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Part One

Large volume volcanism: origins, features and timing

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Large igneous provinces and explosive basaltic volcanism

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1.1 Introduction

Large igneous provinces are recognized from the Precambrian at 3.79 Ga (Ernst, 2013), and extend through well-preserved examples from the Mesozoic and Cenozoic (Ross *et al.*, 2005; Bryan and Ferrari, 2013, and references therein). While originally inferred to consist of a layer-cake sequence of massive and laterally continuous effusive basaltic lava flows, detailed volcanostratigraphy studies have generated a more nuanced view of province architecture, highlighting that many provinces include a significant component of clastic material derived from volcanic and sedimentary formation mechanisms. Conversely, some of the volumetrically largest basaltic volcaniclastic deposits appear to be associated with large igneous provinces (Ross *et al.*, 2005).

The importance of volcaniclastic deposits – and the implications for paleoenvironmental reconstructions, eruption dynamics, and climate impact – is one of the key concepts to emerge from scientific studies of large igneous provinces over the last 25 years. Ross *et al.* (2005) recognized, and highlighted, the near-ubiquitous occurrence of mafic volcaniclastic deposits as an integral component in large igneous provinces. These deposits contain information – some unique – on primary fragmentation mechanisms, eruptive processes, and depositional environments. Mafic volcaniclastic deposits provide a record of what we now recognize as complex temporal and spatial volcanic heterogeneity in large igneous provinces, and allow us to reconstruct their tectonic and physical evolution as an equally significant and complementary story to that of the geochemical evolution of magmatism. We provide a brief overview of mafic volcaniclastic deposits and formation mechanisms, and spotlight recent work highlighting their utility for interpreting large-scale tectonic evolution and climate impact issues related to large igneous province emplacement.

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1.2 Mafic volcanic-derived clastic deposits

Clastic deposits composed of mafic volcanic particles – in any proportion from partly to entirely – can be generated by a wide variety of mechanisms spanning the full range of volcanic to sedimentary processes, and the resultant textures and morphologies are likewise highly variable. Three genetic categories of mafic volcanic-derived clastic deposits, based on formation mechanisms, are *primary* and *reworked volcaniclastic deposits*, and *epiclastic deposits* (White and Houghton, 2006).

1.2.1 Primary volcaniclastic deposits

Primary volcaniclastic deposits are formed from fragmental material deposited as a direct result of explosive or effusive eruptions. There are four end-member types of deposits: autoclastic, pyroclastic, hyaloclastic, and peperitic (White and Houghton, 2006; White *et al*., 2009). The main factors controlling formation of these deposits are magma eruption rates, concentration of magmatic volatiles, and presence and relative abundance of external water, either as freestanding bodies or in saturated sediments. Mobilization of magma-generated particles is unique compared to other sedimentation processes that depend exclusively on gravity, because primary volcanic particles may acquire transport energy from their source – e.g. explosive expansion, lava flow velocity – and may initially be independent of slope or depositional base level (Fisher and Smith, 1991).

Autoclastic deposits are products of auto brecciation, and are generated as effusive lavas that exceed the viscosity-strain rate threshold and fragment (Peterson and Tilling, 1980); rapid cooling promotes groundmass crystallization and crust disruption (Cashman *et al*., 1999). A'a lava flow morphology is characterized by brecciated upper and lower surfaces; slabby or rubbly pahoehoe have broken or brecciated upper crusts and are transitional between pahoehoe and a'a (e.g. Guilbaud *et al*., 2005).

Pyroclastic deposits form from explosive volcanic eruption plumes and jets or pyroclastic density currents and can be generated by magmatic or phreatomagmatic fragmentation mechanisms, or a complicated interplay of both (e.g. Graettinger *et al*., 2013). Magmatic fragmentation represents a minor mechanism for generating mafic volcaniclastic deposits in large igneous provinces, and documented examples are rare. The Columbia River Basalt vent sites in the Roza Member have densely agglutinated and welded spatter and highly vesicular scoria fall deposits (Brown *et al*., 2014).

