Interactions between continent-like ‘drift’, rifting and mantle flow on Venus: gravity interpretations and Earth analogues

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Abstract: Regional shear zones are interpreted from Bouguer gravity data over northern polar to low southern latitudes of Venus. Offset and deflection of horizontal gravity gradient edges (‘worms’) and lineaments interpreted from displacement of Bouguer anomalies portray crustal structures, the geometry of which resembles both regional transient shear zones bounding or cross-cutting cratons and fracture zones in oceanic crust on Earth. High Bouguer anomalies and thinned crust comparable to the Mid-Continent Rift in North America suggest underplating of denser, mantle-derived mafic material beneath extended crust in Sedna and Guinevere planitia on Venus. These rifts are partitioned by transfer faults and flank a zone of mantle upwelling (Eistla Regio) between colinear hot, upwelling mantle plumes. Data support the northward drift and indentation of Lakshmi Planum in western Ishtar Terra and >1000 km of transient displacement between Ovda and Theitis regions. Large displacements of areas of continent-like crust on Venus are interpreted to result from mantle tractions and pressure acting against their deep lithospheric mantle ‘keels’ commensurate with extension in adjacent rifts. Displacements of Lakshmi Planum and Ovda and Theitis regions on Venus, a planet without plate tectonics, cannot be attributed to plate boundary forces (i.e. ridge push and slab pull). Results therefore suggest that a similar, subduction-free geodynamic model may explain deformation features in Archaean greenstone terrains on Earth. Continent-like ‘drift’ on Venus also resembles models for the late Cenozoic–Recent Earth, where westward translation of the Americas and northward displacement of India are interpreted as being driven by mantle flow tractions on the keels of their Precambrian cratons.

Supplementary material: Bouguer gravity and topographic images over a segment of the Mid-Atlantic ridge and Ross Island and surrounds in Antarctica, principal horizontal stress trajectories about mantle plumes on Earth, map and interactive 3D representations of cratonic keels beneath North America from seismic tomography, and a centrifuge simulation for comparison with Venus in support of our tectonic model are available at http://www.geolsoc.org.uk/SUP18736.

Venus, although similar to Earth in size, inferred internal composition and surface gravity, does not show any features that characterize plate tectonics on Earth, namely subduction zones, volcanic arcs, obvious seafloor-spreading ridges offset by transform faults, and large translations and rotations of distinct lithospheric plates (Anderson 1981; Kaula & Phillips 1981; Phillips et al. 1981; Solomon et al. 1991, 1992; Solomon 1993; Phillips & Hansen 1994; Simons et al. 1994, 1997; Grimm 1998; Hansen 2007; Smrekar et al. 2007; Watters & Schultz 2009; McGill et al. 2010; Moeres et al. 2013). It has, nevertheless, been suggested by van Thienen et al. (2004) that it is theoretically possible for subduction and plate tectonics to have occurred in Venus’ past, but for which no evidence remains following Venus’ resurfacing (Strom et al. 1994). The terrestrial planets, with the notable exception of Earth, have traditionally been thought to experience a stagnant lid convection regime where a very viscous–rigid ‘lid’ that covers the entire planet overlies active convection in the underlying hot mantle (Solomatov & Moresi 1996, 1997; Moresi & Solomatov 1998; O’Rourke & Korenaga 2012). More recent and detailed two-dimensional (2D) numerical modelling by Armann & Tackley (2012) suggests that stagnant lid convection, alternating with episodic convection with approximately 150 million-year overturn events, best explains Venus’s tectonic development. Convective cells on Venus are estimated to be around 600–900 km to (exceptionally) 2000 km wide (Solomatov & Moresi 1996). The present lithospheric thickness of Venus is estimated at <150 km by Nimmo & McKenzie (1998) and Smrekar & Parmentier (1996); van Thienen et al. (2004) suggested that the lithosphere may be thicker beneath continent-like planae, and to be thus similar to Earth. Orth & Solomatov (2012) proposed an average lithospheric thickness of between 300 and 500 km, and a crustal
thickness between 20 and 60 km. James et al. (2013) provided estimates of lithospheric thickness between 100 and 200 km, but with lower estimates of 8–25 km for the average crustal thickness, and crustal thicknesses calculated at between 41 and 60 km beneath Lakshmi Planum and surrounding fold belts (Fig. 1).

The geology and broad stratigraphic framework of Venus are portrayed in a global map by Ivanov & Head (2011, 2013). Volcanic zones, broad topographical rises, positive gravity anomalies, radiating rifts and dykes, and annular features such as coronae (Barsukov et al. 1986) are taken as evidence for hotspots or upwelling hot mantle plumes (Barsukov et al. 1986; Phillips et al. 1991; Bindschadler et al. 1992; Smrekar 1994; Smrekar & Stefan 1997; Phillips & Hansen 1998; Ernst & Desnoyers 2004; Basilevsky & Head 2007). Venus Express VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) thermal emissivity

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**Fig. 1.** (a) Combined Magellan radar and elevation image showing the location of areas described in Ishtar Terra, and the lowlands of Sedna and Guinevere planitia. (b) Simplified terrain subdivision and tectonic model for fold and shear belts surrounding Lakshmi Planum of the radar image shown in (c). (c) False-colour Magellan radar image for Lakshmi Planum and surrounds. Black bands are areas of no data. For detailed geological interpretation, see Ivanov & Head (2010a, b) for the Lakshmi Planum area and Marinangeli & Gilmore (2000) for the Akna Montes–Atropos Tessera region in the west of the interpreted area. The geometry of thrusts and transcurrent/transpressional shear zones on the NW, northern and NE margins is interpreted as Himalayan-style indentation and lateral escape (but without plate tectonics) resulting from the northward displacement of Lakshmi Planum in the first shortening event (D1). Thrusts east of Lakshmi Planum and NE-striking dextral shear zones are attributed to a second event (D2) of bulk WSW–ENE shortening. Images are from NASA/JPL; the interpretation in (b) is modified after Harris & Bédard (2014).
measurements were taken by Smrekar et al. (2010) to suggest the presence of young to possibly active hotspot-related volcanism, refuting early ideas that Venus is no longer tectonically or volcanically active (e.g. Kerr 1994). The interpretation of presently active volcanism is, however, questioned by Ivanov & Head (2010c), although they suggest volcanic eruptions have occurred in the last several decades (cf. Bondarenko et al. 2010). The stagnant lid, mantle plume-dominated tectonics of Venus contrast to mobile lid convection on Earth (Moresi & Solomatov 1998) where the lithosphere moves as discrete, rigid plates, and oceanic crust formed at active spreading ridges is consumed at subduction zones. In the tectonic environment presently envisaged for Venus, large, regionally coherent displacements of crustal blocks/terrains have not been considered likely.

