1

Introduction, definition, and general characteristics

1.1 Introduction

Earth history is punctuated by numerous periods of magmatic activity during which especially large volumes of mainly mafic magma were emplaced in a short duration pulse or pulses and are not linked to normal plate-boundary processes. These Large Igneous Provinces (LIPs) can occur in either continental or oceanic settings (or a mixture of the two). Magma volumes can range from < 0.1 Mkm^3 to 80 Mkm^3 and event duration ranges from a single pulse as short as 0.5 Ma to multiple pulses extending over tens of millions of years. Huge silicic provinces can be associated with LIP events as can carbonatites and kimberlites. LIPs are notable for their association with global or regional environmental changes including extinction events, regional topographic changes including domal uplift, breakup or attempted breakup of continents. They have an association with a wide range of ore deposit types, and implications for the oil/gas industry and aquifer flow. Various origins are considered but evidence favors mantle-plume involvement for many LIPs. In this book I provide an overview of all aspects of LIPs starting with the history of the term and a review of definitions.

1.1.1 History of the term

The term "Large Igneous Province" was initially proposed by Coffin and Eldholm (1991, 1992, 1993a, 1993b, 1994) to identify a variety of mafic igneous provinces with areal extents > 0.1 Mkm^2 that represented "massive crustal emplacements of predominantly mafic (Mg- and Fe-rich) extrusive and intrusive rock, and originated via processes other than 'normal' seafloor spreading." The initial database upon which the term LIP was defined, relied almost exclusively on the relatively well-preserved Mesozoic and Cenozoic record of continental flood-basalt provinces, volcanic passive margins, and similar large-volume oceanic magmatism of intraplate origin such as oceanic plateaus, submarine ridges, seamount groups, and ocean-basin flood basalts (Coffin and Eldholm, 1994, 2005). These types of provinces were divided into those that represented massive transient basaltic volcanism occurring over a few

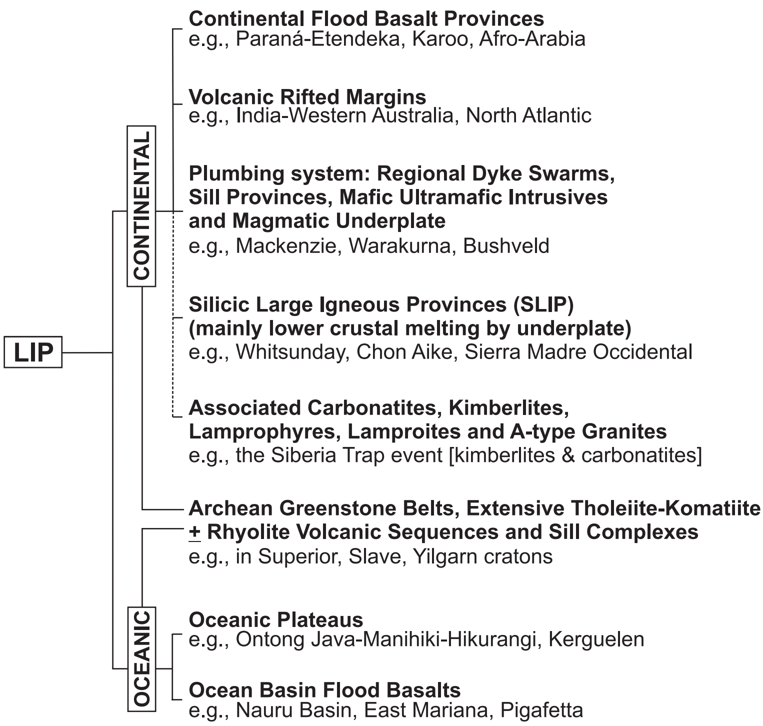

Figure 1.1 Classification of LIPs, based on the initial work of Coffin and Eldholm (1994), but modified to incorporate recent advances in the recognition of ancient LIPs and SLIPs (Bryan and Ernst, 2008). Examples of each type of LIP are given. Modified after Bryan and Ernst (2008) and Ernst and Bell (2010).With kind permission from Springer Science and Business Media.

million years (e.g. continental flood-basalt provinces, volcanic rifted margins, oceanic plateaus, and ocean basin flood basalts) and those representing persistent basaltic volcanism lasting tens to hundreds of million years (e.g. seamount groups, submarine ridges, and areas of anomalous seafloor spreading; Coffin and Eldholm, 2001). The formative work of Coffin and Eldholm, under the umbrella of the term LIP, aided in uniting previously separate research areas. This was particularly significant for linking the then newly recognized oceanic record of anomalous intraplate magmatism with that of the longer-understood continental flood-basalt record.

