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PHYSICAL CONSTRAINTS ON THE CHARACTERISTICS OF NICKEL-SULFIDE ORE IN ULTRAMAFIC LAVAS

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ABSTRACT

The localization of nickel-sulfide ores at the base of ultramafic-komatiitic lava flows is attributed to gravitational settling. The ore occurs in two distinct zones, a lower massive zone immediately overlain by a net-textured zone. The ore sequence can be explained by dynamic modeling. Heat loss through the bottom of the flow causes the sulfide liquid to freeze upwards and produces massive ore. At the same time olivine accumulates on the sulfide liquid owing to heat loss through the top of the lava flow. The ever-growing olivine cumulus pile forces some of the olivine crystals into the sulfide liquid resulting in the development of net-textured ore (the "billiard-ball" model). The relative thicknesses of these two ore units are dependent on the rates of massive ore solidification and olivine accumulation, and on the percentage of olivine phenocrysts of intratelluric origin.

SOMMAIRE

Nous attribuons la localisation des sulfures de nickel à la base de coulées ultramafiques–komatiitiques à une séparation par gravité. Le minerai se trouve en deux zones distinctes: la zone inférieure, massive, est recouverte d'une zone à texture réticulée. La méthode de simulation dynamique rend compte de cette succession de zones. Des pertes de chaleur à la base de la coulée font cristalliser le liquide sulfuré de bas en haut, d'où formation du minerai massif. Simultanément, l'olivine s'accumule sur le liquide sulfuré, par suite des pertes de chaleur à la surface. Le poids croissant des cumulats d'olivine repousse dans la liquide sulfuré certains cristaux d'olivine qui forment ainsi la texture réticulée (c'est le modèle dit des "boules de billard"). L'épaisseur relative des deux zones dépend de la vitesse de formation du minerai massif d'une part et des cumulats d'olivine d'autre part, ainsi que du pourcentage des phénocristaux d'olivine intratellurique.

(Traduit par la Rédaction)

INTRODUCTION

Concentrations of nickel-sulfide ores at the base of ultramafic or komatiitic flows constitute approximately 10% of the world's current economic nickel-sulfide reserves (Naldrett 1973). The ore usually occurs in two discrete units, a massive sulfide ore overlain in sharp contact by a net-textured ore in which the sulfide continuously encloses olivine crystals. The mechanism for concentration and the existence of these two ore units have been explained by gravitational settling processes (Hudson 1972), termed the 'billiard-ball model' (Fig. 1) by Naldrett (1973), or by metamorphic segregation (Barrett *et al.* 1977). Barrett *et al.* argued that gravitational settling cannot be the dominant ore-forming process for three reasons: (i) the presence of massive ore at the base of the flows is inconsistent with their model of gravity settling; (ii) net-textured ore may contain between 50 and 65 vol. % sulfides. This, they argue, is too high a percentage for the interstitial liquid in a cumulate; (iii) small amounts of silicates commonly found in massive sulfides should have floated out of the massive zone while the monosulfide solid solution (MSS) was still liquid.

Their first point is based on Archimedes' principle, which indicates that as olivine crystallizes in the overlying silicate magma and accumulates on the sulfide magma, the weight of the overlying cumulates will force olivine crystals into the sulfide liquid. According to their calculations and field investigations, the height of olivine cumulates above the sulfide zone is usually sufficient to produce ore that is solely net-textured. However, Barrett *et al.* (1977) neglected the possibility that a portion of the massive sulfide layer (MSS) could have crystallized by heat loss to the underlying country rocks prior to the accumulation of substantial amounts of olivine. The principal purpose of

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the present investigation was to model the cooling and solidification of a komatiitic lava flow, to determine whether some of the sulfide liquid could have solidified to form a rigid zone of massive ore before sufficient olivine had accumulated to force its way through to the base of the massive sulfide layer. If this is true, then the relative thicknesses of the massive and net-textured ore may provide constraints on the physical properties of the komatiitic magma, the proportion of phenocrysts in the magma and the conductivity of the country rocks.

OCCURRENCE OF ORE

Most komatiite-related nickel sulfide deposits occur at the base of peridotitic komatiite flows (*e.g.*, Kambalda and Mt. Edward in W. Australia, Langmuir deposits in Ontario), whereas others occur at the base of what have been described as sill-like feeders to such flows (Scotia and Nepean in W. Australia). A typical mineralized flow consists of a lower zone of massive sulfide overlain by a zone of net-textured ore comprising olivine crystals and interstitial sulfides, overlain by weakly mineralized peridotite grading up into unmineralized peridotite. The massive ore usually lies directly on a previously erupted volcanic rock. At the top of the flow a 2–10 m thick zone of 'spinifex' texture represents silicate magma that has supercooled and crystallized as a mass of skeletal and bladed pyroxene and olivine crystals growing downward into the flow from the roof. A profile through a mineralized intrusion would be similar except that the spinifex zone would be absent.

The relative proportions of massive ore to net-textured ore to weakly mineralized peridotite are variable, both within a given deposit and between different deposits. An idea of the interdeposit variability is given in Table 1 where reported thicknesses thought to be representative of a number of deposits are given.

There are few detailed descriptions of net-textured ore in the literature which give the percentage of sulfides within this zone; many of these do not specify whether the percentages quoted are in wt. or vol. %. Where wt. % is not specified we have assumed that the figure given is vol. %. The following values of % sulfides in net-textured ore are given for various shoots and deposits: (1) Lunnon Shoot, Kambalda, 50–65 wt. %, *i.e.*, 40–55 vol. % (Ewers & Hudson 1972); (2) Kambalda general, 20–65% (Ross & Hopkins 1975); (3) Windarra, up to 70% (Roberts 1975); (4) Nepean, 50–65 wt. % (Hudson 1972); (5) Nepean, 45–65% (Barrett *et al.* 1976). Thus the figure of 50–65% quoted by Barrett *et al.* (1977) for the amount of interstitial sulfide commonly found in net-textured ore is not unreasonable.

