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Silicic volcanism: An undervalued component of large igneous provinces and volcanic rifted margins

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ABSTRACT

Silicic volcanic rocks are associated with most, if not all, continental flood basalt provinces and volcanic rifted margins, where they can form substantial parts of the eruptive stratigraphy and have eruptive volumes >10^4 km^3. Poor preservation of silicic volcanic rocks following kilometer-scale uplift and denudation of the volcanic rifted margins, however, can result in only deeper level structural features being exposed (i.e., dike swarms, major intrusions, and deeply subsided intracaldera fills; e.g., North Atlantic igneous province). The role of silicic magmatism in the evolution of a large igneous province and rifted margin may therefore be largely overlooked.

There are silicic-dominated igneous provinces with eruptive volumes comparable to those of mafic large igneous provinces (>10^6 km^3), but that have low proportions of basalt expressed at the surface. Some silicic large igneous provinces are associated with intraplate magmatism and continental breakup (e.g., Jurassic Chon Aike province of South America, Early Cretaceous eastern Australian margin), whereas others are tectonically and geochemically associated with backarc environments (e.g., Sierra Madre Occidental). Silicic volcanic rocks formed in these two environments are similar in terms of total eruptive volumes, dominant lithologies, and rhyolite geochemistry, but show fundamental differences in tectonic setting and basalt geochemistry.

Large-volume ignimbrites are the dominant silicic volcanic rock type of continental flood basalt and silicic large igneous provinces. Individual silicic eruptive units can have thicknesses, areal extents, and volumes that are comparable to, or exceed, in-

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terbedded flood basalt lavas. Caldera complexes, with diameters typically 10–30 km, represent the main eruptive sources for the large volumes of silicic magma, and may range from regional sag structures to complex volcanic-tectonic collapse structures controlled by tectonic stresses and preexisting crustal architecture.

The largest volume silicic igneous provinces occur along accreted continental margins, whereas continental flood basalt provinces have been emplaced on or adjacent to Archean cratons. Large-volume silicic igneous provinces ultimately reflect large-scale crustal melting processes in response to lithospheric extension and high thermal (± mass) input from underlying hot mantle. Partial melting of hydrous, mafic-intermediate composition (amphibolite) crust is critical in generating the large volumes of predominantly I-type silicic igneous melt. In these cases, subduction as much as hundreds of millions of years prior to the emplacement of the silicic igneous province seems crucial in producing a hydrous lower crustal source receptive to melting.

INTRODUCTION

Large igneous provinces are the most significant accumulations of mafic material at the Earth's surface after basaltic and associated intrusive rock emplaced at mid-ocean ridges (Coffin and Eldholm, 1992, 1994). Continental flood basalts, synonymous with mafic large igneous provinces, typically represent short-lived (<5 m.y.), high-rate (0.1 to >1 km^3/yr), large-volume ($\geq 1 \times 10^6$ km^3) eruptive events, mostly related to breakup of continents (White and McKenzie, 1989; Coffin and Eldhom, 1994; Fig. 1). Most research has focused on the geochronology and basaltic geochemistry of continental flood basalt provinces (e.g., papers in Storey et al., 1992; Mahoney and Coffin, 1997). Recent studies have also focused on the flow morphology and internal structures of flood basalt lavas; these studies indicate that the mafic magmas were emplaced as inflated compound pahoehoe lava fields via prolonged, episodic eruptions (e.g., Self et al., 1996, 1997; Thordarson and Self, 1998). However, the stratigraphy, magma generation, and eruption and emplacement processes of any associated silicic volcanic rocks have received less attention because of a sampling bias toward the basalt lavas and/or poor exposure (e.g., Paraná).

Silicic volcanic rocks have long been recognized as being associated with continental flood basalt provinces (e.g., Paraná-Etendeka and North Atlantic igneous provinces). However, the silicic volcanic rocks are generally regarded as being (1) small volume (10^4 km^3); (2) emplaced late in the eruptive sequence/history as their ascent was hindered by their higher viscosity; (3) proximal to the main locus of melt generation; and (4) formed by secondary crustal melting resulting from local heating by basaltic intrusions (e.g., White and McKenzie, 1989; White, 1992).

It is increasingly recognized that some large igneous provinces related to continental breakup are dominated by silicic volcanic rocks, with basalt forming a minor or nonexistent part. Two such silicic large igneous provinces include the Early Cretaceous volcanic rifted margin of eastern Australia (Bryan et al., 1997, 2000), and the Jurassic Chon Aike province of South America and Antarctic Peninsula (Pankhurst et al., 1998, 2000; Riley and Leat, 1999). The petrogenesis of these silicic-dominated large igneous provinces is more complex than typical basaltic large igneous provinces because of their wider variety of volcanic and intrusive compositions. Considerable debate has centered on the relative roles of fractional crystallization, assimilation-fractional crystallization, partial melting, and magma mixing in the generation of the silicic magmas (e.g., see discussions in Pankhurst et al., 1998; Ewart et al., 1998a; Wark, 1991). The calc-alkaline chemistry of the rhyolites also provides ambiguity when interpreting the tectonic setting of magmatism, and as a consequence, the tectonic setting of some large silicic igneous provinces may have previously been wrongly interpreted (e.g., eastern Australia; see Ewart et al., 1992; Bryan et al., 1997).

We propose the term "silicic large igneous province" to describe those volcanic-plutonic provinces with the following characteristics: (1) extrusive volumes of $>10^5$ km^3; (2) compositions are >75 vol% dacite-rhyolite; and (3) rhyodacite-rhyolite compositions near the hydrous granite minimum. We point out that silicic large igneous provinces characterize both intraplate environments (being related to continental breakup), and active convergent margins undergoing extension (being related to backarc or arc rifting; e.g., Sierra Madre Occidental, Mexico; Taupo volcanic zone, New Zealand). The latter examples show a close spatial-temporal relationship to subduction-related tectonism and igneous activity (e.g., Ward, 1995). Silicic igneous provinces from extended intraplate and continental margin settings show similarities in eruptive volumes ($\geq 10^5$ km^3), dominant lithologies (ignimbrite), and composition (intermediate-silicic calc-alkaline I-type magmas), making tectonic discrimination between them difficult.

In this chapter, we review continental flood basalt provinces that have a significant silicic volcanic component, and large igneous provinces that are silicic dominated (Whitsunday volcanic province, eastern Australia; Chon Aike province, South America–Antarctic Peninsula; Fig. 1). We make the following points:

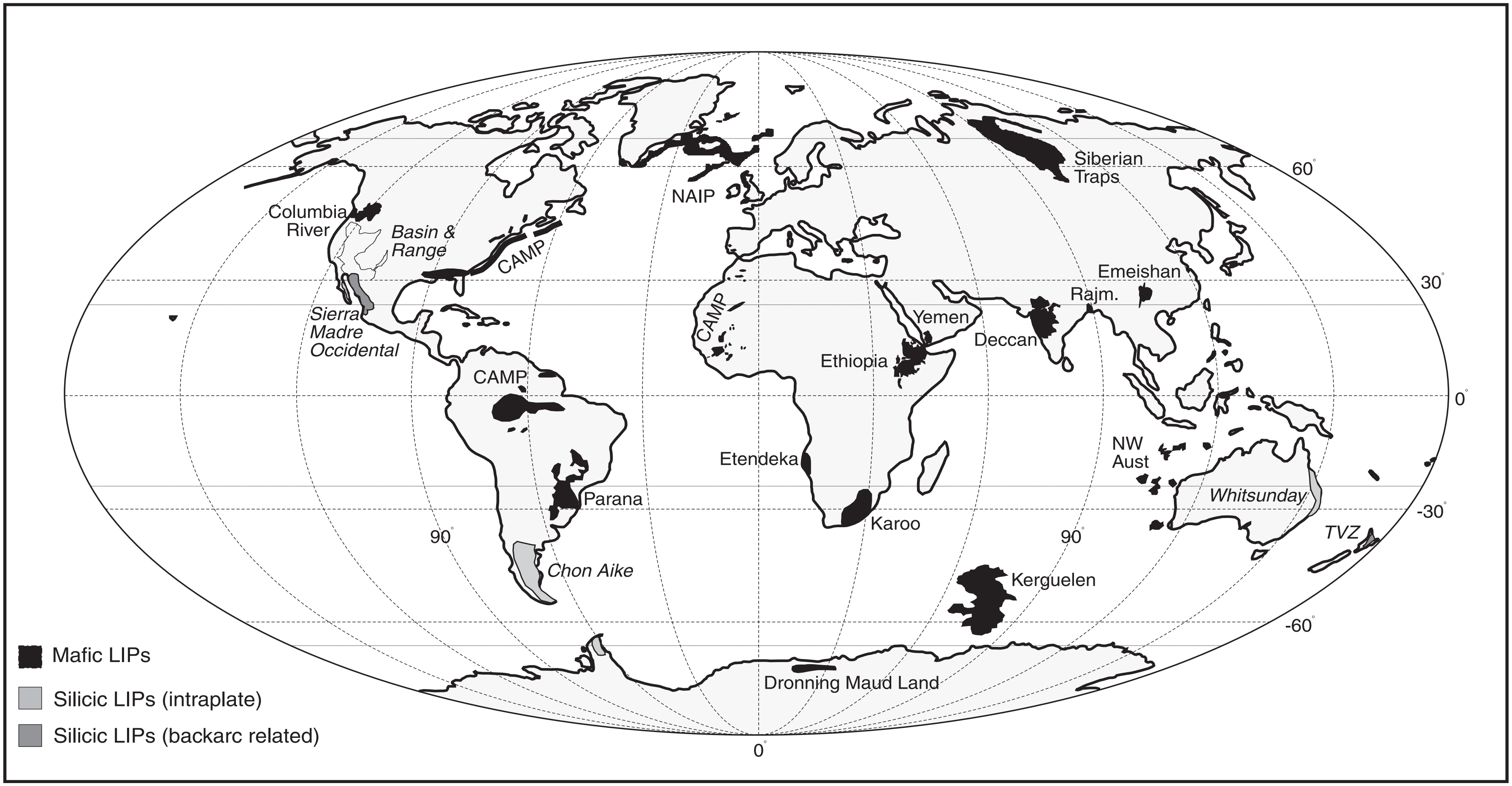

Figure 1. Distribution of large igneous provinces (LIPs) discussed in this chapter; silicic LIPs are in italics. NAIP, North Atlantic igneous province; CAMP, Central Atlantic magmatic province; Rajm. Rajmahal basalts; TVZ, Taupo volcanic zone; NW Aust, Northwest Australian oceanic plateaus: Cuvier, Roo Rise, Scott, Wallaby, and Naturaliste. Modified from Coffin and Eldholm (1994).

1. Silicic magmatism is an integral part of continental flood basalt provinces and can be of large volume (>10^4 km^3).

2. Large silicic igneous provinces exist with extrusive volumes comparable to that defined for mafic large igneous provinces, but are not associated with large extrusive volumes of mafic magma.

3. Silicic large igneous provinces (with ≤10% mafic igneous rocks) and continental flood basalts (with ≤10% silicic igneous rocks) represent end members, and there is an absence of large igneous provinces with subequal proportions of mafic and silicic igneous rocks.

4. Some silicic large igneous provinces are associated with, or may be transitional to, intraplate magmatism (e.g., Whitsunday volcanic province), whereas others are tectonically and geochemically associated with backarc processes (e.g., Sierra Madre Occidental).