Since this first categorization of LIPs by Coffin and Eldholm, substantial progress has been made in extending the LIP record back to the Paleozoic, Proterozoic, and Archean (Ernst and Buchan, 1997, 2001, 2003; Tomlinson and Condie, 2001; Arndt *et al*., 2001; Isley and Abbott, 2002; Fig. 1.1). For many ancient LIPs, where much or all of the volcanic components of the LIP have been lost to erosion, definition has been based on the observed areal extent and inferred volume of intrusive rock (e.g. giant continental dyke swarms, sills, and layered intrusions) that form the exposed plumbing system to LIPs. Also, subsequent usage of the LIP term (e.g. Bryan and Ernst, 2008) focused on the transient LIPs of Coffin and Eldholm (1994), which allows the LIP definition to be reserved for those magmatic events with particularly significant regional to global effects. This approach excludes seamount chains and submarine ridges from the definition of LIPs (see discussion in Chapter 2).

Finally, it has also been recognized that LIPs can be directly linked with massive crustal emplacements of predominantly silicic (> 65 wt% SiO_2) extrusive and intrusive rocks (Chapter 8), with carbonatites, and in some cases with kimberlites (Chapter 9).

1.1.2 LIP definition

The increasing realization that LIPs and their associations are more varied in character, age, and composition than first defined prompted others (e.g. Sheth, 2007; Bryan and Ernst, 2008) to revise and broaden the original definition of LIP. Some alternative definitions are included in Table 1.1.

In this book I use the definition:

> A LIP is a mainly mafic (+ultramafic) magmatic province with areal extent > 0.1 Mkm^2 and igneous volume > 0.1 Mkm^3, that has intraplate characteristics, and is emplaced in a short duration pulse or multiple pulses (less than 1–5 Ma) with a maximum duration of < *c*. 50 Ma. Silicic magmatism (including that of LIP scale, termed Silicic LIPs (SLIPs)) and also carbonatites and kimberlites may be associated.

This definition follows closely that of Bryan and Ernst (2008) (see Table 1.1) with the modification that LIPs sensu stricto are considered to be of mafic (–ultramafic) composition. The related magmatic provinces of dominantly silicic composition are considered a separate but related class of magmatism called SLIPs.

It is important to also recognize LIP "fragments/remnants" (Ernst, 2007a). These are magmatic units which are small (sub-LIP scale), but are thought to belong to a LIP event and to have been reduced in size by erosion or tectonic fragmentation. Such units have essential characteristics which indicate membership in a larger-size event (see Section 2.5). For instance, dolerite dykes (regardless of their preserved length or scale of associated swarm) with an average width of > 10 m are likely to belong to a LIP.

Note, that in this book I will preferentially use the term dolerite rather than the essentially synonymous diabase, except where diabase is part of a formal name.

1.1.3 Importance of LIPs

LIPs are important for testing plume and non-plume models for the generation of LIPs (Chapter 15), as precise time markers for stratigraphic correlations,