Involvement of aquifer or surface water in mafic eruptions leads to large-scale phreatomagmatic volcanism, and can generate deposits with volumes of up to

10^2 to 10^5 km^3 (Ross *et al*., 2005). Phreatomagmatic pyroclastic and hyaloclastic deposits, along with peperite, represent the full spectrum of products from magma–water interaction (Wohletz, 2002). External water is integral for formation, but magmatic volatiles are not precluded, and in the case of phreatomagmatic eruptions, may also play a role in fragmentation. Clast-forming processes during hydromagmatism include four primary mechanisms: magmatic explosivity, steam explosivity, cooling-contraction granulation, and dynamic stressing; all are dependent on the magma to water ratio (Wohletz, 1983; Kokelaar, 1986). Phreatomagmatic pyroclastic deposits are produced by the optimal fuel (magma) to coolant (water or sediment-laden water) mixture to generate explosivity (magma to pure water mass ratio of ~ 0.33: White, 1996), whereas hyaloclastic deposits are volumetrically dominated by water and peperite dominated by wet sediment (wet sediment to magma mass ratios > 1: Wohletz, 2002).

Hyaloclastic deposits are solely generated by quench fragmentation during magma–water interaction, and result from effusive magma contacting abundant water, in either marine or continental settings. Pillow lavas, pillow–palagonite breccias, and hyaloclastites are the most typical products of mafic magma quenching and spalling in a subaqueous environment.

Peperite deposits result from magma interaction with unconsolidated, water-bearing clastic deposits in shallow intrusions, subaqueous or surface environments (White *et al*., 2000; Skilling *et al*., 2002). Experimental and theoretical studies suggest that mechanisms of magma–water interaction and magma–sediment–water interaction may be similar (Kokelaar, 1986), and peperites rely on fluidization and vigorous injection and mixing of water-saturated sediments and lava (Kokelaar, 1982). Recognition of peperite indicates contemporaneity of sedimentation and volcanism (Busby-Spera and White, 1987). Given the ubiquity of environments that could generate peperite, there are relatively few documented examples in large igneous provinces. However, this may be a function of identification rather than absence. Even in the predominantly arid desert environment that the Paraná–Etendeka Large Igneous Province was emplaced into, peperites formed where pahoehoe lava flows interacted with wet lacustrine silts and clays, which collected in low-lying topography of lava flow surfaces (Waichel *et al*., 2007).

1.2.2 Reworked volcaniclastic and epiclastic deposits

Reworked volcaniclastic deposits are composed of particles sourced from primary volcaniclastic deposits that have been redeposited by surface processes (wind, water, ice, gravity) either concurrent with eruption or after a period of immobility. In reworked volcaniclastic deposits, the volcanic processes that create the particles are not the same as those that transport the particles to their final depositional site. *Epiclastic* (or volcanogenic) sediments are formed from weathering and erosion of volcanic rocks, including previously lithified volcaniclastic rocks. Lithification can occur as part of volcanic emplacement (e.g. welding) or as a secondary process of cementation or compaction.

1.3 Spatial and temporal occurrence of mafic volcaniclastic deposits

One of the strengths of mafic volcaniclastic deposits is in the record they preserve of tectono-volcanic facies and province architecture evolution over time. The recognition that pre-volcanic kilometer-scale doming is not an unequivocal feature of large igneous provinces, coupled with recent numerical modeling indicating that large igneous province emplacement can generate substantial and complex patterns of pre- and syn-volcanic subsidence and/or uplift (+/– hundreds to thousands of meters: e.g. Czamanske *et al.*, 1998; Ukstins Peate and Elkins-Tanton, 2009; Elkins-Tanton and Ukstins Peate, 2010; Sobolev *et al.*, 2011), suggests that tectonic evolution may be a significant factor controlling the broad-scale distribution of these deposits. Provinces that contain significant volcaniclastics include the middle-Jurassic Kirkpatrick section of the Ferrar flood basalts in Antarctica, with tuff-breccias up to 400 m thick (Elliot and Flemming, 2008); the Kachchh region in the northwest of the Deccan flood basalts, with lapilli and lithic blocks (Kshirsagar *et al.*, 2011); and the Karoo (McClintock *et al.*, 2008). Here, we briefly describe three additional significant examples: the North Atlantic, the Emeishan and the Siberian.

