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TEXTURES IN KOMATIITES AND VARIOLITIC BASALTS

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1. Introduction

Komatiites and variolitic basalts are widespread in Archean volcanic sequences. Spinifex is a spectacular bladed olivine or pyroxene texture that characterizes komatiite, a rock almost exclusively restricted to the Archean; varioles are cm-scale leucocratic globular structures abundant in many Archean basalts. These striking textures provide valuable information about conditions during emplacement of the host magmas, particularly about how the magmas crystallized.

Many komatiite flows have spinifex textures consisting of arrays of numerous subparallel olivine blades that extend 10's of cm to m's from the flow tops. The habit of the strongly anisotropic crystals is suggestive of fast cooling near the flow margin, yet the crystals form deep within the flows. The large temperature difference between solidus and liquidus of komatiites provides a partial explanation for their formation. In addition, the crystals are sharp-tipped and aligned so that their fastest growing faces were normal to the cooling contacts, suggesting that they grew in a strong chemical-potential gradient, in part created by the crystals themselves, as they modified the composition and temperature of the liquid from which they crystallized.

The term variole is useful in the field, particularly during the study of Archean rocks because the textures are often blurred by alteration. Microscopy reveals that varioles result either from blotchy alteration or magma mingling, or they are a form of plagioclase spherulite. Their internal organization and geochemistry is incompatible with the concept that they are quenched immiscible liquids, as has been suggested by some authors (Gélinas et al., 1977). Most examples of varioles from the SW Abitibi province Canada are plagioclase spherulites. These are always found within aphyric tholeiitic basalts which we infer were superheated when erupted. Together the presence of komatiites and the widespread occurrence of plagioclase spherulitic basalts are indicative of unique thermal conditions in the Archean.

We start this chapter with some background information and an overview of crystal growth mechanisms, followed by a section on spinifex textures in komatiites and variolitic rocks.

Variolites

The term variole has a rich, inconsistent and confusing usage. Initially varioles (Fig 1) were defined as spherical masses (which may or may not be spherulites) found on the weathering surfaces of some basalts and diabases (e.g. Lofgren et al. 1974). Modern literature (e.g.) generally defines a variole as a spherulite in a mafic rock. For instance Bates and Jackson 1980, give the following definition; "A pea-size spherule, usually composed of radiating crystals of plagioclase or pyroxene. This term is generally applied only to such spherical bodies in basic igneous rocks."

Spherulites (Fig. 2) are densely packed arrays of fibrous crystals that emanate from a line or point. Each fibre has a crystallographic orientation slightly different to that of its neighbour; hence their "Maltese cross" extinction pattern when viewed under cross-nicols of the petrographic microscope. Undoubtedly the term spherulite is poor because spherulites need not be spherical (Fig. 3)! For example they can be organized into forms that resemble sheafs or combs. Although feldspar spherulites are the most common, the habit has also been observed in many other minerals (e.g. quartz & pyroxene) and other materials (e.g. high-polymers). Typically spherulites range in scale from 1mm to ~1cm, but exceptional cases of m-scale spherulites have been reported (Smith et al., 2001).

Clearly, there is no logic in using the term variole for a structure in a mafic rock while retaining the term spherulite for the same texture in rocks of different composition! Fowler *et al*. (2002) recommended that because several different mechanisms give rise to cm-scale globular structures on the weathering surfaces of mafic rocks, the term variole should be retained as originally defined, and that it is a useful field term. Because varioles (i.e. cm-scale globular textures) may arise through several mechanisms, and because the alteration and deformation associated with Archean volcanic sequences, particularly mineralized ones, can make macroscopic identification difficult, further enquiry is often required to determine the exact nature of the texture.

1.2. Nucleation & crystal growth

Because komatiites and variolitic rocks are at least in part defined by unusual crystal morphologies, we provide here a brief review based upon theory, experiments, and our own observations. Lasaga (1998 and references therein) provide a detailed treatment of the subject. Although mineral growth in lava may be driven by a number of factors, including magma mixing and loss of volatiles, for the moment we focus on heat loss, the major factor in the environment under consideration.

At equilibrium, a crystal within a silicate melt neither grows nor dissolves. The entrenched term "equilibrium growth" is incorrect, as in fact all growth proceeds away from equilibrium. Growth is an attempt to achieve a new equilibrium in accordance with new conditions (generally T, P, composition) imposed upon the system. For thermally driven crystallization from a melt, undercooling (a difference between the equilibrium temperature and the system temperature) is required. Under far-from-equilibrium conditions (sharp cooling), there is interplay between crystal growth and nucleation rates, influenced by the diffusion of growth constituents and heat, and by crystal growth anisotropies. This can lead to feedback or nonlinearities such that distinctive growth patterns spontaneously emerge. These patterns are termed self-organized (e.g. Ortoleva, 1994) and result from the growth kinetics, not growth on a pre-existing template. Examples of self-organized pattern formation in mineral growth include snowflakes, spherulites, spinifex, oscillatory-zoned crystals, banded sphalerite, fractal olivine and branching galena (e.g. (Fowler and Jensen, 1989; L'Heureux and Fowler, 1996; Nittmann and Stanley, 1986)).

Crystal growth must proceed on a nucleus, a stable ensemble having a critical radius. These are either assembled in the melt by homogeneous nucleation, or are present as pre-existing solid "impurities", so-called heterogeneous nucleation. For homogeneous nucleation, clusters having radii smaller than a critical radii are unstable and will not grow. With increasing undercooling the critical radius size decreases sharply. Figure 4 illustrates the variation in nucleation rate as a function of undercooling. Nucleation does not start directly below the liquidus temperature because there is a nucleation barrier; below the glass transition temperature no nucleation occurs. The maximum in the curve reflects the fact that as the temperature drops the silicate melt becomes more viscous and diffusion of growth species is inhibited. The effect is demonstrated in the margins of sills and dykes where chill margins preserve numerous small crystals. Because it is more "difficult" to assemble a nucleus of critical size from the silicate melt than to add growth species to a crystal, growth rates near to, and far from the liquidus temperature exceed nucleation rates.

Once a stable nucleus forms, crystal growth may proceed. This process includes the diffusion of growth species to the surface, their attachment to the surface, their diffusion to specific growth sites, and diffusion of heat. Under near-to-equilibrium conditions, i.e. very small undercoolings, characteristic of large plutons, crystal growth proceeds by the orderly infilling of growth constituents on kinks, steps or other non-planar surface irregularities. Filling of these sites is preferred because of higher bond energy, i.e. there is a greater loss in energy because bonds are formed both at the ledge and the plane-face, rather than at just the face. At small undercoolings, crystal faces are atomically smooth. With increased undercooling a roughening transition occurs such that the crystal face is no longer smooth at the atomic scale. Thus growth under near to equilibrium growth is controlled by crystal surface diffusion and attachment kinetics such that compact, euhedral, compositionally homogeneous crystals arise.

With further undercooling compositionally zoned crystals may arise. In general the crystal zoning only occurs for minerals that are members of solid-solution series, plagioclase being the archetype (e.g. Shore and Fowler, 1996).

At larger undercoolings, anisotropic, skeletal and dendritic habits may develop. Strongly anisotropic textures such as plate spinifex, comb layering, and so-called cres-cumulate textures are characterized by elongated crystals. In many instances the long axes of the crystals are oriented normal to former cooling contacts, an orientation that reflects anisotropies in crystal growth. Nuclei that are oriented with their fastest growing faces normal to the cooling contacts grow preferentially, and starve less optimally oriented crystals from growth.

Skeletal crystals (Fig. 5 spinifex olivine) form when corners and edges of crystals grow more than planar faces. Corners and edges subtend more solid-angle in the melt than planes and when growth is rapid and diffusion in the melt sluggish, they can grow faster than some of the planar faces. Sections through skeletal grains give the illusion that they are composed of disconnected though crystallographically oriented parts. Dendrites (Fig. 6 have parabolic shaped crystal tips and an ordered morphology characterized by a regular arrangement of side-branches along specific crystallographic axes. Sections through dendritic crystals are also skeletal, and the two habits are not easily discriminated.

Spherulitic morphologies occur at still larger undercoolings below the point where the roughening transition occurs. Growth rate is rapid, diffusion in the liquid is slow and the crystallites become microscopically rough. Rapid growth promotes the accumulation of low melting temperature constituents adjacent to the crystallite-melt boundary locally causing an effective undercooling. Protrusions on the rough crystallite project through the accumulation into the "undercooled" zone andgrow to produce an organized array of fibrous crystals. Spherulite growth occurs directly from the melt at high undercoolings. Similar forms also result from devitrification of glass, though probably only through the intervention of fluids. Spherulites are common in felsic volcanic rocks such as dacites and rhyolites because their silica-rich compositions cause the melt to be polymerized.

Under conditions of very high undercooling, for instance at the margins of a rapidly cooling aphyric volcanic flow, crystal growth (if it proceeds at all) typically produces non-compact branching crystals characterized by several orders of non-crystallographic branching. The crystals are fractal objects (Fowler et al., 1989) that can be modelled using the DLA algorithm (Fowler et al., 1986, 1989). The crystal growth occurs in a steady -state field (e.g. invariant temperature gradient) and is dominantly controlled by the random diffusion of growth constituents in the melt; the constituents freeze the instant they collide with the growing crystal. Branching growth is favoured because random–walking growth constituents are more likely to collide with branch tips than to penetrate deep between the branches. Thus the branches become self-propagating.

Rapid cooling is not the only mechanism capable of producing far-from-equilibrium crystal morphologies in igneous rocks. A sudden loss of volatiles from magma abruptly decreases PH_2O and correspondingly increases the liquidus temperatures of its silicate minerals, producing an effective undercooling. This process was responsible for the formation of branching, skeletal olivine crystals in the Rum intrusion of Scotland (Donaldson, 1974). As shown by Lofgren and Russell (1986), melt history may also play an important role in the development of rock texture. Superheating (raising of the system temperature above that of the liquidus) will destroy pre-existing nuclei, embryonic nuclei, and crystals. Cooling of superheated experimental charges produced non-equilibrium habits at lower undercoolings than charges that were not superheated due to the lack of nuclei.

Varioles in Archean volcanic rocks of the Abitibi Subprovince

Early work on variolitic rocks from the Abitibi Greenstone belt of Québec and Ontario focussed on pillowed, massive and flow-banded melanocratic volcanic rocks. Here, the varioles range in scale from a few mm to several cm in diameter and are generally leucocratic and weather recessively. Internal structures are inconspicuous at the macroscopic scale of observation. Several types of phenomenon may give rise to varioles in these rocks. Gélinas et al. 1974) concluded, based largely upon the major element composition (roughly a low-K rhyolite) and shape, that large cm-scale varioles were produced by liquid silicate immiscibility, whereas mm-scale features were plagioclase spherulites. Philpotts (1977) and Hughes (1977), in contrast, argued that both the small and large structures were spherulites.