Table 1.1 *Some definitions of Large Igneous Provinces*

- "Massive crustal emplacements of predominantly mafic (Mg- and Fe-rich) extrusive and intrusive rock, and originated via processes other than 'normal' seafloor spreading" (Coffin and Eldholm, 1994).
- LIPs "record periods when the outward transfer of material and energy from the Earth's interior operated in a *significantly different mode* than at present" (Mahoney and Coffin, 1997b, p. ix).
- Mainly mafic magma production of at least one million km^3 in less than 1 million years (K. Burke, pers. comm. 2004).
- Such events also constitute a "Pulse of the Earth" (Bleeker, 2004) in the sense of being major magmatic events that are tightly linked to many other aspects of Earth geological history.
- LIP should be used in its broadest sense to designate any igneous provinces with outcrop areas $\geq$ 50,000 km^2, regardless of composition, tectonic setting, or emplacement mechanism. Large volcanic provinces would be distinguished from large plutonic provinces and each would be further subdivided on the basis of composition (Sheth, 2007).
- "The products of transient large-scale magmatic processes 'rooted' in the Earth's mantle that are not predicted by plate tectonics" (Halls *et al*., 2008).
- "Magmatic provinces with areal extents >0.1 Mkm^2, igneous volumes > 0.1 Mkm^3 and maximum lifespans of ~50 Myr that have intraplate tectonic settings or geochemical affinities, and are characterised by igneous pulse(s) of short duration (~1–5 Myr), during which a large proportion (> 75%) of the total igneous volume has been emplaced" (Bryan and Ernst, 2008).
- See also discussion in Cañón-Tapia (2010).
- A LIP is a mainly mafic (+ultramafic) magmatic province with areal extent > 0.1 Mkm^2 and igneous volume > 0.1 Mkm^3, that has intraplate characteristics, and is emplaced in a short duration pulse or multiple pulses (less than 1–5 Ma) with a maximum duration of < *c*. 50 Ma. Silicic magmatism (including that of LIP scale, termed Silicic LIPs (SLIPs)) and also carbonatites and kimberlites may be associated.

as an aid in paleocontinental reconstruction (Chapter 11), as the hosts of major Ni–Cu–platinum-group-element deposits and other metal commodities (Chapter 16). They are also useful as a potential targetting tool in exploration for diamondiferous kimberlites (Chapters 9 and 15), for rare-earth deposits in associated carbonatites (Chapters 9 and 16), and also for hydrocarbon (oil and gas) and water (aquifer) resources (Chapter 16). In addition, they may be helpful in studying climatic effects (Chapter 14) and regional uplift (Chapter 11). Emplacement of a LIP and the onset of breakup (Chapter 12) may also change the local and global plate stress framework and be associated with the initiation of arcs elsewhere in the world (Chapter 13).

1.2 Overview of LIP style through time

Below is provided an overview of the styles of LIPs through time. More detail on each is provided in later chapters.

1.2.1 Mesozoic–Cenozoic LIPs

Most research on LIPs has focused on the dramatic flood basalts (Fig. 1.2) which characterize Mesozoic–Cenozoic events, both continental flood basalts (Chapter 3) and the flood basalts within ocean basins (oceanic plateaus and ocean-basin flood basalts) (Chapter 4). These parts of the LIP record are generally well preserved and have been critical to development of many key concepts for LIPs, most importantly their large size and short duration (or short-duration pulses).

The short duration of emplacement is evident from the main stage of flood-basalt magmatism, which consists of monotonous sequences up to several kilometers thick of large tabular flow units and that commonly lack any significant interlayered sediments; high-precision dating confirms emplacement of the flood basalts in times of 1–5 Ma (Courtillot and Renne, 2003; Jerram and Widdowson, 2005).

Continental flood basalts are dominately mafic (tholeiitic) with minor ultramafic (picritic) and transitional-alkaline components lower in the sequence; silicic magmatism becomes increasingly more significant in the higher levels of the sequence (Chapter 3). Bimodal magmatism is associated with LIP-related rifted margins. Oceanic plateaus and ocean basin flood basalts have variable mantle sources, and continental flood basalts represent the same sublithospheric mantle sources with the added aspect of interaction with lithospheric mantle and crust (e.g. Hofmann, 1997; Condie, 2003: Hawkesworth and Scherstén, 2007; Kerr and Mahoney, 2007).

As mentioned above, the flood basalts of Mesozoic and Cenozoic age (Fig. 1.2; Chapters 3 and 4) are typically the best preserved and best studied. In contrast, the pre-Mesozoic record is more deeply eroded and therefore LIPs of Paleozoic and Proterozoic age are typically recognized by flood-basalt remnants and exposed plumbing systems represented by giant dyke swarms, sill provinces, and layered intrusions (Fig. 1.3; Chapter 5). Oceanic LIPs are incompletely preserved during ocean closure and can occur as obducted deformed sequences in orogenic belts. In the Archean the most promising LIP candidates are greenstone belts containing tholeiite–komatiite sequences (Fig. 1.4; Chapter 6).