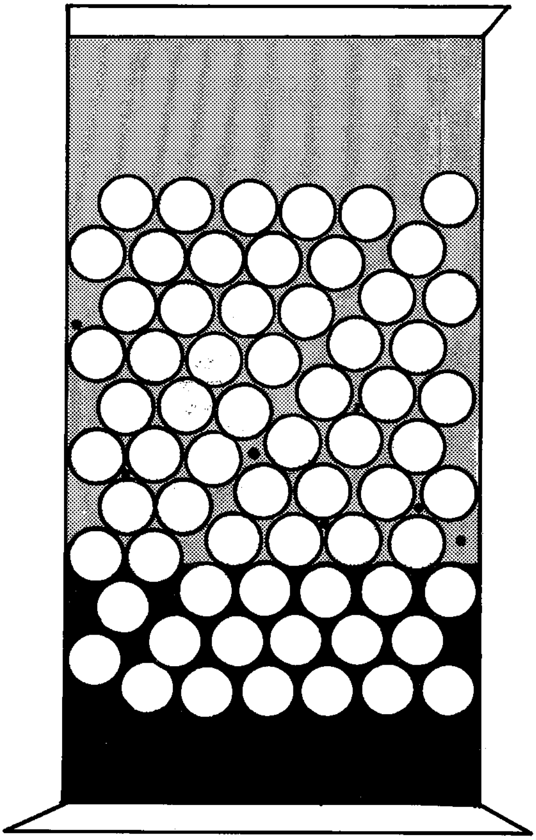

FIG. 1. The 'billiard-ball' model. The analogy is made between the sequence of ore and rock types in a mineralized komatiite flow and a number of billiard balls in a beaker filled with water (light stipple). The balls are slightly denser than the water and sink to the bottom. Mercury is then poured into the mixture and forms a layer at the bottom (massive ore). Some balls are forced down by the weight of the overlying balls so that they are enclosed in a continuous network of mercury (net-textured ore). A few small drops of mercury may get trapped against the overlying balls which are enclosed primarily by water (low-grade disseminated ore in peridotite).

TABLE 1. THICKNESSES (IN METERS) OF DIFFERENT UNITS WITHIN A NUMBER OF ULTRAMAFIC ORE DEPOSITS

Locality	Flow or intrusion	Net ore	Massive ore
Spagoville #2	200	?	4
Spagoville #3	60	12	12
Nepean	15	0.45	0.75
Lunnon	60	3.5	1.5
Scotia	up to 50	up to 18	up to 2
Alexo	?	3	1

THERMAL CALCULATIONS

Governing equations

Certain simplifying assumptions must be made in order to calculate the cooling history of a komatiite flow. The flow is assumed to be extruded instantaneously with parallel top and bottom geometry. The lateral dimensions of the flow are large in comparison to the vertical extent so that a one-dimensional approximation of heat flux is justified. The conductive heat transport in a vertical direction is governed by

$$\rho C_p \left(\frac{\delta T}{\delta t} \right) = \frac{\delta}{\delta z} \left(K \frac{\delta T}{\delta z} \right) \qquad (1)$$

where T represents temperature, ρ is density, C_P is specific heat, K is conductivity, z is the vertical coordinate and t is time. The solution of equation (1) for simple boundary conditions has been outlined by Jaeger (1968). Analytical solutions that incorporate the effects of fractional crystallization, latent heat of solidification, thermal-conductivity differences, *etc.*, are not available; therefore, numerical approximations are required.

The governing finite difference equation for the numerical approximation is

$$T(z, t + \Delta t) = \left[\frac{1 - 2\kappa \Delta t}{(\Delta x)^2} \right] T(z, t) + \frac{\kappa \Delta t}{(\Delta x)^2} \left[T(z - \Delta z, t) + T(z + \Delta z, t) \right] \qquad (2)$$

where κ is the thermal diffusivity; Δt is the time increment and Δz is the distance increment. The temperature at the surface is specified as T = 0°C (or 100°C) and the temperature of the underlying country rock at a depth H is held constant, where H is the total depth of the region under consideration. The region modeled beneath the lava flow was at least five times the thickness of the flow. These conditions are similar to those specified by Jaeger (1968). Because the magma and country rocks have different thermal conductivities, the heat flux through the bottom contact is specified;

$$K_m \frac{\delta T}{\delta z} = K_c \frac{\delta T}{\delta z}$$

where K_m is the conductivity of the magma and K_c is the conductivity of the country rock.

Within the flow an initial crust is expected to develop at the top and bottom, with the interior remaining liquid. The conditions governing whether this liquid will convect or remain stable have an important influence on the cooling history. If one assumes reasonable physical and thermal parameters, the estimated Rayleigh number exceeds 1700, indicating that convection will be a dominant process (Bartlett 1969). Convection will continue until the effective viscosity of the magma increases owing to falling temperature and the increasing amount of crystals within the magma. At some temperature the magma will cease to convect and the flow will cool by conduction. Thermal and mass transfer relations for natural convection are known for only a few simple geometries. As the thermal regime of a naturally convecting magma cannot be calculated, Jaeger (1968) suggested that the heat-transfer process expected for natural convection can be approximated by assuming a large enough conductive heat-transfer coefficient for the magma. In this investigation a magma conductivity of 0.2 cal/sec cm °C was used to approximate convection. This procedure produces a near-uniform temperature distribution throughout the flow.

