9

Physical volcanology

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9.1 Introduction

Most komatiites have been metamorphosed and deformed, and most occur in Archean greenstone belts where exposure may be locally spectacular but normally limited. Archean geology is sometimes like peering through a keyhole at tiny areas of exquisitely preserved detail, and at other times like looking down from the air through a thick ground fog. Only rarely do we have enough detailed knowledge over a large enough area to be able to obtain a clear image of komatiites at the scale of a single eruption. Understanding of komatiite volcanology must therefore be built up from a fragmentary base, by combining detailed local information with broad regional syntheses and comparisons with modern basalt flow fields. Our current state of knowledge is derived largely from areas described elsewhere in this volume, particularly the well-preserved flows of the Abitibi, Barberton and Belingwe belts (Chapters 2, 3), and the well-mineralized, markedly more olivine-rich, but generally less well-preserved flows of the eastern Yilgarn Craton (Chapter 2).

One of the challenges of komatiite research has been to relate the diversity we observe to the volcanic processes that produced it, and to construct a broadly applicable volcanological model for komatiite flow fields. The conclusions have turned out to be of great importance in understanding the origin of komatiite-associated Ni–Cu–PGE deposits (Chapter 10). They are also of great importance in unravelling the tectonic history of greenstone belts.

We have seen in Chapter 8 that komatiite liquids had remarkable physical properties that distinguished them from the nearest modern counterparts, basalts. They had extremely low viscosities and high densities, which lead us to predict that (with all else equal) they would have formed laterally more extensive flow fields (or sill systems) with lower aspect ratios, which may have been emplaced, in some cases, by turbulent flow. They crystallized over a very
wide temperature interval, with much of the interval occupied by crystallization of olivine as the only silicate phase. The combination of the low viscosity and the tendency of olivine to display a wide range of crystal forms depending on the conditions of growth, accounts for much of the observed diversity.

This chapter will focus on two fundamental questions: how komatiites were erupted and emplaced, and how komatiites crystallized. Along the way we will encounter two important paradoxes: komatiites commonly form unusually thick flows despite the low viscosity of the liquids; and komatiite flows contain spectacularly dendritic textures, which imply high cooling rates but which are developed within the slowly-cooled interiors of thick flows.

9.2 Nomenclature and terminology

It is necessary to define some terms at the outset. We adopt much of the nomenclature used by volcanologists who have studied subaerial and submarine basalts in the Hawaiian islands (e.g., Walker (1970)). A lava flow is the product of a single, uninterrupted eruption from the same source, and a lava flow field forms by multiple sequential eruptions from the same source. Cooling units are bodies of igneous rock bounded by distinct continuous cooling surfaces. Simple flows are composed of single cooling units, whereas compound flows are composed of multiple overlapping cooling units formed during the same eruptive event.

Simple flows may be massive, or texturally and/or geochemically differentiated. The terms differentiation and fractionation have been used synonymously in igneous petrology to describe the formation of a variety of rock compositions from a single parental composition. In this chapter differentiation is used to indicate macroscopic textural and/or compositional variations within a single cooling unit due to the physical–chemical segregation of crystalline and liquid components, whether by gravity settling, fractional crystallization or other processes such as flowage differentiation.

Compound flows may be composed of many small rounded tubular units (pillows), multiple thin overlapping sheets (flow lobes), or thicker sheet flows, comprising combinations of volcanioclastic, pillow and/or massive lava (see Dimroth et al. (1978)). Many flows are fed by lava pathways. Lava channels (also called lava trenches) are uncovered lava pathways, whereas lava conduits (larger) and lava tubes (smaller) are covered lava pathways. Lava channels crust over to form lava conduits.

By analogy with sedimentary and metamorphic lithofacies, we define volcanic lithofacies as rocks with similar textural (e.g., aphyric, volcanioclastic, vesicular, spinifex, porphyritic, crescumulate, orthocumulate, mesocumulate,
9.3 Komatiite facies

As described in Chapter 3, komatiite flows and sills vary widely in thickness, structure, texture, degree of internal differentiation, degree of olivine accumulation and composition. Much of this diversity is manifested in a spectacular range of olivine textures, which reflects a wide spectrum of crystallization conditions. Lesher et al. (1984), Lesher (1989), Hill et al. (1989, 1995), Prendergast (2001) and Barnes (2006) have applied facies analysis to komatiites. Expanding their work and using terms analogous to those employed by sedimentologists, we can define a range of komatiite lithofacies, flow facies, facies assemblages, and therefore facies environments. Lithofacies and flow facies are designed to be descriptive and usable in the field where limited exposure often hampers interpretations. Facies assemblages are much more interpretive: some are characterized by distinctive lithofacies and/or flow facies, but many are not. Similarly, some lithofacies and/or flow facies are characteristic of particular facies environments, but many are not.