Although large-volume silicic magmatism ultimately reflects continental extension, hot mantle upwelling, and intrusion of basaltic magma into the crust, a hydrous lower crust is also considered critical for the generation of large volumes of rhyolite magma.

CONTINENTAL FLOOD BASALT PROVINCES WITH SILICIC VOLCANISM

All continental flood basalt provinces of Jurassic to Cretaceous age associated with the breakup of Gondwana have varying amounts of silicic igneous rocks associated with them, as do the Tertiary North Atlantic, Yemen-Ethiopia, and Columbia River provinces (Table 1). Silicic volcanic rocks, previously unrecognized or considered, have also been intersected in the latest drilling program of the Kerguelen oceanic plateau (Ocean Drilling Program [ODP] Leg 183; Frey et al., 2000; Moore et al., 2000), consistent with occurrences of silicic volcanic rocks (lavas, tuffs, and/or bentonites) in the synrift sequences along the Indian and western Australian margins (Kent et al., 1997;

TABLE 1. SUMMARY OF MAFIC LARGE IGNEOUS PROVINCES AND THE ERUPTIVE AGES AND CHARACTER OF ASSOCIATED SILICIC VOLCANISM

Province	Age of flood basalts (Ma)	Age of silicic magmatism (Ma)	Silicic igneous lithologies	References
Emeishan (China)	?253–250	251, 250	Bentonite/tuff, dacitic/trachytic to rhyolitic lavas; Granite, syenite	Chung et al. (1998); Chung and Jahn (1995)
Siberian Traps	250	not known	not known	Renne et al. (1995); Sharma (1997)
Central Atlantic Magmatic Province	205–191 (peak at 200)	201–162; 165, 159	trachyte, alkali rhyolite ignimbrite and breccia, dacitic fallout tuffs, rhyolite and high-K rhyolite; high-K calc-alkaline granite, granite, quartz syenite, syenite	Marzoli et al. (1999); Hames et al. (2000); Heatherington et al. (1999); Heatherington and Mueller (1991); Eby et al. (1992)
Karoo	183–184	179	lava-like dacitic to rhyolite ignimbrite, lava, rhyolite dikes; syenite, granite, granophyre	Encarnación et al. (1996); Cleverly et al. (1984)
Ferrar	183–184	186	pyroclastic fallout deposits (tuff), ?ignimbrite	Encarnación et al. (1996); Faure and Hill (1973); Elliot (1992; 2000)
Paraná-Etendeka	132	132	latite to quartz latite rheoignimbrite, rhyolite dikes, minor rhyolitic lava breccia (Messum); granite, syenite	Ewart et al. (1998a); Renne et al. (1996)
Western Australia–India–Kerguelen	130–100	213, 145–135, 116–113	bentonite and/or silicic tuffs, pre-breakup alkali rhyolite and/or trachyte (northwestern Australia), rhyolite lavas (India)	Frey et al. (1996); Colwell et al. (1994); Moore et al. (2000)
Deccan-Seychelles	66–65	62	trachyte tuff, rhyolite lavas and tuff; syenite, granite	Hofmann et al. (2000); Devey and Stephens (1992); Sethna and Battiwalla (1977); Mahoney (1988)
North Atlantic igneous province	~62-58, 56–53	63–61, 56–52	rhyolite ignimbrite, tuff, lava, dykes; granites	Hamilton et al. (1998); Sinton et al. (1998); Saunders et al. (1997); Bell & Emeleus (1988)
Ethiopia-Yemen	31–26	35–32, 29–28, 19–6	rhyolitic ignimbrite, pyroclastic surge and fallout deposits, lava, dikes; A-type granites	Baker et al. (1996a, b), Ukstins et al. (2000), Kampunzu & Mohr (1991)
Columbia River–Snake River Plain–Yellowstone	17.5–6 (peak between 17–15)	16.5–0.07	rhyolitic ignimbrite, lava, pyroclastic fallout and surge deposits, dikes	Cummings et al. (2000), Chesley and Ruiz (1998), Leeman (1982), Hooper (1997)

Note: Large igneous provinces exhibit the following features: (1) they are dominated by basalt, with minor silicic igneous rocks; (2) silicic volcanism can predate, be coincident with, or postdate the main phase of basalt volcanism; and (3) the silicic rocks are dry, high-temperature eruptives.

Colwell et al., 1994). Only the Siberian Traps have no documented silicic igneous rocks, although the temporally related Emeishan province of China contains dacitic to rhyolitic lavas, tuffs, and associated intrusives (Table 1; Chung et al., 1998). The Paraná-Etendeka province is probably the best known of these provinces for containing silicic volcanic rocks, which have been the focus of several studies (e.g., Milner, 1988; Milner et al., 1992, 1995; Garland et al., 1995; Ewart et al., 1998a). Silicic volcanic rocks only account for a small percentage (typically <5% volume) of continental flood basalt provinces, however, and very large volumes of mafic volcanic rocks (~10^6 km^3) emplaced rapidly (a few million years) are characteristic. In the following section, we examine the role of silicic volcanism in some of the best documented continental flood basalt provinces.

Karoo (Lebombo-Mwenezi)-Ferrar

The Karoo continental flood basalt province (Fig. 1) comprises an extensive series of predominantly mafic rocks and less voluminous silicic rocks that erupted prior to the fragmentation of Gondwana. Mafic magmatism peaked at 183 ± 1 Ma and was followed by smaller volumes of mafic and silicic volcanism to 179 Ma (Duncan et al., 1997). The top of the Karoo volcanic sequence is not preserved. It is important to note that although the basaltic volcanic rocks of the Karoo continental flood basalt are distributed extensively over the southern African continent, the silicic volcanic rocks are concentrated around the continental margins and sites of continental rifting (Duncan et al., 1984), mostly in the Lebombo-Mwenezi region of southern Africa (Fig. 2A). Of the total preserved thickness of the Lebombo and Mwenezi sequences, ~30% is composed of silicic volcanic rocks (Duncan et al., 1984). The Lebombo rhyolites are typically sheetlike, having features common to both lavas and ignimbrites, but have been interpreted as high-temperature (lava-like) ignimbrites (Cleverley, 1979). Individual rhyolite units extend for as much as 60 km along strike, and reach maximum thicknesses of 200 m. The rhyolites have an estimated maximum thickness of 5 km in the Lebombo monocline and an estimated volume of 35 000 km^3 (Cleverly et al., 1984), accounting for <2% of the total volume of the preserved Karoo province. The rhyolites yield ages of 178–180 Ma (Rb-Sr, Allsopp et al., 1984; $^{40}Ar/^{39}Ar$, Duncan et al., 1997), which are younger than the main phase of mafic volcanism at 182–183 Ma (Encarnación et al., 1996; Duncan et al., 1997), although they occur interbedded with basalt lavas.

In the synchronous Antarctic Ferrar province, silicic explosive volcanism mainly preceded, but was also contemporaneous with the eruption of the Ferrar Group tholeiitic basalts, both of which were emplaced into a volcanic-tectonic rift system (Elliot, 1992). The Hanson Formation of the central Transantarctic mountains comprises ~240 m of silicic tuffs, tuffaceous sandstones, and subordinate quartzose sandstones, and is overlain by extrusive basaltic rocks of the Ferrar Group (Elliot, 1992, 2000). A Rb/Sr whole-rock isochron on four tuffs yielded an age of 186 ± 9 Ma (Faure and Hill, 1973), but may be affected by widespread zeolitization (Elliot, 2000). However, we note that this age for the Hanson Formation overlaps with widespread silicic explosive volcanism of the Chon Aike province and the component Brennecke and Mount Poster Formations of the Antarctic Peninsula (Pankhurst et al., 2000; see following). The predominantly sedimentary nature of the Hanson Formation may indicate that it is a distal equivalent of the volcanic-dominated Mount Poster and Brennecke Formations.

The silicic volcanic rocks of the Lebombo monocline are primarily rhyolitic in composition, although a number of samples have lower silica contents, being classified as dacites and rhyodacites (Duncan et al., 1984). Most rhyolites have relatively uniform Sr and Pb initial isotopic ratios similar to those of the flood basalts, suggesting derivation from a similar source (Cleverly et al., 1984). However, the lowermost rhyolites interbedded with basalts (Mkutshane Beds) have strong enrichments in radiogenic Sr and Pb, and have been interpreted to be either crustal melts or strongly contaminated basaltic magmas (Cleverly et al., 1984). Strong enrichment of the incompatible elements (e.g., Nb, Zr, Y, Ba, Rb, Sr), primitive initial Sr and Nd isotopic ratios, and modeling suggest the bulk of the rhyolites were generated as a result of ~10% partial melting of newly underplated Karoo basaltic magma (gabbro sills or cumulate) following crustal thinning and decompressional melting (Cleverly et al., 1984; Harris and Erlank, 1992; Cox, 1993). However, Bristow et al. (1984) concluded that melting of mafic lower crustal material (e.g., mafic granulite) could also be a plausible source for the rhyolites, and consistent with the model of Cleverly et al. (1984). The low ^{18}O values for the Lebombo rhyolites further require large-scale interaction of the source with meteoric water at high temperatures (Harris and Erlank, 1992; Harris, 1995). The widespread basalts and/or dolerites (Lesotho-type of Marsh and Eales, 1984) have calc-alkaline or subduction-related geochemical signatures (Cox, 1983) interpreted to reflect contamination by subcontinental lithospheric mantle (e.g., Sweeney et al., 1994), and the Rooi Rand dike swarm is partly mid-ocean ridge basalt–like (Watkeys et al., 2000).

Paraná-Etendeka

The Paraná-Etendeka province (Fig. 1) was erupted just prior to the opening of the South Atlantic ca. 130 Ma (Renne et al., 1992, 1996; Turner et al., 1994). The province is dominated by mafic lavas; silicic volcanic rocks account for only 3% of the preserved total erupted volume, equivalent to ~20 000 km^3 (Harris and Milner, 1997). However, the silicic volcanic rocks crop out over an estimated combined area of 170 000 km^2, and have proved critical in correlating the eruptive stratigraphies on either side of the South Atlantic Ocean (Milner et al., 1995). More silicic rocks occur as intrusions in central complexes associated with the volcanism (e.g., Messum and Brandberg igneous centers; Martin et al., 1960; Milner and Ewart, 1989; Schmitt et al., 2000; Fig. 2B). The Etendeka region in particu-