The effects of latent heat of crystallization can be treated by using a temperature-dependent specific heat (Jaeger 1968). The modified specific heat is $C' = C + L/(T_L - T_S)$ where C' is the modified specific heat, L is the total heat and T_L-T_S is the temperature interval between the liquidus and solidus. The slow cooling of a magma has in the past been treated as a linear evolution of the latent heat over the crystallization interval. A deviation from this linear evolution of latent heat similar to that of Usselman & Hodge (1978) has been used. The evolution of latent heat is a function of crystallization and thus dependent on the amount crystallizing at a given temperature.

Physical parameters

In order to model any cooling–fractionating process, it is necessary to know the phase relations of the magma and the function of the degree of crystallization with respect to temperature. The initial liquid composition (SiO_2 46.25, Al_2O_3 7.30, FeO 11.09, CaO 6.75, MgO 27.98, Na_2O 0.54 wt. %) was obtained by taking a weighted mean of the analyses presented by Arndt *et al.* (1977, Table 6). The liquidus temperature was estimated to be 1550°C and the crystallization of olivine was modeled using the olivine-fractionation program of Roeder (1975). Olivine is the liquidus phase (minor Cr-spinel may also exist) and continues to be the only phase to crystallize until the clinopyroxene–plagioclase cotectic is reached, at which point olivine was assumed to cease crystallizing. The cotectic temperature used in the thermal models, 1230°C, is similar to that found by Arndt (1976a).

There is about 56% olivine coexisting with the liquid at 1230°C; it was assumed that olivine crystallized linearly with respect to temperature as suggested by Roeder's (1975) model. At the cotectic both clinopyroxene and plagioclase begin to crystallize in about a 1:1 ratio and continue to crystallize to the solidus, taken to be 1200°C. There is no clear evidence that plagioclase is present in Mg-rich komatiites. This may be due to difficulties associated with plagioclase nucleation. However, as the major part of this paper is concerned with the high-temperature portion of the liquidus–solidus interval, differences between the modeled phase relations and the true solution at near solidus temperatures will not seriously affect the conclusion. The assumed phase relations are shown in Figure 2.

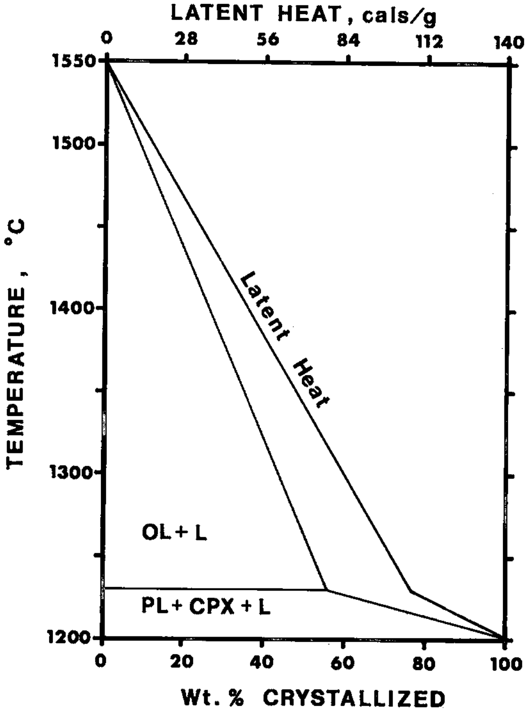

FIG. 2. The assumed phase relations for the modeled komatiite magma as a function of crystallinity. Also shown is the manner the latent heat was evolved as a function of temperature.

TABLE 2. HEATS OF FUSION FOR MINERAL COMPONENTS IN THE MODELED KOMATIITE

	H(cal/g)	H(kcal/mole)
Forsterite[a]	208.2	29.3
Fayalite[b]	108.1	22.0
Anorthite[c]	67.2	18.7
High Albite[b]	51.7	13.5
Diopside[b]	85.4	18.5
Hedenbergite[d]	(55)	(13.8)
$Fo_{90}Fa_{10}$[d]	(194)	(28.6)
$An_{70}Ab_{30}$[d]	(62)	(17.1)
$Di_{80}Hd_{20}$[d]	(78)	(17.6)

[a] Bradley (1962); [b] Robie & Waldbaum (1968); [c] O. J. Kleppa & T. V. Charlu (in Yoder 1976, p. 91); [d] calculated as described in the text.

The total latent heat of the modeled komatiite liquid was calculated using the heat of fusion for the various minerals and their abundances. It was assumed that the heats of fusion are linear between the end members of an ideal solid-solution series. For an olivine $Fo_{90}Fa_{10}$ and using the heats of fusion in Table 2, the heat of fusion was calculated to be 194 cal/g. If the magma crystallized 56% olivine (Fo_{90}), the total contribution of heat released by olivine crystallization would be about 108 cal/g.

For the pyroxene, a composition of $Di_{80}Hd_{20}$ was assumed, but the heat of fusion of hedenbergite is not known. If we assume that the heat of fusion between the Fe and Mg end-members in the pyroxenes shows the same relative change as that between forsterite and fayalite, then the heat of fusion of hedenbergite is about 75% that of diopside, about 13.8 kcal/mole. The heat of fusion of $Di_{80}Hd_{20}$ is estimated to be about 78 cal/g, and assuming 22% pyroxene crystallization, contributes 17 cal/g to the komatiitic magma. Plagioclase (An_{70}) similarly has a heat of fusion of about 62 cal/g and with 22% plagioclase crystallization, 14 cal/g are released to the komatiitic liquid. The total latent heat of the liquid was assumed to be 139 cal/g, which is distributed with respect to temperature as shown in Figure 2.