Fowler et al. (1986) argued against the immiscibility model using trace-element partitioning and textural observations. They demonstrated that the structures were plagioclase spherulites that grew directly from the melt and that their present-day albite mineralogy fortuitously yields a chemical composition similar to “low-K rhyolite”. Microscopic observation of the texture within a few cm of pillow margins reveals the following transition: altered glass and in-situ breccia containing no crystals → altered glass containing sparse mm-scale plagioclase spherical spherulites → larger (cm-scale) more abundant and coarser spherulites → arrays of mutually interfering axiolitic plagioclase and cpx spherulites in which the spherulites are coarser than those near the cooling margins → finally, in some cases, isolated skeletal crystals. In some pillows the spherical spherulites form coalesced clusters. Individual spherulites have planar boundaries indicating they grew into each other. Some larger pillows have spherulite-rich interiors due to flow differentiation of spherulites within former lava tubes. Within the Abitibi subprovince the plagioclase spherulites of basalts are restricted to aphyric tholeiitic lavas. When erupted, these lavas probably were superheated and devoid of nuclei, and when quickly cooled in submarine conditions the few nuclei that formed were rough at the atomic scale and grew rapidly to from spherulites.

Other varioles are observed as leucocratic mm to cm-scale globules that weather in positive relief relative to their mafic host rocks. These too are found within tholeiitic volcanic rocks but are associated with m-scale lobes of rhyolite. Fowler et al. (2002) showed that the cores of these varioles contain small euhedral crystals of quartz and alkali feldspar that served as nuclei for branching crystals of these minerals (Fig. 7). These varioles are clearly neither plagioclase spherulites nor immiscible liquids, but may result from the mingling of basalt and rhyolite (Fowler et al. 2002). The rhyolite was mechanically disrupted during eruption and entrained within the basalt as variably sized entities. Ropchan et al. (2002) described variolitic rocks of this type within the Holloway Au-Mine of the Abitibi. Other varioles observed at this mine are seen to be spherulites either grown from an undercooled and superheated basalt, or grown (possibly as a result of devitrification) within flow banded dacite-rhyolite.

41.1 Spinifex textures in komatiites

It is easy to say roughly what a komatiite is, but very difficult to come up with a rigorous definition. The simple description is that a *komatiite* is an ultramafic volcanic rock (Arndt and Nisbet, 1982). A limit of 18% MgO separates komatiites form less magnesian volcanic rocks such as picrites, ankaramites or magnesian basalts. The term *komatiitic basalt* is applied to volcanic rocks that contain less than 18% MgO and can be related, using petrological, textural or geochemical arguments, to komatiites.

Implicit in the definition of komatiite is the notion — difficult to prove — that komatiites crystallize from liquids that contained more than about 18% MgO. The complications arise from the existence of other volcanic rocks with more than 18% that either formed through the accumulation of olivine from less magnesian liquids, or crystallized from magmas with chemical characteristics quite unlike those of most komatiites. An example of the first type is a phenocryst-charged basaltic liquid (a picrite according to some definitions); an example of the second is meimechite (Arndt et al., 1995; Vasil'yev and Zolotukhin, 1975), a rare alkaline lava with unusual major and trace element composition.

To distinguish komatiite from these other types of highly magnesian volcanic rocks, it is useful to include spinifex texture in the definition. It is present in many, but not all komatiite flows (Nesbitt, 1971). A workable definition of komatiite should include the phrase “komatiite is an ultramafic volcanic rock containing spinifex or related to lavas containing this texture”. With the last part of the definition we can make allowance for the manner in which texture varies within komatiitic units. For example, many komatiite flows have an upper spinifex-textured layer and a lower olivine-cumulate layer; and other flows grade along strike from layered spinifex-textured portions to massive olivine-phyric units. With the inclusion of the phrase about spinifex, the lower olivine-cumulate portions of layered flows or the olivine-phyric units can also be described as komatiite. On the other hand, meimechites, picrites and other rock types that contain no spinifex are excluded. For further discussion, see Le Maitre et al. (1989, 2001) and Kerr and Arndt (2001).

According to the definition given by Arndt (1994),“spinifex is a texture characterized by large, skeletal or dendritic, platy, bladed or acicular grains of olivine or pyroxene, found in the upper parts of komatiitic flows, or, less commonly, at the margins of sills and dikes. The texture is believed to form during relatively rapid, in situ crystallization of ultramafic or highly mafic liquids.” Typically the crystals are extremely anisotropic, on the order of cms or dms in length and approximately a millimeter in thickness.

Within the upper parts of komatiite flows, the type of spinifex texture varies systematically, as illustrated in Fig. 8. Beneath a thin (1-5 cm) glassy, commonly porphyritic chill zone, a layer of “random” spinifex texture contains isolated randomly oriented crystals or cm-scale “booklets” of parallel plates of olivine, in a matrix of fine-grained clinopyroxene and devitrified or altered glass. Below this, the layer of “platy” olivine spinifex has an organized structure wherein arrays of large bladed olivine crystals, a few dm to ms long, are oriented roughly perpendicular to the flow top. In some flows the crystals form parts of sheaf-like structures that open away from flow tops and serve as reliable facing indicators. The lower parts of spinifex komatiite flows are cumulates containing settled solid polyhedral olivine crystals. For detailed descriptions of these textures, see (Donaldson, 1982; Pyke et al., 1973; Shore, 1996)

Pyroxene spinifex is a similar texture that forms in the upper parts of komatiitic basalt flows. In this texture, needle-like crystals, commonly with pigeonite cores and augite margins, lie in a matrix of augite, altered glass and/or plagioclase and oxides. The pyroxene needles range in length from a few mm to several cm and their orientation is either random or perpendicular to the flow top. Detailed descriptions are provided by Arndt and Fleet, (1979) and Fleet and MacRae (1975)

The Origin of Spinifex

One of the first names for spinifex texture in komatiite lavas was “crystalline quench texture”. Viljoen and Viljoen (1969a,b) used this term when they first recognized komatiite as a separate rock type. They described spinifex as a texture characteristic of komatiite, and they noted that the morphology of the dominant minerals resembled those of crystals that form when molten olivine basalt is cooled rapidly.

Nesbitt (1971) formally introduced the term spinifex when he described and classified several different types of skeletal crystals in komatiites from Australia and Canada. He too noted the similarities between the skeletal or dendritic morphologies of olivine and pyroxene crystals in natural spinifex textures and those in experimental charges and silicate slags. He was also first to recognize what has come to be known as the *spinifex paradox*. Spinifex texture is commonly found in the interior of komatiite flows, well below the upper chilled crust. In the thickest units, large dendritic crystals appear to have crystallized at depths 10 or more meters below the surface of the flow. Under such circumstances, the loss of heat from the interior of the flow is controlled by conduction through the upper solidified crust. In a typical 2-m-thick komatiite flow, the cooling rate during crystallization of the lower part of the spinifex layer is only 1 to 3°C per hour. In thicker flows the rate is far lower. In contrast, the morphologies of the olivine or pyroxene crystals in spinifex-textured lavas resemble those produced experimentally at cooling rates never less than about 30°C/hr (Donaldson, 1976, 1982). The discrepancy is well illustrated by Fig. 9, a diagram that shows experimental results of Faure. Simply stated, the *spinifex paradox* refers to the presence, at depths within a komatiite flow where cooling rates must have been low, of elongate skeletal crystals whose morphologies resemble those of crystals that form in experiments at much higher cooling rates.

The first attempt to study experimentally the formation of spinifex textures was that of Donaldson (1976). By extending an approach used by Lofgren (1980) and Lofgren et al. (1974) he developed a scheme whereby the morphology of olivine crystals could be related to the experimental conditions, and particularly to the rate of cooling and/or the degree of undercooling. As illustrated in Fig. 5 and 9, the morphologies of olivine crystals in spinifex-textured komatiites are similar to those of olivine crystallized at cooling rates around 40°C/hr in mafic (basaltic) melts. He was well aware of the spinifex paradox, and suggested two possible solutions. First, that the discrepancy was due in part to the high MgO contents of komatiite liquids, which leads to the development of highly skeletal morphologies at lower cooling rates than in basaltic melts. Second, that the skeletal or dendritic morphologies resulted from rapid crystal growth, but not necessarily from rapid cooling. He did not explain, however, exactly how growth rate could be decoupled from cooling rate in the interior of a lava flow. As mentioned above, once a thick crust develops at the top of a lava, the rate of growth of crystals at the solid-melt interface at the base of the crust will be controlled by the rate at which heat is lost from the lava. The rate of heat loss, the cooling rate, and the rate of crystal growth will all be controlled by the efficiency with which heat is transmitted through the crust.

Attempts to resolve the spinifex paradox were made by Turner et al. (1986) and Shore and Fowler (1998), who attempted to explain how a komatiite could have cooled far more rapidly than predicted by simple conductive cooling models. Turner et al. suggested that a ponded komatiite flow would convect vigorously and cool rapidly. They argued that vigorous internal convection would greatly enhance the rate of heat loss and they proposed cooling rates of 1-100°C h^{-1} soon after emplacement of highly magnesian komatiite. They anticipated that such rapid cooling would cause the interior lava to become highly supersaturated, which would allow skeletal olivine morphologies to form. This explanation is only valid while the crust of the flow remains very thin. As it thickens, the temperature contrast that drives convection becomes less. Once the contrast reaches a certain level, interior convection stops and heat loss is controlled by conduction through the crust. In most recently developed models of the cooling of komatiite, interior convection is limited to the initial stages of cooling of only the most magnesian (MgO >28%) komatiites. Sparks and Turner's model seems unable to explain spinifex textures in the interiors of the majority of komatiites, which form from liquids containing 25% or less MgO.

The spinifex paradox was addressed directly by Shore and Fowler (1998) who undertook a very detailed study of the petrology and textures of komatiites in the classic "Pyke Hill" outcrop in Munro Township, Canada. They proposed two mechanisms that might cause a flow to cool more rapidly than predicted by conductive cooling models. The first is hydrothermal cooling. Shore and Fowler noted that as solidified komatiite cools, it contracts, leading to the formation of a network of fractures in the upper part of the crust. Circulation of seawater through these fractures cools the solidified upper portion of the crust. The efficiency of this process is difficult to judge – although fractures are present in the upper parts of komatiite flows, they are neither abundantly distributed nor continuous. The second mechanism, thermally constrained crystallization, requires heat transfer by radiative and lattice thermal conductivity through the aligned olivine crystals of spinifex textures. Shore and Fowler determined that the *a* crystallographic axis of these crystals is consistently oriented near perpendicular to the flow top. They reported the results of experimental work (refs) demonstrating that heat transfer in olivine is anisotropic and maximal along crystallographic *a*. They calculated that at the high temperatures in magnesian komatiites, the rate of heat transfer along this axis would be 3 to 5 times greater than that of conduction alone. Thus olivine crystals that were favourably aligned with respect to the cooling front would create a steep thermal gradient in the liquid ahead of their tips, thus supporting a self-propagating growth. They recognized, however, that this heat-transfer mechanism would be far less efficient in less magnesian liquids, such as those that crystallize spectacular pyroxene spinifex textures hence the work is not a complete explanation for the formation of spinifex.