Harris & Bédard (2014), however, documented horizontal displacements and polyphase folding and shearing on Venus interpreted from Magellan radar images of Venus’ surface. The most spectacular of these examples is in western Ishtar Terra where regional folds, thrusts, and transcurrent and transpressional shear zones surrounding the craton-like Lakshmi Planum define a geometry identical to structures produced during indentation and lateral escape of the Himalayan–Indochina system on Earth (Harris & Bédard 2014; Fig. 1). Our research builds upon radar interpretations made by Kaula et al. (1992; who described detailed radar images of convergent fold belts, thrusts and regional transcurrent shear systems, but without any regional synthesis) and provides structural evidence for comparisons with indentation and lateral escape tectonics on Earth suggested by Crumpler et al. (1986; expanded upon in Moores et al. 2013), Markov (1986) and Head et al. (1990). This paper presents interpretations of enhanced gravity data on Venus to demonstrate that shear zones bounding Lakshmi Planum (interpreted from radar images) are crustal-scale structures that form part of a coherent regional system of shear zones, which is identified for the first time. Gravity data are also used to highlight regional crustal-scale rifts, the extent of which appears to have been underestimated in prior maps derived from radar images. The nature of the mechanisms causing large horizontal displacements on Venus without plate tectonics is discussed, and the interaction between rifting, transcurrent faulting, and indentation tectonics as recognized in Ishtar Terra are developed, drawing on comparisons with analogous plume-related features on Earth.

Recent geophysical and GPS data, as well as numerical modelling for Earth highlight the importance of horizontal traction on the base of deep continental roots as a force that helps to drive displacement of continents (e.g. Bokelmann 2002a, b; Liu & Bird 2002; Eaton & Frederiksen 2007; Alvarez 2010; Faccenna et al. 2013; Ghosh et al. 2013), in addition to the action of plate boundary forces such as ridge push, slab pull, and trench suction (Forsyth & Uyeda 1975). This implies that, even on Earth, modern plate tectonics is not required for the displacement ('drift') of continents, as is frequently assumed; if there were no plate boundary forces, then continental drift and resulting orogenesis on Earth would probably still occur, albeit more slowly. There is an active debate about when plate tectonics on Earth started, and whether the formation and deformation of Archaean terrains resulted from plate tectonic processes such as subduction and arc accretion (reviewed in Bédard et al. 2013 and Harris & Bédard 2014). Studies of Venus thus help us better understand tectonic processes operative in an Archaean Earth (cf. Anderson 1981; McGill 1983; Morgan 1983; Markov 1986; Markov et al. 1989; Glukhovskiy et al. 1995; Sorokin & Ushakov 2002; Stern 2004; Hansen 2007; Head et al. 2008; Van Kranendonk 2010).

Previous studies of faulting and brittle-ductile shearing on Venus

Despite the absence of plate tectonics, Venus displays diverse volcanic and tectonic features (folds, faults and brittle–ductile shear zones) indicative of regional lithospheric shortening and extension, many of which are similar to those developed on Earth (Crumpler et al. 1986; Head et al. 1990, 1992; Kaula et al. 1992; Solomon et al. 1992; Watters 1992; Hansen et al. 1997; Smrekar et al. 1997; Hansen 2007; Watters & Schultz 2009; McGill et al. 2010; Harris & Bédard 2014). Whilst detailed structural interpretations of radar images (cited above and in the following sections) have been undertaken, they are mainly concerned with relatively small regions and regional tectonic overviews have focused on the distribution of volcanic features (e.g. Pronin & Stefan 1990; Head et al. 1992; Stefan et al. 1992; Price et al. 1996), impact craters (Price et al. 1996), mafic dykes (e.g. Grosfils & Head 1994; Ernst et al. 1995, 2003), wrinkle-ridges and fractures (e.g. Hansen & Olive 2010), and rifts (e.g. Price et al. 1996; Basilevsky & Head 2000). Regional geological mapping coordinated by the USGS (United States Geological Survey) has been based almost exclusively on interpretation of geomorphological features from radar images (Tanaka et al. 2010; e.g. ‘ridge crests’, ‘wrinkle ridges’ or ‘large ridges’ are mapped instead of folds), and guidelines (Tanaka et al. 1994, 2011) advise curtailing the amount of structural elements included in regional maps. The global distribution of principal structural
elements is portrayed by Ivanov & Head (2011); a detailed interpretation of much of the planet is also included in Hansen & Olive (2010).

**Normal faults and regional rifts**

The recognition of rifts on Venus has largely been based on radar-image interpretation of normal-fault-bounded graben as linear rifts radiating from volcanic centres termed novae, concentric, annular rifts rimming coronae (e.g. Solomon et al. 1994; Crumpler et al. 1993; Ernst et al. 1995; McGill et al. 2010; Studt et al. 2011), closely spaced graben in tessera terrains (Gilmore et al. 1998) and as deep (Watters & Schultz 2009) canyons/graben termed chasmata that are thousands of kilometres long (e.g. Solomon et al. 1992). Linear rifts and dyke swarms on Venus have been likened to those on Earth (Solomon 1993; Ernst et al. 1995; Foster & Nimmo 1996), but on Venus, rifts are about 3 times greater in width than plume-related rifts on Earth, which is attributed to the absence of thick sediment infill (Foster & Nimmo 1996). Low magnitudes of crustal extension due to normal faulting were calculated by Connors & Suppe (2001) from slope measurements, although they acknowledged that their calculations of extension did not include the likely contribution of ductile to brittle–ductile extension and necking. Given its high mean surface temperatures (estimated at 462 °C by Seiff et al. 1985 – see NASA http://sse.jpl.nasa.gov/planets/profile.cfm?Object=Venus&Display= Facts&System=Metric (accessed June 2013) – and as deep as 241 and 441 °C for Venus’ southern hemisphere by Mueller et al. 2008), the brittle–ductile transition on Venus is expected to occur at a shallower depth than on Earth (McGill et al. 2010; Violy et al. 2010).

Large volcanic ‘flow fields’ on Venus are equated to terrestrial flood basalts or large igneous provinces (LIPs) in areas of lithospheric extension and thinning linked to mantle upwelling or mantle plumes (Lancaster et al. 1995; Magee & Head 2001; Ernst & Buchan 2003; Ernst & Desnoyers 2004; Ernst et al. 2007; Hansen 2007). Spreading centres and associated oceanic transform faults similar to those on Earth have not, however, been confirmed on Venus (Phillips et al. 1991; Watters & Schultz 2009), although transform-like faults were proposed by Crumpler et al. (1987; an interpretation we do not agree with, as discussed below). Although most models for rifting on Venus infer mantle upwelling or hot thermal plume origins, normal faulting has also been attributed to diapiric (i.e. Rayleigh–Taylor/density-driven) uplift (Hoogenboom & Houseman 2005) and gravitational collapse (e.g. Solomon 1993; Keep & Hansen 1994).