MODELS

Flow conditions and assumptions

The komatiitic flows were modeled as instantaneously emplaced lava with two metres of sulfide liquid located at the base of the flow The lava could actually have been emplaced as either a homogeneous immiscible suspension of sulfide and silicate liquids or the two liquids could have been discrete immiscible layers of the same flow. Experiments by Shima & Naldrett (1975) have demonstrated that the solubility of sulfur in komatiitic liquids is insufficient for all the sulfide present in a typical orebody to have settled out of that portion of the flow immediately overlying it; thus it is doubtful that the flow was emplaced as a single-phase magma from which the sulfide segregated after emplacement. If the flow was a suspension, the settling velocities of the sulfide liquid and any intratelluric phenocrysts present need to be considered.

The settling velocities of a sphere in a less dense liquid are described by Stokes' law:

$$V_s = 2gr^2 (\Delta\rho)/9\eta$$

whe V_s is the settling velocity, g is the gravitational constant, r is the diameter, $\Delta\rho$ is the density contrast between the two phases, and η is the Newtonian-liquid viscosity. The density and viscosity of a silicate liquid with the model komatiite composition, calculated using the methods of Bottinga & Weill (1970, 1972) are 2.77 g/cm^3 and 0.8 poise at 1550°C, respectively. One mm spheres of sulfide liquid (ρ 4.0 g/cm^3) would settle at approximately 3.35 cm/sec, whereas 1 cm spheres of sulfide liquid would settle at 335 cm/sec. If the initial suspension contained 10% olivine phenocrysts, the silicate liquid would still have a similar density but the eruption temperature would be lower (1490°C) and viscosity would be higher (4.4 poise). In order to account for the settling of sulfide liquid in a suspension of olivine and silicate liquid, Stokes' law needs to be modified to account for the suspended olivine. Lewis *et al.* (1949) developed the following empirical expression for settling through a partly crystallized liquid:

$$V_{LGB} = \frac{2gr^2 (\Delta\rho)}{9\eta} (1 - \phi)^{4.65}$$

where ϕ is the degree of crystallinity. For suspensions with 10% olivine phenocrysts, settling velocities of the sulfide liquid droplets decrease to 0.37 cm/sec (r=1 mm) or 37 cm/sec (r=1 cm). The olivine present (1 mm across) would settle appreciably slower, 0.1 cm/sec. Hence, the sulfide liquid would rapidly settle to the base of a 60 m flow, in the order of a few minutes (assuming no contribution of turbulence in restricting gravitational settling) and would be followed closely in time by olivine. It is inevitable that at some instance in time, the olivine and sulfide liquid would arrive together at the base of the flow; however, the olivine would tend to segregate upward through the sulfide liquid to a level dictated by Archimedes' principle. In the models in which the komatiitic magma contained olivine phenocrysts, the initial starting assemblage for the cooling-rate calculations consisted of a layer of massive sulfide liquid, a net-textured layer (its size dependent on the amount of olivine phenocrysts), an olivine accumulation layer, and the overlying slightly fractionated komatiitic liquid.

It should be pointed out that we make the distinction between olivine phenocrysts (intratelluric, *i.e.*, existing in the magma upon eruption) and cumulus olivine (crystallizing from the emplaced liquid). The olivine phenocrysts will settle and physically behave as cumulus crystals (virtually inseparable from the olivine that crystallized after eruption based on morphologies and textures), but the distinction is important in describing the freezing behavior of the massive sulfide zone and the thickness of the resultant net-textured ores.

These settling relationships justify the assumption made throughout this paper, that olivine and sulfide droplets will instantaneously be deposited at the base of the lava flow in the initial stages of crystallization.

Thermal effects of crystallization and gravitational accumulation

The effect of the accumulated crystals and their interstitial liquid alter the physical parameters used in the cooling calculations. Because of the high effective viscosity of the accumulated mush, it is assumed that the heat transfer through the accumulated pile might be best described by conduction rather than convection (Hess 1972). It is also assumed that heat is transferred through the continually thickening upper crust by conduction. These conditions then require that the model of a lava flow undergoing fractional crystallization be divided into distinct zones based on the heat-transfer mechanism: an upper crust which loses heat by conduction, the convecting magma, the conducting cumulus pile, and the basal sulfide liquid, assumed to be conducting heat to the country rocks. Both the upper crust and cumulus pile thicken with time, which greatly decreases the thickness and affects the dynamics of the convecting liquid portion of the flow. The boundary equations at the various contacts are specified as having an equal heat flux (Provost & Bottinga 1972).

The rate of accumulation of crystals at the bottom of the flow is a function of the heat loss of the magma and the rate of crystallization. The greatest amount of heat loss is through the top where the bulk of crystallization occurs. In order to calculate the rate of accumulation, the flow is divided vertically into discrete volumes of uniform size. Crystallization within each volume is calculated on the temperature difference for a given time step for each particular volume and from the empirically determined relationships of % crystallized *versus* temperature (Fig. 2). The amount of crystals *per* unit volume for a time interval then accumulates to form a pile of cumulates with trapped intercumulus liquid. For example, a volume is assumed to have a uniform temperature at a given time $T\ (z,t)$. The temperature at the next time interval $T(z,t+1)$ is calculated and the temperature difference, $T(z,t)-T(z,t+1)$, is used to calculate the amount of crystallization during that time. Once the amount of crystallization for all the volume elements and the associated intercumulus liquid is greater than a unit volume, the bottom-most liquid unit-volume has its heat-transfer mechanism changed from convection to conduction. However, for the purposes of the crystallization calculation, each unit-volume is accounted for in the program separately from those used in the thermal calculations, in order to account for gravitational settling and crystallization of the intercumulus liquid. Once a unit volume achieves the solidus temperature it no longer contributes to the fractionation calculations.