Grove et al (1994, 1997, 1999) proposed a very different solution. They concluded that spinifex texture in the interiors of komatiite units from Barberton in South Africa could not be explained by normal crystallization of anhydrous magma, and they used the spinifex paradox as one of their arguments for the presence of large water contents in these komatiites. According to these authors, the role of water is two-fold. First, the presence of water in a silicate melt impedes crystal nucleation and increases the diffusion rate in the silicate liquid, leading to rapid growth of large crystals. Second, degassing of hydrous komatiite as it approaches the surface dramatically increases the liquidus temperature, producing a strongly supercooled liquid. Spinifex texture then results from rapid crystal growth in the interior of the supercooled komatiite. This mechanism depends, however, of two premises: that komatiites contain high water contents, and that they crystallized as sills. The first premise probably is wrong (Arndt et al., 1998) and the second has been disproven by the recent work of Dann (2000, 2001) who showed that the Barberton komatiites, like those in other regions, erupted as lava flows.

A possible solution to the spinifex paradox

A factor that has been mentioned in many papers on spinifex texture, but has not received sufficient attention, is the role of constrained crystal growth during solidification of the crust of a komatiite flow. *Constrained growth* refers to the crystallization of parallel grains of olivine or pyroxene in the downward-growing crust of a lava flow. The crystals compete with one another for “nutrients”, the atoms of Mg, Fe and Si that are essential components of their crystal frameworks. It is this competition that leads to the preferred, near-perpendicular orientation of the olivine crystals in spinifex textures (Figs. 8, 10, 11, 12).

Erupted komatiite contains a small proportion of olivine phenocrysts that grew either during ascent to the surface or during flowage on the surface. During cooling, some of these phenocrysts become trapped in the crust that forms right at the top of the flow, others settle towards to the base of the flow and become part of the lower cumulate layer. Olivine then nucleates in the layer of crystal-free liquid just beneath the crust. The crystals that grow from these nucleii have highly skeletal morphologies, due to the high cooling rate in the crust of the flow, and they are randomly oriented. As cooling proceeds, these olivine grains continue to grow. Those with a near-vertical orientation are favoured because their tips extend downwards into unfractionated nutrient-rich liquid; those with orientations closer to horizontal find only nutrient-poor liquid or collide with other crystals, and they cease to grow.

The crystallization of olivine produces a residual liquid with a composition different from that of the parental liquid, depleted in Mg and enriched in Si, Al, Ca and Na. Its density is less than that of the parental liquid. As downward growth proceeds, this liquid is expelled and it accumulates as a layer of low-density at the base of the crystal front (Turner et al., 1986). The growing tips of the spinifex crystals are bathed in a liquid depleted in the components they require to grow. Faure (2001) and Faure et al. (in preparation) have suggested that this situation provides an explanation for the unusual habit of spinifex crystals — a solution to the spinifex paradox. They point out that the situation has certain parallels with the accumulation of a zone of nutrient-poor liquid that surrounds rapidly growing crystals in quenched liquids. In such cases the rate of crystal growth exceeds the diffusion rate of the major elements within the silicate liquid, and the elements expelled by the growing crystal accumulate in a layer around the crystal. The skeletal or dendritic morphologies of such crystals result when the crystal sends out protuberances - fine needles or plates - that penetrate the nutrient-poor layer (Fig. 11). Faure et al. suggest that an analogous phenomenon applies to the growth of spinifex crystals – their dendritic habit is a consequence of their growth into the accumulated layer of nutrient-poor liquid.

The solution to the spinifex paradox likely lies in developing a complete understanding of constrained crystallization. As mentioned earlier, it is unlikely that pyroxene spinifex grew by thermally constrained crystallization, because unlike Mg-rich olivine, it is unlikely that pyroxene can effectively transfer IR radiation.

The reason why spinifex only forms in komatiites can be found when we consider the liquidus phase relations of komatiites. As shown in Fig. 13, in the most magnesian komatiites, the difference in temperature between the onset of olivine crystallization at the liquidus, and the solidus is close to 400°C. In contrast, in basaltic magmas, which commonly are saturated in two or more silicate minerals, the difference between the liquidus and solidus is less than 100°C. In the crust of a komatiite flow, a very thick zone develops in which a framework of olivine crystals is enveloped by silicate liquid. This situation facilitates the expulsion of olivine-depleted liquid and favours the accumulation of olivine. As pointed out by Barnes et al. (1983) and Arndt (1986), spinifex lavas are “coagulation cumulates” which contain a higher proportion of the liquidus mineral(s) than the liquid from which they crystallized.

This model, which is currently being tested by experiments in which a komatiite liquid is cooled rapidly in a thermal gradient, may provide an explanation for several other hitherto puzzling aspects of komatiite flows.

1) *Contrasting mineralogy in the upper and lower parts of komatiitic basalt flows.* In many differentiated flows, the mineralogy of spinifex-textured rocks differs from that of the lower cumulates. In Fred's Flow, a thick layered komatiitic basalt in Munro Township (Arndt, 1977b), the succession of liquidus minerals in the spinifex zone is olivine (+ chromite) → pigeonite → augite → plagioclase. In the lower part of the flow, olivine-chromite cumulates are overlain in turn by orthopyroxene-augite cumulates and orthopyroxene-plagiclase cumulates. The contrasting behaviour might be explained if rapid crystallization leads to the build up of olivine-poor, pyroxene-saturated liquid at the base of the growing spinifex layer. Pyroxene spinifex results from crystallization within this layer, whose composition differs from that of liquid lower in the flow from which the cumulus phases crystallize.

2) *The precocious pyroxene problem.* In komatiitic basalts, pyroxene crystallizes sooner than it should, according to equilibrium phase relations. When a sample of olivine-free spinifex-textured lava with pigeonite as the liquidus phases is studied experimentally in the laboratory, it crystallizes olivine first, followed at lower temperatures by augite and plagioclase (Arndt, 1977c; Arndt and Fleet, 1979). The problem is illustrated in Fig. 14. In the trend of compositions of natural lavas the kink at about 15% MgO indicates the onset of pigeonite crystallization; in liquids produced in equilibrium melting experiments, the kink at 12% MgO corresponds to the crystallization of augite immediately followed by plagioclase. This contrast in behaviour is readily explained if the spinifex texture crystallized from a layer of olivine-depleted liquid whose composition was far from that of the equilibrium liquid.

6. Conclusions

Variolites are rocks containing varioles — cm-scale leucocratic globular structures in a fine grained mafic rock. The term variole is best used as a descriptive term in the field. Because Archean rocks are altered and metamorphosed to some degree further work is often required in order to discern their original nature. In our experience, varioles have, with detailed examination, turned out to be one of the following, spherulites, amygdules, blotchy alteration fronts, magma-mingling textures, altered phenocrysts and possibly accretionary lapilli. We are unaware of any varioles in the Abitibi Subprovince that have been proven to result from liquid silicate immiscibility. Many of the tholeiitic basalts of the area are characterized by large and abundant altered plagioclase spherulites that grew directly from the melt. These basalts are always aphyric, demonstrating that they were superheated. They are abundant in many Archean sequences and we their presence supports the concept that Archean thermal regimes were different to those of later Eons.

Spinifex is a texture peculiar to komatiites and for this reason is restricted almost entirely to Archean sequences. The origin of the texture is enigmatic. It is difficult to explain how a texture that appears to require rapid cooling can form deep below the crust of komatiite flows, where the cooling rate should have been low. A possible solution is provided by realisation that many of the characteristics of spinifex —the size, preferred orientation, and habit of the crystals — may be explained by cooling in a thermal gradient, such as exists in the upper part of every lava flow. The formation of spinifex is linked to the temperature difference between liquidus and solidus, which is very large in komatiites. This produces a thick partially molten zone in the upper part of the flow and within this zone the conditions required for the formation of spinifex. The texture highlights the peculiar nature of komatiites, a truly Archean magma type.

References

Arndt, N.T., 1976. Melting relations of ultramafic lavas (komatiites) at 1 atm and high pressure. Carnegie Inst Wash YB, 75: 555-562.

Arndt, N.T., 1977a. Mineralogical and chemical variations in two thick, layered komatiitic lava flows. Carn Inst Wash YB, 76: 494-502.

Arndt, N.T., 1977b. Thick, layered periodotite-gabbro lava flows in Munro Township, Ontario. Can. J. Earth Sci., 14: 2620-2637.

Arndt, N.T., 1977c. Ultrabasic magmas and high-degree melting of the mantle. Contrib. Mineral. Petrol., 64: 205-211.

Arndt, N.T., 1986. Differentiation of komatiite flows. J. Petrol., 27: 279-301.

Arndt, N.T., 1994. Archean komatiites. In: K.C. Condie (Editor), Archean Crustal Evolution. Elsevier, Amsterdam, pp. 11-44.

Arndt, N.T. et al., 1998. Were komatiites wet? Geology, 26: 739-742.

Arndt, N.T. and Fleet, M.E., 1979. Stable and metastable pyroxene crystallization in layered komatiite flows. Am. Mineralogist, 64: 856-864.

Arndt, N.T., Lehnert, K. and Vasil'ev, Y., 1995. Meimechites: highly magnesian alkaline magmas from the subcontinental lithosphere? Lithos, 34: 41-59.

Arndt, N.T. and Nisbet, E.G., 1982. What is a komatiite? In: N.T. Arndt and E.G. Nisbet (Editors), Komatiites. George Allen and Unwin, London, pp. 19-28.

Barnes, S.-J., 1983. A comparative study of olivine and clinopyroxene spinifex flows from Alexo, Abitibi greenstone belt, Canada. Contrib. Mineral. Petrol., 83: 293-308.

Dann, J.C., 2000. The 3.5 Ga Komati Formation, Barberton Greenstone Belt, South Africa, part I: new map and magmatic architecture. S. Afr. J. Earth Sci., 6: 681-730.

Dann, J.C., 2001. Vesicular komatiites, 3.5-Ga Komati Formation, Barberton Greenstone Belt, South Africa: inflation of submarine lavas and origin of spinifex zones. Bull. Volcanol., 63: 462-481.

Donaldson, C.H., 1974. Olivine crystal types in harrisitic rocks of the Rhum pluton and Archean spinifex rocks. Geol. Soc. Am. Bull., 85: 1721-1726.

Donaldson, C.H., 1976. An experimental study of olivine morphology. Contrib. Mineral. Petrol., 57: 187-213.

Donaldson, C.H., 1982. Spinifex-textured komatiites: A review of textures, mineral compositions, and layering. In: N.T. Arndt and E.G. Nisbet (Editors), Komatiites. George Allen and Unwin, London, pp. 211-244.

Faure, F., 2001. Les textures de croissance rapide dans les roches magmatiques basiques et ultrabasiques: étude expérimentale et nanoscopique, Université Blaise Pascal, Clermont Ferrand, 206 pp.

Fleet, M.E. and MacRae, N.D., 1975. A spinifex rock from Munro Township, Ontario. J. Can. Earth Sci., 12: 928-939.

Fowler, A.D., Berger, B., Shore, M., Jones, M.I. and Ropchan, J., 2002. Supercooled rocks: development and significance of varioles, spherulites, dendrites and spinifex in Archean volcanic rocks, Abitibi Greenstone Belt , Canada. Precamb. Res. 115, 311-328.

Fowler, A.D. and Jensen, L.S., 1989. Quantitative trace-element modelling of the crystallization history of the Kinojévis and Blake River Groups, Abitibi Greenstone Belt, Ontario. Can. J. Earth Sci., 26: 1356-1373.

Fowler, A.D., Jensen, L.S. and Peloquin, S.A., 1986. Varioles in Archean basalts: products of spherulitic crystallization. Can. Mineral., 25: 275-289.

