**DYKE-INDUCED GRABEN ON VENUS AND MARS: ANALOGUES FOR EARTH'S ROCK RECORD?** L. B. Aspler[1] and R. E. Ernst[2], [1](23 Newton St. Ottawa, ON, Canada K1S 2S6, nwtgeol@sympatico.ca), [2]Geological Survey of Canada (601 Booth St. Ottawa, ON, Canada, K1A 0E8, rernst@nrcan.gc.ca).

**Introduction:** Graben on Earth are generally attributed to regional extension from plate motions ("lithosphere-activated") or from doming above magma plumes ("mantle-activated"). However, widespread graben, fissure, and fracture systems on Venus and Mars are thought to have formed during, and as a consequence of, the near-horizontal injection of magma in dykes [1-7]. These structures appear to trace the paths of subsurface dykes that propagated laterally under high magma pressure and established the near-surface horizontal extension conducive to normal faulting. Throughout its history, Earth has witnessed magmatic events that produced giant dyke swarms resembling those of Venus and Mars [3, 5]. Nonetheless, few examples of dyke-induced graben have been reported from Earth's rock record, although such graben have been observed in modern settings (e.g., Hawaii, Iceland, Long Valley, Afar, Mt. Etna, Juan de Fuca Ridge [8-12]). Herein we describe four such examples, ranging in age from Paleoproterozoic to Tertiary. Dyke-induced graben may be more commonly preserved on Earth than hitherto appreciated, constituting a unique class of extensional structure analogous to those on Venus and Mars.

**Dyke-induced graben on Venus and Mars:** On Venus, 163 radiating graben systems were observed in a global study using 225 m/pixel Magellan radar data [2]; a detailed study used 75 m/pixel Magellan images, to document 34 radiating swarms (8 of >1000 km radius) and 26 linear swarms in an area 16 million $km^2$ [7]. On Mars, the Tharsis region contains numerous graben systems extending in fanning patterns up to 4000 km from volcanic centres [4-6]. On Venus, graben are typically 1-2 km wide and 10's of m deep, whereas on Mars, graben are 1-5 km wide and 10's to 100's of m deep. On both planets, many graben are underlain by dykes, as indicated by graben-emanating lava flows, an association with sub-parallel pit chains and lines of small shield volcanoes, continuity beyond central uplifts, and a geometric similarity to giant dyke systems on Earth [2, 3, 5, 6]. These graben may be analogues useful for interpreting Earth's rock record.

**Modern dyke-induced graben on Earth:** Extensional faults and dykes are common in modern volcanic regions. In some cases, geodetic, seismic, and field observations document a genetic relationship; initiation of fault movement a few hours after lateral dyke propagation demonstrates that dyking triggers faulting [9, 10]. Although graben are up to several km wide, subsidence is generally trivial (<1 m), constituting only 25-40% of horizontal extension and dyke width [8, 10]. Notable exceptions are at the Juan de Fuca Ridge, where narrow (1-3 m) dykes induced up to 15 m subsidence in narrow (10-100 m) graben [8]. Using the models of Pollard et al. [11] and Mastin and Pollard [12], which indicate a dramatic increase in horizontal extension as dykes approach the surface, Chadwick and Embley [8] attributed this geometric contrast mainly to ambient stress field. Accordingly, in regions "primed" by high ambient horizontal extension, faulting is possible with small perturbations from dykes; deep dykes produce wide shallow graben. In contrast, where large magma volumes and frequent dyking result in low ambient horizontal extension (e.g. rapidly spreading Juan de Fuca Ridge), dykes must travel to shallow levels before tensile strengths of host rocks are exceeded and normal faulting can occur; shallow dykes produce narrow deep graben.

**Dyke-induced graben in Earth's rock record:** Two examples (Kaminak, Franklin) provide a glimpse of dykes and graben preserved at present erosional levels; two (Mull, Gunbarrel) are inferred from seismic and magnetic data. Conglomerates previously thought to have been deposited in a graben originating above a dyke linking parts of the 2.44 Ga Koillismaa complex in Finland [5], have been reinterpreted as hydrothermal breccias [13], and hence record dyke-induced fracturing rather than dyke-induced graben formation.

