THINKING ABOUT LIPS: A BRIEF HISTORY OF IDEAS IN LARGE IGNEOUS PROVINCE RESEARCH

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Abstract

Large igneous provinces (LIPs) are extraordinary igneous and tectonic events that have influenced the planet in profound ways, including the major turnovers in the history of life. The LIP concept, definitions, and terminology first nucleated in a 1990 workshop jointly arranged by Joint Oceanographic Institutions and U.S. Science Support Program, subsequently presented in a series of seminal papers by Millard F. Coffin and Olav Eldholm in the early 1990's. They combined existing data and information from continental flood basalts with the emerging geophysical understanding of oceanic plateaus and rifted continental margins. The new terminology had major implications within the geosciences and beyond. However, when investigating how geoscientists described and interpreted these vast provinces prior to the 1990’s, we are left with a series of questions. Who first realized that LIPs represent extraordinary events in the history of the Earth, what terminology was used, and why were geologists interested in this type of events? Here we discuss some of the key developments in LIP research, including mapping projects, expeditions, international programs, correlations across continents, and the history of the terminology. We focus our discussion on four cases, the Karoo LIP, the Siberian Traps, the North Atlantic Igneous Province, and the Ontong Java Plateau, comprising key examples of LIPs with long histories of study and exploration. We conclude that the past 150 years of LIP-related research and endeavor was largely driven by a need to understand fundamental aspects of Earth evolution, including continental drift, plate tectonic reconstructions, the origin of basalt, mantle processes and plumes, and the role of volcanism in driving mass extinctions and climatic changes.

1. Introduction

Large igneous provinces (LIPs) (Figure 1) were initially defined in the early 1990's as "massive crustal emplacement of predominantly mafic (Mg- and Fe-rich) extrusive and intrusive rock which originate via processes other than 'normal' seafloor spreading" (Coffin and Eldholm, 1992, 1994). There are currently no universally accepted definitions of a LIP, but they are predominantly mafic volcanic provinces that were emplaced in a short time period (1-5 m.y.) covering at least 100,000 km^2 with a volume of more than 100,000 km^3 (*cf.* Ernst, 2014). LIPs are often characterized by having an early onset phase followed by a main phase or acme of eruption and then a waning phase, though some examples (such as the North Atlantic Igneous Province, Ontong Java Plateau, and Kerguelen Plateau) can have more than one pulse (Tejada et al., 1996; Neal et al., 1997; Saunders et al., 1997; Duncan, 2002; Jerram and Widdowson 2005). They are mainly divided in oceanic plateaus (e.g., Kerguelen Plateau, and Ontong Java Plateau), flood basalts along volcanic rifted margins (e.g., the North Atlantic Igneous Province), and intra-continental flood basalt (e.g., Karoo-Ferrar LIP, Siberian Traps), all composed of intrusive and extrusive domains with key volcanic facies and associations (e.g. Jerram, 2002). In addition to the mafic dominated examples listed above, silicic rich provinces are also included in a revised LIP definition (e.g. Bryan et al., 2002). Other noted examples include large dyke and sill swarms, plutonic provinces, and kimberlites and carbonatites (see Bryan and Ernst, 2008; Ernst, 2014).

Coffin and Eldholm's (1992) original catalogue of LIPs was restricted to the past 250 m.y. and contained 11 continental flood basalt provinces, 23 oceanic plateaus, and 33 passive margins. Another 26 provinces were also included, comprising; ocean basin flood basalt, seamount chains, and submarine ridges. In 2014, the full catalogue of LIPs had increased to 211 (Ernst, 2014). The youngest LIP is the Columbia River LIP that erupted about 17 m.y. with a size of 240,000 km^2. The LIP record has also been extended to include Archean greenstone belts (e.g. Ernst and Buchan, 1997), and the oldest LIP in the catalogue is Dominion at 3 Ga (Ernst, 2014). The preservation of LIPs is strongly dependent on their age and subsequent geological history, and some of the older LIPs are only identified based on dike swarms, with liitle or no extrusive components preserved, and their inferred volumes are thus speculative. Note that LIPs with volumes in 1-10 M km^3 range are suggested to be classified as Major LIPs, and those with >10 Mkm^3 as Giant LIPs (*cf.* Ernst, 2014).

The age and duration of LIPs is also particularly challenging, as it is commonly difficult to obtain reliable ages in altered mafic rocks and, in many cases, only a few shallow borehole samples are available from the offshore sections of the provinces. One such example is the North Atlantic Igneous Province (NAIP), where significant basins containing intruded sills occur on the conjugate margins of Norwary/UK and Greenland (e.g. Svensen et al., 2010; Reynolds et al., 2016). Here, only a few of the sills have been sampled and dated from the ca. 75,000 km^2 of intruded sedimentary basins offshore Norway (Svensen et al., 2010), limited examples have been intersected in the UK margin, and none in the offshore Greenland margin (Reynolds et al., 2016), resulting in a vast area of un-sampled and a relatively un-known component of the NAIP. This is scenario is common place in LIPs associated with rifted margins as well as the oceanic LIPs. The total duration of LIP magmatism may be substantial (>5 m.y.) when the total time span of associated small-volume igneous complexes is included (e.g., Jourdan et al., 2005; Jerram and Widdowson 2005). In general, early dating projects concluded that LIP volcanism could last for tens of millions of years (e.g., Ficth and Miller, 1984), but recent improvements in geochronology, such as zircon U-Pb dating, has shown that in many cases the main phase/pulse of LIP activity can be very abrupt and may be shorter than 0.5 m.y. (e.g., Svensen et al., 2012; Blackburn et al., 2013; Burgess and Bowring, 2015). How the emplacement timescale and tempo varies between the different provinces is a key question that will help us understand the evolution of different types of LIPs, as well as the end member styles and association with the mantle anomalies that help form them (e.g., Svensen et al., 2017). As such, LIPs can provide valuable information about their interaction with the surface and atmosphere as well as a link to understanding timescales and processes within the mantle. The magma itself is emplaced as extrusive lavas, volcanogenic sediments, sheet intrusions, and plutons, with magma compositions often showing the full range from ultramafic to silicic, although mafic melts are usually the most common and most voluminous.

The Coffin and Eldholm (1992) paper that first introduced the LIP terminology to an international audience, has a reference list containing 126 entries. Of those, only 2 were published before 1970, including a paper by T.J. Wilson about Hawaii from 1963, and a paper by N. Den et al. (1969) about the north-west Pacific Basin. Thus the paper does not dwell on the earlier understanding of these provinces. Interestingly, the same statement applies to most of the published work on LIPs, including Ernst's (2014) recent 666 pages long book "Large Igneous Provinces". Furthermore, key works on the historical aspects of the developments of geological research, for instance David R. Oldroyd's *Thinking about the Earth* (1996) and Davis Young's *Mind over Magma* (2003) do not shed much light on historical aspects of LIP-related research.

In this contribution we aim at bridging the gap between the modern understanding of LIPs, as developed by Coffin and Eldholm and expanded on in recent studies, and the relevant geological research done previously (the past 150 years), which helped lay the foundations for the concept of LIPs. Here we aim to 1) investigate how LIPs were understood prior to the development of the modern terminology, 2) discuss who first realized that LIPs represent something extraordinary both in size and duration, and 3) show how the terminology and the motivation for LIP research have changed throughout the 20th century. We stress that our intention is not to present a full in-depth review of these topics, but moreover to discuss some of the main ideas and their origin.

2. A history of LIP-related terminology

As emphasized later in this contribution, the early works of Coffin and Eldholm combined the new geophysical offshore data (in particular from oceanic plateaus and volcanic rifted margins) with the existing geological knowledge about the onshore components of continental flood basalts. Thus in order to further understand the history and development of LIP terminology, we first investigate how the terminology related to continental flood basalts developed. The origin of this terminology has not, as far as we know, been widely discussed in the scientific literature. Two notable exceptions are the Basaltic Volcanism Study Project (1981) and a brief chapter on *Magma floods, flood basalts, and surge tectonics* in a book called Surge Tectonics by A.A. Meyerhoff et al. (1996). The Basaltic Volcanism Study Project had a particularly strong influences on Millard Coffin's thinking in developing the LIP concept and framework (Coffin, Pers. Comm. October 2018). The Meyerhoff (1996) contribution is seldom acknowledged as Meyerhoff never embraced plate tectonics and had his own alternative ideas, largely within a framework of the contracting Earth hypothesis ("A contracting Earth is an extremely attractive model for tectonic processes…", Meyerhoff et al. 1996, p. 4), and the so-called surge tectonics. Furthermore, Meyerhoff et al. (1996) did not mention the LIP terminology of Coffin and Eldholm, but rather suggest that "flood basalts" should be replaced by a new term called "magma floods" in order to encompass sills, pipes, and lava of more silicic composition than basalt (ibid, p. 253). Although this specific suggestion has been largely ignored by the scientific community, and despite the shortcomings of the Meyerhoff et al. (1996) approach, their brief overview of continental flood basalt terminology, in particular Archibald Geikie's notion of plateau basalts, is a good starting point for our discussions in the present contribution.

2.1 Geikie's lava plateau

Archibald Geikie (Director of the Geological Survey for Scotland 1867-1881) grouped volcanoes in three types based on their associated deposits (Geikie, 1903). The first is the classical single volcano, the "Vesuvian type", where all the ejected material is coming from one or a few central vents. A second type is characterized by vents, pipes, and volcanic breccias, with the pipes in Massif Central in France as the prime example (the "Puy type") – often without notable lava flows. The third type is what Geikie called the "Plateau type". This group consists of stacked lavas and tuffs, often covering large areas, erupted from fissures rather than central volcanoes (Geikie, 1903, p. 763). Geikie stressed that the plateau lavas were erupted in subaerial settings, chiefly of basaltic composition, but andesites were also common (Ibid). One of the challenges with Geikie's terminology was the lack of criteria to distinguish between plateaus formed during regional fissure eruptions versus truly large-scale floods of basalts. George W. Tyrrell, outlined below, offered a simple solution in a short paper from 1932, which was to have a profound impact on the terminology used.

2.2 Tyrrell and flood basalts

In a study of Miocene basalts in Patagonia, Argentina, Tyrrell (1932) raised the question if those basalts should be interpreted as originating from *flood eruptions* or *plateau eruptions*. He restricted the use of "flood eruptions" and "flood basalts" in the following way:

> "The writer uses these terms for enormous regions of lava flows, overwhelmingly composed of basalt, such as those of the Deccan, the Columbia region of the Northwestern United States, and of the North Atlantic, in which the topographic features of the overflowed region have been swamped by lava as by a flood." (Tyrrell, 1932, p. 382).

Thus “floods” should be restricted to the very largest regions and not to localized eruption centres even though the results may be stacked lava flows (i.e., plateaus). A useful criterion to help distinguish between the two types is by their petrography and geochemistry. Tyrrell argued that flood basalts are often oversaturated with respect to silica whereas plateau basalts are undersaturated. This moreover applies to the subvolcanic domain as well: “The hypabyssal representatives of flood basalts are great sill swarms and dike swarms consisting mainly of quartz-dolerite…”. How these floods of basalts formed however, needed “much further study”. The usage of “flood basalts” was quickly adapted by Sobolev (1936, p. 8) for the Siberian Traps, specifically referring to the terminological clarifications of Tyrrell (1932).