Fowler, A.D., Stanley, H.E. and Daccord, G., 1989. Disequilibrium silicate minerals: fractal and nonfractal features. Nature, 341: 134-138.

Gélinas, L. and Brooks, C., 1974. Archean quench-textured tholeiites. Can. J. Earth Sci., 11: 324-340.

Gélinas, L., Brooks, C. and Trzcienski, W.E., 1977. Archean variolites quenched immiscible liquids. Can. J. Earth Sci., 13: 210-230.

Grove, T.L., Gaetani, G.A. and de Wit, M.J., 1994. Spinifex textures in 3.49 Ga Barberton Mountain Belt komatiites: evidence for crystallization of water-bearing, cool magmas in the Archean. Eos (Transactions, American Geophysical Union), 75 (spring): 354.

Grove, T.L., Gaetani, G.A., Parman, S., Dann, J. and de Wit, M.J., 1996. Origin of spinifex textures in 3.49 Ga komatiite magmas from the Barberton Mountainland South Africa. Eos (Transactions, American Geophysical Union), 77: 281.

Grove, T.L., Parman, S.W. and Dann, J.C., 1999. Conditions of magma generation for Archean komatiites from the Barberton Mountainland, South Africa. In: Y. Fei, C.M. Bertka and B.O. Mysen (Editors), Mantle petrology: field observations and high-pressure experimentation. The Geochemical Society, Houston, pp. 155-167.

Hanski, E.J.,1993. Globular ferropicritic rocks at Pechenga, Kola Peninsula (Russia): Liquid immiscibility versus alteration. Lithos, 29, 197-216.

Hughes, C.J., 1977. Archean variolites – quenched immiscible liquids: Discussion. Can. J. Earth Sci., 14: 137-139.

Kerr, A.C. and Arndt, N.T., 2001. A note on the IUGS reclassification of the high-Mg and picritic volcanic rocks. J. Petrol, 42: 2169-2171.

Lasaga, A.C., 1998. Kinetic Theory in the Earth Sciences. Princeton University Press, 811p.

L'Heureux, I. and Fowler, A.D., 1996. Isothermal constitutive undercooling as a model for oscillatory zoning in plagioclase. Can. Mineral., 34: 1137-1147.

Le Maitre, R.W. et al. (Editors), 1989. A Classification of Igneous Rocks and Glossary of Terms. Blackwell, Oxford, 191 pp.

Lofgren, G.E., 1980. Experimental studies on the dynamic crystallization of silicate melts. In: R.B. Hargraves (Editor), Physics of magmatic processes. Princeton University Press, Princeton, pp. 487-552.

Lofgren, G.E., Donaldson, C.H., Williams, R.J., Mullins, O. and Usselman, T.M., 1974. Experimentally reproduced textures and mineral chemistry of Apollo 15 quartz-normative basalts. Proc. Lunar Sci. Conf., 6: 79-99.

Lofgren, G.E. and Russell, W.J., 1986. Dynamic crystallization of chondrule melts of porphyritic and radial pyroxene composition. Geochim. Cosmochim. Acta, 50: 1715-1726.

Nesbitt, R.W., 1971. Skeletal crystal forms in the ultramafic rocks of the Yilgarn Block, Western Australia: Evidence for an Archaean ultramafic liquid. Geol. Soc. Australia, 3: 331-347.

Nisbet, E.G. et al., 1987. Uniquely fresh 2.7 Ga komatiites from the Belingwe greenstone belt, Zimbabwe. Geology, 15: 1147-1150.

Nittmann, J. and Stanley, H.E., 1986. Tip splitting without interfacial tension and dendritic growth patterns arising from molecular anisotropy. Nature, 321: 663-xx.

Ortoleva, P.J., 1994. Geochemical Self-Organization. Oxford University Press, 411.

Philpotts, A.R., 1977. Archean variolites – quenched immiscible liquids: Discussion. Can. J. Earth Sci., 14: 139-144.

Pyke, D.R., Naldrett, A.J. and Eckstrand, O.R., 1973. Archean ultramafic flows in Munro Township, Ontario. Geol. Soc. Amer., Bull., 84: 955-978.

Ropchan, J.R., Luinstra, B., Benn. K., Ayer,J., Berger, B., Dahn, R., Labine, R., Amelin, Y. & Fowler, A.D., 2002. Host rock and structrural controls on the nature and timing of gold mineralization at the Holloway mine, Abitibi Subprovince, Ontario. Economic Geology, 97, 291-309.

Shore, M., 1996. Cooling and Crustallization of Komatiite Flows. PhD Thesis, University of Ottawa, Ottawa, 211 pp.

Shore, M. and Fowler, A.D., 1996. Oscillatory zoning in minerals: A common phenomenon. Can. Mineral., 34.

Shore, M. and Fowler, A.D., 1998. Optical and thermal anisotropy of olivine, hydrothermal cooling of komatiites and the origin of spinifex texture. GAC-MAC, Program and Abstracts. Geological Association of Canada-Mineralogical

Association of Canada.

Smith, R.K., Tremallo, R.L. and Lofgren, G.E., 2001. Growth of megaspherulites in a rhyolitic vitrophyre. Amer. Mineral., 86: 589-600.

Turner, J.S., Huppert, H.E. and Sparks, R.S.J., 1986. Komatiites II: Experimental and theoretical investigations of post-emplacement cooling and crystallization. J. Petrol., 27: 397-437.

Vasil'yev, Y.R. and Zolotukhin, V.V., 1975. Petrologiya ul'trabazitov severa Siberskoy platformy i nekotoryye problemy ikh genezisa (Petrology of the ultrabasites in the North Siberian Platform and some problems of their origin) (in Russian). Nauka, Novosibirsk.

Viljoen, M.J. and Viljoen, R.P., 1969a. Archaean vulcanity and continental evolution in the Barberton region, Transvaal. In: T.N. Clifford and I. Gass (Editors), African magmatism and tectonics. Oliver and Boyd, Edingburgh, pp. 27-39.

Viljoen, M.J. and Viljoen, R.P., 1969b. The geology and geochemistry of the lower ultramafic unit of the Onverwacht Group and a proposed new class of igneous rocks. Spec. Publ. Geol. Soc. South Africa, 2: 55-85.

Fig captions

Fig. 1 - Image of varioles within meta-basalt from Guibord Twp. Abitibi Geenstone Belt, Ontario, field of view ~1m. The varioles are the light coloured spherical to amoeboid structures. Detailed petrography demonstrates that these varioles are due to variable alteration (e.g. Hanski, 1993)

Fig. 2 - Altered plagioclase spherulite from the margin of a basalt pillow Harker Twp. Abitibi Greenstone Belt, Ontario, field of view ~2cm, plane polarized light. The

spherulite is circular in section, and has a concentric structure which is not uncommon. Viewed under cross-nichols each fibre extiguishes at a slightly different orientation to its neighbours.

Fig. 3 - Altered plagioclase spherulites from a basalt pillow Harker Twp. Abitibi Greenstone Belt, Ontario, field of view ~5mm, X-nichol. Unlike figure 2 the spherulites are not circular in section, instead they emanate from a line (in rough terms) hence they may be classified as “axiolites”

Fig. 4 - Nucleation rate as a function of temperature, T_l is the liquidus temperature and T_g the glass transition temperature. Note that a finite undercooling must be achieved before nucleation occurs, and that no nucleation occurs below the T_g.

Fig. 5 - Spinifex texture in thin section. This sample, from the Zwishewane region in the Barberton belt, is one of the freshest known Archean komatiites (Nisbet et al., 1987). It contains skeletal olivine crystals randomly oriented in a matrix of acicular augite crystals and altered glass.

Fig. 6 - Cr-spinel dendrite from a komatiite flow of Pyke Hill, Munro Twp., Abitibi Greenstone Belt, Ontario, field of view ~150μm, plane polarized light.

Fig. 7 - Detail of variole interpreted to be due to magma mingling from Munro Twp., Abitibi Greenstone Belt, Ontario, field of view ~2mm, The image shows altered phenocrysts of quartz and alkali feldspar with spherulitic overgrowths. These are rhyolite in composition and found as globules in mafic rocks.

Fig. 8 - Spinifex texture in outcrop from the type section of komatiites in the Barberton greenstone belt in South Africa (Viljoen and Viljoen, 1969b). The photo shows textures just below the flow top. A zone of randomly oriented olivine blades (A1) overlies plate spinifex in which books of parallel elongate blades of olivine are oriented at a high angle to the flow top.

Fig. 9 - The relation between olivine morphology and cooling rate, inferred by Donaldson (1974, 1976) from his dynamic crystallization experiments.

Fig. 10 - Diagram illustrating the “spinifex paradox”.

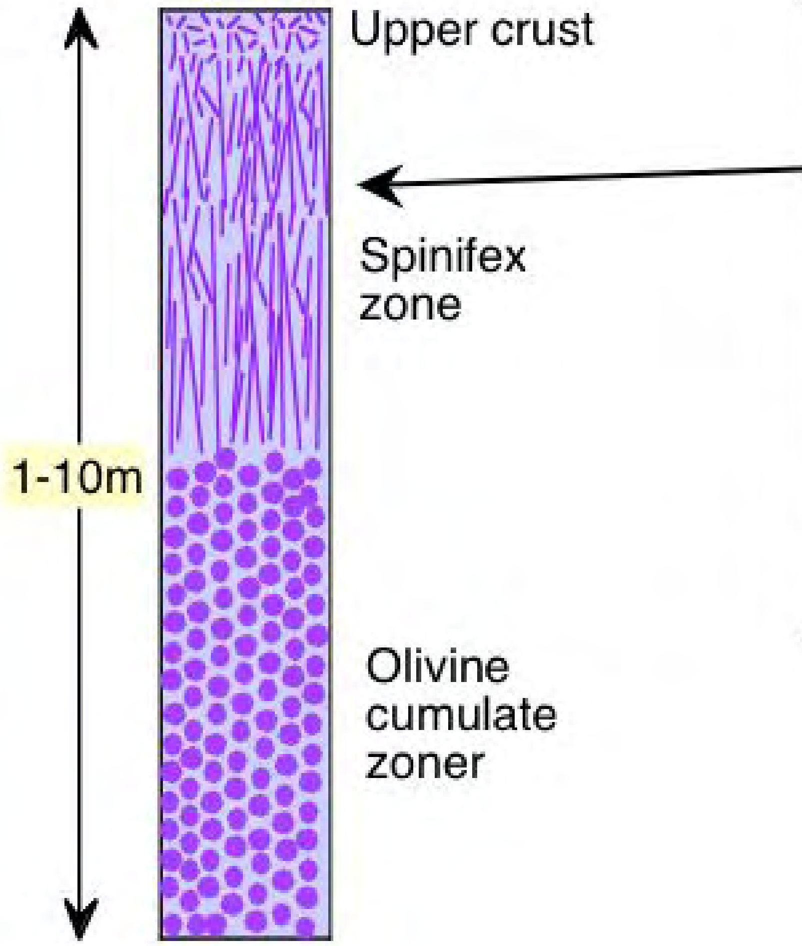
Fig. 11 - Three stages during the solidification of a spinifex-textured komatiite flow.

Fig. 12 - Synthetic spinifex texture in a fayalite slag illustrating constrained growth of olivine and the mechanism that leads to preferred orientation perpendicular to the cooling surface.