Effect of country-rock conductivity

The komatiitic flows overlie a floor of previous basalts or komatiites. Both the komatiites and underlying flows commonly occur as pillows (Ross & Hopkins 1975) providing evidence for a subaqueous environment. The estimated country-rock conductivity may vary greatly owing to the subaqueous environment. Massive dry basalt has a low conductivity K (0.0017 cal/cm sec °C: Jaeger 1968). If the underlying basalt is porous, then a high permeability may be expected and some convection of water driven by high temperature-gradients may occur. However, the thermal gradient is in the wrong direction for convection to be a major factor in the footwall. Because of the uncertainty of the actual thermal conductivity of the country rocks, cooling histories of the flows using a range of estimated thermal conductivities (K=0.005 to 0.050 cal/cm sec °C) are presented. It is believed that the use of the higher thermal conductivities will qualitatively account for the effect of hydrothermal circulation and heat transfer in the country rocks.

Amount of net-textured ore

The thickness of the net-textured ore unit (H_2) resulting from the 'billiard-ball' model can be calculated using Archimedes' principle in the following equation:

$H_1/H_2 = (\rho$ silicate liq $- \rho$ olivine) / (ρ olivine $- \rho$ sulfide liq) where H_1 is the thickness of the cumulus olivine layer. If H_0 equals the height of the initial sulfide liquid the resulting thickness of the massive sulfide unit (H_3) existing with a given height of net-textured ore is $H_3 = H_0 - 0.4H_2$, where 0.4 is derived from the theoretical packing of olivine within a sulfide liquid (*i.e.*, 40% intercumulus sulfide liquid). Using ρ silicate liq. = 2.77 g/cm^3 and the densities of olivine and sulfide liquid 3.14 and 4.0 g/cm^3, respectively, as given by Barrett *et al.* (1977), and an initial sulfide-liquid thickness (H_0) of 2, the equations reduce to: H_2 (net-textured) = H_1 (cumulates) /2.32, and H_3 (resulting massive) = 2 − H_1 (0.1721).

These equations were used in the calculation of the thicknesses of the resulting ore zones based on the calculated amount of olivine accumulation. We assumed that the buoyancy described by Archimedes' principle was instantaneously achieved.

Flow example

Taking a 60 m thick komatiite flow at its liquidus (1550°C) with 2 m of sulfide liquid at its base, the cooling curves calculated show the importance of the country-rock conductivity. Using K_{CR} values of 0.005 and 0.050 cal/cm sec°C for two solutions (Fig., 3), it is evident that the higher the country-rock conductivity, the greater the rate of advance of the lower solid–liquid interface (the same could be said for the upper crust). The silicate solidus (1200°C) is used to denote the solidification of the upper crust. For the lower contact, which

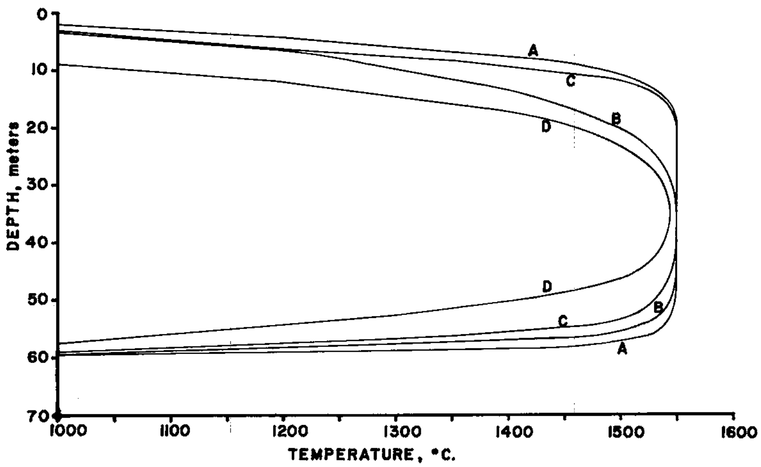

FIG. 3. Solutions for the cooling of two different 60 m komatiite flows. The curves are labeled as follows: *A* (18 days) and *B* (73 days) had a country-rock conductivity of 0.005 cal/cm sec°C, *C* (18 days) and *D* (73 days) had a country-rock conductivity of 0.050 cal/cm sec°C.