2.3 Petrographical provinces

One of the most important developments that preceded the idea of “continental flood basalts” and LIPs is the so-called *petrographical province*. The idea was developed both by Vogelsang in 1872, and independently by Judd in 1886. J.W. Judds’ studies in the 1880’s were conducted on basalts from the British Tertiary province (e.g. Northern Ireland, Hebrides-Scotland) as well as the Faroe Islands, and Iceland (Young, 2003, p. 182). His argument was that volcanic rocks erupted at the same time in different areas may have originated from the same source and thus be genetically linked. The main criteria used, published in 1886, is related to “well-marked peculiarities in mineralogical composition and microscopical structure” (Young, 2003, p. 183). Examples of such provinces include the volcanic and intrusive rocks belonging to the Oslo Rift (as argued by W.C. Brögger in a series of papers in the late 1800’s) and the Italian volcanoes in Tuscany and Naples (Geikie, 1903, p. 707). It should be added that several other terms were used in the early 1900’s, such as “eruptive province” (“erupsjonsprovins”, in Norwegian; Barth, 1928) and “magma province”

("Magmaprovinzen", in German; von Wolff, 1914, p. 154), combining the existing lava plateau and petrographical province terminology. The "eruptive province" was used for basalts with a confined aerial extent (Barth, 1928).

As shown by Young (2003), the petrographical province terminology was developed further by Joseph P. Iddings and Alfred Harker to include geochemical aspects. Harker believed that igneous rocks across vast areas were part of the same province, for instance that the Azores, Canary, and Cape Verde Islands were part of the British Tertiary Province (Young, 2003, p. 187). Holmes (1918) further explored the idea of petrological provinces using new petrological and geochemical analysis of rocks from the British province as well as the Faroes, Iceland, Greenland and other Artic regions, and suggested that the Brito-Arctic province:

> "… may be described as a composite province, characterized throughout by basaltic rocks with a regional variation of composition, that are for the most part of Tertiary age, but which have forerunners of late Jurassic or Cretaceous age in the east, and modern representatives in Iceland.." (Holmes, 1918, p. 220).

Several decades after the concept of petrographical provinces was introduced, Alexander du Toit stated that "despite severe criticism Harker's broad generalizations of the existence of "*petrographical provinces*" still holds" (Du Toit, 1937, p. 46). As will be shown later, Du Toit used the concept as one of the backbones of the continental drift hypothesis – and interpreted the volcanic rocks on either side of the South Atlantic (Karoo and Paranã-Etendeka) to be part of the same petrographical province.

The concept of petrographic provinces became further explored when geochemical analysis of rocks started to become a routine undertaking. The notion of geochemical and petrological provinces was explored in the Karoo (e.g. Cox et al., 1967). In general the notion of chemical stratigraphy ‘chemostratigraphy’ is now widely used to help correlate regionally related volcanic sequences over the vast areal expression of LIPs as well and to help link the rifted segments of flood basalts across volcanic rifted margins (e.g. Peate, 1997, and references therein, as applied to the Paranã-Etendeka to pick one example). In many ways the chemostratigraphic study of LIPs is a natural progression from the original petrographic provinces idea.

2.4 Origin of the “traps” suffix

Several LIPs are named using the “traps” suffix (e.g., the Siberian Traps, the Deccan Traps), referring to the morphologies of outcrops of weathered and stacked lava flows (Figure 2). The origin of the term “traps” is often credited to Colonel W.H. Sykes in a paper from 1833 (e.g., Jain and Gupta, 2013). Sykes (1833) provides an account of the geology of the Deccan and describes his aim in the abstract as to:

> “…offer a few observations on the trap and other formations of India; the amazing extent of the former not appearing to have been appreciated hitherto in European geological works.”

It is not clear when reading Sykes (1833) where the “traps” name originally came from. In one passage however, he cites a description from Captain Frederick Dangerfield who visited the Malwa region in the 1820’s:

> “From the great difference in the resistance made to decomposition by these trap and amygdaloid beds, their exposed ends acquire a very distinct degree of inclination and character; the amygdaloid forming a great slope, and affording a loose mould covered

> with vegetation, the trap retaining its original perpendicularity and dark bareness." (Sykes, 1833, p. 414).

Thus we get an indication that “traps” has had a longer history than previously recognized. Regarding the literal meaning of the Deccan Traps, “Deccan” is derived from Sanscrit and means “south” (Jain and Gupta, 2013). “Traps” is used in the Germanic languages, where it means “staircases” in Norwegian (*trapper*), Swedish (*trapper*), Danish (*trapper*), German (*treppe*), and Dutch (*trap*) (all in plural).

The usage of “traps” can be further traced back to G. W. F. Hegel’s The Philosophy of Nature, first published as part of a book in 1817. In the translated edition to English from 1970, the term is used in the context of “…ascending series of trap rocks…” in a chapter inspired by Abraham Gottlob Werner’s geological thoughts (Hegel, 1970, p. 289). We may thus speculate that “traps” was part of the terminology taught to students in the mining academy in Freiberg where Werner lectured and trained generations of geologists from all over Europe from 1775 and onwards. Werner was the key proponent for the so-called *neptunist* approach to geological processes, where all rock types were interpreted as being deposited from seawater – including layers of basalt (sills and lavas) sandwiched between sedimentary rocks.

Some early 20th century geologists apparently used the “trap” suffix informally, for instance Alexander du Toit (1937), by always using quotation marks, but the term was eventually formalized, and is now synonymous with the classic examples of LIPs (e.g. Siberian Traps, Deccan Traps, etc.).

2.5 Volcanic rifted margins and volcanic basins

Volcanic rifted margins are passive continental margins characterized by seaward dipping reflectors (SDRs) and high-velocity (Vp 7.1-7.8 km/s) lower crustal bodies (LCBs) along the continent-ocean boundary (Eldholm et al., 1995). Commonly used alternative names are volcanic passive continental margins, volcanic passive margins, and volcanic margins. The terminology was initially used by Roberts et al. (1984a) as a title to the Deep Sea Drilling Project (DSDP) Leg 81 synthesis paper "Evolution of volcanic rifted margins: Synthesis of Leg 82 results on the western margin of Rockall Plateau", however the term was not clearly defined. Coffin and Eldholm (1991) later defined a volcanic passive margin as "a passive continental margin characterized by significant volcanism and uplift during continental breakup". The margin formation is commonly associated with extrusive and intrusive activity, and the lower crust is commonly characterized by high-velocity bodies (e.g., the Vøring Margin)." Similarly, Eldholm et al. (1995) described a volcanic margin as a passive margin with "Excessive, transient magmatic activity during the final breakup of the continents and during the initial period of sea floor spreading." Menzies et al. (2002) distinguish volcanic rifted margins characterized by "eruption of flood volcanism during pre-rift and/or syn-rift stages of continental breakup" with non-volcanic margins "that do not contain such a large amount of extrusive and/or intrusive igneous rock and that may exhibit unusual features, such as unroofed mantle periodotites".

Volcanic basin is a terminology used both for both 1) a sedimentary basin with a significant amount of primary intrusive and extrusive igneous rocks, and 2) basins filled entirely with extrusive rocks. Here, we use the first definition (1) following the Svensen et al. (2004) paper "Release of methane from a volcanic basin as a mechanism for initial Eocene global warming", and examples of such basins include the Vøring and Møre basins offshore Norway, the West of Shetland Basin, the Tunguska Basin in Russia, and the Karoo Basin in South Africa, to name but a few. Volcanic basins may be a part of a volcanic rifted margin (e.g. the Vøring Basin) or an intra-continental basin (e.g. the Tunguska and Karoo basins). The sedimentary component of these basins can be markedly intruded by sills, which in-turnare commonly associated with pipe-like hydrothermal vent complexes connecting the sills to the paleo-surface (e.g., Svensen et al., 2006). The basins themselves are also commonly associated with a large extrusive ‘flood basalt’ volcanic component, though this may have been mostly eroded off in some of the older examples, or never present in some cases.

2.6 Origin of the LIP terminology

The Large Igneous Province (LIP) terminology was conceived at the American Association of Petroleum Geologists (AAPG) convention in San Francisco in 1990 (Coffin, Pers. Comm. October 2018). Millard Coffin and Olav Eldholm had worked on the formation of voluminous volcanic complexes on separate sides of the world – Coffin on the Kerguelen Plateau in the Indian Ocean and Eldholm on the Vøring Margin offshore mid-Norway. During a coffee break they realized that they had many common scientific questions relating to the origin and processes forming these gigantic igneous constructions. The solution was to propose a LIP drilling workshop. The four-day workshop was organized in Woods Hole in November the same year (1990), and simply entitled "Large Igneous Provinces" (Coffin and Eldholm, 1991), jointly arranged by Joint Oceanographic Institutions and U.S. Science Support Program. The workshop attendance and contributor list is impressive, and with a few exceptions (e.g. Karl Hinz and Manik Talwani were invited, but were unable to attend) being a who's who list of volcanic margin and oceanic plateau researchers at that time. In hindsight, the workshop was highly successful, leading to the establishment of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Task Group and Commission, several drilling legs in the Indian Ocean and SE Greenland Margin in the 1990's and the establishment of a new, high-impact research topic, encompassing diverse themes such as deep Earth processes, igneous plumbing and eruption systems, and the causes of climate change and mass extinctions in deep time.

A task group on large-volume basaltic provinces, headed by Millard Coffin and John Mahoney, was formed by the IAVCEI in 1992 on the initiative of Keith Cox. The task group was subsequently upgraded to the Large Igneous Provinces Commission, which is currently headed by Richard Ernst (see www.largeigneousprovinces.org). The commission has been particularly important to bring together marine and terrestrial researchers previously working on different aspects of LIPs, and initiated the publication of a book on continental, oceanic, and planetary volcanism in the late 1990's (Mahoney and Coffin, 1997). The commission has subsequently published a "LIP of the Month" paper on its web-pages since 2004 (currently 178 articles) and a LIP record database from recent to Archean times.

3. Discovering and understanding the vast dimensions of LIPs

The three main sub-groups of LIPs are classified based on the emplacement environment: continental flood basalts in continental crust, oceanic plateaus in oceanic crust, and volcanic rifted margins along the continent-ocean transition. Though the difference between continental flood basalt to a volcanic rifted margin is often somewhat blurred, particularly where early studies concentrated on a particular segment of a much larger fragmented LIP. Many continental flood basalts were extensively studied from the late 1800s, and most of the original observations of LIPs are rooted in these early works, including the Siberian Traps, the Karoo, east and west Greenland, and the British Tertiary province. Here we discuss some of the key developments in the early understanding of these areas as well as aspects of how their emplacement histories have developed within the context of recent findings.

3.1 The Karoo LIP and a proposed Gondwana link

The Karoo LIP is one of the world's best exposed LIPs, with the whole Karoo Basin stratigraphy, sills, dikes, and lavas fully accessible. To use the words of Walker and Poldevaart's study of sills from the Karoo Basin (1949, p. 594), "it is in the main a sparsely populated area owing to low rainfall, but these same conditions which hinder agriculture have resulted in magnificent exposures of unweathered rock." Interestingly, large sections of great exposures in Antarctic, such as the Dry Valleys add further to the extent of the initially Africa-restricted Karoo (e.g. Jerram et al., 2010), and formed some of the geological observations by the early Antarctic explorationists (e.g. on the Scott 'Discovery' expedition, see Figure 3). Interestingly, the Antarctica part of the province, termed the Ferrar, lends its name from Hartley T. Ferrar, a geologist on Captain Scott's first Antarctic expedition. Outcrops of dolerites also are found in Australia (e.g. on Tasmania), which are also remnants of this vast province. The majority of the early detailed work, however, was concentrated within the Karoo basin and will form the main focus for this section.