1.2.2 Paleozoic–Proterozoic LIPs

Pre-Mesozoic LIPs are more greatly affected by erosion, which largely removes their flood basalts and exposes their plumbing systems (Fig. 1.3; Chapter 5). Therefore, continental LIPs of Paleozoic and Proterozoic age typically consist of giant dyke swarms (defined as those > 300 km long), sill provinces, large layered intrusions, and

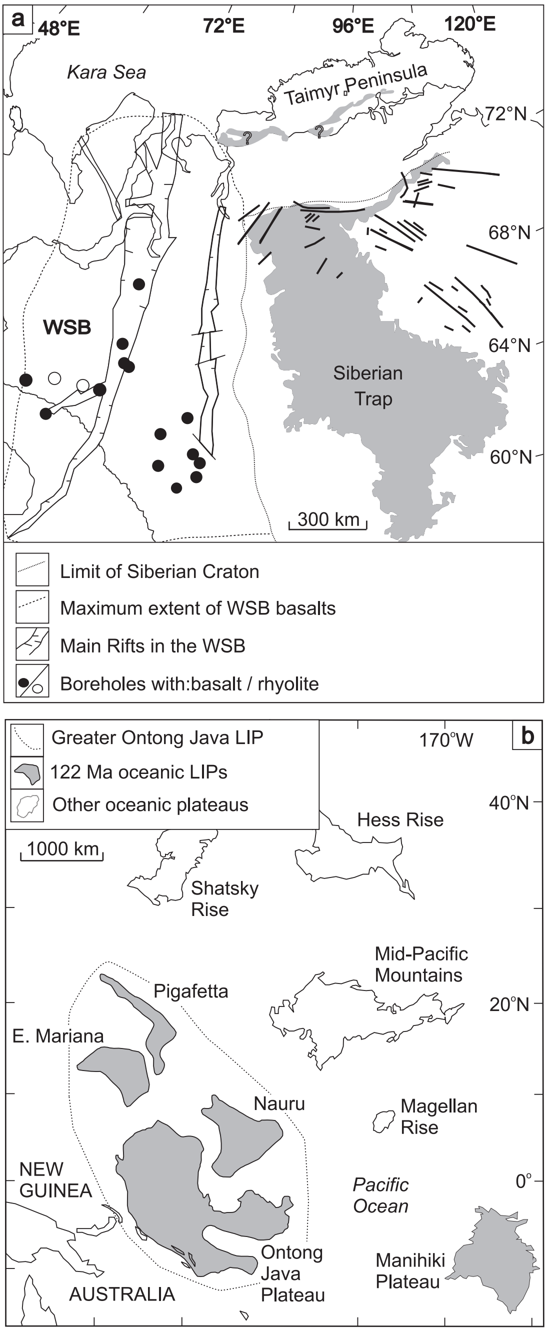

Figure 1.2 Examples of young Mesozoic–Cenozoic LIPs (a) 250 Ma Siberian Trap (b) Greater Ontong Java Plateau and other oceanic plateaus, Manihiki Plateau (122 Ma), Shatsky Rise (147 Ma), Magellan Rise (145 Ma), Mid-Pacific Mountains (*c*. 130–80 Ma), and Hess Rise (*c*. 110 and *c*. 100 Ma). WSB = West Siberian Basin. Modified from Ernst *et al*. (2005). With permission from Elsevier.