1.3.1 East Greenland, North Atlantic Igneous Province

Detailed volcanostratigraphic studies in East Greenland illustrate a cyclicity of phreatomagmatism and subsidence during the initial stages of province emplacement, recording three phases of subaqueous to subaerial volcanism, with progressively less hydrovolcanic influence (and inferred downdropping) in each cycle (Figure 1.1; Ukstins Peate *et al.*, 2003). Initiation of volcanism is represented by subaerially deposited phreatomagmatic lapilli-tuffs with accretionary lapilli and abundant quartz and feldspar grains (~ 50%) sourced from underlying upper shoreface sandstones and mid-Paleocene fluvial clastic deposits (Larsen *et al.*, 2003). Overlying these are a series of hyaloclastites and pillow lavas, some forming foreset-bedded units > 300 m thick (Nielsen *et al.*, 1981), suggesting that water depth increased dramatically with the initiation of basaltic volcanism. Hydromagmatic deposits transition to 500 m of compound lava flows, and the entire volcanic succession forms a shield-like structure with a diameter of ~ 40 km (Ukstins Peate *et al.*, 2003). This is, in turn, overlain by a sequence of mafic volcaniclastic deposits

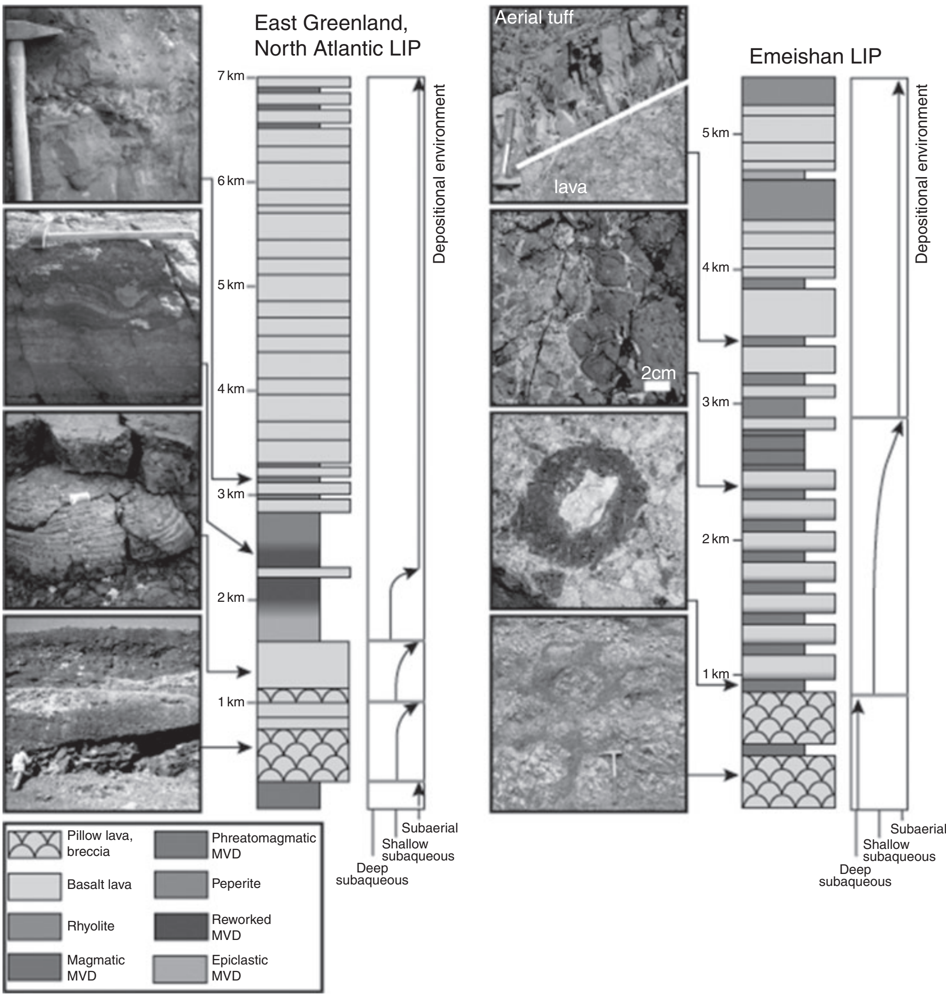

Figure 1.1 Generalized composite stratigraphy of East Greenland, North Atlantic, and Emeishan, China, large igneous provinces (LIPs). While package thicknesses are representative, individual unit thicknesses are schematic, and *x*-axis widths emphasize distinctions in rock types. MVD = mafic volcaniclastic deposit. Intrusive rocks are not shown. East Greenland based on Ukstins Peate *et al*., (2003), and Emeishan based on Ukstins Peate and Bryan (2008, 2009) and Zhu *et al*. (2014). A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.

that preserve a lateral facies change from primary units – including vent sites – in the northeast to reworked volcaniclastic and epiclastic deposits to the southwest.