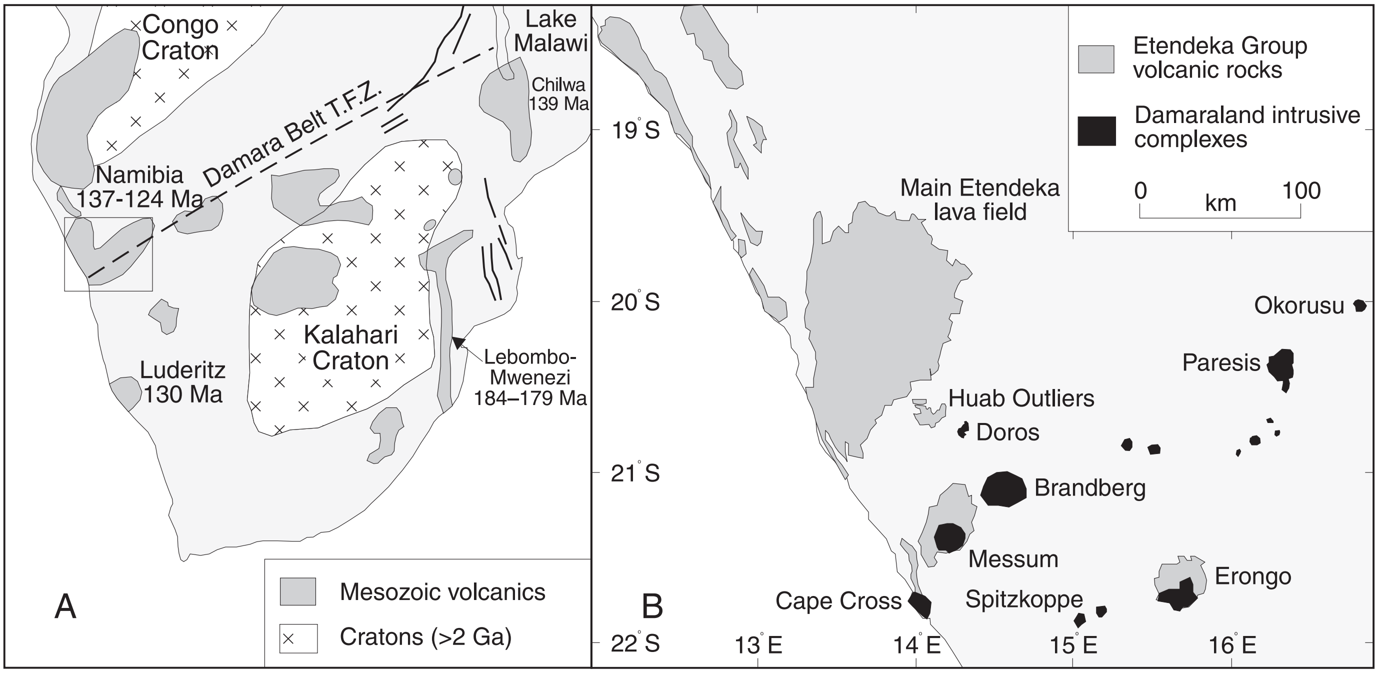

Figure 2**.** A: Distribution of Mesozoic volcanic rocks in southern Africa and structural setting of Early Cretaceous magmatism of the Etendeka province at the western end of a major continental-scale transfer fracture zone (T.F.Z.) separating >2 Ga cratons. Modified from Kampunzu and Popoff (1991). B: Map of northwestern Namibia showing distribution of Etendeka Group volcanic rocks and Damaraland subvolcanic complexes, which define a linear belt trending east-northeast up to 350 km inland. The Messum complex was an eruptive center for some quartz latite units (Milner and Ewart, 1989; Ewart et al. 1998a), and recent studies have also identified the Doros center as a feeder for a lower sequence of flood basalt lavas (Jerram et al., 1999a). After Milner et al. (1992).

lar has proved critical, with some eruptive centers being identified for both mafic (e.g., Doros igneous center, Jerram et al., 1999a) and silicic units (e.g., Messum, Milner et al., 1995; Fig. 2B). Although the silicic components make up only a small volume of the province overall, the dimensions of individual silicic eruptive units are as substantial as those mapped for flood basaltic lavas (see Jerram, this volume). Individual silicic units occur as extensive, flat-lying, low-aspect-ratio sheets with average thicknesses of 70–250 m, strike lengths of >340 km, areal extents of > 25 000 km^2, and eruptive volumes to 6340 km^3 (Milner et al., 1992, 1995; Ewart et al., 1998a). Silicic volcanic rocks occur interbedded with basalt lavas related to the main pulse of flood volcanism, but also characterize the upper parts of the preserved stratigraphy (Fig. 3). An earlier phase of rhyolitic volcanism preceding the eruption of the voluminous quartz latites was identified at Messum (Messum core rhyolites of Ewart et al., 1998b).

The silicic volcanic rocks are referred to as rhyolite or rhyodacite in the Paraná (e.g., Garland et al., 1995), but the terms quartz latite and latite are used in the Etendeka (e.g., Milner, 1988; Milner et al., 1992). In the International Union of Geological Sciences total alkalis-silica classification (Le Maitre, 1989), these rocks plot continuously across the dacite-rhyolite-trachyte fields, and have a distinctive composition (e.g., high Fe, alkalies; low Al in relation to silica content; Ewart et al., 1998a). Thermometry indicates temperatures >1000 °C for the quartz latites, which is reflected in their lava-like, fluidal, and weakly phenocrystic character.

The quartz latite melts have been interpreted in terms of large-scale assimilation-fractional crystallization (AFC) processes, involving high degrees of lower and upper crustal melting, with thermal and material input from hybridized (low Ti-Zr) basaltic magmas (Ewart et al., 1998a, 1998b). The crustal end member has been interpreted to be dry granulitic lower crust (Harris et al., 1990; Harris and Milner, 1997), or the Middle Proterozoic restite source of the Damaran granites; some shallower crustal input is likely (Ewart et al., 1998a). Two chemically different rhyolites have been identified in the southern Uruguay portion of the province and are interpreted as either the products of extensive fractionation and crustal assimilation, or melts of preexisting mafic lower crust with subsequent extreme fractionation (Kirstein et al., 2000).

Deccan Traps

The main phase of mafic volcanism in the Deccan Traps (Fig. 1) occurred close to the Cretaceous-Tertiary boundary ca. 66 Ma (Duncan and Pyle, 1988; Hofmann et al., 2000). Silicic volcanic rocks are known from the Deccan Traps, especially around Bombay (Sethna and Battiwala, 1977; Lightfoot et al.,

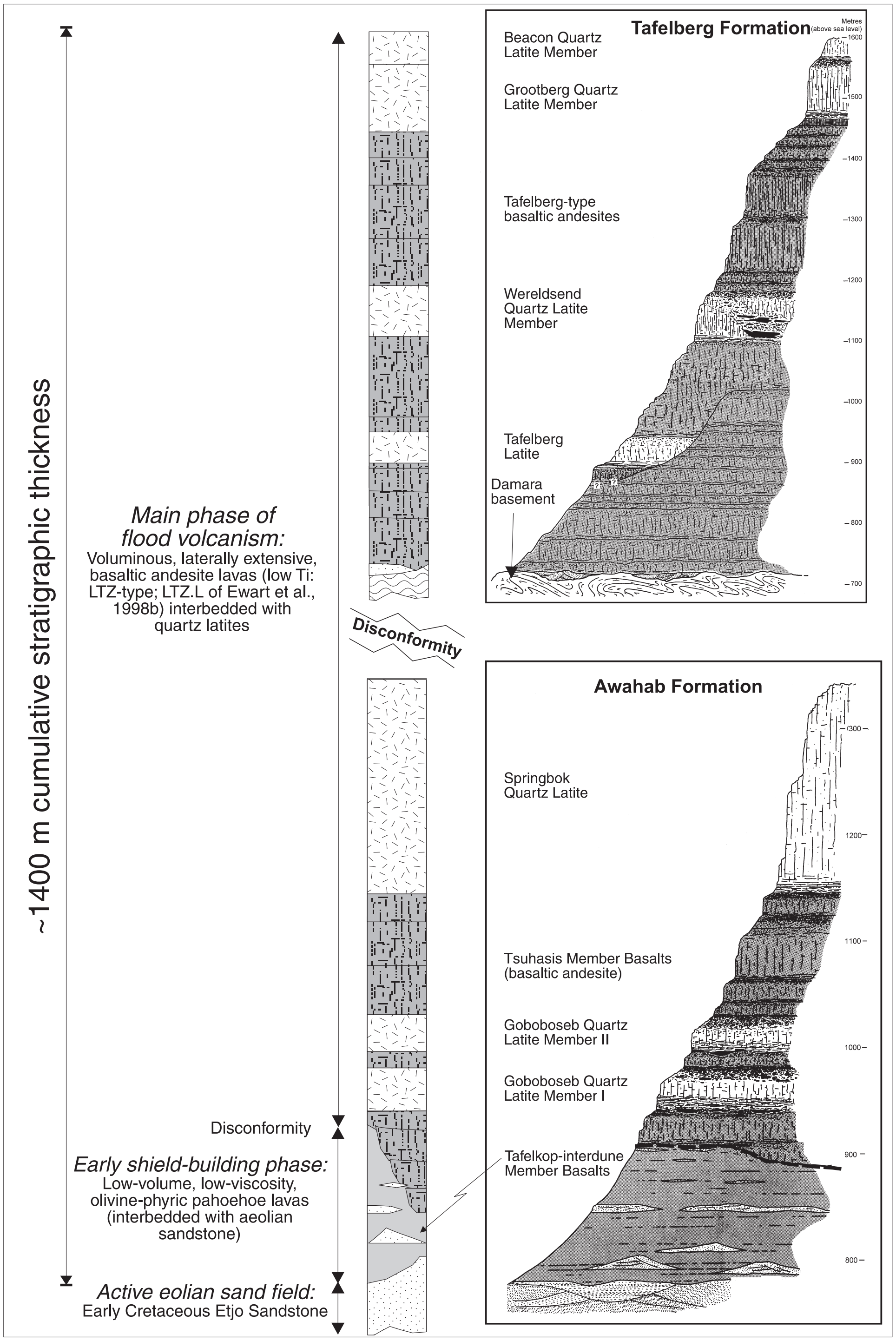

Figure 3. Stratigraphic subdivisions through the Etendeka Group, northwestern Namibia, showing the interbedded nature and thicknesses of quartz latite units within main phase of flood basalt volcanism. Adapted from Milner (1988) and Jerram et al. (1999a, Fig. 5).

1987) within the Narmada lineament (Mahoney, 1988), and from drill holes to the north of the Seychelles (Devey and Stephens, 1992, and references therein). Rhyolites from the Deccan province have an estimated volume of ~500 km^3 (Lightfoot et al., 1987), accounting for <1% of the total eruptive volume. Near Bombay, the rhyolites occur mainly as laterally extensive lavas, cropping out for as much as 20 km along strike; individual units are 20–100 m thick (Lightfoot et al., 1987). The rhyolites yield a younger age than the mafic rocks (61.5 ± 1.9 Ma; Rb/Sr whole-rock isochron age; Lightfoot et al., 1987). However, dacitic tuffs within the main phase of the Deccan flood basalts indicate that the contribution of more evolved volcanism may be greater than previously recognized (Widdowson, 1997; Widdowson et al., 1997).

The silicic volcanic rocks are peralkaline in character, as observed for silicic volcanics from other continental flood basalts (e.g., Ethiopia-Yemen), and trace element signatures indicate significant fractional crystallization in the evolution of the rhyolites (Lightfoot et al., 1987). Low initial $^{87}Sr/^{86}Sr$ ratios and Pb isotopic compositions similar to the associated flood basalts indicate derivation from a primitive mafic source, as observed in the Karoo rhyolites (e.g., Cleverly et al., 1984). The rhyolites were similarly interpreted to have been generated by partial melting of underplated basaltic magma (~10%–15%) with superimposed fractional crystallization (Lightfoot et al., 1987).