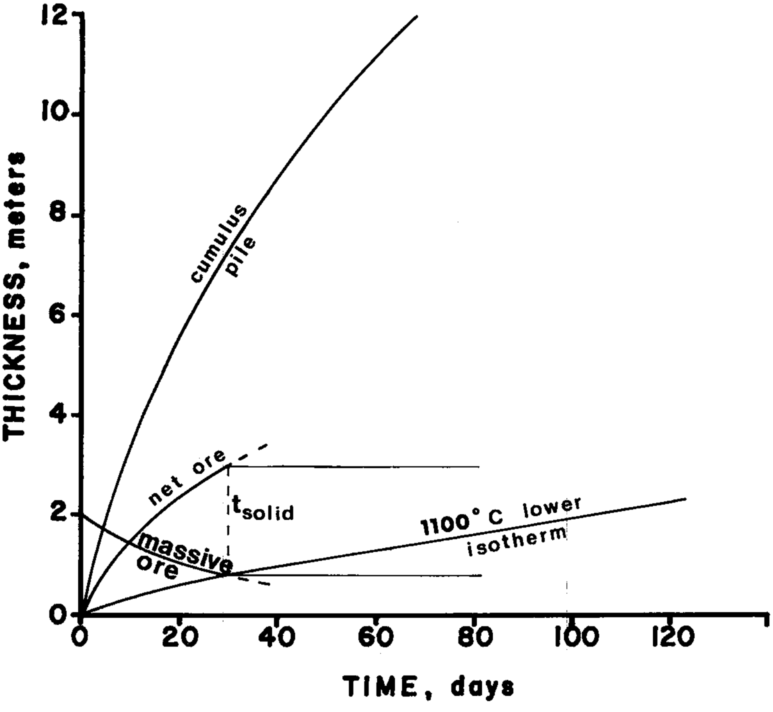

FIG. 4. Graphical representation of the thicknesses of various units with time. As the lower 1100°C isotherm progresses upward and the thickness of the massive sulfide liquid decreases with the increasing cumulus pile (olivine + 40% intercumulus liquid), they intersect at point t_{solid} where the massive sulfide liquid has totally solidified. This time also determines the thickness of the net-textured ore unit.

TABLE 3. RESULTS OF THERMAL CALCULATIONS ON THE SOLIDIFICATION OF NICKEL SULFIDE ORE ZONES

Flow thickness	% Phenocrysts	Eruption Temp. °C	K_{CR}	t_s, days	Cumulus pile at t_s	Massive zone	Net zone	Massive:Net
60 m	0	1550	.005	46	6.2	0.9 m	2.65 m	0.34
60	0	1550	.050	16	3.6	1.38	1.60	0.86
60	5	1520	.005	16	5.7	1.0	2.45	0.41
60	5	1520	.050	6.5	6.2	0.9	2.65	0.34
60	10	1480	.005	1.5	8.2	0.6	3.55	0.17
60	10	1480	.050	1.0	8.2	0.6	3.55	0.17
60[1]	0	1550	.005	9	4.5	0.84	1.94	0.43
60[1]	5	1520	.005	0.5	7.0	0.19	3.01	0.06
60[1]	10	1480	.005	—	—	0	3.33	0
30	0	1550	.005	28	5.7	1.0	2.45	0.41
30	0	1550	.050	12	3.8	1.34	1.65	0.81
30	10	1480	.005	3	5.0	1.14	2.15	0.53
30	10	1480	.050	3	4.9	1.15	2.12	0.54
30	20	1430	.005	0.5	8.7	0.50	3.74	0.13
30	20	1430	.050	0.5	8.3	0.57	3.57	0.16

[1] These calculations utilized 60% intercumulus liquid, others were calculated with 40%.

is of principal interest in this paper, the massive sulfide is assumed to solidify at 1100°C (Craig & Kullerud 1969). Plotting the thickness of the solidified massive sulfide (the 1100°C isotherm) as a function of time describes the rate of advance of the solid–liquid interface of the sulfide liquid. From the calculations of the amount of crystallization of the komatiite as a function of time, the amount of crystallized olivine plus 40% interstitial liquid minus the upper-crust thickness gives the thickness of the cumulus pile. Archimedes' principle and the equations developed in a previous section determine the thicknesses of the resulting net-textured and massive ore as a function of the time-dependent cumulus-pile thickness. These parameters are plotted in Figure 4, which shows the intersection of the 1100°C isotherm with the calculated thickness of massive sulfide. After the time of this intersection, the thicknesses of the massive-sulfide and net-texture units do not vary.

The case illustrated in Figure 4 is for K_{CR} = 0.005 cal/cm sec°C; if the country-rock conductivity were increased, the 1100°C isotherm would advance upward into the flow more rapidly. However, there would also be a more rapid accumulation rate for the cumulus pile. The times necessary for freezing the massive sulfide unit and the resulting thicknesses are given in Table 3.

If the lava flow erupted with olivine phenocrysts, the eruption temperature would be lower; an increase in the proportion of olivine phenocrysts would lead to more rapid cooling than in flows without phenocrysts (Table 3). As a consequence of the lower eruption-temperature, the sulfide liquid solidifies more rapidly. The amount of resulting massive to net-textured ore does not show a simple relationship to the phenocryst content (Figure 5). However, from consideration of Archimedes' principle, no massive ore should result if the phenocryst content is greater than 11.6% for a 60 m thick komatiite flow.

The more rapid cooling behavior and the relationship of phenocryst content to the ratio massive ore: net-textured ore hold for thinner flows (Table 3, Fig. 5) but the maximum amount of phenocrysts can increase. In order to preserve massive ore in a 30 m thick komatiite flow, the maximum phenocryst content upon eruption is 23.2%. This maximum becomes increasingly greater as the flow thickness decreases; it is petrologically unrealistic for very thin flows.

The amount of intercumulus liquid in net-textured ore

Another parameter critical to the above models is the amount of intercumulus liquid associated with both the cumulus olivine and the net-textured ore. The foregoing discussion assumes 40 vol. % intercumulus liquid in a typical cumulate (*cf.*, Wager & Brown 1968). This agrees with olivine-packing experiments (Campbell *et al.* 1978) in a centrifuge furnace at an acceleration of 500 *g*. In these experiments, crushed natural samples containing about 20 modal % olivine were subjected to a temperature 20 – 30°C below their liquidus. Rounded