Komatiite lithofacies

The lithofacies classification of komatiitic rock types is introduced in Chapter 1 (Table 1.1). The main subdivisions are into aphyric and phyrhic quenched flow-top material, spinifex-textured rocks and conventionally
cumulus-textured rocks, ranging from orthocumulates through to accumulates and showing a wide range of olivine morphologies and grain sizes. The relative distributions and proportions of spinifex and cumulus rock types vary widely, and this is one of the defining features of different volcanic environments.

Other lithofacies are much less abundant, but are significant as indicators of environment. Crescumulate rocks exhibit dendritic (commonly called ‘harrisitic’) crystal morphologies, contain a high cumulus component and are normally enclosed within polyhedral olivine cumulates. They are distinct from platy and acicular spinifex which occur in A zones of differentiated flows and have therefore grown downward. Spinifex rocks in some cases contain a component of cumulus crystals, and therefore do not necessarily reflect liquid compositions. They are distinct from crescumulates in containing a much lower cumulus component, and in having strongly dendritic fractal crystal shapes.

As noted in Chapter 3, most komatiite flow tops typically contain few (<1%) vesicles (Pyke et al., 1973; Arndt et al., 1998a) but some komatiite flows enclose strongly vesicular zones or layers, defining a separate mappable lithofacies. Vesicles occur in flow tops (e.g., Dundonald: Eckstrand and Williamson (1985); Barberton: Dann (2001)), in porphyritic lavas (e.g., Lewis and Williams 1973), and in some cumulate rocks (Keele and Nickel, 1974; Stolz and Nesbitt, 1981; Beresford et al., 2000; Hill et al., 2004). Beresford et al. (2000) distinguished amygdales (vesicles filled with late-stage minerals) from segregation vesicles (partially filled with interstitial silicate or sulfide melt). Sulfide-filled segregation vesicles are described and illustrated in Chapter 10.

Volcaniclastic lithofacies are produced by consolidation of volcanic fragments formed by ejection from a vent (pyroclastic), by quenching with water (hydroclastic), by flow fragmentation (autoelastic), or by erosion (epiclastic). Volcaniclastic komatiites are rare, but have been described at Scotia, Western Australia (Page and Schmuelian, 1981), in Sattasvaara, Finland (Saverikko, 1985), on Gorgona Island (Echeverría and Aitken, 1986), in Karasjok, Norway (Barnes and Often, 1990), in the Steep Rock and Lumby Lake greenstone belts, Ontario (Schaefer and Morton, 1991; Tomlinson et al., 1999), at Dachine, French Guiana (Capdevila et al., 1999), at Gabaninha in the Murchison Province, Western Australia (Barley et al., 2000) and in the Wallace greenstone belt, Ontario (Stasewell and Tomlinson, 2000). Some have been interpreted to be pyroclastic, but contain fragments of rock types that do not form pyroclastically (e.g., spinifex-textured or cumulate lava) and are therefore more likely epiclastic. Others contain only fine-grained glassy material and are limited in stratigraphic extent, so they are more likely hydroclastic. We
are not aware of any komatiites *sensu strico* that contain unequivocal spatter and bombs, but komatiitic basalts with such features have been described in the Möykkelma area in Finland (Räsänen *et al.*, 1989) and ferropicrites with such features have been described at Kotselvaara in the Pechenga belt (Green and Melezhik, 1999). *Autoelastic* lavas have been reported at Kambalda by Beresford *et al.* (2002) at Bannockburn (Houlé *et al.* 2005), and are also observed at Sattasvaara in Lapland (Thordarson, pers. comm.), but these are blocky rather than a’a lavas. Komatiitic a’a flows are unknown, and are very unlikely to have formed from such low-viscosity lavas. *Epiclastic* komatiites have been described at Spinifex Ridge by Gélinas *et al.* (1977b), at Karasjok by Barnes and Often (1990), and probably occur locally in most localities.

**Komatiite flow facies**

Komatiites form many of the *flow facies* recognized in basaltic flow fields, particularly submarine basaltic flow fields, including simple and compound volcanielastic units, compound pillowed and lobate flows, simple differentiated and undifferentiated sheet flows, and simple and compound differentiated and undifferentiated lava conduits (Table 9.1).