North Atlantic igneous province

The North Atlantic igneous province is related to the Tertiary opening of the North Atlantic Ocean and the separation of Greenland from northwestern Europe, and North America from Greenland (Fig. 1). Predominantly mafic magmatism occurred in two main phases: phase 1 (ca. 62–58 Ma) produced the terrestrial basaltic lava sequences; and phase 2 (56–53 Ma), linked to the breakup of the northeast Atlantic, produced the bulk of the seaward-dipping reflector sequences along the continental margins and the main series of basalts in central East Greenland (Saunders et al., 1997). Persistent volcanism that is commonly attributed to the Iceland plume has occurred for the past ~60 m.y. in the central region (Fig. 1). The area covered by flood basaltic volcanism, both onshore and offshore, is $\sim 1.3 \times 10^6$ km^2, and the eruptive volume is $\sim 1.8 \times 10^6$ km^3 (Coffin and Eldholm, 1994; Eldholm and Grue, 1994), although White et al. (1987) suggested a total igneous volume, including erupted material and additionsto the deeper crust, of between 5×10^6 and 1×10^7 km^3. A substantial portion of the province is offshore, and whereas the composition of the offshore volcanic sequences is generally regarded as basaltic, an unknown but perhaps significant proportion comprises silicic lavas and tuffs (Sinton et al., 1998).

Volcanism in western Britain was concentrated around the central intrusive complexes that comprise a wide variety of igneous rocks, from peridotite to granite (Saunders et al., 1997). Silicic igneous rocks are an important part of the province, largely occurring within, and typically emplaced early in the evolution of, the intrusive centers (Bell and Emeleus, 1988). Preservation of pyroclastic material is restricted mostly to the remains of caldera complexes (e.g., Rum, Mull, Arran), and thin, sanidine-bearing tuffs occurring throughout the lava fields (Bell and Emeleus, 1988; Emeleus et al., 1996; Bell et al., 1996). Two significant silicic volcanic units also occur in the Antrim Lava Group of Northern Ireland: the Tardree rhyolite complex and the Donalds Hill welded ignimbrite that occur interbedded with, and underlie, the basaltic lava pile, respectively (Meighan et al., 1984; Bell and Emeleus, 1988; Mitchell et al., 1999).

Andesitic to rhyolitic lavas and pyroclastic rocks were emplaced contemporaneously with basaltic lavas at the southeast Greenland margin at 62–61 Ma (Larsen et al., 1995; Sinton et al., 1998). The $^{40}Ar/^{39}Ar$ ages of 62.8 ± 0.6 and 62.4 ± 0.6 Ma for sanidine-bearing tuffs intercalated with the Eigg Lava Formation in western Britain (Pearson et al., 1996) are among the oldest ages for the entire North Atlantic igneous province (Saunders et al., 1997). Several granite intrusions in the British Tertiary igneous province (Arran, Skye) were also emplaced during phase 1 of Saunders et al. (1997). Silicic magmatism continued during phase 2; granites (e.g., Skye) and silicic volcanics were emplaced between ca. 56 and 52 Ma (Hamilton et al., 1998; Saunders et al., 1997). The Gardiner alkaline complex in East Greenland has been interpreted as the source for alkaline tuffs that occur in East Greenland (dated as 53.8 ± 0.3 Ma), Europe, and in North Atlantic cores (Heister et al., 2001). Silicic lavas erupted ca. 55 Ma along the Voring Plateau offshore Norway (Eldholm et al., 1987) and offshore Scotland (Sinton et al., 1998) were followed shortly thereafter by basaltic volcanism. These offshore localities from Europe show a stratigraphic succession from crust-derived intermediate-silicic magmatism to basaltic magmatism (Sinton et al., 1998).

The felsic volcanic rocks range from peraluminous to peralkaline compositions, although peralkaline compositions are absent from the major granite bodies (Meighan et al., 1992). Fractional crystallization has been an important process in their development; however, it is widely accepted that most silicic magmas represent the end products of fractionated, crustally contaminated basaltic melts, the proportion of the crustal component varying from ~10% to ~67% (Dickin and Exley, 1981; Meighan et al., 1992). The rhyolitic pitchstones of Mull, however, contain only small amounts (5%–10%) of basaltic magma, with both lower and upper crustal sources important in their generation (Preston et al., 1998a, 1998b).

Yemen-Ethiopia

Flood volcanism in Yemen-Ethiopia (Fig. 1) occurred between 31 and 26 Ma, with the peak of ages being between 31 and 29 Ma, and was related to the rifting of the Red Sea and the Gulf of Aden (Baker et al., 1996a; Hofmann et al., 1997). The province has an extrusive volume of >350 000 km^3 (Mohr, 1983), dominated by basaltic lavas, but includes a significant proportion of silicic volcanic rocks (Table 1). Rhyolitic ignimbrite, other pyroclastic rocks, and lavas occur toward the middle and top of the flood basalt lava pile in Ethiopia, and ages overlap the peak eruptive ages for the flood basalts (30.6–28.2 ± 0.1 Ma; Hofmann et al., 1997). Rhyolites and associated tuffs from the southern Red Sea Hills, Sudan, also have eruptive ages close to the main pulse of flood volcanism (29.9 ± 0.3 Ma, Kenea et al., 2001). In Yemen, rhyolitic pyroclastic rocks and lesser lava also predominate in the upper parts of the lava succession. The oldest rhyolitic units throughout Yemen are ca. 29.3–29 Ma, and bimodal volcanism continued until 26.5 Ma (Baker et al., 1996a). A period of widespread prerift basaltic and subordinate rhyolitic volcanism also occurred in southern Ethiopia between 45 and 33 Ma, prior to the better known flood basalt volcanic event of the Ethiopian Traps and Yemen (Ebinger et al., 1993, 2000; George et al., 1998). Silicic explosive eruptions, including voluminous rhyolitic ignimbrites, occurred ca. 40, 37, and 33 Ma during this earlier eruptive phase (Levitte et al., 1974; Davidson and Rex, 1980; Ebinger et al., 1993). Silicic volcanism (trachytes to peralkaline rhyolites and phonolites) has continued until recently during development of the Ethiopian rift, several centers being focused along the structural margins of the rift (Woldegabriel et al., 1990; Chernet et al., 1998; Ebinger et al., 2000). Younger (26–14 Ma) silicic magmatism also occurs along the Red Sea rift margin, and is dominated by trachytic to rhyolitic dikes and A-type granites that intrude basement and the flood basalt sequences (Capaldi et al., 1987; Chazot and Bertrand, 1995). The silicic igneous rocks show strong evidence for combined crustal assimilation and fractional crystallization of parental basaltic magmas (e.g., Chazot and Bertrand, 1995; Baker et al., 1996b), whereas crustal assimilation (to 30%) has significantly modified the primary chemistry of the flood basalts (Baker et al., 1996b).

In Yemen, ~50% of the volcanic sequences (~300 m thickness) comprise silicic pyroclastic rocks and, less commonly, rhyolitic lavas (Baker et al., 1996a, 1996b; Ukstins et al., 2000). Within the lower, almost entirely basaltic lava sections are interbedded distal facies of silicic explosive eruptions (fine-grained, 5-m-thick silicic fallout deposits), indicating penecontemporaneous effusive basaltic flood volcanism and explosive silicic volcanism (i.e., multiple vents; Ukstins et al., 2000). Silicic fallout deposits, welded ignimbrite, pyroclastic surge deposits, lavas, breccias, and sedimentary intervals reflecting reworking of silicic pyroclastic material characterize the upper parts of the volcanic stratigraphy in Yemen (Baker et al., 1996a). Individual eruptive units have thicknesses of 90 m, dispersal areas to 30 000 km^2, and eruptive volumes of ~600 km^3 (Ukstins et al., 2000). In the Sana'a area of Yemen, megabreccia containing a tuffaceous matrix and with blocks of dimensions to 70 × 15 × 20 m reflect a caldera-forming eruption at 29 Ma (Ukstins et al., 2000). The silicic volcanics show an up-sequence petrographic variation, tending to more evolved compositions in the upper units (Ukstins et al., 2000).

Summary of continental flood basalt provinces with silicic volcanism

Most, if not all, continental flood basalt provinces contain a significant contribution from silicic volcanism. The following points summarize the important aspects of silicic volcanism in the continental flood basalt provinces.

Low volume, olivine-rich, basalts-picrites represent the early mafic eruptions of continental flood basalts (e.g., North Atlantic igneous province, Etendeka; Jerram et al., 1999a), with slightly more evolved and/or contaminated mafic lavas of much larger volume and varying volumes of silicic volcanism characterizing the main phase of flood volcanism (Fig. 3).

Within the main pulse of flood basaltic volcanism, silicic volcanism can occur throughout and/or very early in the eruptive sequence (e.g., North Atlantic igneous province, Bell and Emeleus, 1988; Sinton et al., 1998; Mitchell et al., 1999; Ferrar, Elliot, 2000). In the Etendeka, Karoo and Yemen examples, silicic volcanics increase in abundance up the volcanic pile (Fig. 3). However, because the eruptive stratigraphy in each case is incompletely preserved, the proportion of silicic volcanism may be underestimated, and their occurrence late in the evolution of a province may be an artefact of preservation.

The interbedded silicic volcanic rocks, combined with palynology and crosscutting relationships of (silicic) intrusives, can be important in obtaining higher precision geochronology for continental flood basalts (e.g., Baker et al., 1996a; Emeleus et al., 1996; Bell et al., 1996; Hamilton et al., 1998).

The processes of rhyolite generation are dominated by crustal melting and assimilation by flood basaltic magmas with superimposed fractional crystallization (AFC; Etendeka, North Atlantic igneous province, Yemen), whereas remelting of mafic cumulate or lower crust is considered important for the Karoo and Deccan rhyolites. Crustal melting typically involved refractory, dry Archean to Proterozoic basement material, and the larger volume rhyolites all require some basaltic input into the magmas, in terms of both heat transfer and material addition. Crustal melting and consequent contamination of the flood basalt magmas is commonplace in the continental flood basalts, although contamination by melts from the subcontinental lithospheric mantle appears to be more important in the Karoo continental flood basalt (Ellam et al., 1992).

The dimensions of some silicic eruptive units, which are as voluminous, if not more so, than the largest recorded flood basaltic lavas, could have significant implications in terms of the environmental impact of continental flood basalt provinces. For example, the Goboboseb and Springbok quartz latite units erupted from Messum (Paraná-Etendeka province) have combined eruptive volumes of >8000 km^3 (Milner et al., 1995). Placed in perspective of crustal thickness, the Springbok quartz latite unit alone would have a magma sphere diameter of 23 km; this is only a minimum estimate of the magma chamber dimension, which is unlikely to have been totally evacuated (Ewart et al., 1998a).

SILICIC LARGE IGNEOUS PROVINCES

Silicic large igneous provinces have extrusive volumes comparable to mafic large igneous provinces, but have minor amounts of mafic magma expressed at the surface. Large volume silicic igneous provinces of Mesozoic to Cenozoic age[1] are recognized from two tectonic settings: those associated with conti-

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[1] Recent studies are indicating the existence of another silicic large igneous province of Permo-Carboniferous age (~320—280 Ma) in the New England fold belt of Eastern Australia (e.g., Holcombe et al., 1997; Allen et al., 1998). The dimensions of this large igneous province remain poorly constrained at present, but silicic igneous rocks define a belt >1900 km long and ≥300 km wide (areal extent of >570 000 km^2), with volcanic sequences up to 1 km thick. The Proterozoic (1600—1585 Ma) Gawler Range volcanics (>25 000 km^2) of South Australia (e.g., Fanning et al., 1988; Giles, 1988; Creaser and White, 1991) may also be the remnants of a silicic large igneous province.

nental breakup (e.g., Whitsunday volcanic province, eastern Australia; Chon Aike province, South America–Antarctic Peninsula), as well as active continental convergent margins undergoing extension (e.g., Sierra Madre Occidental, Mexico; Fig. 1). Despite showing lithological and geochemical similarities, the tectonics for the formation of these silicic igneous provinces are fundamentally different and therefore discussed separately here. In this chapter we also discuss the Taupo volcanic zone of New Zealand in the context of a modern example of a silicic large igneous province developing along an active continental margin. Although the Taupo volcanic zone does not fit our definition of a silicic large igneous province (i.e., eruptive volume), it shows many attributes that would have characterized the other silicic large igneous provinces and are emphasized here.