Alexander L. du Toit was arguably one of the most important geologists in mapping and developing a physical understanding of the structure of a continental flood basalt province in the early 1900s. He joined the Geological Commission of the Cape of Good Hope in 1903 after graduating from the Royal Technical College in Glasgow followed by additional studies at the Royal College of Science in London (Gevers, 1950). Together with his older colleague A.W. Rogers, who had worked for the Commission since 1896, Du Toit mapped the Karoo sedimentary succession, the Drakensberg flood basalts and all the associated sills and dikes that crop out in the Cape of Good Hope province. In the period 1903-1920, and partly together with Rogers, Du Toit extended the surveys to include an area of about 400,000 km^2

across present day South Africa, Lesotho, and the Kalahari. Note that the volcanic rocks in South Africa were poorly studied prior to 1903, as the main focus of the geological surveying appears to have been targeted on identifying natural resources such as coal (e.g., Dunn, 1878).

The insight that Alexander du Toit developed in the period 1903-1920 was groundbreaking, and resulted in a series of detailed regional papers (e.g., Du Toit, 1904, 1912). Since sills and dikes are present in most areas in the Karoo Basin, they play a prominent role in most of his Karoo work. Du Toit summarized his work on sills and dikes in a study published in, where "hypabyssal" is the old term for "sub-volcanic". The paper begins by introducing his agenda: The Karoo dolerites ("injections") have received too little attention in the standard geological literature. The dolerites deserve better, he argues, because they represent the best exposed and largest example worldwide:

> "British writers instance the Tertiary injections in Scotland, American cite the Newark "traps", Canadian the Moyie sills, Australian those of Tasmania, but, until the magnitude of the Brazilian equivalent becomes better known, it is probably not realised that the finest, best exposed and, probably, the greatest of its kind is afforded by the subject of this paper." (Du Toit, 1920)

Note that the Newark traps and Brazilian flood basalts are part of the Central Atlantic Magmatic Province (CAMP), see for example Faust (1975). One of the important aspects Du Toit wrote about was the relationship between sills, dikes, lavas, and explosion pipes. Du Toit (1920) regarded the subvolcanic and the volcanic domains as intimately related as opposed to earlier work. The extrusive phase pre-dated the sills, he argued, but without any significant breaks in time. Figure 4 shows Du Toit's schematic view of the Karoo stratigraphy. The figure includes planar sills and so-called "inwardly inclined ring-shaped sheets", currently known as saucer-shaped sills (e.g., Chevallier and Woodford, 1999; Malthe-Sørenssen et al., 2004). Note that the same conceptual way of interpreting the Karoo stratigraphy, showing the basin sedimentary rocks intersected by the sub-volcanic system, is still widely used (e.g., Chevallier and Woodford, 1999).

Du Toit argued that the entire volcanic system in the Karoo was fed through the basement via thin dikes, not by a massive fissure in the centre of the basin followed by lateral magma emplacement as argued by Du Toit's former colleague Ernest H.L. Schwarz (Du Toit, 1920, p. 34). The abundant phreatic pipes, with and without igneous fragments and facies, were believed to have formed when dikes interacted with groundwater – or exsolved magmatic volatiles. The work related to formation of pipes in the Karoo Basin was continued by Gevers (1928), focusing on outcrops and mapping near Molteno, but were to some extent neglected until the 2000s. The pipes are now interpreted to have played a key role as gas transport channels between contact metamorphic sedimentary rocks and the Jurassic atmosphere (e.g., Svensen et al., 2006, 2007, 2015).

Alexander du Toit realized that the Karoo LIP was both exceptionally well exposed and unusually large. In 1937 he published a reconstruction of the distribution of "late Triassic" volcanic rocks and sills in South America, Africa, Antarctica, and Tasmania. This is probably the first compilation of the continent-scale outcrops of LIPs (Figure 5), including the current Karoo-Ferrar LIP and the Paranã-Etendeka LIP. Based on his large-scale mapping of the extent and thicknesses of sills, du Toit estimated the volume of sills in the Karoo Basin to "somewhere between 50,000 and 100,000 cubic miles" after correcting for erosion (Du Toit, 1920, p. 35). This equals 208,000-417,000 km^3 and is close to modern borehole-based estimates (Svensen et al., 2012; Svensen et al., 2015). Alexander du Toit stressed the importance of the sills and the vastness of the volcanic province in South Africa throughout his career. In his book *The geology of South Africa*, published in three editions between 1926 and 1953 (the latter posthumously), he linked outcrops of volcanic rocks in the whole of southern Africa, including localities near Victoria Falls some 800 kilometers north of Johannesburg, to the Karoo province. Du Toit stated that “the area being so vast – there can be no doubt as to the hugeness of the several tracts over which the erupted matter was locally spread.” (Du Toit, 1926, p. 426).

Research on the Karoo LIP, in particular the petrological aspects of the sills, was followed up by several papers by Walker and Poldevaart during the 1940’s (e.g., Walker and Poldevaart, 1949). As we will discuss later, a new interest in the Karoo LIP developed in the 1970’s following the plate tectonic revolution and new international research projects targeted at understanding mantle processes and the sources of basalt.

3.2 The Siberian Traps, realizing the Russian giant

The Siberian Traps were discovered during the expedition of Alexander Lavrentievich Chekanovskyi (formerly known as Aleksander Piotr Czekanowski), a Polish geologist exiled to Siberia by the Russian authorities for his participation in the Polish-Lithuanian Commonwealth January Uprising in 1863. The Russian Geographical Society instructed him to conduct geological investigations in the Irkutsk region between 1869 and 1871. Chekanovskyi gathered the first reliable information about the geology of the Nizhnyaya (Lower) Tunguska area (in 1873), and the lower parts of Lena and Olenek Rivers (in 1874-1875). Among his findings were coal and graphite deposits along the Nizhnyaya Tunguska River. But there was more. In Chekanovskyi’s expedition diaries (Figure 6), published in 1896 (Chekanovskyi, 1896), he wrote:

> “The best results of this geological study are as follows: the discovery of previously unknown area of igneous rocks of so large extended that it exceeds the size of any other of its kind. These are the traps that occur along the Nizhnyaya Tunguska River

> and from it to the north to Olenek River; they have been traced throughout 6 degrees latitude and 15 degrees longitudes.”

The total length of all Chekanovskyi’s expeditions was about 27,000 km, including a 1990 km long trip along Nizhnyaya Tunguska River. The distance of 6 degrees latitude and 15 degrees longitude spans about 668 km by 1669 km, or an area of 1.1 Mkm^2. Exploration of this NW area of the Siberian Traps and the associated sedimentary basin was intensified due to urgent need for coal for ships, and Dudinka Town on the Yenisei River (100 km west from Norilsk) was used as a port for further shipping through the Northeast Passage.

Vladimir Sobolev (1936) mentioned that the first scientific paper on the petrography of rocks from the Siberian Traps was published in 1891 by K. Chrustschoff, who based his work on rocks collected by J. Lopatin in 1877 along the Podkamennaya (Stony) Tunguska River. Chrustschoff ‘s (1891) paper is very short and does not contain much information about the province, and he simply states that traps (“Trappen”) are common. An interesting development is seen in F. von Wolff’s textbook *Der Vulkanismus* from 1914, where he mentioned “the basic basaltic lavas of the so-called Siberian traps” (Wolff, 1914, p. 152). Furthermore, Wolff stated that “in many respects the Siberian Traps reminds of the thick and widespread Deccan Traps” (Ibid). The source of his information about the Siberian Traps and its characteristics, is however not specified, but we may speculate that the geology of the Siberian Traps was better known in the early 1900’s than hitherto recognized.

Sobolev‘s (1936) book, published when he was only 28 years old, summarized the key work on the Siberian Traps. He discuss the origin and definition of “trap” and used it for basic rocks that were laid as a sub-horizontal intrusions or nappes, often having a stair-like pattern due to weathering of interbedded sedimentary and volcaniclastic rocks. He also mentioned the usefulness of the “trap” term to describe intrusive and extrusive rocks composed of basalts, dolerites and porhyritic diabases (ibid, p.9-10), and presented a classification and petrography of the various rock types, the latter making up the bulk of the book. In addition, the chemical variations of major and trace elements were presented and the crystallization and differentiation of the magma discussed. Moreover, he briefly described the contact metamorphism and ore mineralization related to the sills. Finally, the book ended with a chapter on the geology and petrology of "traps" around the world, where the results from the Siberian Traps were put in a bigger context. Sobolev cited and used results from geological investigations in the Newark traps, Paranã, South Africa, East Antarctica and Tasmania, Deccan Traps, Columbia River basalts, the Tertiary basalts of England, and Abyssinia, to name a few.

Following Sobolevs's comprehensive book, other researchers, especially after World War II, focused on specific petrological problems of the Siberian Traps. Some of these early works (1950's and 60's) include studies of sills and lavas in the economically important mining districts around Norilsk (e.g., Masaitis, 1958; Godlevsky, 1959; Rogover, 1959; Smirnov, 1966). The now famous sill-related Cu-Ni-PGE mineralizations in Norilsk were first properly described in the 1960's and 70's (e.g., Genkin, 1968; Dodin et al., 1971). The ore deposits were, however, already discovered in 1922. The quest for base metals and iron in particular (prospecting in the Angara area from the early 1930s) was the main motivation behind studies that were done further south in the province, where some of the early work include Vilensky (1967), Kavardin et al., (1968), and Surina (1970).

Whereas studies of the geochemical aspects of the Siberian Traps are numerous, the volcanological aspects are poorly documented and the first studies were published as late as in the early 1980's. These include studies on the origin of specific lava textures (Simanovich and Kudryavtsev, 1981), volcanic pipe structures (Sapronov, 1986) and other aspects of the effusive volcanism (e.g., Nemenenok, 1978).

A main challenge with respect to the exploration of the Siberian Traps, is that most of the scientific literature is written in Russian and that is has been difficult for non-Russians to get permission to do fieldwork and to bring samples out of Russia. The problem of communication across barriers is evident in a 1972 paper by the American geologist P.R. Vogt about the cause of the end-Permian mass extinction. Vogt explicitly mentions the lack of evidence for exceptional volcanism coinciding in time with the mass extinction (Vogt, 1972), which may, in part be due to the limited accuracy of radiometric ages at the time (see also section 4.3).