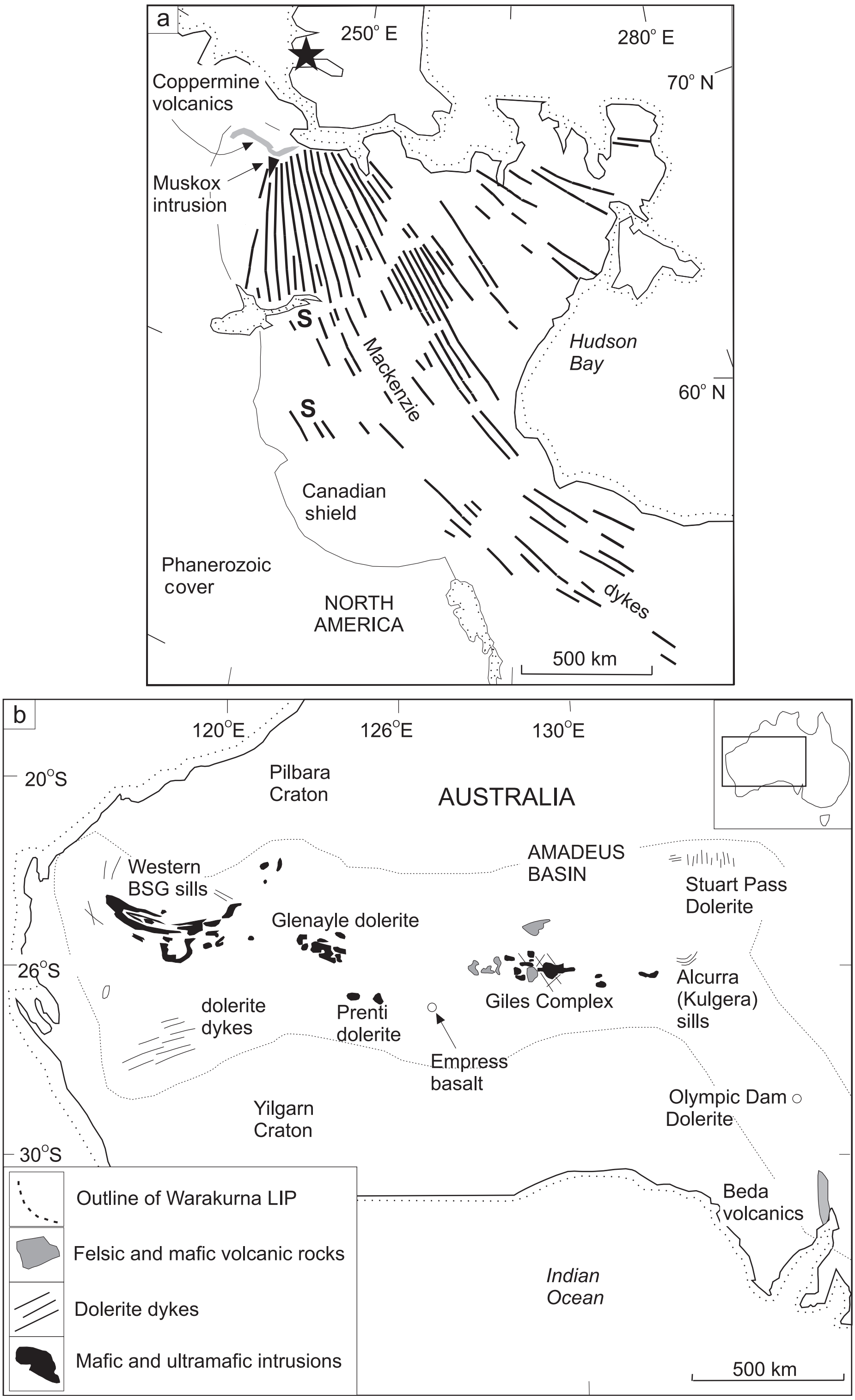

Figure 1.3 Examples of Proterozoic LIPs where erosion has exposed the 'plumbing' system of dykes, sills, and layered intrusion: (a) 1270 Ma Mackenzie event consisting of Mackenzie radiating dyke swarm, Muskox layered intrusion, and Coppermine volcanics, and widely distributed sill provinces ('S') and (b) 1070 Ma Warakurna LIP of central Australia. Modified from Ernst *et al*. (2005). With permission from Elsevier.