Primary deposits consist of *c*. 300 m of: fallout tuffs; surge deposits with abundant accretionary and armored lapilli; bomb beds; and scoria deposits with three-dimensional cone morphology (Ukstins Peate *et al*., 2003). These transition to 1000 m of reworked and epiclastic deposits of siltstone and sandstone containing up to 80% volcanic material: altered basaltic glass (tachylite, palagonite), clinopyroxene crystals, basaltic lava clasts, and pyroclastic lithic fragments, with minor intercalated tuffs. Correlation of reworked and epiclastic deposits highlight the development of regional syn-volcanic basins with cumulative thicknesses > 3000 m (Larsen *et al.*, 2003; Passey and Bell, 2007).

Overlying this is the main phase of flood basalt lavas, with a few thin magmatic tuffs containing Pele's tears and glass shards, concentrated in the lowermost part of the sequence (Ukstins Peate *et al.*, 2003). A final transition from effusive flood lava to highly explosive basaltic phreato-Plinian eruptions occurs in the uppermost sequence, when active lithospheric rifting and subsidence resulted in flooding of the nascent North Atlantic Rift proto-ocean basin (Larsen *et al.*, 2003; Jolley and Widdowson, 2005).

1.3.2 Emeishan large igneous province

Research on the Emeishan large igneous province highlights the utility of mafic volcaniclastic deposits in addressing questions of large-scale tectonic evolution during flood volcanism. A thick and laterally extensive wedge of clastic deposits (170 m thick, 30 to 80 km wide, 400 km long), emplaced near the base of the Emeishan lavas, was initially interpreted as an alluvial fan conglomerate, and was attributed to pre-volcanic, kilometer-scale domal uplift and erosion of underlying carbonate (He *et al.*, 2003). The ubiquity of dense to poorly vesicular blocky sideromelane, pyroclastic textures such as accretionary lapilli, volcanic bombs with bomb sags, and ductile deformation of mafic clasts unequivocally identifies these rocks as phreatomagmatic lapilli-tuffs and tuff-breccias, and likely represent near-vent deposits (Figure 1.1; Ukstins Peate and Bryan, 2008, 2009). The abundance of marine limestone lithic fragments – some containing mafic clasts themselves – and the presence of unbound shelly fossil material, strongly suggests that active carbonate deposition was contemporaneous with volcanism, and that these units were emplaced near sea level (Ukstins Peate and Bryan, 2008, 2009).

Continuing work, focusing on the zone of inferred maximum uplift, has identified a protracted and extensive record of hyaloclastic and phreatomagmatic volcanism (Figure 1.1). Microfossil studies show nascent carbonate platform collapse immediately prior to initiation of volcanism (> 200 m: Sun *et al.*, 2010). The first phase of volcanism is laterally heterogeneous but dominated by phreatomagmatic and subaqueous volcanism. Eruptions through shallow-water carbonates generated thin subaqueous hyaloclastites and subaerial tuff deposits near Daiquo (Ukstins Peate and Bryan, 2008), whereas in the Dali area (the core of inferred maximum uplift), volcanism initiated with a succession (*c*. 750 m) of pillow lavas and hyaloclastites with intercalated marine limestones and submarine tuffs (Zhu *et al*., 2014). Eruptions transitioned to phreatomagmatic lapilli-tuffs and tuff-breccias intercalated with basaltic lava sheet flows displaying peperitic basal zones and carbonates (*c*. 2000 m: Zhu *et al*., 2014), suggesting a very shallow subaqueous to subaerial depositional environment. This is overlain by $>$ 2500 m of thick a'a and pahoehoe basalts and rhyolite lavas, intercalated with minor, thin (~ 1 m), oxidized basaltic tuffs dominated by glassy vesicular ash shards (Zhu *et al*., 2014), likely derived from subaerial phreatomagmatic to magmatic pyroclastic eruptions.