One of the first collaboration projects between Western and Russian geologists was on the volcanic and sub-volcanic systems in Norilsk, and took place as late as the 1990s, involving Antony Naldrett, Peter Lightfoot, Gerald Czamanske, and Nick Arndt amongst others. The collaboration did however not include joint fieldwork, but samples were sent out of Russia by Valery Fedorenko (Russian collaborator) for analysis, and a series of papers were published jointly with Russian co-authors from 1990 to 2006 (e.g., Lightfoot et al., 1990; Carlson et al., 2006). It should also be mentioned that we (Planke, Polozov, and Svensen) initiated a Norwegian-Russian collaboration with joint expeditions to East Siberia in 2004, 2006, 2010, and 2015, studying outcrop localities and samples from abandoned core sheds targeted at sills, sedimentary rocks, and volcanic pipes (Svensen et al., 2009). In the late 2000’s we were involved in a NSF project led by Linda Elkin-Tanton to study the Siberian Traps together with an international group with specific focus on U-Pb dating, paleomagnetism and petrological characteristic research, involving two PhD students (Benjamin Black and Seth D. Burgess). Some of the results were summarized in the book *Volcanism and Global Environmental Change* (Schmidt et al., 2015).

The Siberian Traps is emplaced into a series of vast sedimentary basins collectively known as the Tunguska Basin, and an understanding of the volcanic and sub-volcanic system requires detailed information about sediment stratigraphy and basin evolution (e.g., Svensen et al., 2009). Interest in the petroleum provinces in the Tunguska Basin resulted in useful overview papers such as the one by Meyerhoff et al. (1980). Meyerhoff, the geologist behind the surge tectonics hypothesis, worked for Standard Oil for 10 years and as a publication manager for the American Association of Petroleum Geologists. He was called on by the Soviet government to carry out energy surveys, including in East Siberia (Boucot, 1995). Deep drilling in the Tunguska Basin, both for stratigraphic and petroleum purposes, showed that sills are present throughout the basin that contains up to 10 km of stratigraphy (e.g. Svensen et al., 2018).

One hundred and twenty years after Chekanovskyi's expedition, Russian scientists from Novosibirsk gathered available geological, geophysical and petroleum geology information from mapping, seismic surveys and deep drilling in Siberia. The aim was to estimate the areal extent, thickness, and volume of the Siberian Traps. The results showed that the Siberian Traps volume (without taking into account the volcanic rocks in the western Siberia basins) is 1,769,000 km^3, including 776,000 km^3 of dolerite sills, 332,000 km^3 of pyroclastic rocks and 661,000 km^3 of basalt flows (Vasiliev et al., 2000). Earlier estimates gave results of a total of 911,000 km^3, including the volume of sills (cf. Basaltic Volcanism Study Project, 1981, p. 34), based on Russian results from the 1960's, in particular by V.L. Masaitis (Svensen et al., 2018).

The results stress that sub-volcanic intrusions represent a major phase of LIP development, as Alexander du Toit also demonstrated in the Karoo Basin. This particular point has been a focus of recent studies within the Siberian traps, where the links between sill emplacement, location of degassing-related pipes, and the onset of flood volcanism, have been important topics of consideration (e.g. Jerram et al., 2016a; Polozov et al., 2016; Black ref; Burgess and Bowring, 2015; Svensen et al., 2018).

3.3 The British Tertiary and its wider North Atlantic Igneous Province

The products of Tertiary or, more accurately, Paleogene volcanism in western Scotland and the north of Ireland underpin much of the spectacular scenery in these areas, attracting visitors since the 17th Century. The province also represents the mainstay of studies which underpin our early understanding of igneous/volcanic units as well as the building blocks towards recognizing the North Atlantic Igneous Province (NAIP) as a major LIP (e.g. Saunders et al. 1997; Emeleus and Bell, 2005; Jerram and Widdowson 2005). As such there is a long and rich history of studies involving these volcanic rocks outcropping in both Scotland and Ireland.

In the North of Ireland region (e.g. Ulster), early interest focused particularly on the columnar-jointed basaltic rocks of the Giant's Causeway in County Antrim. From the late 17th century onwards, these spectacular basaltic formations receive frequent mention in the Philosophical Transactions of the Royal Society and elsewhere and, furthermore, the wide circulation in Europe of Susannah Drury's very beautiful and extremely accurate paintings of the Giant's Causeway led to comparisons with volcanic rocks elsewhere (Hamilton, 1790; Tomkeieff, 1940). Towards the end of the 18th Century, rocks on the Antrim Coast also played a critical role in the heated debates on the origins of basalt and other igneous rocks, and the opposing Plutonist and Neptunist viewpoints were recounted in some detail by Portlock (1843) in his classic report on the geology of the counties of Londonderry, Tyrone, and Fermanagh.

Western Scotland's mountainous coastline and islands, provided a more complete record of the Palaeogene volcanic events, and attracted innumerable geologists since the late 18th Century, with dramatic features such as mountainous volcanic centers and the columns of 'Fingle Cave' (e.g. Johnson, 1775). Examples of such landscapes were remarkably captured in the early 19th century with illustrations by John Macculloch (1819) in his "*Description of the Western Islands*" book, and later in his geological map of Scotland (Macculloch, 1836). During the mid to late 19th century, notable contributions to the igneous geology of Scotland's Highlands and Islands were made by, amongst others, Geikie and Judd. Their publications are numerous and detailed (see, for example, the listing in Bailey et al., 1924 and Harker, 1904, 1908) but two stand out: Geikie's Ancient Volcanoes of Great Britain (1897) and Judd's The Tertiary volcanoes of the Western Isles of Scotland (1889). Geikie's and Judd's views on key issues diverged in important respects, especially regarding the origins of the lava fields of Mull and Skye. Their deep and sometimes acrimonious disagreements (e.g., Judd, 1889 and discussion thereof) were not resolved in the protagonists' lifetimes and arose in part from the all-to-common desire to make the evidence conform to perceived grand designs: Judd claimed to recognize a progressive change with time from granite- to basalt-dominated magmatism, Geikie espoused the opposite view and, critically for Judd's reputation, showed beyond doubt that on Skye the latter sequence pertained. So was spawned the so called British Tertiary Volcanic Province (also termed British Tertiary Igneous Province), which we know today as the British Paleogene Igneous Province (BPIP, though some still like and use the older terminology). Early thoughts on the larger connections that would make up the North Atlantic Igneous Province were also brewing. Geikie noted the similarities between the volcanic successions of the Faroes and Iceland (Geikie, 1880), which was further expanded by Holmes's 'Brito-Arctic' province (Holmes, 1918) including also Greenland rocks, and termed the 'Thulean Province' was introduced (Richie, 1935), as thoughts on the regional studies looked out towards linkages farther afield (see also Saunders et al., 1997).

By the latter half of the 19th century and the early part of the 20th century, the full extent and complexity of the Paleogene lavas and intrusions had been gradually revealed as the Geological Survey of Great Britain's systematic mapping of Scotland at the 'Six Inch' scale extended to the North-West Highlands and Islands. These investigations culminated in the publication of a classic series of maps and memoirs covering the Skye Cuillin and Red Hills (Harker, 1904), Rum and the Small Isles of Inverness-shire (Harker, 1908), Mull (Bailey et al., 1924), Arran (Tyrrell, 1928) and, finally, Ardnamurchan (Richey and Thomas, 1930). The systematic investigation of these areas was initiated by Geikie who engaged the eminent petrologist (and mountaineer) Alfred Harker, of University of Cambridge, to map and describe the geology of the Skye Cuillin and Red Hills (Harker, 1904) and, subsequently, that of Rum and the other Small Isles of Inverness-shire (Eigg, Canna and Muck; Harker, 1908).

An investigation of considerable importance for the BPIP arose through the wartime activities of the Geological Survey. E.B. Bailey and J.E. Richey visited Rum to assess the economic potential of chromite and other minerals in the layered ultrabasic rocks and Bailey took this opportunity to make a rapid resurvey of the island, checking many of Harker's original observations and the validity of his conclusions. The Geological Survey produced a much revised edition of the classic 'Tertiary volcanic districts of Scotland' (Richey, 1948), and a description of the north Skye lavas and sills was published (Anderson and Dunham, 1966), but research into the Paleogene igneous rocks became concentrated principally in British universities, including Glasgow (Arran), Edinburgh (Rum, Slieve Gullion, Skye), Durham/Oxford (Rum, Skye) and King's College, London (Ardnamurchan) (see Emeleus and Bell, 2005).

The onshore exposure of the Paleogene rocks in Greenland provided the other half of the story in terms of the main outcropping parts of the NAIP. Access here was clearly far more restricted than in the British Isles, but early work by Wager (e.g. 1934) and Wager and Deer (1939) introduced some aspects of the lava and intrusive sequences, and as stated the seminal Wager and Brown (1958) book on layered igneous intrusions acted as a catalyst to understanding the plutonic links of the province. L. R. Wager, G. M. Brown, and W. A. Deer's descriptions of the Skaergaard layered gabbro, a Paleogene intrusion in East Greenland (Wager and Deer, 1939; Wager and Brown, 1958), exercised a profound influence on igneous petrogenesis and it was immediately recognized that many features described were of relevance to mafic rocks in the central complexes of the BPIP. Attention focused particularly on the layered gabbros and ultrabasic rocks of Skye, and of Rum where Brown (1956) and Wadsworth (1961) added much detail to Harker's (1908) initial survey and proposed a new classification for these 'cumulate' rocks based on interpretation of their distinctive textures and mineral compositions. The layered rocks of Rum formed towards the end of the life of the central complex and consequentially are relatively undisturbed and unaltered. These factors, combined with good and accessible exposure, have provided an exceptionally favorable locality for the study of igneous processes: in effect, one can look into the relatively undisturbed remains of a high-level magma chamber, somewhat frozen in time (Emeleus et al., 1996; Jerram and Bryan 2015). As such the links started to be made with the BPIP and further afield in Greenland. The layered rocks of Rum, Skye and the Skaergaard intrusions forming a fertile ground for modern petrological studies ever since (e.g. McBirney and Noyes, 1979; O'Driscoll et al., 2007; Emeleus and Troll, 2011; Holness et al., 2012), including some of the best geologically mapped examples of such igneous centers e.g. Rum (1:50,000 BGS map, by Emeleus, 1994) and the Skye Central Complex (1:25,000 BGS map, by Bell, 2005).

The lava sequences of Greenland themselves became the focus of many study efforts after the war (e.g. Brooks, 1973; Deer, 1976) and following significant mapping and study campaigns, primarily through the work of the Danish Geological survey/GEUS and others (e.g. Noe-Nygaard, 1974; Clarke and Pederson, 1976; Upton, 1980; ; Larsen et al., 1989; Larsen et al., 1992). The distribution and sheer scale of the province was starting to be realized, but it was not until the link with the offshore sections was made that the full scale of the province became clear.

Studies into the geophysical responses of the rocks in the BPIP started to shed further light on their distribution and extent. Despite the apparent preponderance of low density granitic rocks in many central complexes, these almost invariably have well-defined positive Bouguer gravity anomalies, indicative of substantial bodies of high density, mafic rocks at depth. An early investigation of the Irish central complexes by Cooke and Murphy (1951) was followed by detailed examinations of the Scottish centres by Bott, McQuillin, Tuson and others (see Emeleus and Bell, 2005) where interpretation of the anomalies suggests that each centre has a localized, steep-sided root composed of ultrabasic and/or gabbroic rocks probably responsible for the accompanying granitic rocks though processes of crystal fractionation together with melting and assimilation of the adjoining crustal rocks. Offshore seismic reflection and gravity surveys west of Scotland and Ireland led to the discovery of numerous central complexes (e.g. Hitchen and Ritchie, 1987; Ritchie and Hitchen, 1996), including the Blackstones Centre where dredging confirmed the presence of plutonic igneous rocks including gabbro and thermally altered metasedimentary rocks (McQuillin et al., 1975), while seismic reflection confirmed the shallow depth (c. 2 km) of Paleocene granites in the Skye centre (e.g. Goulty et al., 1992). This was to contribute and build on an ever increasing offshore record that was being planned and acquired from farther afield, and would help to fully link up the NAIP.