Associated with continental plate breakup

Two silicic large igneous provinces related to continental plate breakup have been recognized in the rock record: the Early Cretaceous Whitsunday volcanic province of eastern Australia (Ewart et al., 1992; Bryan et al., 1997, 2000), and the Jurassic Chon Aike province of South America and the Antarctic Peninsula (Pankhurst et al., 1998; 2000; Riley and Leat, 1999; Feráud et al., 1999; Riley et al., 2001). These provinces differ from well-known continental flood basalts by being overwhelmingly dominated (>80% volume) by intermediate to silicic magma compositions, with basalt being a minor component. These silicic large igneous provinces are (1) volumetrically dominated by ignimbrite; (2) active over prolonged periods (to 40 m.y.); and (3) spatially and temporally related to other mafic large igneous provinces and plate breakup (Bryan et al., 2000). The volcanic rocks typically show calc-alkaline affinities that resemble modern destructive plate margin volcanic rocks rather than bimodal or alkalic volcanism associated with continental flood basalts and continental rifts.

Whitsunday volcanic province. The Early Cretaceous Whitsunday volcanic province is part of a silicic-dominated pyroclastic volcanic belt that extended along the northeast Australian coast (Fig. 4) and was >900 km in strike length, >1 km thick, and had an extrusive volume >10^5 km^3 (Clarke et al., 1971; Bryan et al., 1997). The remainder of the silicic large igneous province is interpreted to have been eroded and/or rifted from the Australian continent, now occurring on submerged continental ridges and marginal plateaus following continental breakup and seafloor spreading in the Late Cretaceous and Tertiary. The original extent of the volcanic belt is thought to have been >2500 km along the present eastern Australian plate margin, and igneous rocks of Early Cretaceous age are widespread elsewhere in eastern Gondwana, occurring in New Zealand, Lord Howe Rise, and Marie Byrd Land (see references in Bryan et al., 2000). Most of the eruptive products of silicic volcanism, however, are preserved as huge volumes of coeval volcanogenic sediment in adjacent sedimentary basins of eastern Australia (Fig. 4), where the volume of the volcanogenic sediment alone

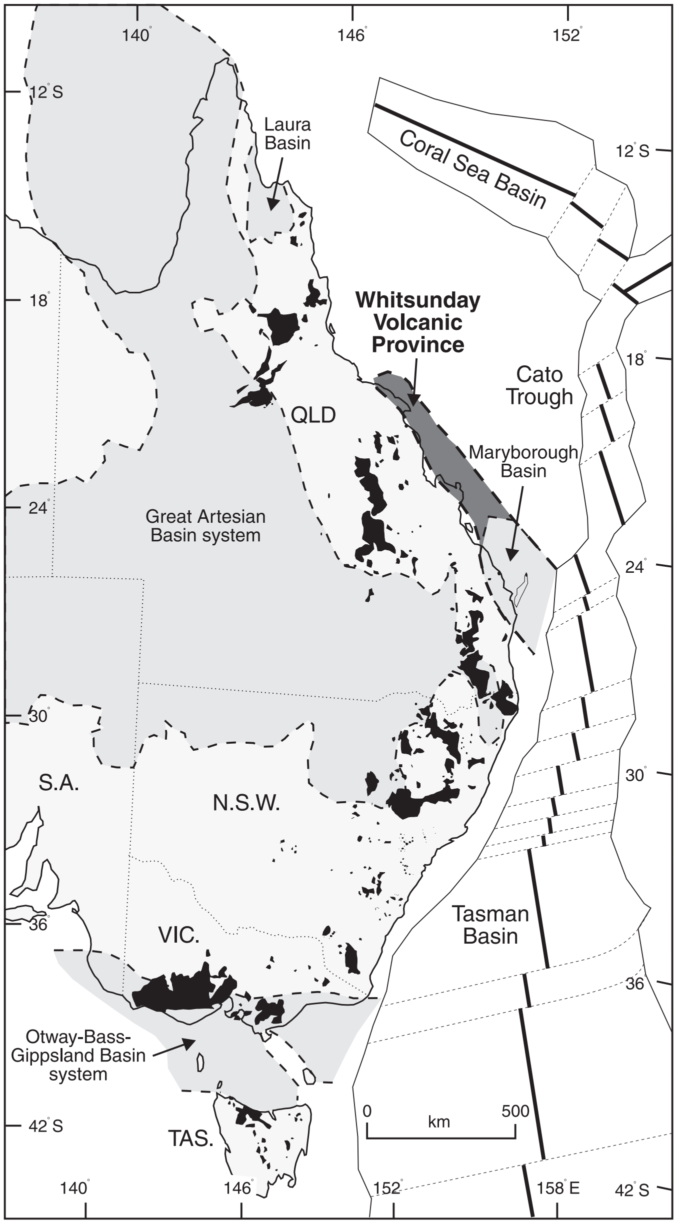

Figure 4. Location of the silicic-dominated Whitsunday volcanic province (132-95 Ma) and Early Cretaceous sedimentary basins of eastern Australia that contain >1.4×10^6 km^3 of coeval large igneous province-derived volcanogenic sediment (Bryan et al., 1997). Large igneous province magmatism was followed by: (1) kilometer-scale uplift of eastern margin of Australia beginning ca. 100-95 Ma (e.g., O'Sullivan et al., 1995, 1999); (2) seafloor spreading in Tasman Basin-Cato Trough-Coral Sea Basin occurring between 84 and 56 Ma (e.g., Veevers et al., 1991); and (3) intraplate alkaline volcanism (80-0 Ma, shown in black) that was partly synchronous with seafloor spreading, and that defines a broken belt 4400 km long along the highlands of eastern Australia. Intraplate alkaline volcanism occurred within 500 km of coastline, and has an extrusive volume of >20 000 km^3 (Johnson, 1989). QLD, Queensland; N.S.W., New South Wales; VIC., Victoria, TAS., Tasmania; S.A., South Australia.

($>1.4 \times 10^6$ km^3; Bryan et al., 1997) exceeds that of several mafic continental flood basalts. Such substantial volumes of coeval volcanogenic sediment are not characteristic of other large igneous provinces, and voluminous pyroclastic eruptions were an important factor in generating fine-grained volcanic material that was rapidly delivered into these sedimentary basin systems (Bryan et al., 1997, 2000).

The main period of volcanic activity occurred between 120 and 105 Ma (Ewart et al., 1992). Lithologically, the volcanic sequences are volumetrically dominated by welded dacitic-rhyolitic lithic-rich ignimbrite, and some interpreted intracaldera ignimbrite units are as thick as 1 km (Clarke et al., 1971; Ewart et al., 1992; Bryan et al., 2000). Coarse lithic lag breccias containing clasts to 6 m diameter (Ewart et al., 1992) commonly cap the ignimbrites in proximal sections and record the onset of caldera collapse. The volcanic sequences record a multiple vent, but caldera-dominated, low-relief volcanic region (Bryan et al., 2000). Volcanism appears to have evolved from an early explosive phase dominated by intermediate compositions, to a later, bimodal effusive-explosive phase characterized by rhyolitic ignimbrites and lavas; and primitive basaltic lavas and/or intrusives (Bryan et al., 2000). The ignimbrite-dominated sequences are intruded by gabbro and/or dolerite to rhyolite dikes (to 50 m width), sills, comagmatic granite (Ewart et al., 1992), and rarely in the intra-caldera sequences, by welded pyroclastic dikes, interpreted to be vents for some of the ignimbrite-forming eruptions (Bryan et al., 2000).

Chemically, the suite ranges continuously from basalt to high-silica rhyolite, with calc-alkalic to high-K affinities (Ewart et al., 1992). The range of compositions is interpreted as being generated by two-component magma mixing and fractional crystallization superimposed to produce the rhyolites. The two magma components are (1) a volumetrically dominant partial melt of relatively young, nonradiogenic calc-alkaline crust; and (2) a within-plate tholeiitic basalt of enriched-MORB affinity (Ewart et al., 1992; Stephens et al., 1995).

Chon Aike province. The Chon Aike province of Patagonia (Fig. 5) extends from the Atlantic Coast to the Chilean side of the Andes (Pankhurst et al., 1998) and is correlated with the Jurassic silicic volcanic rocks of the Antarctic Peninsula (Riley and Leat, 1999). In eastern Patagonia, the volcanic rocks are predominantly flat lying and undeformed where they overlie crystalline basement rocks of Precambrian to earliest Jurassic age and Lower Jurassic rift-related sedimentary rocks. In contrast, silicic volcanic rocks of the Andean Cordillera form relatively narrow outcrops, which are locally deformed, tilted, and strongly affected by hydrothermal alteration.

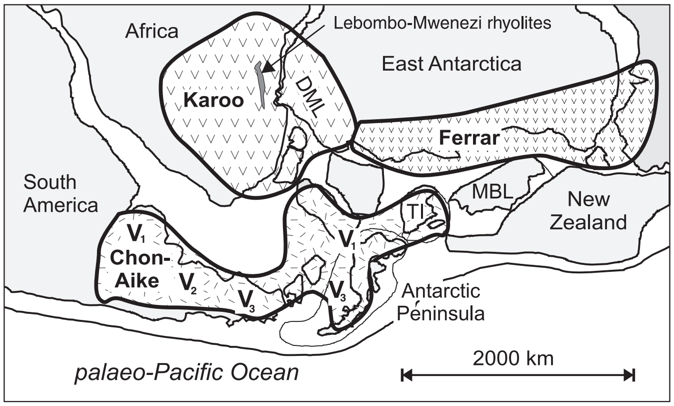

Figure 5. Reconstruction of western Gondwana prior to breakup showing the spatial relationship of the Jurassic Karoo and Ferrar continental flood basalt provinces to the silicic Chon Aike province. Note marginal setting and general migration of volcanic phases (V_1 to V_3) within Chon Aike province away from the locus of basaltic flood volcanism. DML, Dronning Maud Land; MBL, Marie Byrd Land; TI, Thurston Island. Modified after Pankhurst et al. (1998, 2000).

The province is dominated by phenocryst-poor ignimbrites, sourced from multiple caldera centers (e.g., Aragón et al., 1996; Riley and Leat, 1999), and vary in degree of welding from high-grade rheomorphic ignimbrites with parataxitic textures, to the volumetrically dominant, nonwelded lithic-rich ignimbrites. Volumetrically minor rhyolite lavas, fallout deposits, debris-flow deposits, and epiclastic deposits are interbedded with the ignimbrites. The province is chemically bimodal, but is dominated by rhyolite, with only rare intermediate (basaltic andesite and/or andesite) compositions.