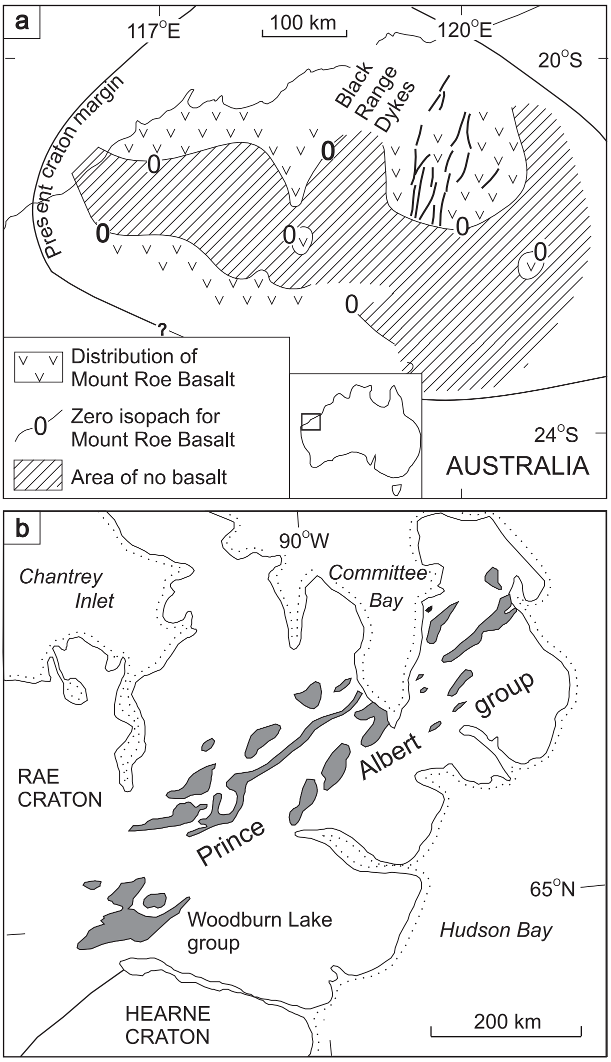

Figure 1.4 Examples of Archean LIPs (a) Part of Fortescue group of Pilbara craton, specifically showing the distribution of lowermost 2780 Ma Mount Roe sequence and associated Black Range feeder dykes (see also Section 6.2.4). (b) 2730–2700 Ma Prince Albert, Woodburn Lake, and Mary River groups in the Rae craton of northern Canada. Modified from Ernst *et al*. (2005). Original of part (a) after Thorne and Trendall (2001). With permission from Elsevier.

remnants of flood basalts (Ernst and Buchan, 1997, 2001a). Like their Mesozoic–Cenozoic flood-basalt equivalents, this class of intrusive-dominated LIPs has large areal extents and volumes, exhibits short-duration pulses, and has "intraplate" character, consistent with definition as a LIP (Coffin and Eldholm, 1994, 2001, 2005; Ernst *et al*., 2005; Bryan and Ernst, 2008; Bryan and Ferrari, 2013).

1.2.3 Archean LIPs

Erosional remnants of typical Archean flood-basalt provinces include the Fortescue sequence of the Pilbara craton in Australia (Fig. 1.4a) and the Ventersdorp sequence of the Kaapvaal craton in southern Africa (Chapter 6). However, most Archean volcanic rocks occur as deformed and fault-fragmented packages termed greenstone belts. One class of greenstone belts contains mafic to silicic igneous rocks with calc-alkaline geochemical signatures and is interpreted to be arc-related. The other major class of greenstone belts consists of tholeiite–komatiite sequences, which are the best candidates for being remnants of Archean LIPs (e.g. the Prince Albert and related greenstone belts of the Rae craton, North America; Fig. 1.4b). In terms of setting, these Archean LIPs include accreted oceanic plateaus and also those emplaced in a continental platform setting. More details on the Archean LIPs are provided in Chapter 6.

1.3 LIPs on other planets

Intraplate magmatism, including events of LIP scale, are present on other planets. Comparison of large-volume intraplate magmatism on other planets with those on Earth provides insights to the LIP record on Earth. In Chapter 7 I review the LIP analog record of Mars, Venus, the Moon, Mercury, and Io.

1.4 Global LIP barcode record of Earth

The terrestrial global LIP record can be expressed as a barcode diagram (Fig. 1.5). From the present day to about 180 Ma the record consists of both continental LIPs and oceanic LIPs and has a combined rate of about 1 per 10 Ma (Coffin and Eldholm, 2001; Ernst *et al*., 2005). From about 180 Ma to 2600 Ma the frequency of LIP production (mainly continental LIPs) is relatively constant back to 2.6 Ga, occurring with an average frequency of about 1 per 20 Ma (Chapter 11). Since most oceanic plateaus do not survive subduction and are difficult to recognize in pre-Mesozoic orogenic belts, the pre-Mesozoic record underestimates the LIP production. If one assumes that the frequency of oceanic LIP record observed in the Mesozoic–Cenozoic continues back in time, then average LIP production (including both continental and oceanic LIPs) back to the Archean may be closer to one event every 10 Ma. However, as noted by N. Dobretsov (personal communication, 2007), and discussed in Section 11.8, multiple independent LIPs can occur at the same time (plume clusters) and skew the average LIP production rate to smaller values. By his estimate the average continental LIP production is closer to 1 per 30 Ma, and so the combined oceanic and continental production would be closer to 1 per 15 Ma. A more detailed analysis of the LIP record through time is provided in Chapter 11, including the recognition of variations correlated to the supercontinent cycle.

