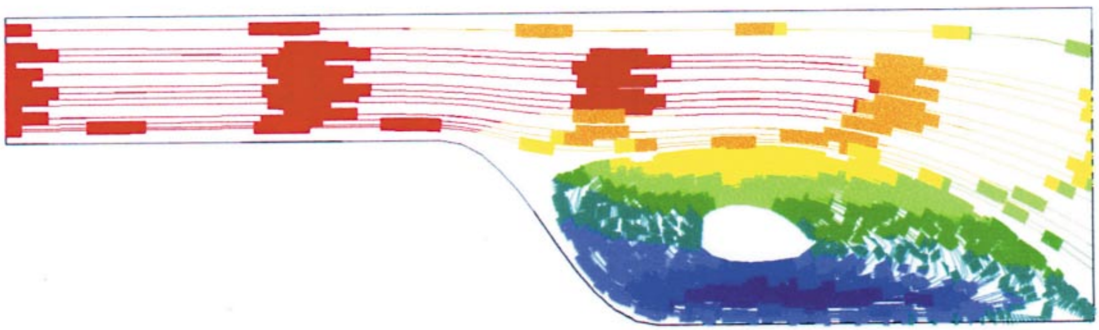

FIG. 2. This is the same configuration as Figure 1, except that the Reynolds number has been increased by a factor of 10 (which can be done by increasing the velocity by 10). Note that the mixing process has become much more powerful in the back eddy, hence the potential deposit would be more massive. Note also that little mixing occurs in the eye of the eddy, which would thus be expected to be more barren of sulfides.

FIG. 3. This is the same configuration as Figure 2, but from a distance, to show a longer run of the flow. Note that the sulfides would taper off downstream in this case.

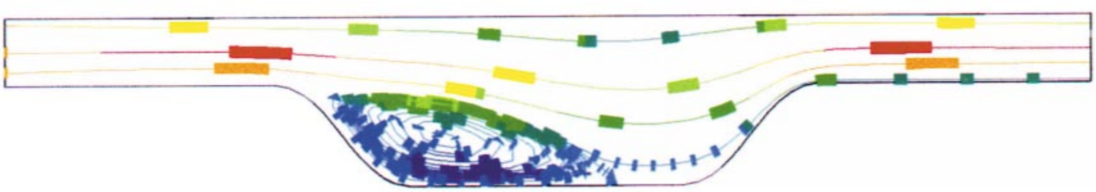

FIG. 4. This figure represents a low Reynolds number (450) flow over a hollow. A small back eddy develops against the upstream wall of the hollow and would be the anticipated zone of deposition of sulfides.

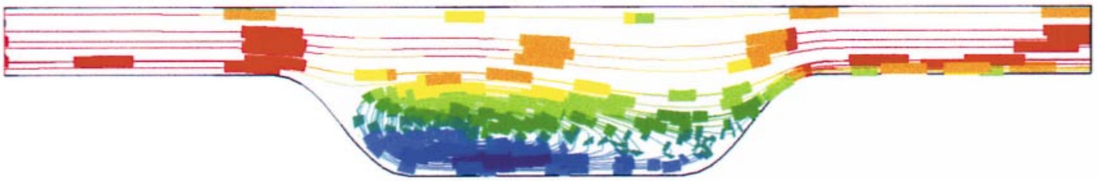

FIG. 5. This is the same configuration as Figure 4 but 10 times more intense. Now the eddy completely fills the embayment, but does not extend into the mainstream of the flow. The efficacy of this environment in collecting massive sulfides is obviously much greater that in Figure 4, where the flow is less intense by a factor of 10. Figure 24.9 in Naldrett & Campbell (1982), constructed from their field interpretations, illustrates the growth in an embayment of a massive sulfide zone from flows of komatiitic lava. Their figure is similar to that depicted here. Hence the finite-element analyses support their interpretation. Figures 1, 2 and 3 indicate other configurations of the channel that might also be conducive to the formation of massive sulfide deposits.