This offshore realm was to become a vital linchpin in our understanding of the extent of the NAIP. Sparked by the scientific successes in the understanding of seafloor geology and geophysics in the 1960's (see section 3.4), a period with global oceanic geophysical surveys and sampling continued into the 1970's and 1980's. One of the focus areas was the northeast Atlantic Ocean. This work was led by Lamont-Doherty Earth Observatory (LDEO), with five

Vema cruises between 1966 and 1973 focusing on the geological history and plate tectonic evolution of the Norwegian-Greenland Sea and the Norwegian continental margin (Talwani and Eldholm, 1972; 1977). Several DSDP drilling legs followed, both on the Rockall Plateau (Laughton et al., 1972; Roberts et al., 1984b) and on the mid-Norwegian margin (Talwani et al., 1976). The introduction of multi-channel and wide-angle seismic surveys in the Norwegian-Greenland Sea by LDEO and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover in the 1970's allowed for a much improved imaging of the crustal structure and associated sedimentary basins across the conjugate continental margins (Hinz, 1981; Mutter et al., 1982; 1984; Hinz et al., 1987). The seismic cruises on the Norwegian margin in the 1960's discovered a high-amplitude acoustic basement below layered sequences. The top basement reflection included regional escarpments and correlated with the top of oceanic crust. Subsequently, SDRs were imaged on multi-channel seismic data below the top basement reflection (Figure 7). Wide-angle seismic data revealed an anomalous crustal velocity structure, with thickened crust and a high-velocity lower crustal body ($V_p > 7$ km/s) along the continent-ocean boundary (Mutter et al., 1984).

The first indications of the nature of the basement reflections came as early as in 1970 when DSDP Hole 117 penetrated 5 m of basaltic extrusive rocks of subaerial or shallow marine origin on the Rockall Plateau. The basalts were dated as late Paleocene based on biostratigraphy of sediments above and in cracks. Four years later, three basement sites were drilled on the Vøring Plateau, recovering Paleocene/Eocene basalts. In 1976 a transect was drilled across the Hatton Bank-Rockall Plateau sampling basalts and volcaniclastic sediments, and the concept of Volcanic Rifted Margins was established (Roberts et al., 1984a). The drilling of the more than 1-km deep Ocean Drilling Program (ODP) Hole 642E on the Vøring Plateau in 1984 was particularly pivotal in that it penetrated significant basalts and was able to help prove the notion that seaward dipping reflectors are breakup-related sub-aerial flood basalts (e.g., Eldholm et al., 1987). Along the East Greenland margin significant studies by the Danish Lithosphere Centre during the 1980s-90s, further cemented knowledge of the distribution of the offshore volcanics and their relationship with continental breakup (e.g. Larsen et al., 1994 and references therein). Recent drilling penetrations along the West Greenland side have also further expanded our knowledge of the overall distribution of volcanics further west (e.g. Nelson et al., 2015; see also Abdelmalak et al., 2018).

Maps of the distribution of the NAIP appeared in various forms (see Morton and Parson, 1988), with the linking of the region to the Iceland Plume being also realized (e.g. White and McKenzie, 1989). New understanding of the volcanic rifted margin structure was synthesized (Eldholm et al., 1995), and estimates of the total volumes of the NAIP extrusive and total igneous crustal volumes (1.8×10^6 km^3 vs. 6.6×10^6 km^3) were calculated (Eldholm and Grue, 1994). With modern age dating of the province, the pieces were brought together, establishing two main stages of volcanic activity (62-60 Ma and 55-56 Ma). Another major step forward came from the ever increasing 2D and 3D seismic data becoming available, primarily through exploration efforts. These data would also help to transform the way in which we look at the NAIP, and LIPs in general, as now the onshore and offshore records could be combined (e.g. Planke et al., 2000; Jerram et al., 2009). Moreover the methods by which volcanic units can be identified and mapped out from these 2D and 3D data-sets has sparked the advent of seismic volcanostratigraphy (Planke et al., 2000), sill and hydrothermal vent complex mapping (Berndt et al., 2001; Planke et al., 2015), and igneous seismic geomorphology (Planke et al., 2017), which now help underpin the way in which volcanic rifted margins are characterized in the offshore domain (e.g. Abdelmalak et al., 2016; Abdelmalak et al., 2018).

3.4 The oceanic turn, submarine exploration and the Ontong Java Plateau

The nature of much of the ocean floor and continental margins were basically unknown until the middle of the 1900's. Interestingly, this was to change with the introduction of new marine geophysical and Earth technologies for seismic, gravity, and magnetic surveying and seabed sampling in the post-war era. In the early days, numerous marine cruises were organized by the three main US oceanographic institutions, the LDEO, Woods Hole Oceanographic Institute (WHOI), and Scripps Institution of Oceanography. The cruises were motivation from a combination of scientific, strategic, and resource mapping perspectives. Three research vessels, the Atlantis, Vema, and Conrad explored the deep oceans globally, completing more than 3,000,000 nautical miles of data collection by their retirements. This corresponds to circumnavigation the world about 140 times (e.g., http://www.ldeo.columbia.edu/research/office-of-marine-operations/history/).

The wealth of new data triggered development of a new hypothesis of global importance, building on the earlier work of Wagner, du Toit, Holmes and others. The seafloor spreading hypothesis of Hess (1962) and Vine and Matthews (1963) was constrained by new observations of the topography, velocity structure, and linear magnetic anomalies of the oceanic crust. This hypothesis developed rapidly into the plate tectonic hypothesis, commonly regarded as being accepted by the scientific community at a symposium at The Royal Society, London, in 1965 (Blacket et al., 1965). The Deep Sea Drilling Project (DSDP) was subsequently launched in 1966, and the purpose-built drilling vessel Glomar Challenger was completed in 1968 (www.deepseadrilling.org). One of the major achievements of this 15-year drilling program was during Leg 3 when core data along a transect across the South Atlantic Ocean provided the proof of continental drift and seafloor spreading, and supporting the plate tectonic hypothesis by biostratigraphic dating of sediments overlying oceanic crust with magnetic anomalies (Maxwell et al., 1970). On the other side of the globe, extensive surveys were also undertaken in the Indian, Pacific, and Southern oceans. Here they targeted anomalous massive oceanic plateaus, such as the Ontong Java and Kerguelen.

The combination of seismic surveying and drilling in the 1970's and 1980's provided the observations necessary to discover the igneous nature of these oceanic plateaus and the submerged sections of rifted margins. Combining this knowledge with the extensive research already done on continental flood basalts resulted in the main LIP concept and terminology. As mentioned earlier, this terminology was first used during a workshop to promote drilling of volcanic margins and oceanic plateaus in 1990 (Coffin and Eldholm, 1991), leading to a series of scientific papers on LIPs (Coffin and Eldholm, 1992; 1993a; 1993b; 1994; Eldholm and Coffin, 2000), successful volcanic rifted margin and oceanic plateau drilling, and new workshops on LIPs and continental breakup (Erzinger, 1997; Coffin et al., 2006; Sawyer et al., 2007). A great catalyst to the development of the LIP idea was the understanding gained of the nature of the large oceanic LIPs, and to this extent the Ontong Java Plateau is one of the best understood examples.

The Ontong Java Plateau (OJP) is situated in the western equatorial Pacific east of Papua New Guinea and ever since the discovery of the island of Ontong Java and the Solomon Islands by Alvaro de Mendana in 1567, the region has been repeatedly explored. The first early exploratory cruises to explore the sea floor were those of HMS Challenger (1874-1875), the Gazelle (1874-1876), and the SMS Planet (1907-1911). Fairbridge (1962) provides an excellent and very complete summary of these early expeditions through 1956, and Kroenke (1972) describes the exploration of the Ontong Java Plateau region through 1970. The OJP is divided into the high plateau and eastern salient, the later being dissected by the Stewart Basin (Figure 8). The plateau surface rises to depths of ~1700 m in the central region of the high plateau but lies generally between 2 and 3 km water depth and is roughly isostatically compensated (Sandwell and McKenzie, 1989). The OJP is still ~1-2 km higher and has subsided less than the surrounding oceanic crust (e.g., Stein and Stein, 1992; Berger et al., 1992). This has resulted in normal faulting around the plateau margins (e.g., Kroenke, 1972). Much of the plateau surface is relatively smooth, but the high plateau is punctuated by several sizable seamounts (including Ontong Java, Kapingamarangi, Mukuoro, and Ngatik, atolls, and Tauu, Nuguria, Nukumanu, and Tulun islands) and physiography around the margins of the plateau is complicated (e.g., Kroenke, 1972; Berger et al., 1992, 1993).

Numerous names have been assigned to this submarine feature. It was first called the Ontong Java Rise by Fairbridge in the 1950s after the largest atoll centrally located in the south half of the high plateau. The name was subsequently established in the 1958 edition of the Times Atlas and again by Fairbridge (1962, 1966). Chase et al. (1968) and Heezen (1969) preferred to call the area the Solomon Rise, whereas Ewing et al. (1968, 1969) referred to this feature as the Solomon Islands Plateau (originally used by Murray, 1895). Dietrich and Ulbrich (1968) named the plateau the Carolinen-Salomonen Schwelle, and the Pergamon World Atlas (1968) called it the Caroline-Solomon Rise. The Russian charts of this time called the plateau “Val Kapingamarangi”, whereas Coleman (1966) used the term Ontong Java Platform. In his Ph.D. dissertation, Loren Kroenke (1972) preferred the term “Ontong Java Plateau” because the region morphologically resembles a submarine plateau. This name has been used in the scientific literature since that time as it avoids confusion with the term the Solomon Islands Plateau.

The OJP is bounded to the northwest by the Lyra Basin, to the north by the East Mariana and Pigafetta Basins, by the Nauru Basin to the northeast, and the Ellice Basin to the southeast (Figure 8). While a predominantly submarine ocean plateau, exposures of OJP basalt outcrop on the islands of Santa Isabel, Malaita, and Makira in the Solomon Islands because the south-western edge has collided with the Australian plate, which has caused buckling of the plateau raising portions of it above sea level (Petterson et al., 1997, 1999). In fact, the arrival of the OJP at the subduction caused a reversal in sudduction direction as the over-thickened oceanic crust blocked the southeast dipping subduction zone (Coleman and Kroenke, 1981; Cooper and Taylor, 1985). In marine geophysical studies of the Solomon Islands region, Miura et al. (2004) and Phinney et al. (2004) concluded that while the upper portion of the OJP was being obducted, the lower portion was being subducted, starting to re-establish subduction of the Pacific plate to the south-east.