The eruptive ages of silicic volcanic rocks from Patagonia and the Antarctic Peninsula have been defined by U-Pb ion microprobe dating (Pankhurst et al., 2000) and ^{40}Ar/^{39}Ar geochronology (Féraud et al., 1999). The age data indicate that volcanism continued for as long as 30 m.y., from the Early Jurassic to Late Jurassic, but occurred in three main phases (Table 2). The first phase of volcanism (188–178 Ma; V_1 of Pankhurst et al., 2000; Fig. 5) has a peak eruptive age of 184 ± 2 Ma, and brackets the peak of flood basalt volcanism of the Karoo and Ferrar provinces at 183 ± 1 Ma (e.g., Encarnación et al., 1996). The Tobífera Formation of southernmost Patagonia, however, yielded ages of 178 and 171 Ma (Pankhurst et al., 2000) and may partly span the interval between V_1 and V_2 (172–162 Ma). The final episode, V_3 (157–153 Ma), is confined

TABLE 2. SUMMARY OF AGES AND RELATIVE ERUPTIVE VOLUMES FOR THE THREE ERUPTIVE PHASES IDENTIFIED FOR THE CHON AIKE PROVINCE

Eruptive Phase	Formations	Age (Ma)	Volume (km^3)
V1	Marifil (northeastern Patagonia) Brennecke, Mount Poster (southern Antarctic Peninsula)	188–178	45 000
V2	Chon Aike (Argentina) Mapple (Antarctic Peninsula)	172–162	130 000
V3	El Quemado (western Argentina) Ibañez (Chile)	157-153	55 000

Note: Data after Pankhurst et al., 1998; 2000.

to the Andean volcanic outcrops of Argentina and Chile (Table 2), although small granite bodies of this age occur both in western Patagonia and in the western Antarctic Peninsula, and may be subvolcanic equivalents. The three eruptive phases define an age progression of magmatism from an intraplate to continental margin setting, away from the locus of flood basalt volcanism in the Karoo province (Pankhurst et al., 2000; Fig. 5). Concomitant with the age progression is a change in rhyolite composition from intraplate (higher Nb, Zr; V_1) to calc-alkaline (lower Nb, Zr; V_2 and V_3) geochemical signatures. The Middle Jurassic silicic volcanic rocks of the Mapple Formation (Antarctic Peninsula) and those of the Chon Aike Formation (South America) are thought to have been generated as a result of anatexis of Grenvillian age hydrous mafic lower crust of andesitic composition, linked to pre-Middle Jurassic subduction, and superimposed fractional crystallization (Pankhurst and Rapela, 1995; Riley et al., 2001).

Associated with active continental convergent margins

These silicic igneous provinces are generally related to continental extension preceding backarc basin formation. They have extrusive volumes of the order of 10^4–10^5 km^3 and volcanic activity can be prolonged for 10–20 m.y. The silicic magmas commonly possess a more hydrous mineralogy (e.g., Ewart, 1979), and I-type calc-alkaline magma compositions.

Sierra Madre Occidental. The mid-Tertiary Sierra Madre Occidental province is the largest silicic volcanic province in North America (Fig. 1), comprising more than 350 calderas (Swanson and McDowell, 1984) in a volcanic-plutonic belt ~1200 km long and 200 km wide in northern Mexico (Ward, 1995), and with an estimated extrusive volume of as much as 250 000 km^3 (Cameron et al., 1980). Magmatism mostly occurred over a relatively short period (27–34 Ma, McDowell and Clabaugh, 1979; 28–31 Ma, Nieto-Samaniego et al., 1999). However, the province was contiguous with widespread, predominantly explosive silicic volcanism (ignimbrite flare-up) in the Basin and Range province of the western United States (Fig. 1), where >35 000 km^3 of dacitic to rhyolitic ignimbrite was emplaced between 31 and 20 Ma (Best and Christiansen, 1991; Lipman, 1984; Ward, 1991). The Sierra Madre Occidental formed at a time when andesitic (suprasubduction zone) magmatism was rare and during the period of greatest divergence of the Pacific and North American plates, resulting in extension of the continental margin (Ward, 1991). The province was emplaced through basement that varied from Precambrian ("Grenville", ≥1 Ga) to Phanerozoic "exotic" terranes accreted to the continental margin in the Mesozoic (Albrecht and Goldstein, 2000).

The Sierra Madre Occidental province is dominated by rhyolitic ignimbrites, with rare mafic to intermediate rocks, ranging in composition from 50 to 76 wt% SiO_2 (e.g., Wark, 1991; Albrecht and Goldstein, 2000). The volcanics have medium- to high-K calc-alkaline compositions; however, spatial differences exist in trace element (i.e., low and high Nb, Zr, Th, Rb suites) and isotopic compositions that reflect the age and composition of the basement through which the volcanics were erupted (Albrecht and Goldstein, 2000). Initial $^{87}Sr/^{86}Sr$ ratios range from 0.7044 to ~0.710, and show no systematic variation with rock composition (Wark, 1991; Albrecht and Goldstein, 2000). There is a divergence of opinion about the origin of the voluminous rhyolites. Some workers interpreted the rhyolites to have formed by lower crustal melting (e.g., Elston, 1984; Ruiz et al., 1988). Widespread partial melting of lower crust (due to heating by emplaced basalt) is also generally considered as the mechanism to account for the voluminous mid-Tertiary silicic volcanism of the western United States (e.g., Lipman and Glazner, 1991). In contrast, fractional crystallization of precursor, more mafic magmas (basalt-andesite) to produce the rhyolites has also been proposed (e.g., Cameron et al., 1980; Cameron and Hanson, 1982; Wark, 1991). Volume considerations, however, tend to argue against the derivation of the voluminous rhyolites by fractional crystallization alone (see also Pankhurst and Rapela, 1995), and Cameron et al. (1980) suggested that 80% of the mass of a basaltic andesite magma had to have been removed by fractional crystallization to produce the rhyolites. The relationship between volcanic compositions, isotopic ratios, and the age of basement reflects the strong effect of continental crust on the chemistry of the silicic magmas, and crustal contributions to basaltic magmas are 20%–70% (Albrecht and Goldstein, 2000).

Taupo volcanic zone. The Taupo volcanic zone (Fig. 1) is an exceptionally active area of young volcanism (>90% is rhyolitic), heat flow, and tectonism accompanying rapid extension of continental crust (Wilson et al., 1984, 1995; Stern, 1985; Houghton et al., 1995). The Taupo volcanic zone is ~300 km long (200 km of which is on land) to 60 km wide, and comprises volcanic deposits ~2 km thick. It represents the youngest (1.6 Ma) and most southward expression of backarc to arc-rifting in the Taupo-Hikurangi arc-trench system (Cole, 1990; Wilson et al., 1995). Precursor explosive silicic volcanism of Miocene-Pliocene age occurs in the Coromandel volcanic zone to the northwest.

Bimodal but volumetrically dominant rhyolite volcanism characterizes the Taupo volcanic zone (Cole, 1990; Wilson et al., 1995). Rhyolite (15 000 km^3 bulk volume) is erupted mostly during caldera-forming ignimbrite eruptions from the central zone; arc-related andesite is an order of magnitude less abundant, and basalt and dacite are relatively minor in volume (<100 km^3 each; Wilson et al., 1995). At least 34 caldera-forming eruptions have occurred over the past 1.6 m.y.; several eruptions produced ignimbrites >300 km^3, and the 340 ka Whakamaru group ignimbrites have a volume of >1000 km^3 (Houghton et al., 1995; Brown et al., 1998). Basalts have been erupted from several locations within the Taupo volcanic zone (Cole, 1990), and all erupted examples represent small, monogenetic events 2–3 orders of magnitude smaller than the largest rhyolite eruptive events (Wilson et al., 1995). The Taupo volcanic zone basalts have geochemical signatures similar to other backarc basin basalts from oceanic-arc systems, with upwelling mantle involved in "unzipping" a segment of continental lithosphere (Gamble et al., 1993).

Generation of the rhyolites has been attributed to (1) fractionation of mantle-derived melts (e.g., Blattner and Reid, 1982; Conrad et al., 1988); (2) crustal melting of either basement greywacke-argillite (e.g., Ewart and Stipp, 1968; Cole, 1981) or igneous basement (Cole, 1990; Graham et al., 1992) in response to thermal input from the mantle; or (3) a combination of assimilation and fractional crystallization (e.g., McCulloch et al., 1994). The predominantly metaluminous character of the rhyolites, and Pb isotope studies (e.g., Graham et al., 1992; Brown et al., 1998), however, do not indicate substantial partial melting of, or significant contamination by, an aluminous radiogenic crustal component. Seismic studies in conjunction with petrogenetic models suggest that there is a substantial volume of mafic cumulate (or restite) material flooring the Taupo volcanic zone at >15 km depth (e.g., Hochstein et al., 1993; McCulloch et al., 1994; Wilson et al., 1995). Many rhyolitic ignimbrites in the Taupo volcanic zone display evidence for fractionation within a large magma system from a less evolved primary magma, but these primary magmas are complex with distinct trace element characteristics inherited from a heterogeneous source area, variable degrees of partial melting, and/or magma mixing (Brown et al., 1998).

DISCUSSION

The preceding outline illustrates that silicic volcanic rocks occur within most, if not all, the continental flood basalt provinces. Although silicic volcanics compose a small overall portion of continental flood basalts, they are locally dominant (e.g., Lebombo) or form considerable parts of the eruptive stratigraphy (e.g., 50% in the Etendeka province and Yemen; Milner et al., 1992; Ukstins et al., 2000). In contrast, some large igneous provinces have very large volumes of silicic igneous rock without associated large volumes of mafic rock (e.g., Whitsunday volcanic province, Chon Aike province). Silicic large igneous provinces occur in both intraplate and convergent margin settings, with the latter examples related to backarc processes. The outline also illustrates that in terms of proportions of mafic to silicic igneous rock, no spectrum of large igneous provinces exists. Mafic and silicic large igneous provinces represent end members, each comprising <10% of silicic or mafic igneous rock, respectively, and large igneous provinces with subequal proportions of mafic to silicic igneous rocks are absent from the geologic record.

Relative eruptive age of silicic volcanism in continental flood basalt provinces

Despite previous assumptions that silicic volcanism postdates flood basalt volcanism, there is no consistent pattern among the continental flood basalt provinces. Several continental flood basalt provinces show multiple pulses of silicic volcanism that are apparent when data from the Karoo, Ferrar, and Chon Aike provinces are combined. In the Ferrar province, silicic volcanism mainly preceded the eruption of tholeiitic basalts, but also accompanied, at low intensity, Ferrar mafic magmatism (Elliot, 1992). The latest geochronology from the Chon Aike province (Pankhurst et al., 2000) indicates that the first phase of silicic volcanism ($V_{1;}$ 188–178 Ma; Table 2), although spatially separate, predated and temporally overlapped the peak phase of Ferrar-Karoo magmatism at 183 Ma (e.g., Encarnación et al., 1996; Duncan et al., 1997), possibly correlating with silicic volcanic and volcaniclastic rocks (Hanson Formation; Elliot, 2000) underlying the Ferrar basalts. A younger phase of silicic volcanism, the 178 Ma Lebombo rhyolites, occurred in the Karoo province, postdating both the Karoo flood basalts and the MORB-like Rooi Rand dike swarm (Watkeys et al., 2000).