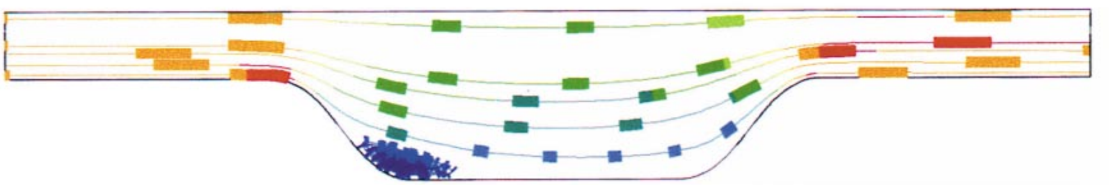

FIG. 6. This is the same configuration as in Figures 4 and 5, but the flow is 10 times more intense than in Figure 5 and 100 times more intense than in Figure 4. In this case, the flow hurdles the hollow, and there is little circulation in it, and therefore little gathering of sulfides. This scenario immediately implies that there are optimum conditions with respect to the Reynolds number for the formation of massive sulfides in embayments.

the lava. The more vigorous the flow, the more vigorous the back eddy, and the more effective the scavenging of Ni from the melt. Viewing the ledge from a distance shows that the particulate matter gathered in the eddy tapers off downstream (Fig. 3). The middle portions of the eddy do not mix well; they would be expected to reflect relatively barren zones.

Flow over hollows reveals a similar structure. For a low *Re* (450), *i.e.*, a mild flow, a small back eddy forms against the upstream wall. One would anticipate this to be the zone of deposition of massive sulfides (Fig. 4). Increasing the Reynolds number 10 times causes the eddy to completely fill the hollow, which would provide a much greater yield of massive sulfides (Fig. 5). Increasing *Re* by a factor of 10 again (*Re* = 45,000) yields a flow so fast that it simply hurdles the embayment without forming a significant eddy, and little would be trapped there (Fig. 6). This implies that if the flow is too deep or too fast or both (any combination that yields a high *Re*), there will be little deposition of massive sulfides in embayments.

The obvious interpretation is that there is an optimum Reynolds number for entrapment of particulate matter in the embayment. In order to scavenge enough nickel into the sulfides to provide an economic reserve, the sulfides must be exposed to a sufficiently large volume of silicate melt. This requires a large *R* factor, which is the ratio of silicate melt to sulfide content. We note that although a thick flow would be conducive to a large *R* factor, if the slope down which it plunges is too steep, material might not collect in the embayments. This is because increasing the thickness of the flow increases the Reynolds number, which will further serve to increase the velocity, as will a significant slope. On the other hand, the implication is that thin flows down steep slopes may still yield economic reserves. Note that the hollows behave much as postulated in Naldrett & Campbell (1982, Fig. 24.9).

The question is certain to arise as to the manner by which the structure of the eddies are preserved in the frozen lava field. The structure is preserved because of the temperature dependence of the viscosity of the flow. The viscosity of lavas will increase with time through three factors: 1) changing composition as the melt evolves (increasing silica content), 2) increasing polymerization as the melt cools, 3) increasing suspended load as the melt cools. The latter of these factors applies even if there is no temperature dependence, and will occur in flash floods as the water picks up and carries along more and more material. When the suspended load approaches about 60%, the fluid will experience "cohesive freezing", a sedimentological term. That is, on reaching a suspended load in the region of 60%, the flow will suddenly set like concrete. Increasing viscosity will stabilize fluid structure, and cohesive freezing, which sets in suddenly, will preserve it (*e.g.*, Middleton & Southard 1985). For the komatiite situation, as the eddies gather more material, they will become more and more competent until about 60% crystal content, at which point they "freeze" in place. Note that this means of gathering up sulfides does not require that they settle out. They continue to gather in the back eddy, as does debris on the downstream side of a large boulder in a river, until the eddy is so choked with material that it gums up. Although we do not dismiss the possibility that sulfides may settle out, it is useful to note that the criterion for material to settle out is that the settling velocity exceed the flow velocity of the carrying fluid (Middleton & Southard 1985). This is readily demonstrated in a desert sandstorm. The most optimistic maximum settling velocity for sulfides a millimeter across in a komatiite melt is less than a cm/s. As the lava flow initially proceeds at rates of meters/second, it is clear that embayments are a far more effective means for gathering sulfides. This reasoning supports the field observation that embayments are vital to massive sulfide deposits (Naldrett & Campbell 1982).