The OJP covers are area of approximately 2 x 10^6 km^2 (Coffin and Eldholm, 1993, 1994). To put this into perspective, this represents an area similar to that of Alaska (1.7 x 10^6 km^2), Greenland (2.2 x 10^6 km^2), or Western Europe (2.3 x 10^6 km^2). The thickness of the OJP has been determined using combined seismic-gravity data, which produces crustal thicknesses in the 30-43 km range, with an estimated average around 36 km (e.g., Furumoto et al., 1970, 1976; Murauchi et al., 1973; Hussong et al., 1979; Miura et al., 1996; Richardson et al., 2000; Gladczenko et al., 1997). The volume of the OJP is enormous and has been determined to be between 44.4 x 10^6 km^3 and 56.7 x 10^6 km^3 (e.g., Gladczenko et al., 1997). The lower estimate is assuming the OJP formed on pre-existing oceanic crust and the higher assumes it formed at a spreading center. This huge outpouring of magma represents a significant magmatic event in Earth history that has been attributed to a massive mantle plume that surfaced during the Cretaceous (e.g., Mahoney, 1987; Larson, 1991; Mahoney and Spencer, 1991). This huge amount of magma has left a lasting effect on the mantle source, because beneath the OJP a seismically slow region extends to 300 km beneath the plateau (Richardson et al., 2000) that has been interpreted to represent the depleted mantle root that is moving with the plateau (Klosko et al., 2001).

Outcrops of OJP basalt on the Solomon Islands of Santa Isabel, Malaita, and Makira were initially investigated without the realization that they were related to the OJP. For example, the Sigana Basalts on Santa Isabel yielded Ar-Ar ages of ~90 Ma (Tejada et al.,

1996) and these form the basement of the northern portion of the island, which is divided by the E-W Kaipito-Korighole Fault system (Hawkins and Barron, 1991). This fault system separates the Pacific Province from the Central Province, two of the three the geologic provinces that form the Solomon Islands (Coleman, 1965). Rare alkali dikes (the Sigana Alkalic Suite – Tejada et al., 1996) intrude the Sigana Basalts.

Malaita is comprised of folded sequences that expose tholeiitic basalts in the cores of eroded anticlines (Rickwood, 1957; Hughes and Turner, 1976, 1977; Petterson et al., 1997), termed the Malaita Older Series with ages of ~122 Ma (Tejada et al., 1996, 2002). Younger alaklic basalts are interleaved with the Late Cretaceous sediments overlying the Malaita Older Series (Hughes and Turner, 1976), which are mineralogically and texturally similar to the Younger Series of lavas in North Malaita (Barron, 1993; McGrail & Petterson, 1995), and are called the North Malaita Alkalic Suite that comprise the Maramasike Formation that have an Ar-Ar age of ~44 Ma (Tejada et al., 1996). Originally, this formation was considered older than a single 34 Ma zircon age from the Malaita alnöite pipes (Davis, 1978), but more detailed age dating from several alnoite pipes on Malaita show such intrusives occurred for at least 18 Ma between 34-52 Ma (Simonetti and Neal, 2010). Such pipe-like intrusives have also been noted in seismic data from the submarine portions of the OJP (Kroenke, 1972; Nixon, 1980).

Reconnaissance mapping of Makira (San Cristobal) was reported by Grover (1958). The western part of the Makira was first mapped in the 1970s (Jeffrey et al., 1975), with the mapping completed in the 1990s (Petterson et al., 2009). This comprehensive mapping effort showed that the island is comprised of two main sequences - the Makira Basement Complex (MBC) and the unconformably overlying Makira Cover Sequence (MCS). Available Ar-Ar whole rock radiometric age data indicates Cretaceous to Oligocene (98 - 34 Ma) for the Makira Basement Complex, with the majority of lavas having similar geochemical characteristics to OJP lavas described from other islands and from drill cores obtained through scientific ocean drilling (Birkhold-VanDyke et al., 1996; Petterson et al., 2009). The ages and compositions of basalts from Makira suggested pulses of OJP magmatism at ~90 Ma, ~64 Ma, and 36 Ma, and were intermixed with MORB-type lavas (Birkhold-VanDyke, 2000; Petterson et al., 2009). The MBC forms the great bulk (up to 90%) of the volume of Makira of which basaltic lithologies comprise >65%, and locally almost 100% of the sequence. The MBC comprises both extrusive and intrusive mafic and ultramafic bodies and were termed the Wairahiti Volcanic Group (Petterson et al., 2009). Interbedded sedimentary limestones, cherts, sandstones, and basaltic breccias (termed the Waihaoru Sedimentary Group) are found within the MBC.

Scientific ocean drilling on the OJP

Submarine basement basalt lavas of the OJP has been cored by three scientific ocean drilling expeditions: DSDP Leg 30 (Site 289)drilled 9.2 m into basaltic basement and recovered 4.1 m of core (Stoeser, 1975).

In 1990, ODP Leg 130 drilled two sites into the high plateau that recovered OJP basement lavas (Sites 803 and 807 – Kroenke, Berger, Janacek et al., 1991). Site 803 (Hole D) drilled ~25 m into basement and recovered 9.1 m of basalt core, whereas Site 807 (Hole C) drilled ~149 m into basement and recovered 89.5 m of core that were subdivided into seven units (A-G). Units A, C, E-G were basaltic, whereas Units B and D were thin limestone interbeds (Unit B: 1424.6-1425.1 meters below sea floor or mbsf; Unit D: 1441.9-1442.0 mbsf) (Kroenke, Berger, Janacek et al., 1991).

In 2000, ODP Leg 192 drilled five sites into the OJP, four into the high plateau (Sites 1183, 1185, 1186, 1187) and the first one (Site 1184) into the eastern salient (Mahoney, Fitton, Wallace et al., 2001).

- Site 1183 drilled 80.7 m into basaltic basement and recovered 44.2 m of core;
- Site 1184 drilled 337.7 m into below pelagic sediment cover and recovered 278.9 m of mafic volcaniclastic sediments, containing the first evidence of plateau emergence with accretionary lapilli and six horizons containing carbonized wood remains (Thordarson, 2004);
- Site 1185 hit basement in two holes: Hole 1185A penetrated 16.7 m of basaltic basement and 11.17 m of core recovered; hole 1185B penetrated 216.6 m of basaltic basement and 90.68 m of core was recovered;
- Site 1186 drilled 65.4 m into basaltic basement and recovered 39.36 m of core;
- Site 1187 drilled 135.8 m of basaltic basement and recovered 100.87 m of core.

OJP basalt compositions and age

Mahoney et al. (1993a,b) documented distinct basalt units at Site 807 of ODP Leg 130. Unit A was geochemically and isotopically distinct from the basalts in the Units C-G. These distinct basalt types were separated at Site 807 by the 0.5 m Unit B limestone unit. All basalts gave 40Ar/39Ar ages of ~122 Ma. The basalts from Site 803 had similar compositions to those from Units C-G at Site 807, but yielded 40Ar/39Ar ages of ~90 Ma. These two ages were documented on the islands of Santa Isabel and Malaita (Tejada et al., 1996, 2002). In 1993, extensive fieldwork on the island of Maliata was undertaken by Michael Petterson (British Geological Survey), John Mahoney (University of Hawaii), and Clive Neal

(University of Notre Dame), who collected a stratigraphic sequence of basalt samples was collected across the Kwaio anticline (cf. Petterson et al., 1997), along the Singgalo River in the west and the Kwaimbaita River in the east. Geochemical analyses showed the same compositions as at Site 807 Units C-G, some 1200 km away, and also on Santa Isabel (Tejada et al., 1996). Tejada et al. (2002) renamed the Unit A basalts the Singgalo Formation and the Units C-G basalts the Kwaimbaita Formation, after the type localities in Malaita. Basalts from the Kwaimbaita Formation are the most abundant type and are found across the OJP, and are evolved tholeiites (6-8 wt.% MgO; e.g., Tejada et al., 2002). Leg 192 discovered the most primitive OJP basalts to date, which were named the Kroenke Formation in honor of Loren Kroenke who has devoted his life to the study of the Pacific and the Ontong Java Plateau in particular (Mahoney, Fitton, Wallace et al., 2001; Fitton and Goddard, 2004). Other formations include; the Kwaimbaita, Wairahito (Birkhold, 2000; Shafer et al., 2004; Tejada et al., 2002). Isotopically, Kroenke, Kwaimbaita, and Wairahito are identical, suggesting they have a genetic relationship through crystal fractionation (cf. Fitton and Goddard, 2004), but the Singgalo-type basalts are isotopically distinct (Mahoney et al., 1993a,b; Tejada et al., 2002, 2004) and form the last unit to be erupted on the OJP.

The Greater Ontong Java Plateau (Ontong Java Nui)

In 2006 Brian Taylor used seafloor fabric data to conclude that three western Pacific oceanic plateaus – Ontong Java, Manihiki, and Hikurangi (Figure 8) – formed during one event (Taylor, 2006). Chandler et al. (2012, 2015) and Hochmuth et al. (2015) reported results from kinematic plate reconstructions to demonstrate the plausibility of the three plateaus forming as one large super-plateau, and subsequently were rifted apart.

Seafloor fabric data are consistent with at least the Manihiki and Hikurangi plateaus being originally one and have conjugate margins that were formed with the Osbourn Trough (a former spreading center; Billen and Stock, 2000) opened up and separated them (Taylor, 2006). Paleolatitude and fracture zone data have also been used to support the formation of this “super-plateau” or Ontong Java Nui (Chandler et al., 2012, 2015; Hochmuth et al., 2015). Hoernle et al. (2010) and Timm et al. (2011) showed isotopic similarities between the Hikurangi (Plateau A basalts), the low-Ti Manihiki basalts, and the OJP Kwaimbaita/Kroenke basalts, and the Hikurangi Plateau B, the Manihiki high-Ti basalts and the DSDP Site 317 basalts with basalts from the OJP Singgalo formation. However, the Manihiki low-Ti basalts exhibit distinctly more depleted trace element patterns that those from the OJP. In comparing the 40Ar/39Ar ages of basalts from all three plateaus, all three erupted basalts of similar compositions at ~122 Ma and ~90 Ma. Seamounts on the Hikurangi and Manihiki plateaus around 60 Ma along with lavas from the OJP from Makira and Santa Isabel (Figure 7). From the data currently available, it would appear that these three plateaus form synchronously and had a common origin.

If this hypothesis were to be validated, it would mean the volume of magma erupted would have been at least double that calculated for the OJP (e.g., Coffin and Eldholm, 1993, 1994). If Ontong Java Nui was formed by a superplume (cf. Larson, 1991), eruptions of at least part should have been subaerial, but until ODP Leg 192, no evidence of plateau emergence had been found, which was used to cast doubt on a plume origin. Site 1184 on the eastern salient of the OJP recovered a long sequence of volcaniclastic sediments that contained definitive evidence of emergent volcanism (see above; Thordarson, 2004). In the reconstructions of the three oceanic plateaus, the center would be over the eastern salient, which is where the greatest amount of surface uplift should be if this Cretaceous magmatic event was caused by a surfacing mantle plume.