**Strike-slip faulting**

Regional transcurrent (strike-slip) faults with up to 450 km of displacement on individual faults, and with cumulative transcurrent displacement of up to 2000 km, were identified in early studies of Venus (e.g. Crumpler et al. 1986, 1987; Crumpler & Head 1988; Sukhanov & Pronin 1988; Kozak & Schaber 1989; Vorder Bruegge et al. 1990) and are implicit in the interpretations of Head et al. (1990), Pohn & Schaber (1992) interpreted strike-slip fault geometries that they likened to indentation-style tectonics on Earth, and conjugate strike-slip faults were interpreted by Watters (1992). The presence of broad brittle–ductile shear zones, as well as discrete faults, was also recognized early in Venus mapping. For example, Vorder Bruegge et al. (1990) drew comparisons between en échelon folds and pull-apart graben with similar structures formed during wrenching along the San Andreas fault system on Earth (cf. Wilcox et al. 1973; Sylvester 1988). Additionally, Hansen (1992) and Kaula et al. (1992) interpreted sigmoidal deflection of fold-axial traces and their angular relationship to, and truncation by, transcurrent faults as equivalent to regional-scale S/C structures (drawing comparison with structures in mylonitic rocks described by Berthé et al. 1979). Despite these early interpretations, Solomon et al. (1992, p. 13 199) and Solomon (1993, p. 50) stated that ‘few large-offset strike slip faults … have been observed’ and interpreted strike-slip faults as local features developed to accommodate horizontal displacements during crustal shortening or stretching. Bindschadler et al. (1992) considered that development of long strike-slip faults on Venus is inhibited by the absence of water. The ensuing misperception for limited transcurrent displacements on Venus (as noted by Fernández et al. 2010) has been carried forward in subsequent reviews of faulting on planetary bodies (e.g. Schultz 1999; Schultz et al. 2010) and comparisons between the tectonics of Venus and Earth (e.g. Montési 2013). Numerous radar interpretation studies carried out since Solomon (1993) have, nevertheless, continued to illustrate the presence of conjugate strike-slip faults (e.g. Willis & Hansen 1996; Hansen 2007; Yin & Taylor 2011) and regional strike-slip faults and transcurrent wrench zones with displacements of up to hundreds or even thousands of kilometres along them have been mapped (e.g. Raitala 1994, 1996; Brown & Grimm 1995; Ansan et al. 1996; Hansen & Willis 1996; Koenig & Aydin 1998; Tuckwell & Ghail 2003; Kumar 2005; Romeo et al. 2005; Chetty et al. 2010; Fernández et al. 2010). Mechanisms for the formation of regional strike-slip faults and the relationship (if any) to rifting (as postulated by Markov et al. 1989) have, nevertheless, remained uncertain.
Strike-slip faults are found on other planetary bodies as well as on Earth and Venus, such as Mars (Schultz 1989; Bistacchi et al. 2004; Anguita et al. 2006; Okubo & Schultz 2006; Borracchini et al. 2007; Yin 2012), Mercury (Massironi et al. 2012, 2014), Jupiter’s moons Europa (Hoppe et al. 1999; Tufts et al. 1999; Kattenhorn 2004; Aydin 2006; Kattenhorn & Marshall 2006), Io (Bunte et al. 2010) and Ganymede (Pappalardo & Collins 2005), and Saturn’s moon Enceladus (Smith-Konter & Pappalardo 2008; Patthoff & Kattenhorn 2011). Arguments that formation of strike-slip faults implies the existence of rigid plates and, hence, modern plate tectonic processes (Pohn & Schaber 1992; Sleep 1994; Yin 2012) are clearly refuted by Fernández et al. (2010). Concepts for tectonic mechanisms for regional lateral displacements without plate tectonics are developed below.

Folds and reverse/thrust faults

Folds (including, but not limited to, ‘ridge belts’ and ‘wrinkle ridges’) deform volcanic plains, and regional folds and reverse/thrust faults have developed along the margins of plateaux, tesserae and coronae (e.g. Head et al. 1990; Suppe & Connors 1992). The formation of these contractional features is variably attributed to compensation of extension in adjacent rifts (Markov et al. 1989), local shortening and crustal thickening (Solomon 1993), flexure and underthrusting of young lithosphere against a more rigid block (Head et al. 1990), gravitational spreading due to elevation differences (Smrekar & Solomon 1992), thermal expansion (Solomon et al. 1999) or contraction (McGill et al. 2010), mantle downwelling (Markov et al. 1989; Kiefer & Hager 1991; Bindschadler et al. 1992), or the far-field contraction resulting from mantle flow about upwelling hot plumes (Mège & Ernst 2001). As on Earth, refolded folds on Venus (e.g. Harris & Bédard 2014) are taken as evidence for changes in the orientation of the regional stress and/or displacement field.

Bouguer gravity field and crustal thickness of Venus

A detailed map of the free-air gravity field of Venus was acquired during the 1993 Magellan mission from accelerations and decelerations calculated from line-of-sight doppler shift, where aerobraking was used to establish a low orbit with 36% ellipticity (Solomon 1993; Kaula 1996; Konopliv & Sjogren 1996) (during aerobraking, Magellan’s apoapsis was lowered from 8500 to 500 km; its periapsis was 180 km). (Differences between free-air and Bouguer gravity, and their implications relevant to planetary geological interpretations, are explained in simple terms by Lakdawalla 2012.) Gravity data from the previous Venera (Barsukov et al. 1986) and Pioneer Venus Orbiter missions (Solomon 1993) infill many areas lacking Magellan data. As shown by comparison with early satellite gravity for Earth (e.g. Sandwell 1992), the spatial resolution of 110 km for the final, processed Magellan gravity data obtained near the equator and of 180 km at higher latitudes (Kaula 1996) makes these data suitable for regional-scale mapping of crustal- to lithospheric-scale features (especially where the total horizontal gradient is used to delineate structural features). Gravity anomalies have been used in geoid, admittance and flexural rigidity calculations (Solomon 1993 and references therein; Konopliv & Sjogren 1996; Simons et al. 1997; Barnett et al. 2000; Anderson & Smrekar 2006; Wieczorek 2007) to calculate crustal thickness (Simons et al. 1997; Anderson & Smrekar 2006; Wieczorek 2007; James et al. 2013, whose data we present below) and to create models that support the presence of mantle plumes (Bindschadler et al. 1992; Herrick & Phillips 1992; Solomon 1993; Kiefer & Peterson 2003; Vezolainen et al. 2003). Previous studies of regional free-air anomalies suggest that:

- gravity lows are due to less dense crust that extends deeper into the mantle or areas of higher temperature and less dense crust;
- there is a high correlation on Venus between the free-air gravitational field and topography, suggesting deep compensation through convective upwelling or downwelling (Solomon 1993; Rummel 2005).

