APPLYING THE TERRESTRIAL LARGE IGNEOUS PROVINCES (LIPs) CONTEXT TO LARGE-SCALE MAGMATISM ON OTHER PLANETARY BODIES. Richard E. Ernst[1,2], Kenneth L. Buchan[3], Simon M. Jowitt[4], and Nasrrddine Youbi[5,6]. [1]Department of Earth Sciences, Carleton University, Ottawa, Canada K1S 5B6, richard.ernst@ernstgeosciences.com, [2]Faculty of Geology and Geography, Tomsk State University, Tomsk, Russia, [3]Geological Survey of Canada, Natural Resources Canada, Ottawa, Canada K1A 0E8, kenneth.buchan@canada.ca. [4]Department of Geoscience, University of Nevada, Las Vegas, Las Vegas, NV 89154-4010, USA. [5]Department of Geology, Faculty of Sciences-Semlalia, Cadi Ayyad University, Marrakesh, Morocco. [6]Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

Introduction: The most important class of intraplate magmatism on Earth is termed Large Igneous Provinces (LIPs). Here we provide a summary of the rapidly evolving understanding of terrestrial LIPs to provide insights into large-scale magmatism on other planetary bodies.

LIPs on Earth: LIPs represent large volume (>0.1 Mkm^3; frequently above >1 Mkm^3; proxied by areal extents of >0.1 km^2 / >1 Mkm^2), mainly mafic (-ultramafic) magmatic events of intraplate affinity that occur in both continental and oceanic settings. They are typically of short duration (<1 myr) or consist of multiple short pulses over a maximum of a few 10s of myr [1]. Individual LIPs comprise volcanic packages (flood basalts), and a plumbing system of dyke swarms, sill complexes, layered intrusions, and crustal underplates. LIP events occur at a variable rate, on average every 20-30 myr.

The origin of LIP's has been controversial with a range of mechanisms proposed including mantle plumes, lithospheric delamination, rift related decompression melting, and edge convection [1]. Accurate and precise age dating (emphasizing the sub-million-year duration of many of these huge events), the presence of giant radiating mafic dyke swarms, seismic tomography, and compositional data for elevated mantle potential temperatures, provide a strong case for a LIP link with mantle plumes whose buoyancy is mainly thermal. Here, we compare the largest types of planetary magmatism [2-5] with constraints from the terrestrial LIP record, noting differences that arise from lack of erosion (Venus, Moon, Mercury), absence of plate tectonics (all), different sizes of bodies (Moon, Mars, Mercury) and different lithospheric thicknesses (Moon and others).

Planetary LIPs and their plumbing systems (see also [2-4]): LIP-type flood basalts are present on Venus as flow fields and shield plains, and on Mars as widespread magmatism (e.g. early Hesperian pulse) and in the walls of Valles Marineris, on Mercury as smooth plains and on the Moon as lunar maria. Venus and Mars also contain major volcanic edifices (large shield volcanoes) with lateral extents of hundreds of km. On Earth, continental shield volcanoes associated with LIPs are rare, although examples include the c. 30 Ma Afro-Arabian LIP. Large terrestrial shield volcanoes are linked with oceanic LIPs, as exemplified by the huge Tamu volcano associated with the c. 150 Ma Shatsky oceanic LIP.

Many giant dyke swarms are associated with terrestrial LIPs. Probable analogues are also present as giant graben-fissure systems on other planetary bodies. Giant radiating systems, thought to be underlain by dykes, are common on Venus and Mars. Mercury has one radiating example (Pantheon) (e.g. [5]), and there are possible lunar examples [5-7]. Radiating dyke swarms on Venus and Mars can be emplaced laterally for hundreds to several thousands of km, analogous to those on Earth. Circumferential graben-fissure systems associated with numerous coronae on Venus and with volcanic edifices on Mars, have been proposed as a possible analogue of a newly recognized class of terrestrial giant LIP-related circumferential dyke swarms [8, 9].

Terrestrial LIPs contain important intrusive components in the form of mafic sills and mafic-ultramafic intrusions. Such bodies must also be present in the crust beneath LIPs on Mars and Venus, and perhaps on Mercury and the Moon. Sills have also been recognized in disrupted terranes on Mars (from melting of cryosphere), and possibly on the moon (associated with floor-fractured craters), but have not yet identified on Venus or Mercury. Possible exposed layered intrusions have also been observed on Mars [10] and may be recognized on the Moon from gravity surveys [6].