Fig. 13 - Diagram of percentage liquid vs temperature illustrating the large difference in the liquidus-solidus gap between komatiite and basalt. The data used to draw the diagram are from Arndt (1976).

Fig. 14 - MgO-CaO-Al_2O_3 diagram, data from Arndt (1977a), showing different trends between the compositions of natural komatiitic basalts and the equilibrium crystallization trend. The kink away from CaO marks the onset of clinopyroxene crystallization which appears to start earlier in the natural samples than under equilibrium conditions.

Section through a komatiite flow



The cooling rate 2 m beneath the top of a komatiite flow should be low (~1-5°C/h), but the dendritic morphologies of olivine crystals in spinifex textures resemble those of crystals that form at high cooling rates in dynamic crystallisation experiments

Fig. 8

Skeletal form indicates that the growth rate exceeded the diffusion rate of major elements

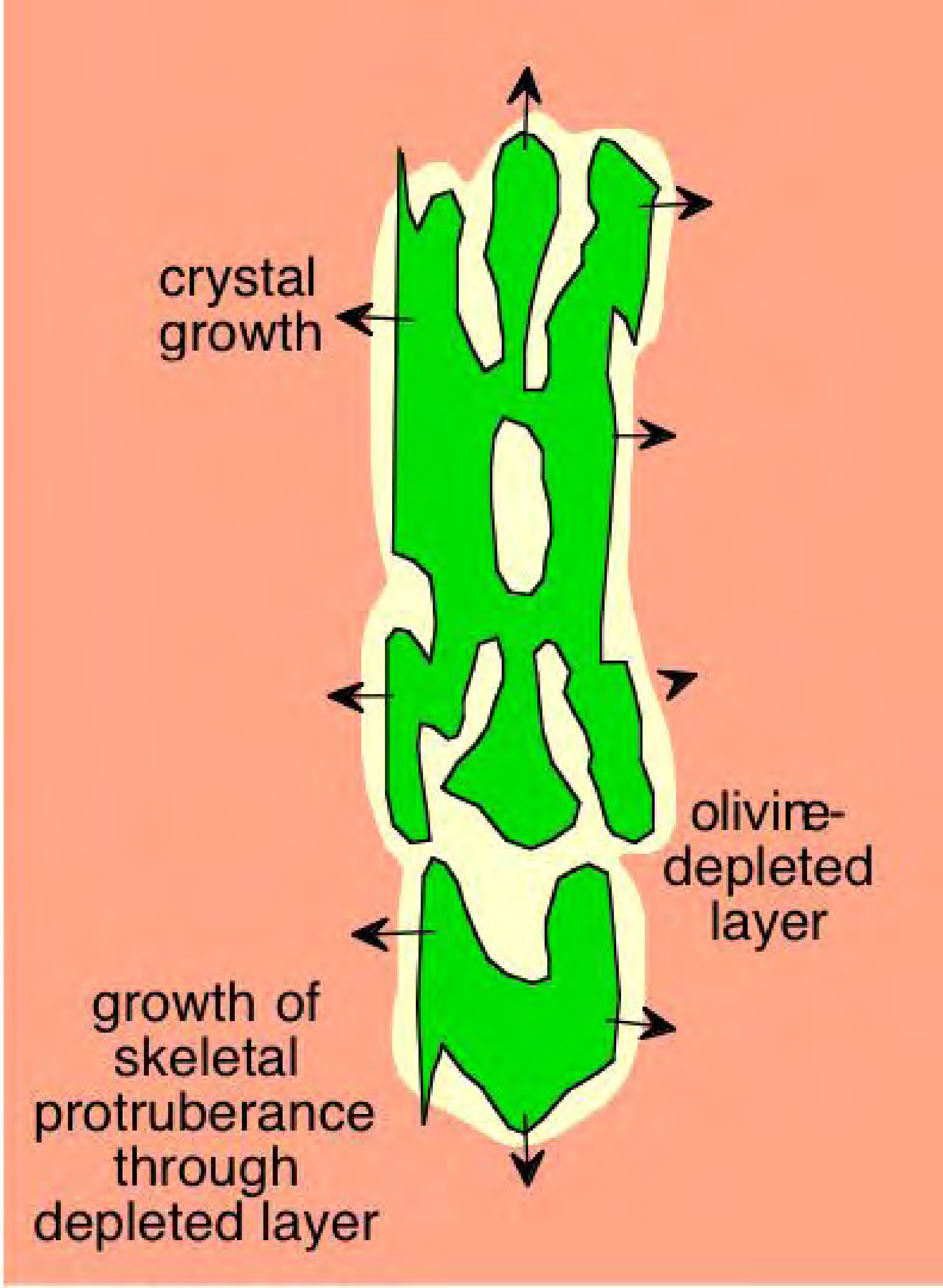
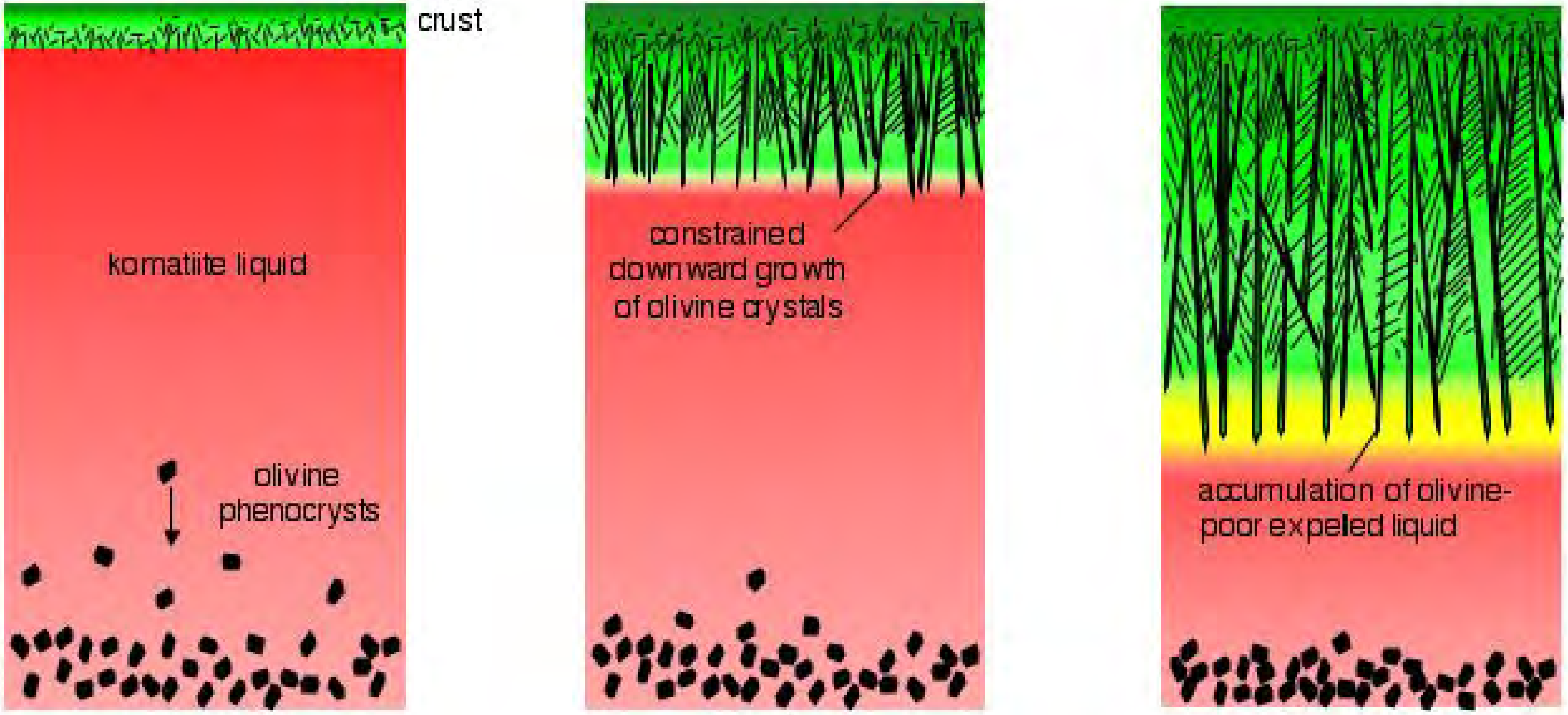


Fig. 9

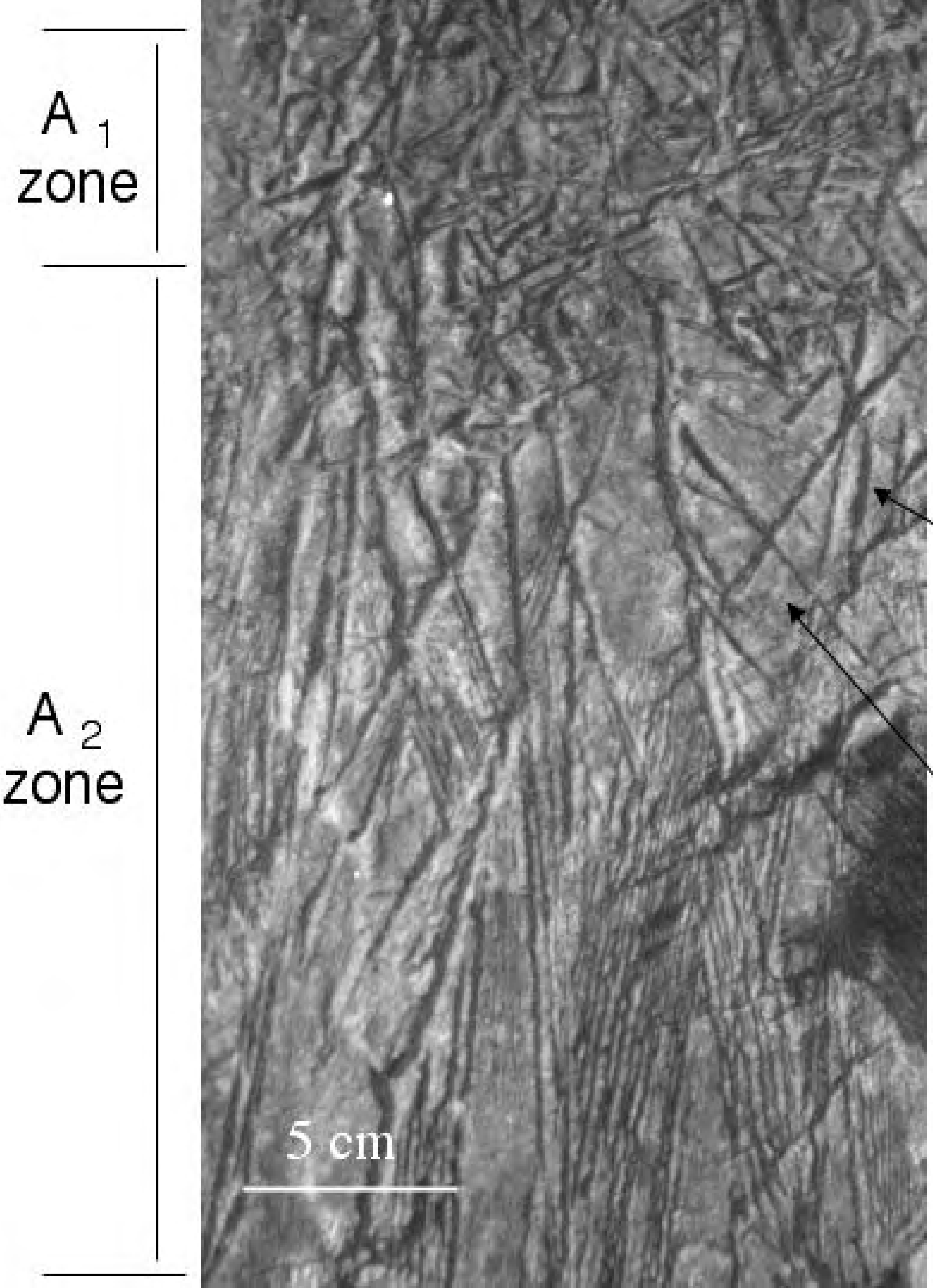


Stage 1: phenocrysts settle to the base; a thin crust forms at the top

Stage 2. Spinifex texture forms through downward growth of olivine crystals. Constrained growth controls their orientation