The Bouguer gravitational anomaly field for Venus (Sjogren & Konopliv 2008; developed from the original 1997 gravity data updated with degree 180 harmonic coefficients by Konopliv et al. 1999) was calculated by these authors using a reference density of 2900 kg m$^{-3}$ based on average basaltic crust (which contrasts to 2650 kg m$^{-3}$ generally used on Earth, the average density of felsic/continental crust). Despite the excellent gravity coverage, Bouguer anomaly maps have not been (to our knowledge) previously used in interpreting regional, crustal-scale faults on Venus. Spectrally filtered and enhanced gravity data and edges in the horizontal gradient of Bouguer gravity (commonly termed gravity ‘worms’) are regularly used for mapping regional-scale faults/shear zones and lithological contacts on Earth (e.g. Blakely & Simpson 1986; Archibald et al. 1999; Bierlein et al. 2006; Vos et al. 2006; Austin & Blenkinsop 2008; Heath et al. 2009; Henson et al. 2010; Glen et al. 2013; Dufréchou et al. 2014; Harris & Bédard 2014),
including the entire Earth (Horowitz et al. 2000). The same approach is applied to Venus in the following subsections.

The total Bouguer gravity field for northern polar to low southern latitudes of Venus, covering the Ishtar and western Aphrodite terrae and the Sedna, southern Snegurochkha and Niobe planitiae presented in Figure 2a (place names not shown in this figure are shown in Fig. 1), shows that:

- Ishtar Terra (whose geology is described by Kaula et al. 1992; Marinangeli & Gilmore 2000; Ivanov & Head 2008, 2010a, b) and Aphrodite Terra (including Ovda Regio mapped by Bleamaster & Hansen 2005) are marked by regional Bouguer lows down to −300 mGal.

- Subcircular Bouguer lows in the SW of the map correspond to Beta and Phoebe regionen, which are elevated volcanic centres with thick crust and radiating graben (including Devana Chasma) interpreted to overlie upwelling mantle plumes (Kiefer & Peterson 2003; Vezolainen et al. 2003). Beta Regio is interpreted to overlie a cluster of mantle plumes by Ernst et al. (2007).

- An ESE–WNW-trending broad Bouguer high (up to c. 130 mGal) is developed over the 1500–2000 km-wide ‘lowland’ volcanic plains (Stofan et al. 1987) of Sedna Planitia south of Ishtar Terra. An approximately 5000 km-long Bouguer gravity high bifurcates south of Lakshmi Planum. The northern branch continues for about 14 000 km towards the east and passes approximately 1500 km to the north of Aphrodite Terra, where it is locally punctuated by Bouguer lows over volcanic centres, including Bell and Tellus regionen. The southern branch, which strikes more southeasterly, corresponds to Guinevere Planitia and ends abruptly after about 7000 km to the west of Ovda Regio.

- The two linear gravity highs of Sedna and Guinevere planitiae are separated by Eistla Regio, a region of lesser Bouguer anomalies dominated by tight groups of volcanos and coronae, attributed to underlying plume clusters by Ernst et al. (2007).

- North of Ishtar Terra, Snegurochkha Planitia, a region marked by volcanic plains formed in a tensile stress field (Hurwitz & Head 2012), is also marked by a broad, diffuse gravity high. This polar region lies outside the area covered by the present research and has not been examined further.

Figure 2b portrays high-frequency (i.e. ‘shallow-source’) components of the Bouguer field (cf. data defined by the shallow slope of the MGNP180U power spectrum plot of Wieczorek (2007, fig. 4), equating to a spherical harmonic degree ˃40).

Thickness variations of Venus’ crust calculated from inversion of gravity data by James et al. (2013) were gridded and are presented in 2D and 3D in Figure 3. From the comparison of total and ‘shallow-source’ Bouguer gravity and crustal thickness images, it can be seen that:

- Lakshmi Planum has a uniformly thick crust (Fig. 3a), yet can be divided into a northern shallow-source gravity high and a southern shallow-source gravity low (Fig. 2b). Similar marked lateral changes occur across all of Ishtar Terra where they correspond to strong gradients highlighted by gravity ‘worms’ (Fig. 2b). Jull & Arkani-Hamed (1995) and Arkani-Hamed (1996) suggested that the density perturbations over Ishtar Terra that were determined from a similar spectral analysis of gravity data required lateral variations in rock type, and that crust beneath Ishtar Terra and surrounding mountain belts may contain considerable amounts of low-density material. We concur with their conclusions and suggest that gravity lows in Lakshmi Planum may indicate either the presence of low-density, most probably felsic, rocks in the upper crust underlying the surface basaltic flows mapped by Ivanov & Head (2010a, b) or, as the contact between shallow-source gravity highs and lows coincides with their mapped textural boundaries, some flows mapped as basaltic may instead be more felsic. Although Venus has been thought to be dominated by basaltic crust, there is increasing evidence from emissivity data for felsic volcanism, and tessera/highlands material may also be felsic in composition (Nikolaeva et al. 1992; Hashimoto et al. 2008; Helbert et al. 2008; Mueller et al. 2008; Basilevsky et al. 2012), which is supported by petrological modelling (Shellnutt 2013). Given that felsic magma may be generated in oceanic plateaux on Earth above high-temperature mantle plumes and/or spreading ridges such as Iceland (Annen et al. 2006; Willbold et al. 2009), the presence of granites or felsic lavas in the craton-like areas of Ishtar and Aphrodite terrae is consistent with models for initial crustal thickening and plateau formation above an upwelling mantle plume. Felsic crust is not only less dense but also rheologically much weaker (more ductile) than mafic crust; this may have strong consequences for enhancing crustal deformation intensity and, especially, crustal thickening (T. Gerya, pers. comm. 2013) if felsic crust is also present on the margins of these craton-like plateaux.