1.3.3 Siberian flood basalts

The Siberian flood basalts contain intercalated volcaniclastics to varying extent throughout the most studied sections of that province, for example in Noril'sk (e.g. Fedorenko *et al*., 1996). A vast literature on the Siberian province exists, but here we focus on the understudied volcaniclastics and present some new results. The most significant volcaniclastics in the Siberian province are the thick, primarily phreatomagmatic deposits underlying the lavas. In the northeast and northwest sections the majority of the basal volcaniclastics are less than 30 m in thickness, and are sometimes absent (Figure 1.2). In the central, eastern and southern regions, however, the volcaniclastics are voluminously present in largely massive, featureless outcrops.

Along almost 200 km of the Angara River north of Ust Ilim'sk, all the river cliffs consist of volcaniclastics, and visible outcrops are as much as 250 m thick, with erosional upper and unexposed basal contacts (Naumov and Ankudimova, 1995). Volcaniclastic units are massive, unbedded and sediment-rich, though near the Kata River there is local bedding and accretionary lapilli. Some outcrops have lithic blocks of underlying sedimentary strata; peperites and sediment dikes indicate an active aquifer and driving force for eruption from depth. Notably absent are pillow basalts and hyaloclastites.

Similar deposits occur along 200 km of the Nizhnaya Tunguska River, stretching east–west past the middle Siberian town of Tura. In Tura, drill cores indicate at least 500 m of tuffs transitioning to overlying effusive lavas (Drenov, 1985). These drill cores demonstrate that voluminous phreatomagmatism immediately preceded the main stage of effusive lava emplacement.

1.4 Evidence for volatile loads, temperatures and plume heights

Chemicals released by volcanism will have the greatest effect on global climate, both in terms of destructive chemical reactions and longevity, if they reach the

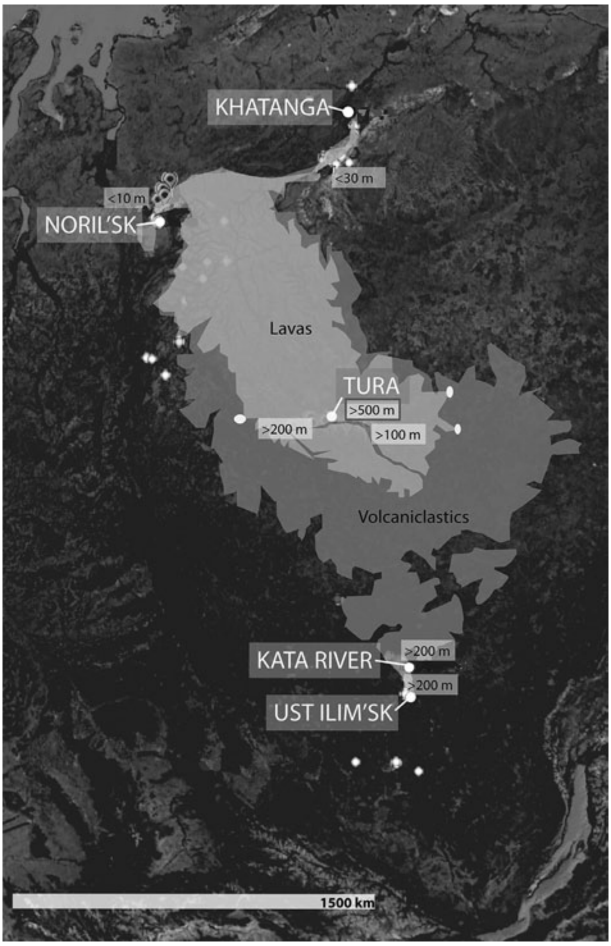

Figure 1.2 Map of the Siberian flood basalts showing the approximate location of uppermost bedrock lavas and underlying volcaniclastics (after Svensen *et al.*, 2009). Sample locations from Elkins-Tanton's field trips are shown as scattered dots. Thicknesses indicate outcrops seen on these trips, with the exception of the Tura dill core (> 500 m), from Drenov (1985). The samples north of Ust Ulim'sk are on the Angara River, and those east and west of Tura are on the Nizhnaya Tungusska River.

stratosphere. Material is rapidly washed from the troposphere by rain. Basaltic magmas are generally less gas-rich (with the possible exception of sulfur) and less viscous than more silicic eruptions, and are generally less explosive without interactions with external volatiles. However, basaltic Hawaiian-style fire fountains are capable of injecting material into the stratosphere (Stothers *et al.*, 1986; Woods, 1993). This is corroborated by the Laki eruption (Iceland 1783–1784, Thordarson *et al.*, 1996). Laki was largely effusive, but it had significant