Magmatic underplating is a significant component of LIP events on Earth and represents the accumulation of partial melts along the base of the crust above a plume. Underplated magmatism must also be fundamentally important to planetary LIP analogues, and is, for instance, incorporated in some models of corona formation (e.g. [9, 11]).

Plume / LIP clusters: On Earth, mantle plumes occur singly and in regional spatial clusters, the latter sometimes called super-plumes or superplume events (cf. [12]). The most convincing plume clusters are found in the young terrestrial record, where the majority of LIPs are derived from the margins of deep mantle LLSVPs (Large Low Shear Velocity Provinces) presently underlying the Pacific ("Jason") and Africa ("Tuzo") geoid highs and a smaller one near the Europe Asia boundary ("Perm") [13]. These deep mantle features have existed for at least 300 and possibly 500 Ma [13], potentially refuting alternative views that these features are a product of the plate tectonics cycle (i.e., are slab graveyards) that are newly created in each supercontinent cycle. Possible planetary LLSVP equivalents are present on Mars (Tharsis and Elysium) and Venus (e.g. BAT region).

Related magmatic types: Terrestrial LIPs are associated with silicic magmatism, carbonatites and kimberlites [1]. On Earth, major volumes of silicic magmatism are linked to partial melting of lower crustal material during magmatic underplating, a process that has likely occurred on Venus and Mars and may have (in the absence of water-assisted melting) generated A-type granites and high-temperature rhyolites. On Venus, most magmatism is inferred to be mafic, but small regions of presumed silicic magmatism ("pancake domes") have been identified and some crustal plateaus may be partly silicic (e.g. [5]). Long sinuous canali on Venus may have carbonatite composition. Given their terrestrial setting, kimberlites would likely only occur on other terrestrial bodies in areas with thick lithosphere.

Environmental impacts: LIP events on Earth are known to have caused significant environmental and atmospheric changes that include both global warming (due to greenhouse gas release) and global cooling (due to SO_2 release and conversion to sulphate and/or due to weathering), and acid rain [e.g. [14]). Such dramatic environmental changes due to LIPs are linked with mass extinctions. Notably, the Siberian Trap (252 Ma), Central Atlantic Magmatic Province or CAMP (201 Ma) and the Deccan (66 Ma) LIPs have U-Pb ages which precisely match the Permian–Triassic, Triassic–Jurassic, and Cretaceous–Tertiary boundary extinctions, respectively. This suggests that LIP events on other planetary bodies would have similarly affected the atmospheres of these planets. On Venus, voluminous LIP volcanism produced high levels of CO_2 that led to run-away greenhouse effect, and high levels of SO_2 that caused acid rain. On Mars, volcanism and CO_2 emissions also led to periods of global warming (e.g. [15]). Additional planetary atmospheric effects are suggested by the terrestrial LIP record.

On Earth, it is now recognized that a significant component of the gas flux from LIP events comes from interaction of intrusive with volatile rich host rocks, which produces massive release of gases through brecciated zones called Hydrothermal Vent Complexes (HVCs) that reach the surface from depths of up to 8 km [16]. Could HVCs be a factor on Mars?

Link with ore deposits: Terrestrial LIPs represent significant reservoirs of energy and metals that can either drive or contribute to a variety of metallogenic systems, and also affect hydrocarbon and aquifer systems [1, 17]. LIPs can provide the energy, fluids, and/or metals for mineral deposit types such as orthomagmatic Ni-Cu-PGE sulphides, native Cu, hydrothermal volcanogenic massive sulfide (VMS) and iron oxide-copper-gold (IOCG). Dykes and sills can be barriers to sub-surface fluid flow and/or as reaction zones that control mineralizing. Surface weathering of LIP rocks can also form Ni–Co laterites, and Al bauxites from exposed LIP mafic-ultramafic rocks. This in turn indicates that LIP events (or analogues) on Mars, Venus, the Moon and Mercury may also have generated significant mineralization (e.g. [18,19]). For example, LIP magmatism on Mars has the potential to have generated orthomagmatic Ni-Cu-PGE sulfide and cumulate chromite mineralization. The weathering of these basalts (as well as any magmatic sulfides) may have generated gossans and abiotic banded iron formations that are somewhat analogous to some of the weathering-related LIP mineralization on Earth (e.g. bauxites, laterites). Lunar maria may be associated with the genesis of Fe-Ti-V, Cr, and potentially native Fe-Ni metal mineralization.

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