The phenomenon of cohesive freezing also sets a limit on the maximum run or reach of a komatiite flow. The flow cools along its path, and if the temperature loss is 2°C per kilometer of run, cohesive freezing should have set in approximately 150 km from the source.

How Does the Sulfur Get into the Magma? The Merits of Thermal Erosion

The literature on the formation of nickel deposits in komatiites is conflicting. Some authors contend that contamination of the komatiitic lava by sediments underlying the flows is crucial to the formation of nickel deposits. This contamination arises by thermal erosion of substrate by the flowing lava (*e.g.*, Williams *et al.* 1998). On the other hand, Foster *et al.* (1996) cited values of Re/Os to argue that Archean nickel deposits arise from *uncontaminated* komatiites. These authors dismissed ground melting and assimilation of sulfidic sediments in ore genesis. Perring *et al.* (1996) found, however, that anomalous enrichments in SiO_2, FeO, TiO_2, and Zr, which correlate with regional variations in the composition of substrate metasedimentary rock, coupled with field evidence for trough structures at the base of lava-flow channel sequences, provide strong evidence for supracrustal thermal erosion by komatiite lavas.

Greeley *et al.* (1998) maintained, for lavas in general, that "the details of whether lava flows form by predominantly erosional (thermal or mechanical) or constructional processes ... remain debatable" and that "evidence for erosion by komatiite lavas is equivocal". However, they interpreted many field features as downcuttings due to thermal erosion. These authors noted that lava flows will follow pre-existing topography such as riverbeds, and that it is not possible to distinguish between lava channels formed by erosion and those formed by levee construction. Constructional (*i.e.*, "leveed") channels are recognized as regularly occurring features in the volcanic landscape.

Riverbeds typically feature undercuttings (*e.g.*, Morisawa 1985). A case cited by Greeley *et al.* (1998, Fig. 4b) to demonstrate lava undercutting as well shows that the lava flow has filled the channel well above the undercutting. This raises the question as to why the rest of the channel was not cut back. Of nearly 2000 lava-tube segments, these authors found 32 candidates for erosion of the substrate. In other words, only 1.6% of all lava tubes examined are alleged to demonstrate thermal erosion. These investigators considered exposure of paleosols as evidence of thermal erosion. However, no evidence of melting or attack on these paleosols by the lava was reported, except in one instance of fused preflow strata only 1 or 2 cm thick. Whether or not there was actual communication between the melt and the preflow sediment was not reported.

Kauahikaua (1999) attributed receding levels of flows in lava tubes to thermal erosion of the tube floor, but did not report any measurements of the level of the flow referenced to the base of the flow itself (*i.e.*, from the bottom up). All measurements to the flow surface have been from the skylights in the roof with the assumption that falling levels of flows were due to deepening of the channel by thermal erosion. Until measurements are made from the floor up to the surface of the flow, there are no certain conclusions to be made.