Stage 3: Accumulation of low-density expelled liquid at the base of the spinifex layer influences the habit and composition of spinifex crystals

Fig. 10



large blades of olivine, now altered to chlorite or serpentine

fine-grained pyroxene and altered glass in the groundmass

Fig. 4

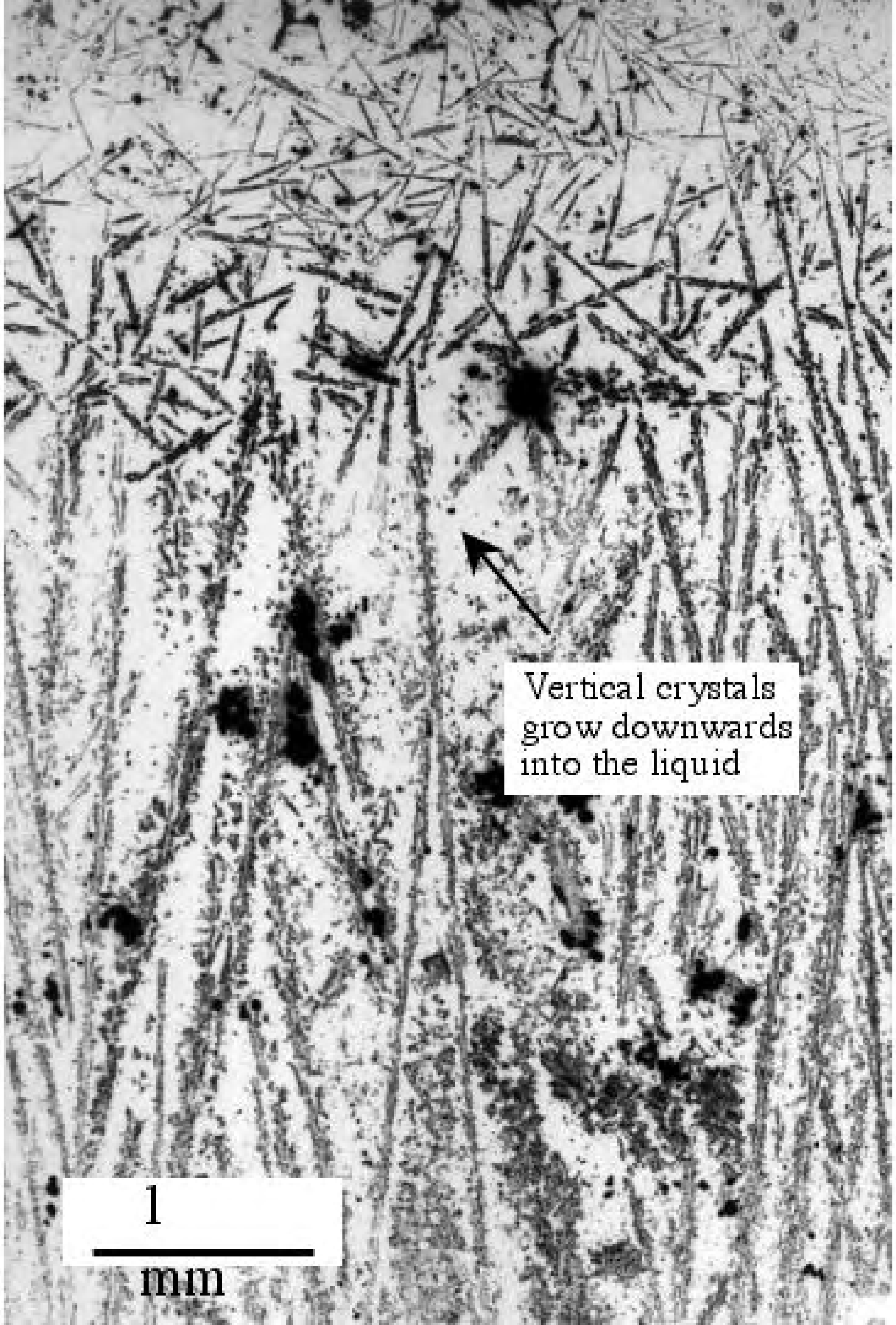


Fig. 11

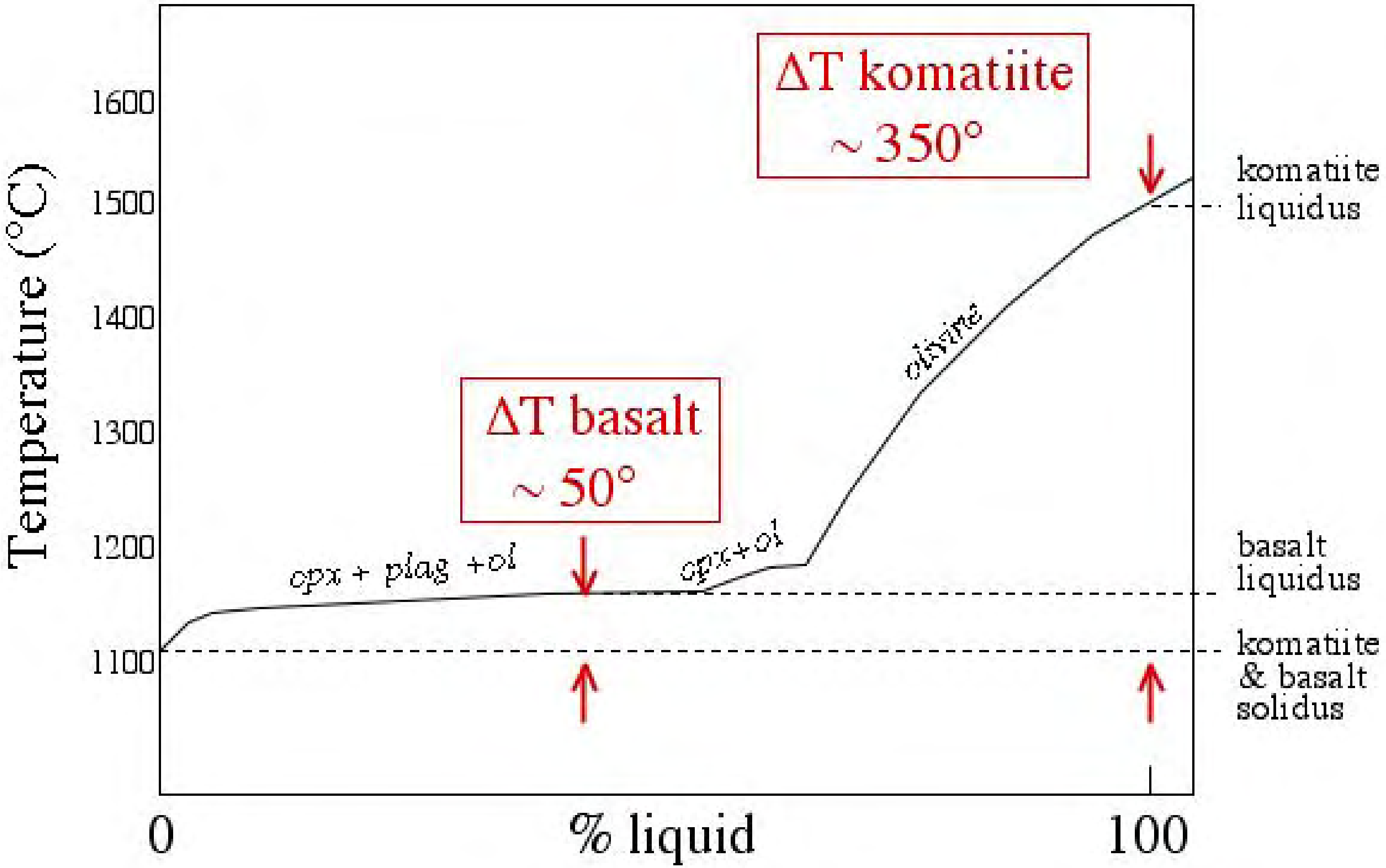

ΔT komatiite
~ 350°
ΔT basalt
~ 50°
Temperature (°C)
1600
1500
1400
1300
1200
1100
0
% liquid
100
komatiite liquidus
basalt liquidus
komatiite & basalt solidus
opx + plag +ol
opx+ol
olivine