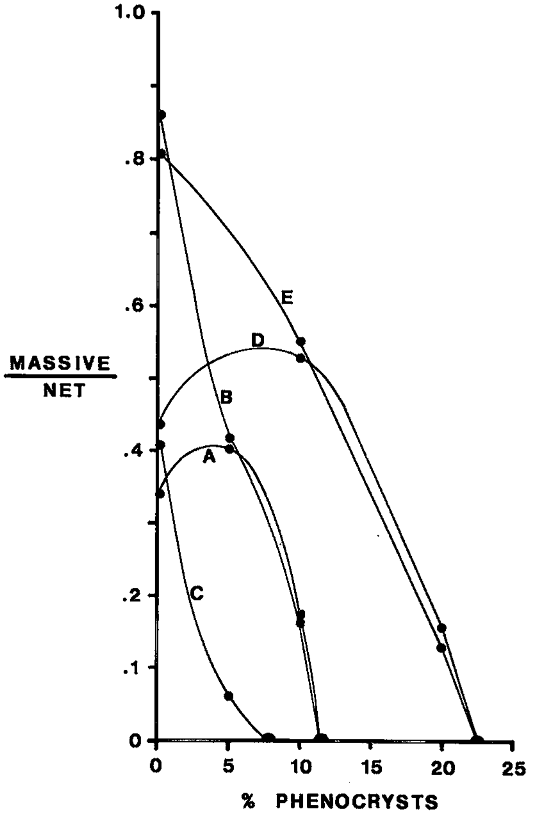

FIG. 5. The relationship between the ratio of massive to net-textured ore and the phenocryst content upon eruption. *A* and *B* represent a 60 m flow with country-rock conductivities of 0.005 and 0.050 cal/cm sec°C, respectively; *D* and *E* are for a 30 m flow with country-rock conductivities as for the 60 m flow ($A = D$; $B = E$). *C* is for a 60 m flow, 0.005 cal/cm sec°C and 60% intercumulus liquid.

unmelted olivines settled to the bottom of the capsule to produce a graded layer with 40% intercumulus liquid (Fig. 6a).

A second series of experiments produced quite different results. The samples were heated above their liquidus for a period of one hour and quenched to room temperature. The quenched glass (with a few minute seed crystals) were then run at a temperature 20 - 30°C below the liquidus and at 500 *g*, resulting in loosely packed euhedral olivine crystals at the bottom of the capsule with 62% intercumulus liquid (Fig. 6b). The similarly between this figure and the 65% cited by Barrett *et al.* (1977) for the maximum amount of interstitial sulfides in net-textured ore is striking.

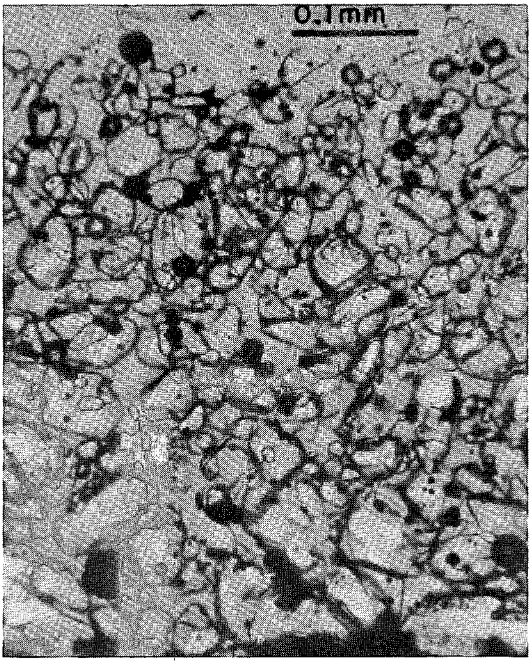

FIG. 6a. Rounded unmelted olivine crystals which have settled to the bottom of the capsule. The amount of intercumulus liquid is 40%. Plane-polarized light, bar scale = 0.1 mm. After Campbell *et al.* (1978).

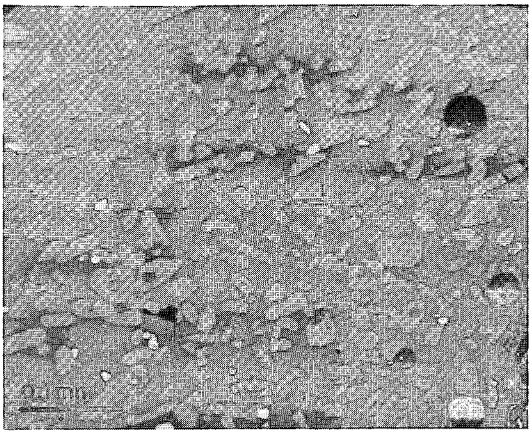

FIG. 6b. Loosely packed chains of olivine crystals which have collected at the bottom of the capsule. The euhedral olivine crystals were grown during the experiment at a temperature 20–30°C below the liquidus. The amount of intercumulus liquid is 62%. Reflected light, bar scale = 0.1 mm. After Campbell *et al.* (1978).

Campbell *et al.* (1978) argued that most of the olivines in the second series of experiments nucleated heterogeneously within the capsule, initially against the seed crystals and thereafter against the newly-formed olivines. The result was a number of chains of olivine crystals that packed poorly compared to the residual olivines in the first series of experiments, which settled as individual grains. This reasoning can be extended to crystal settling in lava flows and magma chambers (Campbell 1978), where crystals are more likely to settle as chains or rafts than as individual crystals.

The observations of Barrett *et al.* (1977) support the above hypothesis for olivine settling in komatiites. The interstitial sulfide liquid in net-textured ore has protected the cumulus olivines from orthocumulate and adcumulate growth and so preserved the original cumulate porosity. In this respect the cumulus olivines of net-textured ore contrast with those of the silicate layer above the ore, which must have undergone appreciable orthocumulate growth and possibly some adcumulate growth, reducing the apparent amount of intercumulus material.

The effect of 60% intercumulus liquid on the resultant ore is evident from Figure 5 and Table 3. Cooling is more rapid than in the models utilizing 40% intercumulus liquid. The resultant ratio massive ore: net-textured ore also indicates that fewer intratelluric phenocrysts could have been in the erupted komatiite.