In examining the question of thermal erosion, it is useful to draw attention to the behavior of melted candle wax running down the side of a candle. The wax does not attack the candle but simply builds up on the outer surface of the candle, shielding the candle from the flow of melt down its side. The candle experiences no thermal erosion, as can readily be seen by pulling off the solidified flow that ran down the side of the candle. This "kitchen" experiment can be enhanced using multicolored waxes. The same phenomenon is experienced at Niagara Falls during winter. Water cascading over the ice does not erode the ice but continually builds up the ice by freezing to it. This is because the ice is at temperatures considerably lower than that of the yet unfrozen water. Thermal erosion must await the spring. Whether similar behavior is to be expected for komatiitic flows depends on the degree of dynamic similitude or scaling. The important parameter relating dynamic similitude between the candle wax analogue and the komatiitic melt is the Stefan number $Ste = c_p(T - T_m)/L$, where c_p is the heat capacity, T is the mainstream temperature, T_m is the melting point, and L is the latent heat of fusion. For candle wax, *Ste* is approximately 5, and for a komatiitic liquid, it is about 4. For basalts, *Ste* is approximately 2.6, with the implication that it will take the basalt about three times as long to lay down the same thickness of chill zone as candle wax.

The Science Citation Index lists 76 papers written in the past ten years on thermal erosion. Fifty of these are from the geological sciences. The others relate to rocket nozzles, electrical plasmas, *etc*. There are no papers from those industries that regularly deal with high-temperature melts. Thermal erosion in the sense employed in the volcanological literature is not seen in industry, where continuous casting of melts of high temperatures (up to 2500°C in some cases) are performed to large tonnages. These melts are "teemed" (poured) into unconsolidated sand, clay or mud tundishes (flumes or channels) for days during production runs. The melt quickly forms a quenched skin (chill zone) on the sides of the flume over which the melt continues to run for the duration of the pour. The boundary between the containment of the molten flow and the flow itself immediately acquires a temperature halfway between ambient and that of the melt (*e.g.,* see Kreith & Bohn 1993). The severity of this initial abrupt change in temperature across the boundary is mitigated with time. The observation that the interface between hot and cold material comes immediately to a temperature halfway between the two at the instant of contact has also been noted, of course, in the context of lava flowing over cold substrate. Keszthelyi (1995) reported, on the basis of observations in Hawai'i, that "the interior of the flows were all at 1135±5°C" and that the surfaces over which the lava advanced were at about 70°C. The mid-point between these two temperatures is their average, *i.e.,* (1135 ± 5°C + 70°C)/2 or 603°C. Figure 2 of Keszthelyi's paper shows this to be the case: at time = 0, the temperature at the lava–substrate interface is about 600°C. The severity of this initial abrupt change in temperature across the boundary is mitigated with time, as is also reflected in Figure 2 of Keszthelyi (1995).

The temperature to which the bounding substrate immediately comes (600°C) is well below the solidus of both the melt and the substrate on which it flows. A quench margin will form, providing insulation from the overlying stream of lava. This situation seems to apply to a stream of lava (Kauahikaua *et al.* 1998, Fig. 8), which shows growth of a bottom crust with time in a Hawaiian lava tube. The thickness of the insulating crust at the bottom of the tube increased three meters over a period of a year while lava was being supplied to the tube. The observation is more in accord with the industrial experience that a chill zone grows at the bottom of the channel of the flowing melt.

Chemical communication between the underlying material (the channel wall) and the melt is not reported in the industrial literature, and there seem to be no references to it. Inquiries to metal-refining industries indicate that the chill zone armors the walls of the channel against the melt. The term "thermal erosion" also seems to be unknown in foundry parlance (pers. commun., 1999, Drs. R Poole, D. Wynblad, J. Wicks of Amplats Platinum Refining, and S van Wyk of Highveld Steel). Nor is the term found in the foundry literature or in steel-making journals or other relevant technical publications (660 records since 1982 checked). On the other hand, komatiites quenched against substrate have been observed (C.T. Barrie, pers. commun., 1999), which is more in common with the industrial experience. The thermal conductivities of metals run as high as four orders of magnitude greater than that of lavas (Kreith & Bohn 1993). As industrial melts, they are commonly at temperatures 1000°C higher than lavas and flow turbulently (they are low-Prandtl-number fluids). Hence by order of magnitudes, they should be much more efficacious at thermal erosion than lavas. They do not thermally erode. This brings into question the reality of thermal erosion by lavas.