Fig. 12

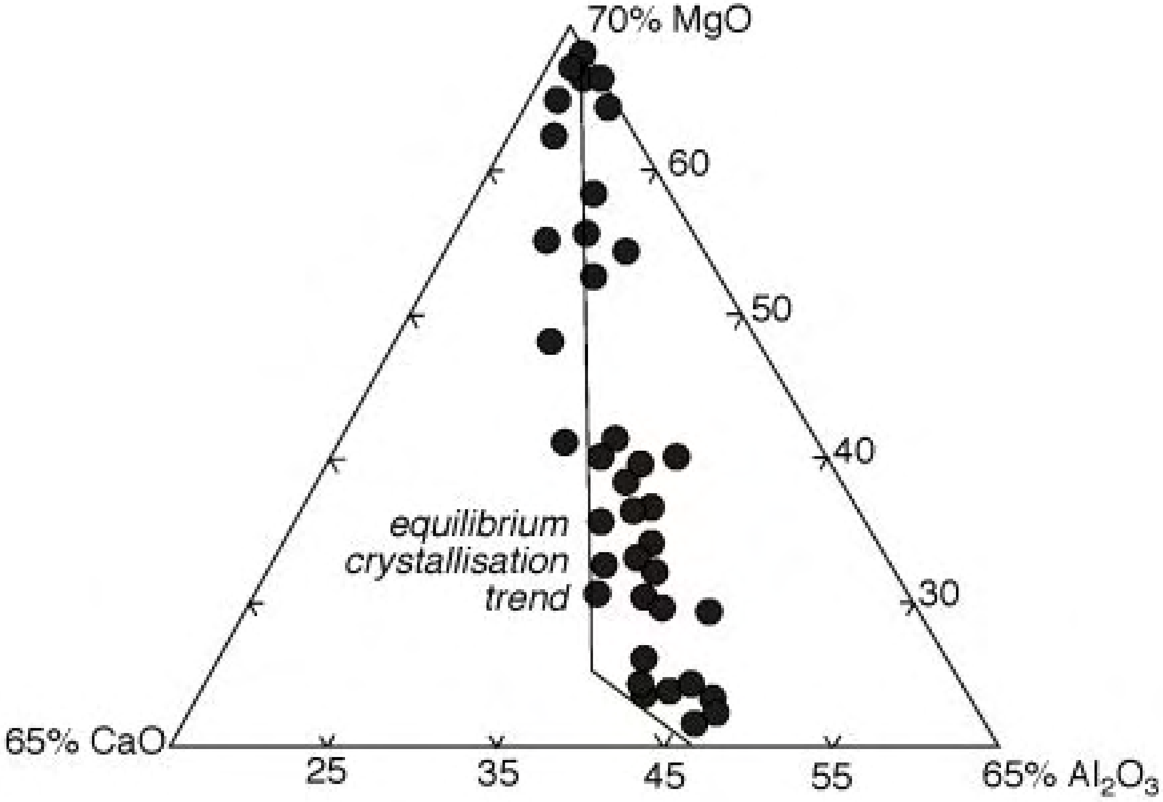
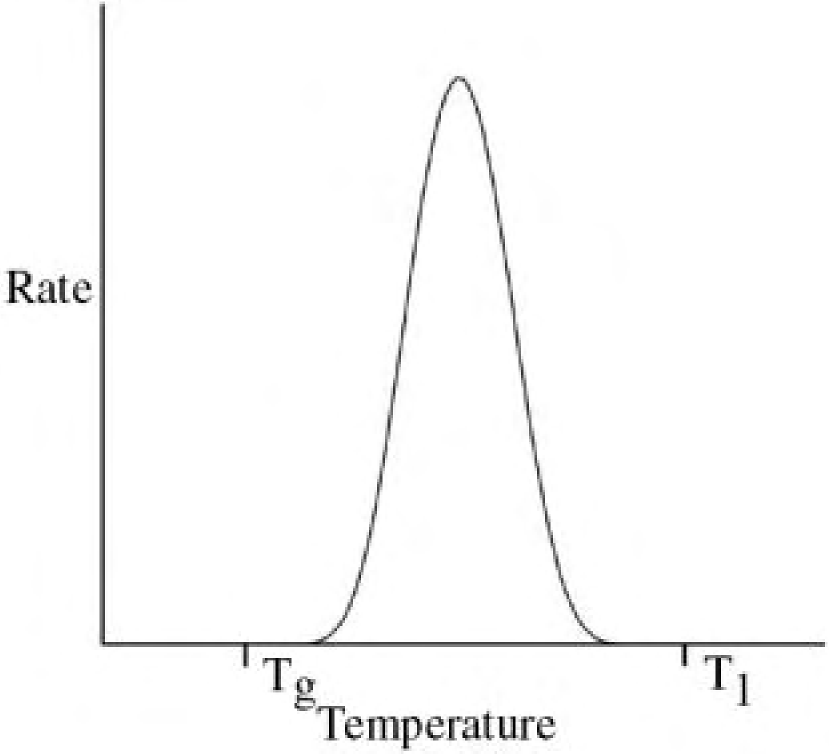
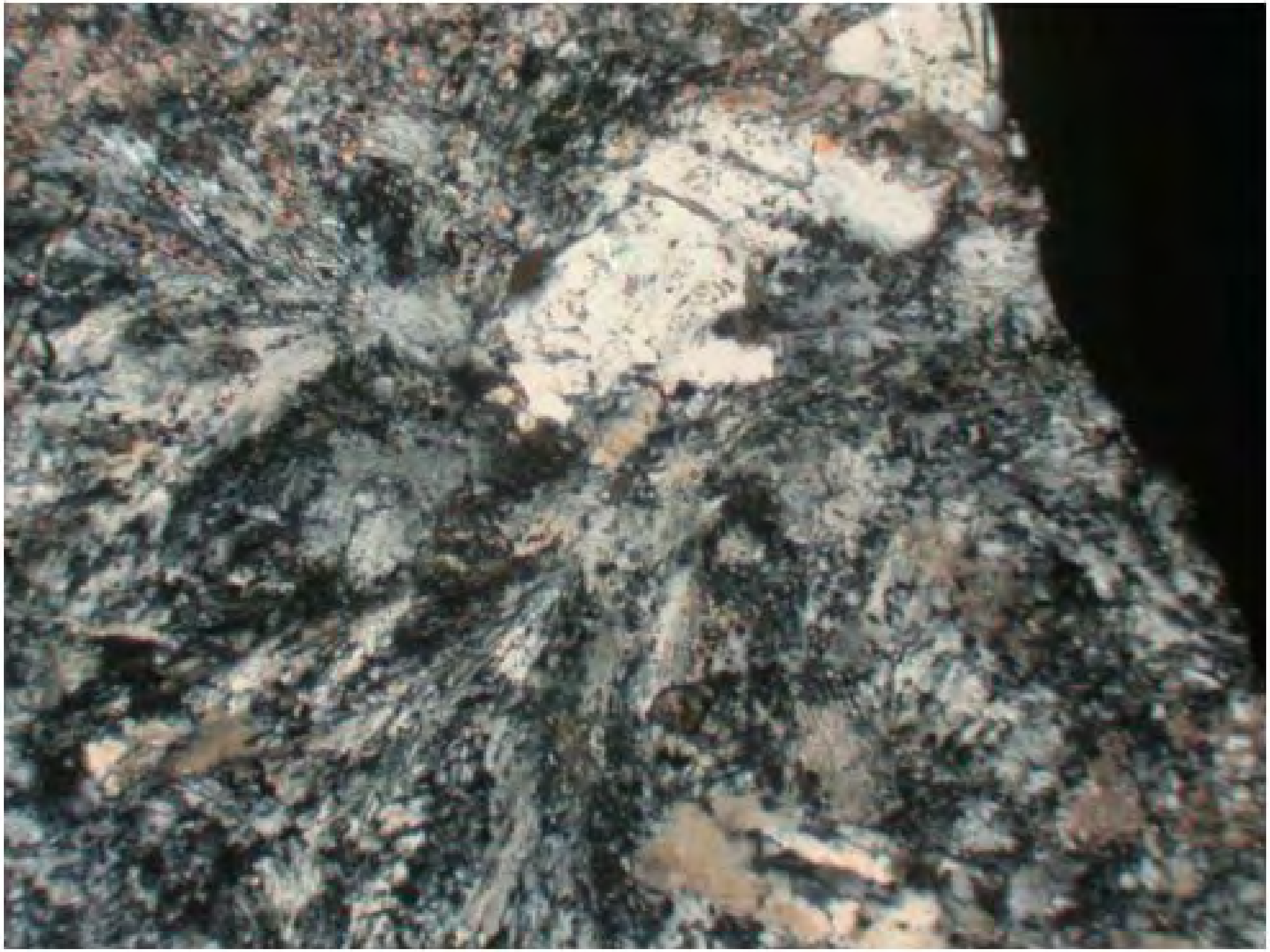

70% MgO
60
50
40
30
equilibrium
crystallisation
trend
65% CaO
25
35
45
55
65% Al2O3