Sheets and conduit facies exhibiting many of the same lithofacies as flows may also form in invasive (downward burrowing) flows, deeply erosive flows, intrusive sills, or feeder conduits. For example, the differentiated sills at Dundonald Beach (Arndt *et al.*, 2004b) and Boston Creek (Houlé *et al.*, 2001) exhibit many of the compositional and textural characteristics of differentiated flows, and were originally interpreted as flows (see Muir and Comba (1979), Stone *et al.* (1987)). Because the contact relationships that are required to distinguish between extrusive, invasive and intrusive modes of emplacement are often not exposed, we have grouped them all under flow facies.

Very-low-viscosity high-Mg komatiites normally form compound flow lobes rather than compound pillowed flows, but pillows occasionally form in low-Mg komatiites (e.g., Belingwe: Nisbet *et al.* (1977)) and commonly form in komatiitic basalts.

Archean geologists normally encounter komatiites in small outcrops and drill cores, so one-dimensional profiles through individual cooling units are commonly used as a basis for their description and interpretation. Many of the *flow facies* in Table 9.1 can be portrayed on a simple matrix (Figure 9.1) of two variables: (1) the amount of excess olivine (vertical axis) and (2) the degree of *in situ* textural and compositional differentiation (horizontal axis).

The first variable is the amount of accumulated olivine, calculated by comparing the weighted average bulk composition of the unit with the aphyric
### Table 9.1. Komatiite flow facies

<table>
<thead>
<tr>
<th>Flow facies</th>
<th>Most common lithofacies&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Examples&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pyroclastic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>Pyroclastic (cg-fg, heterogeneous, often heterolithic)</td>
<td>Koselvaara (ferropicrite), Möykkeläm (komatiitic basalt), Dismal Ashrock (Steep Rock)?</td>
</tr>
<tr>
<td>Distal</td>
<td>Pyroclastic (fg tuffaceous)</td>
<td>Upper Onverwacht (Barberton)</td>
</tr>
<tr>
<td><strong>Pillow/lobe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pillow</td>
<td>Thin massive aphyric, massive porphyritic</td>
<td>High-Mg komatiite: not known</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low-Mg komatiite: Belingwe, eastern Munro Twp.</td>
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<tr>
<td></td>
<td></td>
<td>Komatiitic basalt: Cape Smith Belt (Chukotat Group), Pontiac Group (Baby Group)</td>
</tr>
<tr>
<td>Undifferentiated</td>
<td></td>
<td>Pyke Hill, Belingwe, Kambalda (Tripod Hill member), parts of most komatiite sequences</td>
</tr>
<tr>
<td>lobe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differentiated</td>
<td>Thin massive aphyric, massive porphyritic</td>
<td></td>
</tr>
<tr>
<td>lobe</td>
<td>Spinifex-orthocumulate</td>
<td></td>
</tr>
<tr>
<td><strong>Sheet</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Undifferentiated</td>
<td>Massive aphyric, massive porphyritic, massive ortho-meso- adcumulate, spinifex greatly subordinate or absent</td>
<td>Extrusive: Kambalda (Silver Lake member), Scotia, Spinifex Ridge, Silver Swan</td>
</tr>
<tr>
<td>Differentiated</td>
<td>Spinifex-orthocumulate, spinifex-mesocumulate, with or without gabbro</td>
<td>Extrusive: Kambalda (Silver Lake member)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intrusive: Boston Creek, Damba-Silwane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unknown: Kurrajong (Walter Williams)</td>
</tr>
<tr>
<td><strong>Channel/conduit/chonolith</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Undifferentiated</td>
<td>Massive mesocumulate or adcumulate</td>
<td>Extrusive: Scotia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Invasive: Katinniq, Perseverance?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intrusive: Thompson, Mt Keith, Perseverance?</td>
</tr>
<tr>
<td>Differentiated</td>
<td>Spinifex-adcumulate, spinifex-mesocumulate or gabbro-adcumulate</td>
<td>Extrusive: Kambalda (basal host units), Alexo-Dundonald, Shaw Dome, Silver Swan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intrusive: Dumont, Thompson</td>
</tr>
</tbody>
</table>

<sup>a</sup> Lithofacies in Table 1.2.