Greeley *et al.* (1998) cited a number of investigators who have observed that basaltic lavas cool less than a degree per kilometer of run. Armoring must have occurred between the lava and the substrate to inhibit efficient transfer of heat to the substrate. The observation that lava flows do not lose heat rapidly implies great difficulty for thermal erosion. To thermally erode requires that significant amounts of heat be absorbed by the substrate, which entails removing significant amounts of heat from the melt itself. The substrate must be raised from an ambient temperature of approximately 0°–20°C to its melting point, possibly by 800°C to bring the sediments above their melting point. This in turn requires a concomitant drop in the temperature of the overlying lavas. Further, latent heat of fusion must then be provided to permit melting, which requires a further contribution of heat from the lavas. For a drop of lava temperature of just one degree per kilometer of run, then hundreds of hours of flow over the same section of substrate are required to bring its temperature anywhere near its melting point.

Some evaluations of theoretical considerations support the concept of thermal erosion (Huppert & Sparks 1985). In this literature, relationships for pipe flow are applied to model open-channel flow (Williams *et al.* 1998). Turbulence is taken to occur in open-channel flow if *Re* is greater than 600 (Morisawa 1985). For flow in pipes, the transition from laminar to turbulent flow occurs for $Re > 2000$, the value to which Williams *et al.* (1998) refer. Their film coefficients are based on pipe flow and not open-channel flow. There is a difference (*e.g.,* Bonilla 1957). As Williams *et al.* (1998) specifically stated, their "equation (10) is valid for $Re >$ 10,000", and they do treat of turbulence. However, the descriptive equation that they employ allows no temperature variation in the vertical; all variations are confined to the downstream direction only. This simplification does not allow the development of a temperature gradient across the melt–substrate interface and precludes the development of a quench margin or thickening of the melt at the cold interface. This approach always maintains the substrate interface at the mainstream temperature of the flow. This cannot occur in the real world.

It should be emphasized that the review here is not intended to dismiss thermal erosion in any sort of environment. Certainly hot water spilled on ice will corrode the ice if the ice is not far removed from its melting point. This is not the situation for the substrate underlying komatiitic flows. The surface environment into which they are introduced is at temperatures far below the freezing point of the komatiites. This fact was not recognized in the early experimental work that led to the thermal erosion paradigm (*e.g.*, Huppert & Sparks 1985). In these experiments, hot water was poured on wax-like material, the wax-like material held at room temperature. The wax-like material should have been well below the freezing point of water in these experiments in order to mimic the actual conditions found in nature.

To initiate remelting of the chilled zone that armors the substrate requires not only that its temperature be brought back up to the solidus, but likely halfway to the liquidus in order to at least initiate any significant mechanical erosion during the short duration of the flow. Further, latent heat of fusion must be provided to the substrate as well as bringing it to temperature in order to incorporate it into the flow. Greeley *et al.* (1998) cited work in preparation showing that "purely thermal erosion is very difficult unless the substrate is of much lower melting point than the eroding fluid, or the flow occurs beneath a crust … for sustained periods (>200 years)".

Channels in flows of carbonatitic lava have been taken as evidence of thermal erosion; rates of thermal erosion in carbonatites are reported to have been measured (Pinkerton *et al.* 1995). Erosion rates were determined by "using a tape measure inserted into the active flow". No other information is given. An important piece would be the datum or reference level from which the measurements were made, and whether or not the measurements were made to the bottom of the channel referenced to this datum. Again, as discussed above, such methodology is inconclusive, barring the difficulty of cleaning the tape measure after it was inserted in the flow. Figure 7 is a photograph of such a channel (provided by J. Harmer, South African Council of Geosciences); it was taken in the same area as that studied by Pinkerton *et al.* (1995). Lobate structures can be seen extending from the channel, which is evidence for levee buildup, not erosion. We were able to secure similar channels with wax but observed no thermal erosion, as discussed below.