- The linear gravity highs south of Ishtar Terra in the total Bouguer gravity portrayed in Figure 2a correspond to belts of thinned crust
Fig. 2. (a) Bouguer gravity for the area of Venus examined in this study. Reference density is 2900 kg m\(^{-3}\). The ‘continent-like’ Ishtar and Aphrodite terrae, and Beta and Phoebe regiones (interpreted to overlay mantle plumes or plume clusters) are marked by Bouguer gravity lows. Bouguer highs in Sedna and Guinevere planitias (which are not present on the short-wavelength component in b) correspond to thinned crust (Fig. 3) and mark dense mafic underplated mantle material beneath rift zones. Localized subcircular areas of lower Bouguer gravity that punctuate the linear highs lie above interpreted mantle plume centres or plume clusters from Ernst et al. (2007). Dots marking edges in the horizontal gradient (i.e. gravity ‘worms’) highlight lithological contacts and faults. Transcurrent shear and transfer zones (rift area) are interpreted from offset of gravity anomalies and worms. The rectangle shows the area in Figure 1b, c. The offset of gravity worms on either side of Lakshmi Planum confirms the indentation model based on radar-image interpretation (Harris & Bédard 2014). (b) Short wavelength (i.e. shallow-source) Bouguer gravity for the same area as in (a) overlain by worms and shear interpretation. Short-wavelength highs and lows over Ishtar and Aphrodite terrae suggest variations in lithology of the upper crust; this is supported by the correspondence between the boundary between anomalies and mapped morphological contacts in Lakshmi Planum mapped by Ivanov & Head (2010a), and raises the likelihood for there being more felsic flow units in addition to basalts in Venus’ highlands. Names of interpreted plume clusters are given in the caption to Figure 3.
Fig. 3. Crustal thickness and structural interpretation. Images were prepared from data calculated and provided by P. James (presented in James et al. 2013). (a) Map view. The pattern of structures is explained by two generations of rift-bounding normal faults; however, the lack of any geochronological data on Venus precludes any validation that structures with the same orientation are contemporaneous. The ensuing displacements of areas of continent-like crust in terrae imply changes in regional stress field. Superposed faults are interpreted from gravity (Fig. 2). Volcanic centres: 1, western Eistla; 2, central Eistla; 3, Bell Regio; 4, eastern Eistla; 5, Beta Regio; 6, Laufey; 7, Mnemosyne, the Arachnoid cluster Bereghinya, are interpreted to overlie plume clusters, for which the minimum diameter is estimated (from Ernst et al. 2007). (b) 3D view of the same area as in (a) viewed from underneath, colour-coded for thickness. The two ‘continent-like’ regions of Lakshmi Planum and Ovda Regio correspond to areas of thicker crust than the surrounding plains. Thick crustal ‘roots’ underlie fold belts on the north and NW margins of the interpreted Lakshmi Planum D1 indentor (Fig. 2). The thickest crust occurs beneath Maxwell Montes, where folding and underthrusting (Keep & Hansen 1994) are interpreted to have occurred in the subsequent (D2) event. Although eastern Ovda Regio is offset by a dextral shear zone consistent with the implied D1 approximately north–south shortening, radar interpretation (Fig. 5) presents evidence for its sinistral reactivation, consistent with the model for an orthogonal rotation of principal stresses between D1 and D2.
in Figure 3. The lack of a similar gravity high in the high-frequency/shallow-source gravity component in Figure 2b indicates a deep, high-density source for the Bouguer highs in Figure 2a. This can most readily be explained by the presence of denser, underplated mantle-derived mafic rocks beneath the zone of thinned crust. The interpreted rift correlates to the Guinevere, Sedna and Leda (Lenedaya) planitias/volcanic lowland plains (Markov 1986). The Guinevere and Sedna planitias are interpreted as being characterized by extensional structures by Sullivan & Head (1984), which is consistent with this rift interpretation. Data from Magee & Head (2001) indicate that the interpreted rift contains over $2 \times 10^6$ km$^2$ of volcanic flow fields. However, only several segments, especially those bordering areas of geoid lows, are interpreted as rifts in the global map of the distribution of rift zones on Venus by Ernst et al. (2007) and Krassilnikov et al. (2012).

**Interpretation of regional fault and shear zones**

**Interpretations of gravity and crustal thickness images.** Horizontal offsets of Bouguer gravity anomalies, and offset and ductile deflection (‘drag’) of ‘worm’ edges in the total horizontal gradient, define a series of linear features (Fig. 2a). The constant horizontal displacement components along their length, the observed offset of both total Bouguer and short wavelength anomalies, and the 100 km-scale resolution of gravity data together indicate that many of these lineaments are crustal-scale transcurrent shear zones. The location and sense of horizontal displacement along shear zones interpreted from gravity images in western Ishtar Terra (Fig. 2) coincides precisely to those of transcurrent–transpressional shear zones interpreted on the margins of Lakshmi Planum from radar images (Harris & Bedard 2014; Fig. 1b). Sinistral shears on the NW margin of Lakshmi Planum are approximately 1000 km long and the curved, dextral shear zone on its NE margin is around 1800 km long. In these companion studies, Lakshmi Planum is interpreted as having acted as a rigid indenter, forming mountain belts on its northern, SE and NW margins. Gravity data thus greatly strengthen this hypothesis, and attest to the crustal scale of the structures previously interpreted only from radar images. The geometry of these structures resembles the Himalayan–Indochina system on Earth formed due to the indentation of India into Eurasia, and the length of the shear zone on the eastern margin of Lakshmi Planum is similar to the length of the Sagaing fault system on the eastern margin of the Indian indenter (Searle 2006). A similar, indenter-like geometry is defined by shear zones in SE Ishtar Terra (Fig. 2). In western Aphrodite Terra, Ovda and Thetis regions (which correspond to Bouguer gravity lows similar to Ishtar Terra) are offset by an approximately 2500 km-long, NNW-striking dextral shear zone. Two dextral shears, approximately 1300 and 800 km long, offset the southern margin of Ovda Regio.

The linear gravity highs in Guinevere and Sedna planitias, interpreted above as broad rifts, are also cut or bounded by gravity lineaments with apparent horizontal offsets. This is especially evident in Guinevere Planitia, in the central part of the map area, where gravity highs are offset or bounded by NNW-striking linear faults. Gravity ‘worms’ in the centre of the map area (e.g. at locations A and B in Fig. 2a) are approximately orthogonal to the bounding faults against which they are truncated, and are oblique to the overall trend of the gravity high. This contrasts to the ductile or brittle–ductile deflection (‘drag’) of ‘worms’ along similarly orientated dextral shears that cut the same linear gravity high SW of Lakshmi Planum (e.g. location C in Fig. 2a). Blocks A and B are separated by a fault with dextral horizontal offset, but displacement sense(s) are less clear on their other margins.