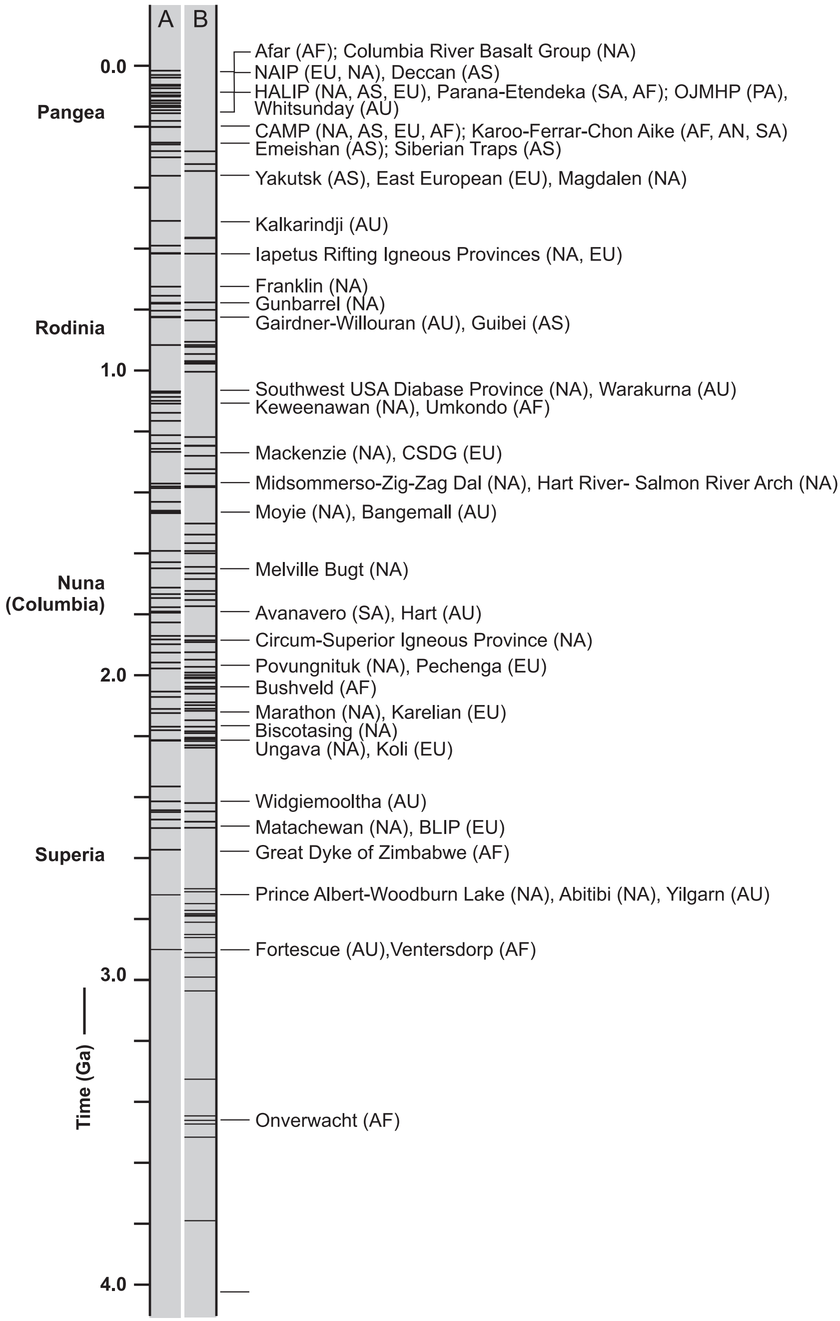

Figure 1.5 Global barcode for Earth. Column A contains events which satisfied the full criteria of Bryan and Ernst (2008) and herein and which are therefore LIPs sensu stricto. The Whitsunday and Chon Aike SLIPs are also shown. Column B contains events which are