To demonstrate the importance of having the experimental substrate, *i.e.*, the wax, at temperatures well below its melting point to even begin to replicate the environment of lava, we placed layers of wax into a freezer whose internal temperature was –40°C and left the wax several days to come to temperature. This has never been done before, all previous experiments reported in the literature conducted with waxy substrate at or about standard temperature and pressure. The freezer was not large enough to continue the experiment within it, so the wax had to be retrieved. Hot, melted wax was continuously poured on the cold wax within minutes of its removal from the freezer. Upon contact with the –40°C wax, a crust was immediately formed over which the rest of the hot wax continued to flow. However, in no instance did this crust ever bond to the cold wax, let alone incorporate any of it. That is, the hot wax never stuck to the cold wax. In fact, the crust formed from the hot wax would simply slide from the cold wax on lifting one side of the cold wax. In one instance, the crust was blown off the cold waxy substrate when a window was left open during a hard squall.

We further discovered that when the substrate wax came to room temperature and we had fixed the crust with pins so that it would not slide off, we could generally pass water between the two. This opened up the possibility of another interpretation of sedimentary material between layers of lava: the sediments could have been carried between two layers of lava (one overlying the other) after the lavas were emplaced. It has been observed that although lava may exit a vent at a steady flow-rate, the flow will often over-ride itself successively, to leave a series of layers stacked one on top of the other. It seems, therefore, that the appearance of sediments between layers cannot be taken as definite evidence of separate injections of lava instead of a steady outpouring.

We further noted that channeling of the form observed in the photograph of the carbonatite flows (Fig. 7) also occurred in the wax (Fig. 8). In the case of the wax, this is clearly levee buildup as opposed to thermal erosion, as the wax never penetrated the substrate.

We offer these observations as definitive only in the sense that they indicate the use of wax as an experimental analogue has not reached a level of rigor to provide reliable insight into the behavior of lava flows.

It could be argued that any seafloor over which komatiitic lavas may have run was devoid of relief, hence channeling had to have occurred by thermal erosion. This view might be derived from a belief that the present seafloors lack relief and, accordingly, Archean seafloors also should lack relief. Although today's ocean floor from the shoreline to the first 200 m of depth is, on average, relatively smooth, it is still rough compared to the abyssal depths. From the 200 m depth on out to the break in the continental shelves, the sea floor is riddled with gullies and even possesses canyons of great depth, *e.g.*, the Hudson Canyon off New York [see any descriptive oceanography text such as Kennett (1982); also William Ryan, LDEO, pers. commun., 1999). In the higher latitudes, the sea floor from the shoreline to the first 200 m of depth is, in these times, heavily gouged by glaciation. Whether significant topography on the seafloor was present at the time of emplacement of the

FIG. 7. A channel in a flow of carbonatitic lava. Such channels are commonly taken as evidence of thermal erosion, but note the lobate structure extending away from the channel, which would suggest levee construction instead.

Raglan komatiites, in northern Quebec, does not seem to be reported. The Raglan deposits are believed to have been emplaced in a tectonically active region akin to a Red Sea type of environment (Barnes *et al.* 1997). The common occurrence of turbidites there (St-Onge & Lucas 1993) argues for significant sea-floor relief, as does the volcanic and tectonic activity (earthquakes) associated with that type of environment. Thus seafloor topography offers a source of embayments in which to collect massive sulfides. A great deal of relief is found in the submerged portions of the Pacific Ocean shield volcanoes (J. Smith, Univ. of Hawai'i, pers. commun., 1999).

Growing concern about the viability of thermal erosion has led to consideration of mechanical erosion in its stead. Mechanical erosion will not occur if there is a

FIG. 8. A similar channel formed from flowing wax. The wax, however, never penetrated the substrate, hence the channel was formed by levee construction and not by thermal erosion.

chill zone armoring the substrate. This is apparently the case reflected by the growth of crust on the floor of the lava tube discussed above. If there is no armoring, extrapolation from the glass industry [see Rice (1981) for references] indicates maximum removal of consolidated substrate floor at the rate of about 3 cm/week. This assumes a thick flow (~100 m) to secure flow velocities in the order of meters/second. Such a flow could cover an ~1000 km distance in about a week if it did not choke owing to cohesive freezing. If the sulfide content of the substrate ran about 1%, and if all the mechanically eroded material was incorporated into the lava, the contribution of the substrate to the sulfide content of the flow would run about 10^{-4}%.