In the North Atlantic igneous province, silicic magmatism occurred during both phases of breakup of the northeast Atlantic. Silicic volcanic rocks are not only interbedded with the flood basalt lavas, but also represent some of the oldest volcanic products of this event (e.g., Mitchell et al., 1999; Sinton et al., 1998). Silicic pyroclastic activity appears to have occurred throughout the evolution of the Mull igneous center (Bell and Emeleus, 1988). In the Etendeka province, latites and quartz latites occur interbedded with basalt lavas during the main phase of flood basalt volcanism (Fig. 3), whereas an earlier phase of rhyolitic volcanism is recorded in the Messum Igneous Complex (Ewart et al., 1998b). Repeated episodes of silicic volcanism occurred prior to and during development of the Ethiopian Rift and Traps, although the silicic volcanics tend to occur toward the middle and top of the flood basalt lava piles (e.g., Ebinger et al., 1993; Baker et al., 1996a; Hofmann et al., 1997). Results from recent ODP drilling of the Kerguelen Plateau suggest that plateau growth by flood basalt volcanism between 110 and 115 Ma concluded with explosive subaerial silicic volcanism (Frey et al., 2000; Moore et al., 2000). However, the earliest eruptive history of the plateau remains undefined, and older silicic ash layers (bentonites) have been recovered from the margins of other submerged oceanic plateaus off the northwest Australian margin (Colwell et al., 1994; Von Rad and Thurow, 1992).

Thus, although most continental flood basalts were erupted during a time period of ~1 m.y., there is no consistent pattern to the eruption of silicic magmas, which may either precede (e.g., Ferrar), be coincident with (e.g., Paraná-Etendeka), or postdate (Karoo-Lebombo) the peak of basaltic flood volcanism.

Eruptive volume, areal extent, and nature of silicic volcanism associated with continental flood basalt provinces

The preservation of silicic volcanic rocks associated with continental flood basalts and along volcanic rifted margins can be limited by regional uplift (typically 1–2 km) and exhumation following emplacement, which results in significant erosion of the volcanic pile. As a consequence of these events, the silicic volcanic rocks are unlikely to be preserved where they occur predominantly in the upper parts of the stratigraphy. Only the deeper level features may be preserved, such as silicic dike swarms, granite intrusions, ring complexes, and deeply subsided caldera collapse structures (e.g., Arran and Rum igneous centers, North Atlantic igneous province; Bell and Emeleus, 1988).

A common assumption has been that the silicic volcanic rocks are small in volume (when compared to the associated flood basalts) and thus areal extent. The areal extent and eruptive volume of individual quartz latite sheets from the Paraná-Etendeka province are comparable to, and often exceed, those of flood basalt lavas (Milner et al., 1995; Jerram, this volume). As further work is undertaken on continental flood basalt provinces the products of other individual silicic eruptions are being recognized as having large areal extents (10^4 km^2), thickness, and eruptive volumes (e.g., Mitchell et al., 1999; Ukstins et al., 2000).

The silicic volcanic component of continental flood basalt and silicic large igneous provinces is dominantly ignimbrite (often from caldera-forming eruptions); thin, widespread silicic ash-grade beds (tuffs, bentonites) are also significant (cf. McPhie et al., 2000). The lava-like character of the quartz latites of the Parana-Etendeka province is a reflection of their high eruptive temperatures and low magma viscosities (i.e., magma composition), and they have been interpreted as rheomorphic ignimbrites (Milner et al., 1992). Preservation of highly vesicular pumice and cuspate shard textures, typical of lower grade, calc-alkaline ignimbrites, should not be expected from eruptions of such magmas, and the occurrence of spatter and globule textures is more likely (see Hay et al., 1979; Milner et al., 1992). Coeval rhyolitic volcanics in southern Uruguay exhibit lower eruptive temperatures (850–950 °C) and have well-developed ignimbrite textures (Kirstein et al., 2000).

It has also been assumed that because of their higher viscosity, the ascent and consequent eruption of silicic magmas will be hindered, and therefore they will be emplaced late in the eruptive history of continental flood basaltprovinces (e.g., White, 1992). This assumption is clearly invalidated by the quartz latites of the Paraná-Etendeka province that have viscosities approaching andesite (10^5 poise, Milner et al., 1992). Evidence such as globule textures further supports a low magma viscosity (Milner, 1988; Milner et al., 1992). Age data and stratigraphic information from the continental flood basalt provinces illustrate that silicic agmas are not always emplaced late in the eruptive history (e.g., Etendeka, Fig.3; Ferrar, North Atlantic igneous province). The simultaneous existence of mafic and silicic magmas is also evident in the Messum Igneous Complex (Ewart et al., 1998b).

Such massive outpourings of silicic volcanism have the potential to dramatically alter and affect the environment into which they erupt (Jerram, this volume). In the Etendeka region, for example, the early phase of volcanism was characterized by the dynamic interaction between the flood basalt lavas and an active eolian sand field (Jerram et al., 1999b, 2000). The first occurrence of large-volume silicic eruptive units in the Etendeka (Goboboseb Member) marks the point in the stratigraphy where no further record of eolian deposition occurs (Jerram et al., 1999b, 2000; Fig. 3).

The explosive eruptive style has been important in producing widespread silicic volcanic deposits such as ignimbrite sheets, Plinian fallout deposits, and distal ash layers occurring interbedded with the flood basalt lavas (e.g., Yemen; Ukstins et al., 2000; Ferrar province, Elliot, 1992; North Atlantic igneous province, Bell and Emeleus, 1988; Heister et al., 2001; northwest Australian margin, von Rad and Thurow, 1992). Widespread silicic ash layers may represent important marker horizons in an otherwise monotonous basaltic volcanic stratigraphy. The pyroclastic mode of fragmentation and dispersal also promotes large volumes of fine-grained volcanogenic sediment to be reworked into sedimentary basins, and the depositional record of any sedimentary basins adjacent to large igneous provinces can provide insightful information on the eruptive history of these provinces (e.g., eastern Australia, Bryan et al., 1997).

Eruptive centers for silicic volcanism in mafic and silicic large igneous provinces

Recognizing eruptive vent systems for flood basalt lavas has been extremely difficult due to a combination of burial by younger lavas, lack of exposure, lack of proximal-distal variation in lava facies, and because near-vent features such as spatter cones and ramparts can be easily eroded. Eruptive vents for flood basalts are generally considered to be fissure systems fed by dike swarms, following the identification of a linear feeder dike system at least 200 km wide and 450 km long for the Roza Member of the Columbia River Basalts (Swanson et al., 1975). Recent findings have also identified a shield volcanic feature as a source for some flood basalts, associated with the Doros layered gabbro complex in northwest Namibia (Fig. 2B; Jerram et al., 1999a; Jerram and Robbe, 2001; Marsh et al., 2001).

Geochemistry has been used to correlate silicic volcanic rocks with their eruptive sources. The Messum Igneous Complex has been identified as the eruptive center for the Goboboseb and Springbok quartz latite units in the Etendeka, based on the occurrence of chemically and mineralogically equivalent quartz monzonite plugs and a laccolith immediately peripheral to Messum (Milner and Ewart, 1989). In the North Atlantic igneous province, mineral compositions have been used to link alkaline tuffs in East Greenland, the North Sea, and Denmark with the Gardiner alkaline complex in East Greenland (Heister et al., 2001).

Caldera complexes represent the dominant eruptive source for silicic volcanic rocks associated with continental flood basalts and silicic large igneous provinces. Within the silicic large igneous provinces, caldera complexes are part of a multiple vent volcanic system that includes numerous extracaldera (and intracaldera) effusive vents (e.g., monogenetic scoria and/or spatter cones, tuff rings and/or cones or maars for mafic volcanic rocks, and lava domes or flow/dome complexes for the more silicic volcanic compositions; e.g., Bryan et al., 2000). Thick dike swarms, often spatially associated with proximal lithofacies, are probably feeders to the effusive vents. Such multiple vent configuration is best illustrated by the interstratification of proximal and/or near-vent and distal volcanic lithofacies.

Evidence for calderas as source vents for the large-volume ignimbrites includes coarse lithic lag breccia facies and megabreccias within the ignimbrite eruptive units, and ponding relationships. Calderas, however, have proved difficult to identify, especially in the silicic large igneous provinces because of the scale of volcanism ($\geq 10^5$ km^2), burial, exhumation, faulting, and later deformation.

Caldera dimensions, although often difficult to define, appear to range between 10 and 30 km diameter in the continental flood basalt provinces and silicic large igneous provinces. The Messum Igneous Complex is roughly circular in plan and ~18 km in diameter, whereas the neighboring Brandberg igneous center is ~30 km in diameter (Fig. 2B). Caldera dimensions in the Whitsunday volcanic province are probably 10–20 km, based on ponding relationships and distribution of proximal volcanic lithofacies such as lithic lag breccias. The Mount Poster Formation of the Antarctic Peninsula (V_1) is believed to form an intracaldera succession of monotonous welded ignimbrites, to 1 km in thickness, that define a caldera structure 30–40 km in diameter (Riley et al., 2001).

An important point is that caldera complexes may not be classical circular collapse structures (e.g., Valles-type), but involve collapse along volcanic-tectonic structures controlled by the preexisting crustal architecture and extension orientation. The vent regions and hence collapse structures may be more akin to graben-type structures (e.g., Moore and Kokelaar, 1998). Several phases of collapse and resurgence (e.g., Messum, Brandberg, Rhum) provide further complication to the eruptive history and vent structure of silicic eruptive centers (Ewart et al., 1998b; Emeleus et al., 1985). The Messum Igneous Complex is interpreted as a caldera structure superimposed on a large regional sag structure resulting from massive magma withdrawal (>8000 km^3) during quartz latite eruptions (Milner and Ewart, 1989; Ewart et al., 1998b). Despite the proximity of the Messum and Brandberg igneous complexes in the Etendeka province, these two enormous silicic plumbing systems appear to have acted independently (A. Ewart, 2000, personal commun.).

Available evidence indicates that silicic volcanic rocks (or their eruptive centers) are not necessarily proximal to the main locus of (mafic) melt generation, which is exacerbated by their wide dispersal from pyroclastic transport processes (buoyant Plinian-type columns and pyroclastic density currents). Multiple eruptive centers or caldera complexes occur in continental flood basalt provinces (e.g., Paraná-Etendeka, North Atlantic igneous province) and silicic large igneous provinces (Whitsunday volcanic province, Chon Aike province). Many modern continental silicic calderas are sited at lineament intersections (e.g., Valles, Long Valley) and the same crustal anisotropy or structure is probably the most important control on caldera location in large igneous provinces. The igneous centers and/or calderas of the Etendeka province show a clear alignment defining a east-northeast–trending zone up to 350 km long from Cape Cross at the coast to Paresis and Okorusu in central Namibia (Schmitt et al., 2000; Fig. 2B); their locations are controlled by basement lineaments (e.g., the Omaruru and Autseib lineaments and the Ugab terrane, Clemson et al., 1999). Recent studies of silicic explosive volcanism associated with basaltic flood volcanism in Ethiopia-Yemen suggest that caldera complexes may also have migrated with time (Ukstins et al., 2000).