**Displacement senses along crustal-scale shear zones in western Aphrodite Terra.** Dextral strike-slip offsets of the thick crustal blocks/Bouguer gravity lows that correspond to Ovda and Thetis regions in western Aphrodite Terra, as previously interpreted by Crumpler et al. (1987) from analysis of radar and topographical images (but subsequently interpreted as oceanic fracture zone/transform faults on Earth, instead of strike-slip/transcurrent faults by Crumpler & Head 1988), is apparent on both crustal thickness and gravity images (Figs 2a & 3a). A radar image of the area immediately east of the gravity lineament in Figure 4a, however, portrays transcurrent shear zones where sinistral displacements are evident from horizontal offsets and the deflection of marker layers. Sinistral shears both parallel and step en échelon along the NW-striking feature interpreted from gravity. These sinistral shear zones, NE-striking dextral shears and east–west-trending graben are similar in geometry to subsidiary structures in transcurrent shear zones mapped on Earth and developed in analogue models (Riedel 1929; Tchalenko 1968, 1970; Wilcox et al. 1973; Mueller & Harris 1988; Mueller et al. 1988; Sylvester 1988; Richard et al. 1995), and define a sinistral wrench regime (Fig. 4b). In this wrench model, en échelon-stepping sinistral shears are interpreted as Riedel shears, and NE-striking dextral shears constitute secondary Riedel (R’)-shears (Riedel 1929; Tchalenko 1968, 1970). An
Orthogonal change in the orientations of principal strain axes is thus required, from north–south shortening/east–west extension during the dextral offset of regional blocks observed on gravity images, to bulk east–west shortening and north–south extension during sinistral wrench reactivation. These changes in principal strain axes deduced from the geometry and offset of transcurrent shears is corroborated by the same changes in principal strain axes deduced from refolded fold interference patterns and folding of early formed thrusts within Ovda Regio, documented by Harris & Bédard (2014). Our evidence for shear-zone reactivation and change in displacement sense also reconciles previously apparent contradictions in displacement sense (i.e. sinistral by Tuckwell & Ghail 2003 v. dextral by Kumar 2005) established for segments of the nearby 1000 km-long, 50–200 km-wide Thetis Boundary Shear Zone system separating the eastern Ovda and NW Thetis regiones.

Fig. 4. Radar interpretation of western Aphrodite Terra (interpretation criteria are outlined in Harris & Bédard 2014). (a) False-colour Magellan radar image. (b) Lineament interpretation. The geometry of interpreted transcurrent shears and graben defines a sinistral wrench system. A, ductile deflection (‘drag’) of foliations indicates sinistral shear displacement; B, foliations wrap internally fractured competent (?) body; C, localized tensile fractures/normal faults; D, Riedel shears; E, sinistral transpressional shears; F, the ‘drag’ of foliations indicate that dextral shears cut older fracture sets in tesserae. (c) False-colour radar image over eastern Ovda and western Thetis regiones showing main shears interpreted from Bouguer gravity in Figure 2, generated through combining left- and right-looking images to minimize areas of no data (white lines and rectangles). The shear system interpreted in (b) is parallel to, and eastward of, the gravity lineament (note, however, that the positions of gravity lineaments are approximate given the data resolution). As dextral displacement along this structure is apparent on Bouguer gravity (Fig. 2), sinistral shearing in (b) is interpreted as D2 reactivation of an existing crustal-scale shear corridor. This interpretation is consistent with the permutations in principal strain axes deduced from overprinting folds and thrusts in Ovda Regio west of this shear zone (c), portrayed by Harris & Bédard (2014).
Tectonics on Earth resulting from mantle plumes and global mantle flow

Before developing a tectonic model to explain our Venus observations, this section briefly reviews salient characteristics of tectonics on Earth related to mantle plumes and global mantle flow. On Earth we have a far better understanding of tectonic processes and 3D geometry through integrated field studies constrained by geochronology, stress measurements and more detailed geophysical data than for Venus. Although there has been much debate as to the existence and tectonic roles of mantle plumes on Earth (e.g. Artyushkov 1973; Forsyth & Uyeda 1975; Anderson 2000, 2013; Foulger 2010; Burke & Cannon 2014), seismic tomography (such as Lithgow-Bertelloni & Silver 1998; Montelli et al. 2006; Boschi et al. 2007; Chang & Van der Lee 2011, whose data is plotted in 2D and 3D in Fig. 5) incontestably shows the presence of deep hot mantle upwellings and cold downwellings. Recent magnetotelluric (e.g. Kelbert et al. 2012) and seismic tomographic data portray far more complex patterns of mantle upwelling and downwellings than early isolated plume models, including vertical walls, horizontal ‘fingers’ at the base of the oceanic aesthenosphere paralleling overlying plate motion (French et al. 2013), and spatial clusters of smaller plumes instead of single ‘superplumes’ (Schubert et al. 2014). Three-dimensional numerical modelling suggests that several plumes may rise from deeper upwelling walls/planiform structures (Hanjalić & Kenjereš 2006; Gait et al. 2008) in addition to forming isolated, ‘mushroom-like’ plumes, and that their form may change with time (Gait et al. 2008). Continental flood basalt/LIPs on Earth (Pirajno 2000, 2007; Ernst & Buchan 2003; Campbell 2005) – for example, the Columbia River Province (Hooper et al. 2007; Camp & Hanan 2008), the Deccan traps (Cande & Stigman 2011; Sen & Chandrasekharam 2011), the Siberian traps (Saunders et al. 2005; Kiselev et al. 2012; Howarth et al. 2014), and the North American Mid-Continent Rift, as well as rifts in Arabia, East Africa, West Antarctica and Iceland (discussed later) – are attributed to mantle plumes. Their structural features and tomographic and gravity expressions help us to interpret the Venus gravity data, and to formulate tectonic models that can explain the interplay between rifting and lateral displacements on Venus.