Mechanical erosion is not supported by field observation in Namibia, where the Etendeka flood basalts have *preserved,* not destroyed, the substrate. In this case, the substrate consists of an ancient eolian system of sand dunes of heights to 100 m and wavelengths of 1.3 km. The flood basalts drowned the system of dunes, preserving even ripples on the face of these dunes with which the basalt is in direct contact (Mountney *et al.* 1999). These features should not be preserved if there were significant mechanical or thermal erosion. Loose sand lacks at least as much competence as clayey sea-floor sediments.

It is possible that komatiite flows incorporate sediments at the flow front as the flow plows through soft sea-floor sediments. This is a variation on the theme of mechanical erosion, the difficulties of which have been noted above. How such contamination is communicated back upstream is problematical. There would be little opportunity to scavenge the rest of the melt of its metal content. One possibility is that as the flow front crosses a depression, some of the debris at the flow front drops into an eddy that may attend the depression, and becomes locked in the eddy to stay there to communicate with the rest of the flow as it passes over it.

Perhaps the most telling argument against thermal erosion is the observation that lavas flowing across black sands of Hawai'i, which contain iron-rich olivine and glass, simply acquire a chilled margin and do not mechanically or thermally erode these beach sands. The same is to be said for lava flows crossing macadam roads. These flows ignite volatiles but simply bake the asphalt in place; there is no mechanical or thermal erosion. Road restoration is facilitated by simply removing the solidified lava. The asphalt and even the white lines need not be replaced (supporting photographs supplied by Falconbridge Ltd.). If the lava will not thermally erode macadam roads, it is difficult to envision how they would erode pelitic sediments.

The above discussion does not resolve uncertainties regarding the source of the sulfur. It may then be useful to entertain the possibility that the komatiitic flows broke out of a reservoir that was in contact with sulfur-bearing sediments (*e.g.*, extruded after some time of residence in a sill-like magma chamber). The sulfur was incorporated through assimilation of host rocks while the magma was in residence in some sill-like feature before breaking out to flow down the surface or into some other chamber. This would be akin to some of the models proposed by Naldrett and coworkers (*e.g.*, Naldrett *et al.* 1998) for Voisey's Bay and Noril'sk.

Conclusions

Finite-element modeling and appeals to standard formulae employed in assessing characteristics of open-channel flow and suspended particulate load yield the following:

1. Komatiitic lavas should flow with velocities ranging from m/s to tens of m/s, the speed dependent on slope and flow thickness.
2. Komatiitic lavas should carry stratifications of suspended loads of crystals, the bed load leading to olivine-rich komatiite, the next highest load rich in sulfides, and the uppermost portion of the flow of more evolved composition.
3. These stratifications should be on the order of several tens of meters across.
4. Primocrysts such as chromian spinel should accumulate at the interfaces of these stratifications.
5. Assuming that sulfides already are in solution in the magma at the time of extrusion, sulfides should become supersaturated and start coming out of solution about 40 km or so from the source.
6. Finite-element modeling strongly supports the need for embayments to accumulate massive sulfides.
7. There is a dependence of the propensity of an embayment to gather massive sulfides on Reynolds number, and there is an optimum Reynolds number for the formation of massive sulfides.
8. This work supports some of the views of Naldrett and coworkers on the importance of embayments and suggests that more attention be devoted to the recent models of Naldrett and coworkers on Voisey's Bay and Noril'sk.
9. As expressed in this review, we do not support the concept of thermal erosion by lava flows. Particularly encouraging is the recognition that these processes can be quantified. This approach will assist in the location of targets, providing reserve estimation, and will further the understanding of the emplacement of komatiite-hosted nickel deposits.

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