*Kaminak dykes and Spi Group, western Churchill Province, Nunavut, Canada.* Emplaced at ~ 2.45 Ga, a time of global mafic magmatism, the Kaminak dykes record the earliest stages in the protracted breakup of a Kenorland, a possible Neoarchean supercontinent [14]. Plagioclase megacryst-bearing gabbros cut Neoarchean supracrustal and allied plutonic rocks, are near-vertical, and N- NE-trending. Concentrated at Kaminak Lake, they are <1 m to several 10's of m wide; some may be traced along strike for several km. Exposed near Kaminak Lake, the Spi Group is a subaqueous to subaerial rift sequence deposited unconformably above Neoarchean basement and preserved in a single NNE-trending syncline, <1 km wide and up to 10 km long [15, 16]. It consists of a lower mafic volcanic-sandstone unit (75-100 m thick) and an upper conglomerate unit (400 m thick). Beavon [15] emphasized the similarity between Spi Group basalts containing plagioclase megacrysts and the Kaminak dykes. In addition, the axial trace of the syncline preserving the Spi Group is sub-parallel to nearby Kaminak dykes. Beavon [15] suggested that the Spi Group may represent deposition in a local basin formed during dyke emplacement. In support of this interpretation, the Spi Group and the Kaminak dykes have virtually identical geochemical, rare earth element, and Nd-isotopic signatures [17].

*Franklin dyke swarm and Natkusiak Formation, Victoria Island, NWT, Canada.* Voluminous mafic magmatism, comprising the Gunbarrel (780 Ma) and Franklin (723 Ma) events in northern Canada [18], heralded breakup of the supercontinent Rodinia [19]. Franklin dykes extend >1200 km from a plume centre near Victoria Island. Unconformably beneath the Natkusiak flood basalts, several narrow (<0.5 km) graben sub-parallel nearby Franklin dykes, and are filled by debris flow diamictites 25-100 m thick [20]. Bounding faults fail to penetrate overlying basalt flows, indicating a local transition from dyking and graben formation to subaerial volcanism [20].

*Mull dykes and mini-graben, southern North Sea.* Seismic and marine magnetic data from the southern North Sea has revealed a series of graben considered cogenetic with subjacent dykes [21]. Linear magnetic anomalies reflect the continuation of the Mull swarm (56 Ma) in Great Britain, emplaced during opening of the Atlantic Ocean [22]. The graben coincide with the dykes, appearing on seismic lines as narrow (<0.5-2 km), sub-parallel channel-like features (up to 300 m thick) that extend for 70-80 km [21]. They are symmetric in cross section and, bounded by inward-dipping listric normal faults, display an infill pattern in which sedimentary units onlap and thin outward, extending up to 3 km away from graben edges [21].

*Gunbarrel dyke swarm and Shaler Supergroup, Mackenzie Valley, Northwest Territories, Canada.* The full regional extent and geometry of dykes related to the breakup of Rodinia is uncertain because of Phanerozoic cover in the Mackenzie Valley region, which separates exposures in the Canadian Shield from those in the Canadian Cordillera. A set of N- and NW-trending dykes, extending from north of Great Bear Lake to the Mackenzie Delta, has been identified using highpass filter images of aeromagnetic data. A seismic line [23] across the projection of these dykes reveals a 2 km wide, 750 m deep graben similar to those in the North Sea. We suggest a genetic relationship between this graben, filled by ~780 Ma rocks of the Shaler Supergroup [23], and a subjacent dyke.

**Discussion:** Wide, shallow dyke-induced graben, such as found in regions of high ambient extensional stress on modern Earth, are unlikely to be preserved unless their formation is followed immediately by burial due to regional basin subsidence. Narrow, deep dyke-induced graben, such as found at ocean spreading centres with voluminous dyking and low ambient extensional stress (e.g. Juan de Fuca Ridge) compare better to ancient examples, which contain thick volcano-sedimentary sections and record significant subsidence. But, because oceanic crust is consumed by subduction, these also have a low preservation potential. Preserved due to minimal surface erosion and lack of plate tectonics, dyke-induced graben on Venus and Mars display significant subsidence, and thus may be better analogues for ancient examples on Earth, despite differences in crustal thickness, density, and structure. In view of the abundance of dyke-induced graben on Venus and Mars, we suggest that many similar structures have gone unrecognized in Earth's rock record. These may be discovered by future studies integrating field, geochemical, seismic, and magnetic data. Such graben have the potential to host small paleoplacer (gold, diamond, platinum group element), massive sulphide, and hydrocarbon deposits.

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