Fig. 13

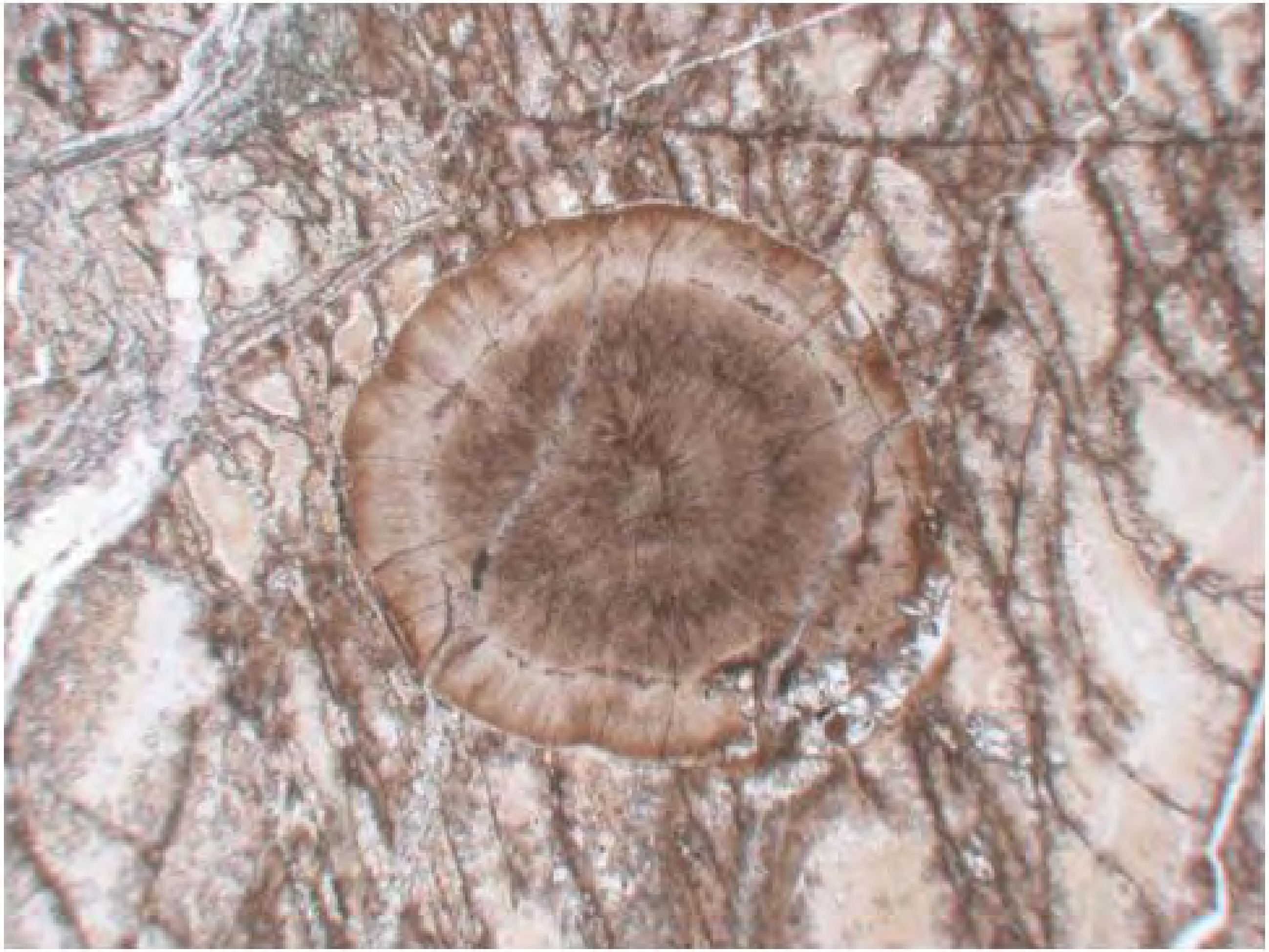
Nucleation Rate Vs. Temperature



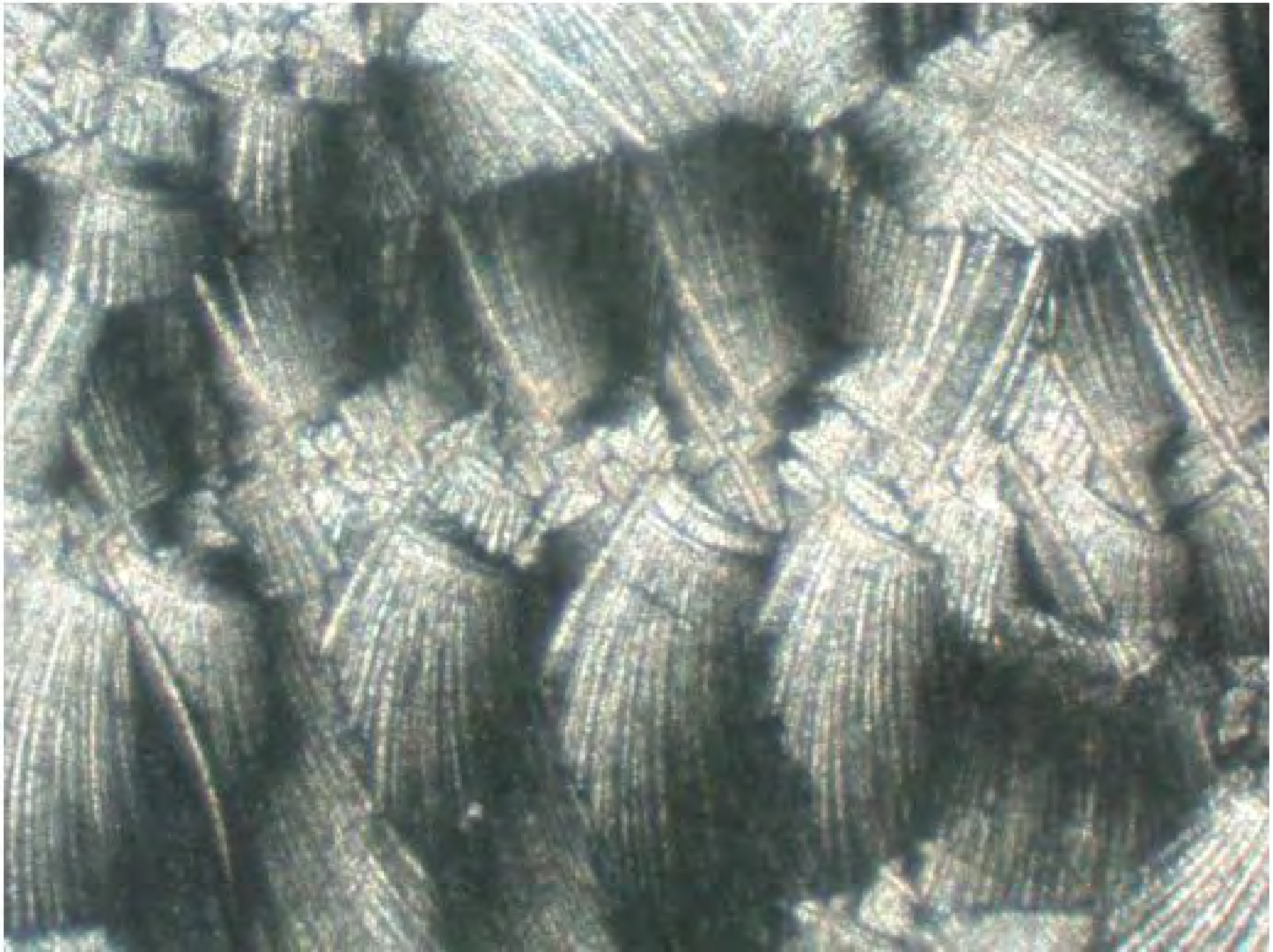
Variole (magma mingling)



Variole (Plagioclase Spherulite)

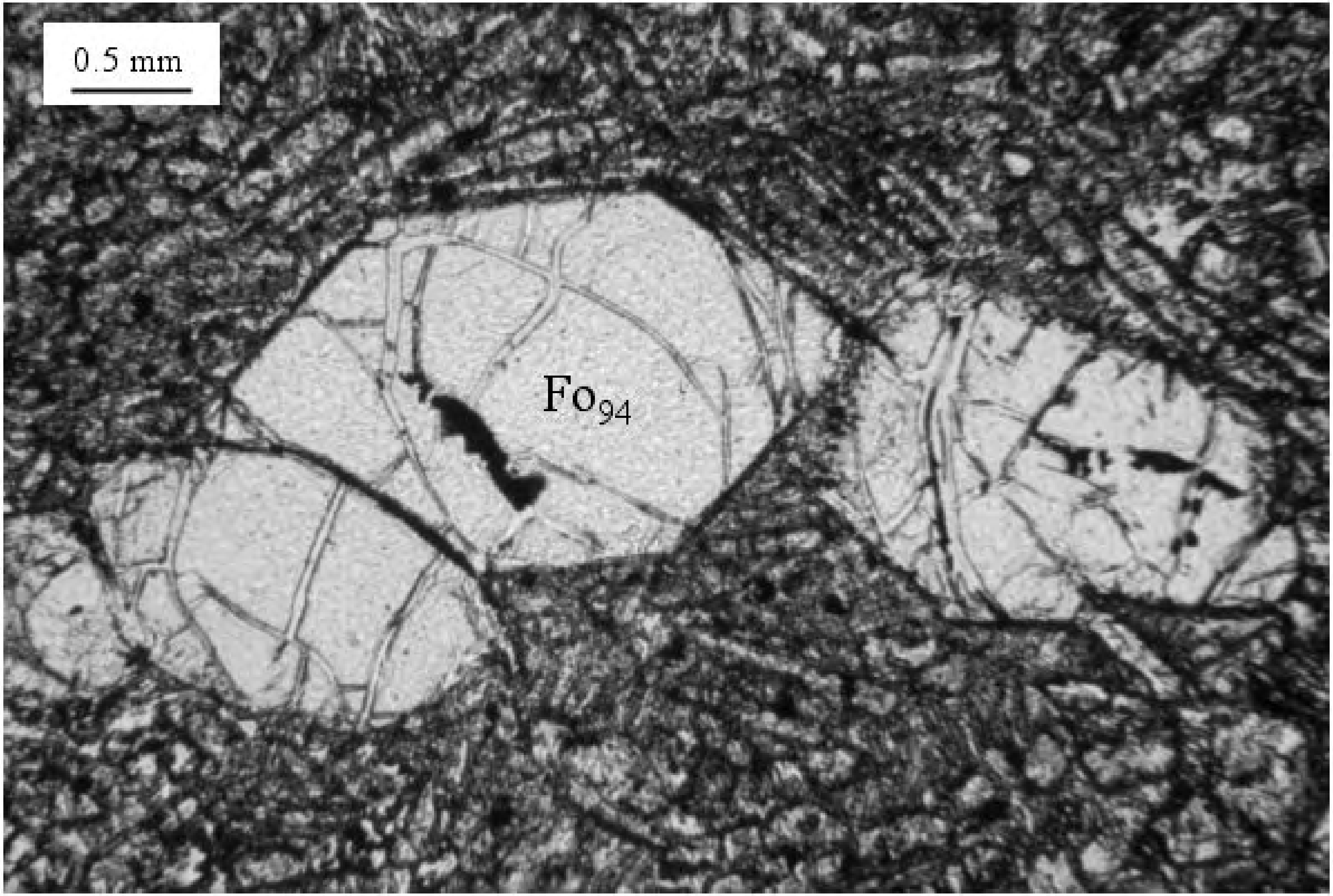


Variole(axiolitic plag. Spherulite)



Spinifex-textured komatiite
from Zimbabwe - ~22% MgO

Fig. 5



Quenched flow top from Alexo, Canada ~28% MgO (T_{liq} ~ 1560°C)

Fig. 6

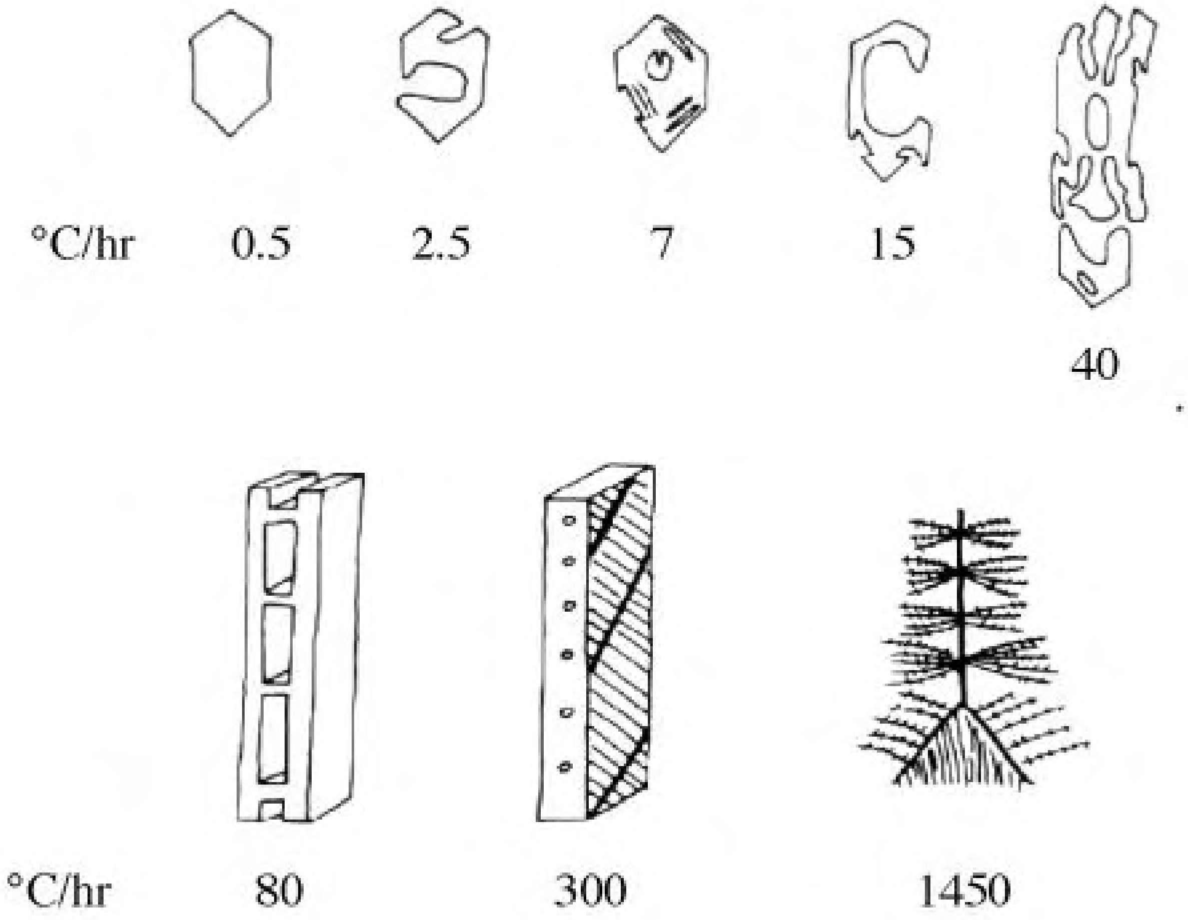


Fig. 7

Varioles (Blotchy Alteration)