Regional stress patterns about mantle plumes

Upwelling mantle plumes contribute to, and may be the prime origin of, regional stress patterns for some areas on Earth. For example, Cobbold (2008) noted that maximum horizontal principal stress axes in western Europe and Scandinavia (portrayed in the World Stress Map of Heidbach et al. 2008, 2010) converge on the Iceland mantle plume. Cobbold (2008) and Le Breton et al. (2012) suggested that compressive stresses generated by the Iceland plume explain thrust mechanisms of recent earthquakes in Scandinavia, post-Neogene basin inversion around Iceland, and contribute to basin inversion and onshore crustal shortening on North Atlantic margins. In an Early Tertiary tectonic reconstruction, Mège & Ernst (2001) showed that fold-axial traces in sedimentary rocks of the NW European shelf are concentrically arranged about the same mantle plume that now underlies Iceland when, at 60–50 Ma, Greenland was situated above it. Mège & Ernst (2001) attributed the implied radial shortening to plume-derived horizontal stresses. Similarly, the horizontal compressive stress trajectory in East Africa and Arabia is also controlled by upwelling mantle plumes. Mouterheau et al. (2012) contended that, whilst early shortening and thrusting in the Zagros is subduction and collision-related, the main driving force for Arabian plate motion since approximately 12 Ma is horizontal flow originating from upwelling mantle plumes responsible for the intracrustal extension that created the Red Sea and East African rifts (Fig. 5). Furthermore, 2D numerical modelling by Burov et al. (2007) and Guillou-Frottier et al. (2012) illustrates how plume impingement beneath shallow crust induces compressional stresses in (and, in some models, horizontal displacement of) an adjacent thicker, ‘cratonic’ crustal block. Zones of mantle downwelling also change the stress field in the overlying crust; for example, in the models of Behn et al. (2004), large compressive stresses developed in the upper crust over a zone of mantle downwelling located ahead of a continent being driven laterally by mantle flow from an upwelling plume. Horizontal projections of the instantaneous flow trajectories in numerical simulations of Hanjalić & Kenjereš (2006) at Rayleigh numbers similar to those used in other Venus simulations (e.g. Robin et al. 2007), although not aimed at modelling geological structures, also suggest that linear zones of focused horizontal displacement may develop between convection cells. The effect of such linear flow discontinuities on an overlying crustal ‘lid’ was not simulated. If such structures were to develop on Venus, could they produce the network of regional transcurrent shears we interpret from gravity, instead of conventional ideas of bulk regional shortening? Further numerical and physical models are required to test this hypothesis.

On Venus, structures formed during bulk shortening, such as wrinkle ridges and associated conjugate strike-slip faults concentric about the volcanic
Fig. 5. S-wave seismic tomography over rifts in East Africa and Arabia showing upwelling hot and downwelling cold mantle plumes. Maps and 3D isosurfaces present velocity data from Chang & Van der Lee (2011) compared to reference model ‘MEAN’ of Marone et al. (2004). (a) Elevation. The majority of the interpreted mantle plumes from Chang & Van der Lee (2011) and a compiled list of plume locations (see Anderson: http://www.mantleplumes.org/CompleteHotspot.html (accessed June 2013)) correspond to areas of high topography. (b) & (c) Velocity differences at 70 and 1000 km depth, respectively. Warm colours correspond to higher temperatures that are interpreted as mantle upwelling by Chang & Van der Lee (2011). (d) & (e) 3D isosurfaces of velocity differences from 50 to 1400 km depth. Data portrayed in (d) show upwelling and downwelling plumes along a slice parallel to the Red Sea, indicated in (b), viewed from below the Earth’s surface (i.e. looking upwards at the map of the Red Sea). Isosurfaces in (e), viewed looking obliquely downwards (see the inset for the orientation), show plume heads merging beneath the crust. (This region is, however, complex in detail as plumes interact with whole mantle flow, resulting in a northward entrainment of upwelling mantle material: Faccenna et al. 2013.)
centres in volcanic plains and folds in crustal plateaux, were also attributed to plumes by Mège & Ernst (2001).

**Relationships between rifts and mantle upwelling**

*Gravity signature, topographical expression and stress patterns.* The 1115–1086 Ma (Heaman et al. 2007), approximately 2500 km-long, Mid-Continental Rift in the north-central USA and southernmost Canada in the Lake Superior region cuts Precambrian terrains (Fig. 6), and is marked for the most part by long linear Bouguer gravity highs (Behrendt et al. 1988, 1990; Hinze et al. 1997; Miller 2007 and references therein; Stein et al. 2011). The gravity signature of the Mid-Continental Rift closely resembles the Bouguer gravity pattern of the interpreted rift zones on Venus described above.

The Mid-Continental Rift contains an approximately 30 km-thick sequence of volcanic and sedimentary rocks (Behrendt et al. 1988; Hinze et al. 1997), largely covered by younger, Phanerozoic sediments (Miller 2007). Behrendt et al. (1988, p. 81) considered that its northern part ‘may contain the greatest thickness of intracratonic rift deposits on Earth’. The rift is underlain by a zone of dense, underplated mafic mantle-derived rocks, which are responsible for its marked gravity high (Behrendt et al. 1988; Chandler et al. 1989; Thomas & Teskey 1994; Allen et al. 2006; Merino et al. 2013).

An anomalously deep and generally flat Moho (developed syn- to post-rifting) is apparent on seismic profiles (e.g. Allen et al. 2006). Hinze et al. (1997) and Miller (2007) described successive stages in the tectonic model for rifting as resulting from impingement of an anomalously hot mantle plume at the base of the lithosphere, where the two arms of the rift radiate from the proposed plume head. This plume model, originally proposed by Burke & Dewey (1973), is supported by geological and geochemical data provided by Miller (2007 and references therein). Extension terminated before the rift–drift transition and the development of oceanic crust, presumably due to a change to regional shortening inboard of the Grenville Orogen during which the Mid-Continental Rift underwent minor compressional overprinting. Similarly, positive Bouguer anomalies also mark the 500 km-long and 100 km-wide Bransfield Rift in the Antarctic South Shetland Islands–Bransfield Strait area (Catalán et al. 2012), an actively extending marginal basin where rifting is superposed upon an inactive continental volcanic arc (Lawyer et al. 1995; Fretzdorff et al. 2004). Forward modelling by Catalán et al. (2012) again suggested that thinned continental crust of the Bransfield Rift is underlain by a zone of anomalous, upwelled mantle.

In broad rifts that develop due to mantle flow about an active, upwelling hot plume, the area above the causative plume may correspond to a topographical high, which may or may not be cut by active rifts, and thicker crust than surrounding rifts. For example, Iceland is a topographical high cut by active normal and transform faults and fractures (Fig. 7a, b). Iceland and its surrounding shelf correspond to a region of lower Bouguer anomalies (Fig. 7c) that punctuate the general Bouguer highs along the Reykjanes and Kolbeinsey ridges. The interpreted mantle plume in Iceland is marked by a negative Bouguer gravity anomaly (Darbyshire et al. 2000); the deep source of this anomaly produces a long-wavelength Bouguer low (Fig. 7d). Similarly, Ross Island in West Antarctica, which is interpreted to overlie the Erebus mantle plume (Kyle et al. 1992; Storey et al. 1999; Gupta et al. 2009; Mt Erebus Volcano Observatory: http://erebus.nmt.edu/index.php/volcanology/51-volcanological-evolution (accessed June 2013)), is a topographical high flanked by intracontinental rifts (see the review by Elliot 2013). It also corresponds to an isolated negative Bouguer anomaly in a zone of rifted crust otherwise marked by Bouguer highs.