It is evident from the compositions recovered from Manihiki and Hikrangi plateaus that *some* of the basalts certainly show similarities to those from the OJP, but there are others (i.e., the low-Ti basalts from Manihiki – Timm et al., 2011). Golowin et al. (2018) have published data from R/V Sonne samples collected by a remotely operated vehicle (SO225) and concluded that the sources of the Ontong Java and Manihiki Plateaus were compositionally different. These could represent two large domains of a single superplume or two contemporaneous but separate plumes. Another issue is that the thickest crust on the OJP, Manihiki, and Hikurangi plateaus is on the high plateau of the OJP, which is on the northwest margin of the unified three plateaus. Was this the focus of lava flows from the plume flowing from the center of the eruption and forming the over thickened high plateau? Was the OJP high plateau then too thick to rift and only the thinner portions to the southeast were broken off? The fact that the only evidence for emergence is on the eastern salient of the OJP suggests this is where the focus of future drilling and dredging should occur. Clearly, more exploration is needed to resolve the origins of basalts from the OJP, Manihiki, and Hikurangi Plateaus and whether these three oceanic plateaus, which have erupted basalts contemporaneously, are actually related.

4. Implications and directions

We have so far outlined and discussed some of the key developments in LIP-related research since the 1800’s. We have highlighted that LIP research has mirrored the shifting ideas about how the Earth works – and its history in deep time, in particular the formation of mountain belts, rift zones, the movements and breaking up of continents, and plate tectonics. The LIP terminology, largely developed in the early 1990’s, has in our view been extremely important in laying out a new and understandable framework that was rapidly adapted by specialists across the geosciences. We have largely glossed over several themes, for brevity, that became important from the 1960's and the 1970's and onwards, for instance the geophysical exploration of the oceanic crust. Other themes are not included here but are still important, for instance LIP formation and the role of mantle plumes (e.g., Morgan, 1971; Vogt, 1972), and the usage of LIPs for calculating the longitudinal positions of continental blocks during the entire Phanerozoic (e.g. Torsvik et al., 2008, 2014). These themes represent dynamic research topics at the research front internationally, with numerous papers published every year and reasonably updated available reviews (e.g., Condie, 2001; Burke, 2011; Ernst, 2014), but an in depth review of these themes is beyond the scope of the present contribution. We summarize our finding here by briefly discussing the evolution of ideas related to the sources of LIP basalts and the understanding of emplacement age, in some ways reflecting the way researchers over the years have grappled with both the scale and the impact of LIPs.

4.1 Earth revolutions and the source of basalt

In South Africa, Alexander du Toit eventually got tired of mapping and analyzing sills (cf. Gevers, 1950), and shifted his focus from geological mapping, volcanic rocks, ground water and kimberlites, to becoming one of the main proponents of the continental drift hypothesis. He gained supporters across the world sending him samples and field observations in support of continental drift, but had many opponents too, particularly in the United States (Oreskes, 1999). Du Toit's shift of interest is articulated in the "hypabyssal injections" paper, which ends with a brief discussion on the role of volcanism in the larger geodynamic picture and the history of the continents (Du Toit, 1920). Understanding sills and volcanism was clearly not his final thematic destination, but merely used as a phenomenon to understand the larger revolutions that have shaped the Earth. His message was that sills and lavas played a key role in understanding the history of the continents, as explained in depth in his book from 1937 with the title "*Our wandering continents*". Among his seven criteria for continental drift, number four is related to volcanic activity (Du Toit, 1937, p. 52) including: a) batholiths emplaced at the same time in equivalent fold belts, b) plateau basalts and dike swarms, and c) similar petrographical provinces for instance in Brazil and southern Africa. Volcanic activity, including plateau basalts provinces, is regarded as a product of large-scale shear and fracture zones developed as the continents moved:

> "Presumably connected with such crustal rupture is the enormous spread of late Cretaceous or early Eocene Deccan "traps" of western India that occupy over 500,000 sq. km – mainly basalts erupted from fissures…" (Ibid, p. 103)

Alexander du Toit was one of many geologists that saw large sale geodynamic processes in the presence of continental flood basalts, going back to at least the 1870's by the work of Joseph LeConte and continued by Geikie and Reginald A. Daly (cf. Oreskes, 1999). LeConte (1872) wrote that:

> "By this theory, as by every other theory of mountain formation, it is necessary to suppose that there have been in the history of the earth periods of comparative quiet: during which the forces of change were gathering, and periods of revolutionary change-periods of gradually increasing horizontal pressure, and periods of yielding and consequent mountain formation. These latter would be also periods of great fissure-eruptions, and these, during the more quiet subsequent period, would be followed by volcanoes gradually decreasing in activity."

Note that LeConte used the term "lava floods" in the pre-Tyrrell sense. The interest in both lava floods and petrographical provinces was a key part of understanding the history of the continents, and the association between volcanism, mountain ranges and compressional tectonics stressed by, for instance, Alfred Harker (Young, 2003, p. 186), and Daly in 1909 and throughout the 1920's (Oreskes, 1999). Daly visited the Karoo LIP (and the Bushveld complex) in 1922 as a part of the so-called Shaler Memorial Expedition (Oreskes, 1999, p. 91). The Americans Daly and Frederick E. Wright were guided by the Dutch professor G.A.F. Molenaar and Alexander du Toit, and the party collected samples of Karoo sills that Daly later studied together with the Norwegian petrologist T.F.W. Barth (Daly and Barth, 1930). Du Toit's subsequent travel to South America to study the geological similarities between Southern Africa and South America came by as a result of common interest (i.e., the continental drift theory) and the friendship with Daly and Wright. Wright secured funding for du Toit from the Carnegie Institution for a five-month travel to Argentina, Uruguay, and Brazil (Oreskes, 1999, p.159-161).

In the early 1970s the international Geodynamics Project (GP) was established to gain more insight into mantle processes and geochemistry following the discovery of plate tectonics. According to Nicolaysen (1984), the project stood on the shoulders of the achievements of the international "Upper Mantle Project" of the 1960s. The Upper Mantle Project was sponsored by the International Council of Scientific Unions and had a geophysical and seismological focus (e.g., Hart, 1964; Oliver, 1966). During a kimberlite conference in Cape Town in 1973, researchers from the UK and South Africa met in a coffee break and realized that they were planning independent GP-related Karoo projects. They decided to collaborate (Erlank, 1984). Between 1974 and 1980, six universities were involved from the South African side (Nicolaysen, 1984), focusing on topics such as magma composition and tectonics, and Karoo volcanism and Gondwana breakup (Erlank, 1984). The results were published jointly in 1984 by the Geological Society of South Africa, edited by A.J. Erlank. The volume included papers on major and trace element systematics (local to LIP scale; e.g., Marsh and Eales, 1984), lead isotope analyses, and Rb-Sr and $^{40}Ar/^{39}Ar$

geochronology (Fitch and Miller, 1984). The Karoo project signaled a renewed interest in continental flood basalts. In 1981, the so-called Basaltic Volcanism Study Project resulted in the Pergamon Press book *Basaltic Volcanism on the Terrestrial Planets* (Basaltic Volcanism Study Project, 1981). Others were to follow. One example is the 1988 book *Continental flood basalts*, edited by J. D. Macdougall, sharing the petrological and geochemical interest of the GP, and representing the first compilation of geology and geochemistry of all the major continental flood basalt provinces. Moreover, the book "Large Igneous Provinces: Continental, Oceanic, and Planetary Volcanism," edited by John Mahoney and Mike Coffin (1997), was the first compilation of terrestrial, oceanic, and planetary LIPs, arising from the IAVCEI Commission on LIPs.

An attractive cause for the excess volume of melt that is associated with LIPs came in the form of the 'plume hypothesis' developing within the literature around this time, where hot upwelling plumes of mantle are envisaged to impinge on the lithosphere at key stages though Earth's history (e.g. Morgan, 1971; Courtillot et al., 2003). These can often be manifest by 'hot spots' on the earths surface which link nicely back to LIPs they are associated with (e.g. NAIP, Paranã-Etendeka, and Deccan), where with others the association is less clear. Also with plate reconstructions, links can been made with deep 'plume generation zones' and the location of LIPs, linking long lived core-mantle boundary anomalies with LIP expressions on the surface (e.g. Burke et al., 2008; Torsvik et al., 2014; Jerram et al., 2016b). Others have criticized the wholesale use of the plume model in the generation of the melting anomalies associated with LIPs, citing passive extension of the lithosphere with decompression, and locally enriched areas of mantle within a 'rift model' of melting anomalies (e.g. Foulger 2007). In many respects these debates and questions are still on-going and are clearly beyond the scope of this contribution. However, the large volumes/extents of LIPs and their short pulses within the geological record (see section 4.3), as discovered by the examples and historic studies that have been touched on here, will need to be reconciled within any existing and/or future models of the ‘source of the basalt’.

4.3 Age and tempo of LIP volcanism

A crucial development in our understanding of LIPs is the progressing advances in geochronological methods applied to mafic extrusives and intrusives; from the early efforts to date whole-rock samples mainly by the K-Ar and Rb-Sr methods, mineral separates using 40Ar/39Ar, to modern high precision single zircon U-Pb dating. By using examples from the Siberian Traps and the Karoo LIP we illustrate (Figure 9) how the view on LIP timing and tempo, and thus the view on processes involved and impacts on the environment related to the LIPs, has changed during the last decades.

Early K-Ar whole rock geochronology of the Siberian Traps conducted in the 1970’s indicated a time span of more than 100 m.y. for effusive and intrusive activity, as summarized in Baksi (1991) and, as such, early workers (e.g. Vogt, 1972) made little connection with the Siberian Traps and the end-Permian extinction. Evidence from the field, however, was argued to indicate a shorter history of volcanism (Zolotukhin and Al’Mukhamedov, 1988). A closer inspection of the original data reveal a clustering of the data between ca 260 and 230 Ma for basalts and dolerites, whereas younger and older ages derived from tephras, indicating that alteration and open system behavior affected the results (Baksi and Farrar 1991). After the early dating efforts by the Russian scientists, a second wave of geochronological studies were instigated in the early to mid-1990’s (Baksi and Ferrar 1991; Renne and Basu 1991; Campbell et al. 1992; Basu et al. 1995; Dalrymple et al. 1995). These results gave a new and remarkable improvement in our understanding of the tempo and timing of the Siberian Traps. For instance, the combined mineral (plagioclase and biotite) and whole rock $^{40}Ar/^{39}Ar$ ages of

Renne and Basu (1991), Basu et al. (1995), and Dalrymple et al. (1995), narrowed down the duration of the main pulse of volcanism to less than 10 m.y. (Figure 9). Scatter in ages for individual samples resulting from, at that time, unresolved issues with the 40Ar/39Ar methodology. An early ion probe (SHRIMP) zircon U-Pb study (Campbell et al. 1992) also gave ages confirming a <10 m.y. duration of LIP volcanism. One of the consequence of this improved geochronology, was a synchronicity between the Siberian Traps and the end-Permian mass extinction at the <10 m.y. level (e.g. Renne and Basu 1991; Campbell et al 1992). A third phase in the age determination of the Siberian Traps, with greater accuracy and precision started with the first isotope dilution thermal ionization mass spectrometry (ID-TIMS) zircon U-Pb date of the Norilsk 1 intrusion (251.2 ± 0.3 Ma (2σ); Kamo et al. 1996). This was followed up by zircon and perovskite U-Pb ID-TIMS ages of two lavas from the lower and upper part of the lava series of Siberian Traps giving 251.7 ± 0.4 Ma (2σ; perovskite) and 251.1 ± 0.3 Ma (2σ; zircon), respectively (Kamo et al. 2003). This emphasized that the main pulse of volcanism most likely was confined to less than 1 m.y. and that the age of the main pulse overlapped the age of the P-T boundary as determined at that time (Bowring et al. 1998), within <1 m.y.