<sup>b</sup> Locations in Chapter 1.
Fig. 9.1. Schematic profiles through komatiite cooling units, representing a matrix of variability in degree of flow-through and olivine accumulation (vertical) and degree of static internal differentiation (horizontal). The width of each profile is proportional to MgO. Modified from Lesher et al. (1984), Lesher and Keays (2002), and Barnes (2006).
chilled margins (see below). The second variable represents the degree of internal differentiation due to a combination of fractional crystallization in the upper parts of the flows and accumulation of olivine (or less commonly pyroxene) in the lower parts. The narrow D-shaped profiles on the lower left represent units that have not accumulated much olivine and have not differentiated significantly, including massive, pillowed/lobate and pyroclastic facies. The wide D-shaped profiles on the upper left represent units with bulk compositions that are enriched in olivine relative to their chilled margins and therefore contain a large component of accumulated olivine. The S-shaped profiles on the lower right represent units that have differentiated \textit{in situ} under closed system conditions to produce olivine cumulates in the lower parts (B zones) and less magnesian lavas in the upper parts (A3 zones), but they have bulk compositions similar to the chilled margins and therefore contain little excess olivine. The transitional profiles in the centre and on the upper right represent units with complex histories of early flow-through and accumulation of olivine, followed by late ponding and differentiation. The interplay of the two variables generates the observed spectrum of flow facies between end-members represented by massive undifferentiated non-cumulate units (lower left), differentiated non-cumulate units (lower right), undifferentiated adcumulate units (upper left) and differentiated cumulate units (middle and upper right).

\textit{Komatiite facies assemblages and facies environments}

Some komatiite flow facies occur together consistently enough to define \textit{facies assemblages} (Table 9.2) and some facies and facies assemblages can be used to define \textit{facies environments} (Table 9.3). Of the facies assemblages represented in Table 9.2, 'compound flow lobes' and 'compound sheet flows' are by far the most common, but as discussed in Chapter 10, channel/conduit facies assemblages are less common but economically very important. We consider the hypothetical geometry of komatiite flow fields and the relationship of these facies assemblages to one another at the conclusion of this chapter.

\textbf{9.4 Komatiite flows and flow fields: size, structure and emplacement processes}

\textit{Size and scale}

As discussed in Chapter 3, the dimensions of komatiite flows vary considerably. Their lengths range from tens of metres in the case of individual lobes within compound flows to correlatable cooling units at least kilometres, and
Table 9.2. Komatiite facies assemblages

<table>
<thead>
<tr>
<th>Facies assemblage</th>
<th>Characteristic flow facies&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Examples&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compound flow lobes</td>
<td>Multiple thin lava lobes with little or no interflow sediment; very common</td>
<td>Alexo-Dundonald, Belingwe, Kambalda (Tripod Hill member), Mt Clifford, Pyke Hill, Shaw Dome</td>
</tr>
<tr>
<td>Multiple/compound sheet flows</td>
<td>Multiple thick, laterally extensive, variably differentiated sheet facies lacking conduits</td>
<td>Spinifex Ridge</td>
</tr>
<tr>
<td>Thick composite sheets</td>
<td>Single or multiple thick differentiated or undifferentiated mesocumulate or adcumulate sheet facies</td>
<td>Shaw Dome (Lower Komatiite Horizon), Walter Williams Formation, Murrin Murrin, Boston Creek (ferropicrite)</td>
</tr>
<tr>
<td>Channelized sheet flows</td>
<td>Thick poorly- to strongly-differentiated mesocumulate conduit facies flanked by differentiated sheet facies with variable degrees of differentiation</td>
<td>Kambalda (Silver Lake Member), Raglan (Cross Lake Member)</td>
</tr>
<tr>
<td>Channel/ conduit complex</td>
<td>Multiple, thick, poorly-differentiated meso- to adcumulate conduit facies, in some cases flanked by peperites in sediment-dominated environments</td>
<td>Extrusive: Alexo&lt;br&gt;Deeply erosive: Raglan (Katinniq Member)&lt;br&gt;Invasive or intrusive: Mt Keith, Perseverance&lt;br&gt;Intrusive: Damba-Silwane, Dumont, Thompson&lt;br&gt;Munro Twp lava lake, Lion Hills, Lake Harris?</td>
</tr>
<tr>
<td>Lava lake</td>
<td>Difficult to unequivocally identify, but should be topographically-controlled and areally restricted, relatively thick, and composed of single or multiple, predominantly porphyritic or differentiated spinifex-cumulate facies</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Flow facies in Table 9.1.
<sup>b</sup> Locations in Chapter 1.

probably tens of kilometres long. The largest individually correlatable cooling unit, the Walter William Formation in the East Yilgarn, is at least 130 km long, but may well be a sill rather than a flow. The sizes of flow fields are difficult to estimate because of limits of outcrop and the deformation that has affected most greenstone belts, but have been well established on the scale of at least 80 km in Zimbabwe (Prendergast, 2003) and Abitibi, and at least 60 km in the East Yilgarn. There is good reason to suppose that they could have been ten.