DISCUSSION

The solutions of thermal models of komatiites and their associated nickel sulfide ores suggest that stratification of the orebodies into layers of massive and net-textured ore is the result of crystal-settling processes. Three observations support this view: (i) where the two ore types occur together they are always in the correct crystal-settling sequence; massive ore always underlies net-textured ore; (ii) the contacts between ore types and between ore and country rock are always sharp, as predicted by the 'billiard-ball' model; (iii) there is excellent agreement between the amount of matrix sulfide in net-textured ore (65%) and experimental determinations of the amount of interstitial liquid trapped between settled olivine crystals (Campbell *et al.* 1978).

Figure 7 depicts the primary role of crystal settling in the ore-forming process. Three stages are recognized; an initial stage (t_0), an intermediate stage (t_1) and the time of massive sulfide solidification ($t_2 = t_s$).

The thermal model presented in this paper indicates that there is a maximum amount of intratelluric phenocrysts that must not be exceeded if a flow is to produce a zone of massive sulfides. For a 30 m thick flow with a 2 m thick layer of liquid sulfides at its base, the maximum content of intratelluric phenocrysts is ~ 20%, but for a 60 m flow it is only ~ 10%.

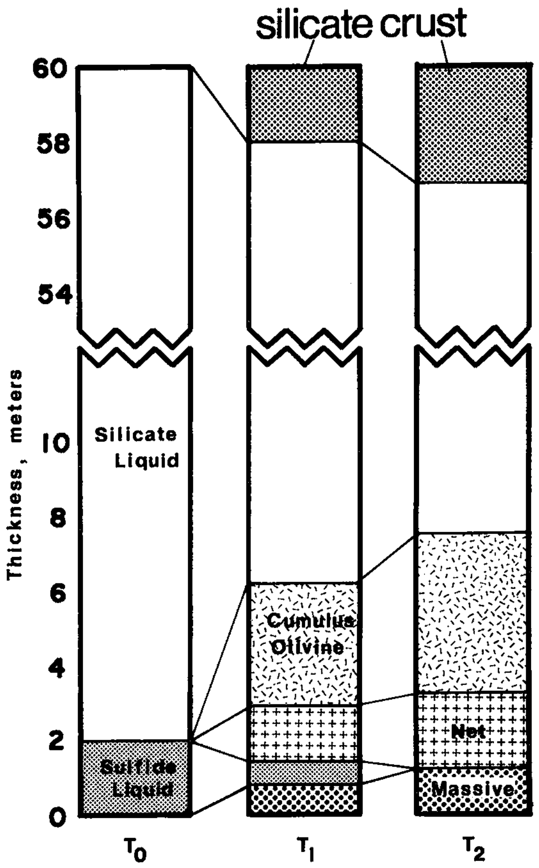

FIG. 7. Schematic sketch of the relationships with cooling between the various units, t_0 (= initial), t_1 and t_2 (= t_s, massive sulfide solidification).

The MgO content of the liquid of an ore-bearing flow, as indicated by the composition of the upper chilled zone, is close to 30%, whereas the weighted average for the flow (spinifex top and cumulate base) is usually in the range 35–40% MgO. This has generally been taken to indicate that the flows had a high intratelluric phenocryst content (Ross & Keays 1979). The weighted average for the MgO content of the flows is usually made for a columm of rock above ore. Such an average is unlikely to be representative of the three-dimensional flow. If ores are found near the vent (Williams 1979), the average MgO con-

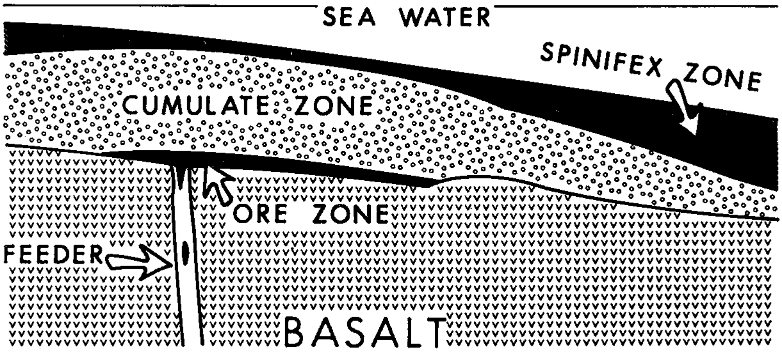

FIG. 8. Diagrammatic longitudinal section through an ore-bearing komatiitic flow.

tent of the flow above the ore can be expected to be higher than that of the bulk composition of the flow. It is generally considered that the flows are ponded in cross-section, with the ore and olivine cumulates being concentrated at the lowest point. It is also reasonable to expect that the sulfide liquid will be dammed in longitudinal section, as shown in Figure 8. If flow from the vent is continuous or occurs as a series of pulses, the intratelluric and early-crystallizing olivines can be expected to collect close to the vent. These olivines will continue to collect as the magma is continually being replaced by fresh liquid extruded from the vent. Flows may therefore be expected to have an asymmetric MgO distribution as shown in Figure 8.

The form of most komatiitic lava flows indicates that they were probably fluid in nature. It is therefore unlikely that the komatiitic lava erupted choked with phenocrysts (Lajoie & Gélinas 1978). The low phenocryst content of the chilled margins of komatiitic flows supports this view.

If it can be shown, contrary to our current expectations, that the intratelluric phenocryst content of certain ore-bearing komatiitic flows was greater than 15%, it may be necessary to invoke a two-stage model in which the massive ore erupted slightly ahead of the silicate liquid and had a chance to develop an upper chilled surface before emplacement of the remainder of the flow (*cf.*, Ross & Hopkins 1975).

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