The most recent improvement of the Siberian LIP chronology follows a major effort to understand where zircons can be found in individual mafic rocks and outcrops (e.g. Burgess et al. 2016) and important methodological advances during the last decade or so, partly spurred by the EARTHTIME initiative (www.earth-time.org). EARTHTIME and advances in mass spectrometer technology have geochronologists allowed the measurements of small single zircons with high precision and accuracy as well as avoiding inter-laboratory biases due to the use of different tracers. Moreover, the chemical abrasion method (Mattinson 2005) enabling the resolution of problems with residual Pb-loss, the introduction of low sub-pg Pb blank zircon dissolution routines, the use of common SI-traceable, accurately and precisely calibrated U-Pb tracers (Condon et al. 2015) have been of great importance for improved geochronology.

Burgess and Bowring (2015) dated two lavas and 17 sills from the Siberian LIP showing that the most voluminous pulse of intrusive magmatism occurred within ca. 550 ka (Figure 9) and that the onset was synchronous with the Permian-Triassic extinction interval and negative carbon isotope excursion (Burgess et al. 2014) at the 0.04% level. The high-resolution age models now obtainable for LIPs combined with equally high resolution chronostratigraphic models for boundary events such as the end-Permian, enables the robust testing of temporal relationships of LIPs and these events, and different hypotheses for the direct causal links on decamillennial timescales.

Our understanding of the timing and tempo of the Karoo LIP follows much the same development as described above for the Siberian Traps. An early phase of K-Ar and Rb-Sr geochronological data derived through the 1960's, -70's and -80's (summarized in Fitch and Miller 1984), was followed by a second phase in the 1990's with significant refinements (Encarnacion et al. 1996; Duncan et al. 1997) and a third phase of refinements from the mid-2000's (Svensen et al. 2007; 2012) (Figure 9). Only recently modern high precision data of similar precision to that described from the Siberian Traps have been published from the Karoo LIP (Sell et al. 2014; Burgess et al. 2015). There are, however, some interesting aspect of the geochronological history of the Karoo LIP worth mentioning.

The early geochronology of volcanic rocks in southern Africa gave overlapping ages spanning the whole of the Jurassic period and well into the Cretaceous (Fitch and Miller 1984 and references therein). This probably contributed to the grouping of a number of volcanic sequences and intrusive suites unrelated into the Karoo LIP (such as the Parana-Etendeka province). As a consequence, the Karoo LIP was interpreted as a very long-lived, multipulsed LIP (Fitch and Miller 1984). The notion of the Karoo LIP as a rather long-lived (up to ~5 m.y.) LIP has been maintained by Jourdan et al. (2008), contrary to the view of Duncan et al. (1997) who through an extensive dating campaign of lavas, sills and dikes indicated that the Karoo LIP was a short lived event on the order of 1-2 m.y. The interpretation of Duncan et al. (1997) was strongly supported through extensive U-Pb zircon dating of sills in the Karoo Basin by Svensen et al. (2012) that indicated a short-lived main igneous pulse on the order of less than 1 m.y. Only two sills of the Karoo LIP have been dated by chemical abrasion ID-TIMS using the EARTHTIME tracer and these fall within 800 ka, both overlapping the range obtained in Svensen et al. (2012) (Corfu et al. 2016). In order to evaluate the precise duration of the Karoo LIP and the tempo of emplacement across southern Africa, more high-precision zircon U-Pb geochronology is needed. Clearly the advances in geochronological techniques have, in many ways, reflected the technological advances of modern times. Early workers that had little or no direct measurements of the timing of the LIPs they studied, were still often compelled to comment on the direct similarities of rocks that were geographically disparate from each other (sometimes with continental divides). So much so it was often the case that they would speculate as to their similar origins temporally. Indeed, many of these early observations and questions, also helped drive the studies that ultimately helped provide the detailed geochronology that we enjoy, and endeavor to create, in the present.

4.4 Climatic and environmental consequences

The links between LIPs and environmental changes has been stressed since the 1980’s and, as we have shown the importance of LIP geochronology, these have become even more comparable as the dating methods of igneous rocks have improved. It is currently well established that LIPs and environmental changes coincide in time, although the direct casual links are continuously debated (e.g., Rampino and Stothers, 1988; Wignall, 2001; Svensen and Jamtveit, 2010; Bond and Wignall, 2014; Ernst, 2014). The suggested consequences of LIPs include mass extinctions (e.g., the Siberian Traps, the Central Atlantic Magmatic Province), negative carbon isotope excursions and global warming (e.g., the Karoo LIP, the North Atlantic Igneous Province), and oceanic anoxic events (e.g., the Ontong-Java Plateau, the High Arctic LIP). The combination of modern dating methods and novel geochemical proxies has further strengthen the LIP-environment connection. One of numerous examples is the Cretaceous OAE-1a, which developed at the time of the initial eruption of the Ontong Java Plateau at ~122 Ma. In a sedimentary sequence through OAE-1a in Italy, Tejada et al. (2009) showed, through Os isotopes, that a large input of mantle Os was delivered to the oceans that changed the Os isotopic ratio to be identical to that of that of Ontong Java Plateau basalts. Other proxies for volcanic eruptions, such as mercury, are currently being explored as to providing other ways to measure volcanic signals and their stratigraphic relationships with e.g., carbon isotope anomalies and biostratigraphy (e.g., Percival et al., 2015).

The reasons for the relatively recent interest in the environmental consequences of LIPs go beyond the geochronology and proxy data development. Until the 1960’s and onwards, the understanding of how volcanic systems influence the climate system, and the environment in general, was poorly understood. Early studies of e.g., the Katmai eruption in 1912 suggested a 15-20% reduction in solar radiation due to injections of volcanic ash to the stratospheric (Brookes, 1950, p. 113). The 1963 eruption from Agung in Indonesia and the 1991 Pinatubo eruption in the Philippines were game changers that led to a new wave of research on the atmospheric and climatic consequences of volcanic eruptions, where the atmospheric consequences were measured in real time (e.g., Massop, 1965; Newell, 1970; McCormick et al., 1995). These eruptions provided the first test cases of the effects of a high level SO_2 injection that motivated and paved the road for understanding the consequences of large historical eruptions (e.g., Rampino and Self, 1982), and eventually CO_2 and SO_2 degassing from LIPs (e.g., McLean et al., 1985; Courtillot et al., 1986; Rampino and Volk, 1988; Jones et al. 2016). In addition, the research on the LIP-related volcanic basins showed that vast quantities of additional gases may be generated and released during contact metamorphism of sedimentary rocks around sills (e.g., Svensen et al., 2004, 2009), emphasizing the need for a holistic view on LIP emplacement and how this can relate to Earth changes through time.

5. Concluding remarks

LIPs have been identified and defined on the backbone of centuries of geological research. Historically, this was undertaken based on local and regional studies, often with limited access to a more global picture, and in many cases in extreme or challenging locations. Nevertheless, the early pioneering works soon converged on the idea that there were very large volcanic events that punctuated our Earth's history, converging into the LIPs definitions and examples that we know today. In this contribution, we have touched on the differences and similarities between past and present views on LIPs and the roles they have played in Earth evolution. We conclude that:

- The past 100 years, LIPs have been recognized and understood as unusual igneous and volcanic events that were triggered by large-scale geodynamic changes.
- Within the framework of early studies, some of the key terms (e.g. flood basalt, trap, province, volcanic basins etc.) became more widely used as ways to express these large volcanic events ad associations were explored. Several of these terms date back to research and teaching routed in the 18th and19th centuries.

- Radical improvements of geochronological methodologies the last three decades have shifted our view on LIPs as long-lived, anomalous events (up to several 10’s of m.y.), to geologically rapid volcanic phenomena with main voluminous pulses unfolding on timescales mostly below 1 m.y.
- Together with high-resolution stratigraphy, relevant proxies, and Earth System modelling, LIP processes provides a window into the interior workings of the connecting planet.
- LIP-related research holds the promise for resolving the causes of the Earth’s major revolutions including mass extinctions and rapid climatic change.
- Studies into some of the key LIPs (e.g. the four cases outlined here), has shown that in any one example there are specific elements that only seem to be expressed by the unique set of circumstances found at each LIP. However, on a broader view they share many similarities, which have enabled their definition, required the development of linked ideas and models about their evolution, and will fuel further research into these extra-ordinary Earth events.

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Figure captions

Figure 1. Overview of Large Igneous Provinces. Figure from Coffin et al. (2006b).

Figure 2. Examples of the classic 'Trap' morphology of flood basalts; a) The Siberian Traps, Russia, b) Deccan Traps, India, c) The Ethiopian LIP, d) The North Atlantic Igneous Province, Greenland, e) The North Atlantic Igneous Province, Mull lava series, Scotland, f) The Paranã-Etendeka Province, Namibia.

Figure 3. Large dolerite sills at Finger Mountain, Antarctica, as part of the Karoo-Ferrar province. Inset photo (image courtesy of Bruce Marsh) from Scott's original discovery expedition taken from the base of the cliffs indicated by arrow.

Figure 4. Du Toit’s stratigraphic column of the Karoo Basin including the volcanic and sub-volcanic stages (Du Toit, 1920, p. 4). The black lines represent dikes.

Figure 5. Du Toit LIP reconstruction from 1937 (p. 93). The black areas are “volcanics” and the cross-hatched areas represent “intrusive dolerite”.

Figure 6. Title page of Alexander Chekanovskyi’s report following his reconnaissance fieldwork in East Siberia in the period 1869-1875. He was the first to report the presence of a large tract with volcanic rocks in East Siberia, an important outcome of the expedition.

Figure 7. Early examples of volcanic facies identified in offshore parts of LIPs. A) Seaward dipping reflectors and sediment basalt transition from a transect along the Vøring Basin on the Norwegian Margin (Hinze, 1981). B) Seaward dipping reflectors identified in a profile over the South East part of the Kerguelen Plateau (Colwell et al., 1987).

Figure 8. Present day tectonic configuration of the Ontong Java, Manihiki, and Hikurangi plateaus in the west and south-west Pacific. Modified from Hoernle et al. (2010).

Figure 9. Geochronological results from the Karoo and Siberian LIPs plotted against year of publication. Ages that are included are those that were considered robust and representing the timing (and tempo) of LIP magmatism at the time of publication. The excerpt of the geological time scale is after Cohen et al. (2018). a) Fitch and Miller (1984); b) Encarnacion

et al. (1996); c) Duncan et al. (1997); d) Svensen et al. (2007); e) Jourdan et al. (2008); f) Svensen et al. (2012), updated in Corfu et al. (2016); g) Sell et al. (2014); h) Burgess et al. (2015); i) Palfy et al. (2000); j) Naumov and Makhina (1977); k) Renne and Basu (1991); l) Campbell et al. (1992); m) Basu et al. (1995); n) Dalrymple et al. (1995); o) Burgess et al. (2014); p) Kamo et al. 1996; q) Kamo et al. (2003); r) Reichow et al. 2009; s) Burgess et al. (2015). Abbreviations: SHRIMP: Sensitive high resolution ion micro probe; ID-TIMS: isotope dilution thermal ionization mass spectrometry; AA: Air abraded; CA: chemically abraded.