Generation of large-volume silicic igneous provinces

Although rhyolites can occur in a variety of tectonic settings, both oceanic and continental, large-volume ($>10^4$ km^3) silicic volcanism is restricted to continental margin settings, and to a lesser extent, continental interiors when associated with continental flood basalts. The silicic volcanic rocks associated with the continental flood basalt provinces listed in Table 1 are widely believed to be the end result of varying amounts of assimilation of partial melts of either anhydrous granulitic lower crust or mafic underplate at high temperatures by basaltic magmas, followed by extended fractional crystallization. For silicic large igneous provinces where the volume of silicic magma generated is at least an order of magnitude bigger, partial melting of lower crust is essential, the most suitable source materials being hydrated, calc-alkaline, and high-K calc-alkaline andesites and basaltic andesites and/or amphibolites (e.g., Roberts and Clemens, 1993). Basement to the Whitsunday volcanic province and Chon Aike province, and in part the Sierra Madre Occidental, comprises Paleozoic-Mesozoic volcanic and sedimentary rocks accreted and/or deposited along the continental margin. The involvement of Mesozoic to Paleozoic crust in magma genesis is supported by Nd model T_{DM} ages for the Whitsunday volcanic province (see Ewart et al., 1992), whereas mid-Late Proterozoic (Grenvillian) model ages are indicated for the crustal source in the eastern (interior) part of the Chon Aike province (Pankhurst and Rapela, 1995; Riley et al., 2001). These older depleted model ages may reflect either that of the sedimentary provenance or formation of the crust (Pankhurst et al., 1998). Nevertheless, the long history of subduction and intrusion of hydrous melts into the lower crust along the proto-Pacific margin is considered crucial for the generation of the large-volume rhyolites of the Chon Aike province (Riley et al., 2001). This difference in lower crustal materials between mafic and silicic large igneous provinces (i.e., the presence of anhydrous or hydrous crust) led Stephens et al. (1995) to coin the term “wet” large igneous province to describe silicic large igneous provinces such as the Whitsunday volcanic province and Chon Aike province.

Table 3 illustrates the key processes that lead to the development of silicic large igneous provinces or continental flood

TABLE 3. SUMMARY OF THE IMPORTANT CRUSTAL PRECONDITIONS, MAGMATIC PROCESSES AND ERUPTED PRODUCTS THAT LEAD TO THE DEVELOPMENT OF MAFIC AND SILICIC LARGE IGNEOUS PROVINCES

	Mafic Large Igneous Province	Silicic Large Igneous Provinces
Crustal setting	Craton interior	Accreted orogenic margin
Crustal composition and age	Refractory Archean–Proterozoic, dry mafic and/or silicic, brittle crust	Fertile Proterozoic–Phanerozoic, hydrous crust with a large I-type (calc-alkaline) meta-igneous component
Driving processes	Thermal and mass transfer into crust caused by hot mantle upwelling, and lithospheric extension	
Nature of crust and/or magma interaction	Crust with low preexisting geothermal gradient, melts to produce low volume, high temperature (dry) ternary granite minimum magma	Widespread partial melting of crust (~20%) to produce large volumes of hydrous, ternary granite minimum magma.
Thermal and mass transfer characteristics	Crust-penetrating structures readily transfer mafic melt to surface. Mafic magma can be hermally and chemically insulated from crust by chilling along reservoir margins limiting further crustal melting.	Density/buoyancy filter caused by silicic melt zone, and lack of well-defined crust-penetrating structures, suppresses rise/transfer of mafic magma. Containment of mafic melt promotes further increase in temperture and degree of crustal partial melting.
Magmatic processes and geochemical signature	Magma processes dominated by FC/AFC producing large volumes of variably contaminated within-plate basalt. Volumetrically minor silicic magma generated by AFC/PM. Melting of mafic underplate may occur.	Magma processes dominated by mixing and AFC producing large volume, volatile-rich rhyolitic- rhyodacitic melt with calc-alkaline signature and highly contaminated mafic-intermediate magmas.
Eruption characteristics	Effusive, flood basalt lava-dominated volcanism. Variable proportions of silicic pyroclastic rocks and lesser lavas from calderas, central igneous complexes ± fissures.	Explosive silicic-dominated volcanism erupted from multiple caldera complexes with minor mafic-intermediate lavas. Highly variable, upper crustal structure/rheology controls character of upper crustal magma reservoirs & eruptive centres (plutons, calderas, rifts)

basalt provinces with associated large-volume rhyolites. The presence of a fertile crustal source appears to be the main difference between silicic and mafic large igneous province formation. Large degrees of crustal partial melting, essential to produce the large volumes of rhyolitic magma, are controlled by the water content and composition of the crust and the large thermal input from the mantle. Although the thermal budget for mafic and silicic large igneous provinces is considered the same, hydrous crustal material will be more receptive to melting, and will begin to melt at lower temperatures. In contrast, melting of a refractory dry crust will be limited by prior depletions in minimum melt components and preexisting low geothermal gradient. Subsequent melting events will not only require higher temperatures to remelt, but produce less silicic (rhyodacitic) compositions.

Ancient and active convergent margins tend to be characterized by a fertile, hydrous lower crust that can readily melt. Long-lived subduction promotes the development of a hydrated lower crust and lithospheric mantle that can extend for several hundred kilometers from the active margin (e.g., Karoo, western United States; Fitton et al., 1988; Davis et al., 1993), particularly if significant lateral accretion has occurred over time. Previous subduction episodes may also have been important in the development of low-Ti source regions for some continental flood basalts (e.g., Hawkesworth et al., 1988). Heating and partial melting of a hydrous, mafic crust will generate intermediate to silicic composition melts (55%–75% SiO_2; Rapp and Watson, 1995). The silicic melts can act as a density barrier, preventing the mafic magmas from reaching the surface (cf. Huppert and Sparks, 1988), as will a lack of deep, crust-penetrating structures that can transfer mafic magma to the surface.

In contrast, continental flood basalts are emplaced on or adjacent to Archean cratons (Anderson, 1999), where the crust is relatively old (Proterozoic-Archean) and refractory, and any lower crustal melting would occur only at very high temperatures. Extensive mafic dike swarms (e.g., Central Atlantic magmatic province) imply a brittle crust with deep-penetrating structures that can channel mafic melt to the surface. In the cases of continental flood basalt provinces that have significant volumes of silicic volcanism, crustal melting and assimilation are generated by achieving such high temperatures at the base of the crust, caused by sustained thermal and material input of mafic magma. The Paraná-Etendeka rhyolites, for example, are anhydrous and had an eruption temperature in excess of 1050 °C (Harris and Milner, 1997), consistent with partial melting and assimilation of anhydrous crustal material at very high temperatures.

Distinguishing between intraplate and backarc-related silicic large igneous provinces

Large-volume silicic igneous provinces are not unique to continental breakup, but can characterize any continental region undergoing extension that is underlain by hot mantle and has a hydrous lower crust receptive to melting. This can occur in continental intraplate and subduction-related tectonic environments. The similarities in eruptive volumes, rhyolite geochemistry, and the ignimbrite-dominated character of the silicic igneous provinces related to plate breakup and those from extensional convergent continental margin settings makes distinguishing the two difficult.

Understanding the regional tectonic framework is a critical factor in determining the origin of such provinces. Detailed regional time-space analysis for western North America, for example, has shown that the Sierra Madre Occidental formed when suprasubduction zone andesitic volcanism was rare, and divergence between the Pacific and North American plates was greatest, and followed a period of rapid subduction, andesitic volcanism, trench-normal contraction, and widespread deformation during the Laramide orogeny (Ward, 1991, 1995). In contrast some silicic large igneous provinces tend not to show such an intimate space-time relationship to convergent margin tectonism, and like mafic large igneous provinces, have been emplaced into intraplate regions remote from plate-margin related tectonics and commonly undergoing rifting.

The Whitsunday volcanic province and Chon Aike province were emplaced into intraplate environments, and show strong evidence for being spatially and temporally related to continental plate breakup (Fig. 4). They are characterized by large volume (>10^5 km^3), overwhelmingly rhyodacite-rhyolite compositions approaching the hydrous granite minimum that strongly suggest melting of a hydrous crust as the predominant source. However, associated mafic magma compositions show evidence of an intraplate signature that is important in defining a fundamentally intraplate (versus active convergent margin) tectonic setting.

CONCLUSIONS

Flood basalt lavas are now thought to have been emplaced as inflated pahoehoe-like lavas (e.g., Self et al., 1996; Thordarson and Self, 1998) that are relatively slow advancing (as low as 0.2–1.4 m/s; Keszthelyi and Self, 1998), from low eruptive rate (e.g., ~4000 m^3/s average total eruption rate for Roza Member; Self et al., 1997) and long-lived eruptions (years to tens of years; Thordarson and Self, 1998). In contrast, large-volume ignimbrites, which represent the dominant silicic volcanic rock type of continental flood basalts and silicic large igneous provinces, are emplaced from short-lived (hours to weeks), high rate (10^6 m^3/s, >2×10^8 kg/s; e.g., Carey and Sigurdsson, 1989), highly explosive eruptions. In many continental flood basalt provinces, individual silicic eruptive units commonly have thicknesses, areal extents, and volumes that are comparable to, and exceed those of, flood basalt lavas. Regional uplift of 1–2 km is not a prerequisite nor indicated to generate either basaltic or silicic volcanic rocks with large areal extent or run-out distances. However, regional surface uplift and exhumation following emplacement of the large igneous province (typically 1–2 km) can result in significant erosion of the volcanic pile, and silicic volcanics are unlikely to be preserved, especially if they occur predominantly in the upper parts of the stratigraphy. Only the deeper level features may be preserved, such as silicic dike swarms, granites, and the lower levels of caldera collapse structures (e.g., North Atlantic igneous province, Bell and Emeleus, 1988).

Recent detailed studies of continental flood basalt provinces are revealing complex spatial-temporal relationships between silicic and mafic volcanism. In general, the silicic magmas are erupted from caldera-type centers, different from the fissure-type feeder dike systems commonly invoked for flood basalt lavas. However, the simultaneous existence of mafic and silicic magmas in some eruptive centers (e.g., Messum Igneous Complex, Ewart et al., 1998b), suggests that (large) calderas could be the site of both basaltic lava and rhyolitic ignimbrite-forming eruptions.

It is also important to point out that the plume model was developed in part because of the requirement for continental flood basalts that large volumes of (mafic) magma be produced over short periods (~1 m.y.). In contrast, silicic large igneous provinces comprise similar volumes of magma produced over a much longer duration (e.g., up to 40 m.y.). Therefore, the generation of silicic large igneous provinces requires melting of hot mantle and sustained mantle upwelling rather than the transient impact of a large plume head as in plume models commonly applied to mafic large igneous provinces (e.g., Campbell and Griffiths, 1990; White and McKenzie, 1989).

The generation of large volumes of crustal melt in fundamentally intraplate settings requires high heat influx to the crust transported by mantle-derived mafic magmas. This amount of mantle melting requires that the mantle be hotter than normal but within the range of mantle temperatures expected for the generation of continental flood basalts. The key to generating large volumes of silicic magma preserved in silicic large igneous provinces is the prior formation of hydrous, highly fusible mafic lower crust. Partial melting (~20%–25%) of this fusible crust will generate melts of intermediate to silicic composition (Rapp and Watson, 1995; Roberts and Clemens, 1993). We conclude that earlier subduction was crucial in developing a hydrous, fusible lower crust (i.e., mafic to intermediate, transitional to high-K calc-alkaline metaigneous source), and consistent with their development along or near continental margins.

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