We conclude that, from comparison with these rift examples on Earth, the long, linear gravity highs of Sedna and Guinevere planitias on Venus similarly mark broad rifts of basaltic crust that are underplated by higher-density cumulates and mantle that cause their Bouguer highs. As is the case for the Mid-Continental Rift, upper crustal faults are largely obscured by an overlying, late- to post-rift sequence (extensive lava flows on Venus), suggesting that the significance of these broad rifts may have been underestimated in previous studies based on radar mapping of surface features. Elevated areas with moderate Bouguer anomalies and slightly thicker crust within Eistla Regio, which are interpreted as overlying plume clusters by Ernst et al. (2007), show distinct similarities to Iceland and Ross Island, where upwelling plumes are postulated, supporting their plume interpretation. This further suggests that Eistla Regio is a topographical high that formed directly above a linear array of upwelling mantle plumes and plume clusters, and that this positive structure formed along the axis of a single rift encompassing both Sedna and Guinevere planitias.

*Plume interaction in the Red Sea and East African rifts.* Whilst Ernst & Buchan (2003) suggested that plumes in the geological record are characterized by areas of domal uplift, triple-point junction rifting and LIPs, more complex patterns also occur (e.g. Şengör & Natal’ in 2001; Harris et al. 2004),
with long linear rifts developing due to linkages between mantle plumes (cf. May 1971). Chang & Van der Lee (2011) illustrated from an S-wave seismic tomographical velocity model that rifts in Arabia and East Africa link well-defined, distinct, upwelling hot mantle plumes in a similar manner to analogue tank experiments summarized by Harris et al. (2004). Three-dimensional isosurfaces

Fig. 6. Mid-Continent Rift, a plume-related rift in the NE USA and southern Canadian Great Lakes area. (a) Bouguer geology. The long, linear gravity high is attributed to the underplating of dense mafic rocks. A similar explanation is proposed to explain the linear Bouguer gravity highs on Venus in Figure 2a, which also correspond to thin crust (Fig. 3). (b) A simplified geological map, combining the interpretation of (a) and USGS geological map data (http://mrdata.usgs.gov/geology/state/).
Fig. 7. Topography and gravity surrounding Iceland. (a) Tectonic setting. Iceland lies above a mantle plume along an active spreading ridge that is offset by rectilinear (Charlie Gibbs) and curved (Jan Mayen) fracture zones. See Le Breton et al. (2012) for illustrations of stages in rifting leading to this geometry. (b) SRTM30 Plus (Shuttle Radar Topography Mission 30 Plus) 30 arcsecond-resolution elevation image (Becker et al. 2009), enhanced to highlight structural features using a combination of vertical and horizontal gradients. Iceland and the surrounding shelf constitute an elliptical elevated area above the Iceland mantle plume. (c) EGM08 (Pavlis et al. 2012) Bouguer gravity anomaly with superposed edges in the total horizontal gradient upwards continued to four levels corresponding to source depths of 15, 20, 25 and 30 km (note that extreme data corrugation of variable orientation precludes worm calculation for shallower levels as too many artefacts are created). Iceland and its surrounding shelf correspond to an elliptical area with anomalies of lower magnitude than surrounding rift areas. Gravity worms highlight linear features subparallel to spreading ridges and transform faults. A similar pattern of worms and Bouguer anomalies is seen over the Sedna and Guinevere planitas on Venus (Fig. 2a). (d) Long-wavelength Bouguer anomaly image over Iceland showing a gravity low reflecting lower-density rocks associated with the underlying mantle plume. Volcanoes are from the Smithsonian Institution Global Volcanism Program database; geology, and faults and fissures are from the GIS version of Jóhannesson & Sæmundsson (2009). Late Pliocene–Lower Pleistocene bedrock shows a symmetry of geological units about the central, active spreading centres.
Fig. 5d, e) show that the individual plumes coalesce in the upper mantle to produce a broad linear zone of upwelling. The alignment of interpreted upwelling mantle plumes and plume clusters in Eistla Regio (Fig. 3) is therefore analogously interpreted as a linear zone of mantle upwelling (shown schematically in Figs 7 & 8).

Lateral displacements accompanying upwelling mantle plumes and global mantle flow

Plume-related horizontal mantle flow. Upwelling mantle plumes generate a viscous force due to radial flow in the plume head that is approximately proportional to the plume’s volume flux (Westaway 1993). Lithgow-Bertelloni & Silver (1998), Behn et al. (2004), Bobrov & Baranov (2011), van Hinsbergen et al. (2011) and Husson (2012) showed that (on Earth) large horizontal components of global mantle flow may arise from deep mantle upwellings, and that convective mantle drag/plume-generated flow is a significant force for driving adjacent plate motions (substantiating early ideas for the role of mantle plumes in driving plate motion mooted by Morgan 1971 and Wilson 1973). For example:

- Regional mantle flow ensuing from deep mantle upwelling beneath South Africa, documented by Lithgow-Bertelloni & Silver (1998), is a major factor in driving microplate motion as far as the Mediterranean (Faccenna & Becker 2010).
- Cande & Stegman (2011) proposed that the rapid acceleration of India between about 65 and 50 Ma (i.e. prior to its collision with Eurasia) was derived from the ‘plume-push’ force of the Réunion mantle plume. The origin of the Decan Traps LIP is also credited to the Réunion plume. From numerical modelling, van Hinsbergen et al. (2011) attributed another period of acceleration in India’s displacement at around 90 Ma to be entirely related to the ‘push’ force from the Marion/Morondova mantle plume head, but suggest that the second approximately 65 and 50 Ma acceleration results from a combination of plume-push from the Réunion and Marion plumes and increased ridge push and slab pull forces. The ongoing northward displacement of India documented from GPS measurements is similarly connected with global mantle flow tractions at the base of the Indian continental lithosphere (Alvarez 2010).

Displacement of the Americas due to mantle flow.

The westward drift of the Americas in a hotspot reference frame (Gripp & Gordon 2002; Husson et al. 2012) corresponds roughly to the beginning of active subduction tectonics on the west coast, with major orogenic pulses being associated with the accretion of island arc and oceanic plateau terranes (Coney et al. 1980; Dickinson 2006; Nelson & Colpron 2007; Ramos 2009). Can plate tectonic boundary forces account for the westward drift of the American continents? Ridge push against the eastern coast of the Americas would have been a steady westward force since the opening of the Atlantic Ocean. However, the application of a ridge push force sufficient to drive the Americas west and to create the Cordilleras requires that huge compressive stresses be transmitted through the intervening oceanic lithosphere and its junction with the continental lithosphere. Since some of the oldest, coldest, densest oceanic crust on Earth (c. 185 Ma old: Bryan et al. 1977) is located along the east coast of North America, where it is underlain by cold, oceanic mantle lithosphere and is capped...
by thick packages of sedimentary rocks (Steckler & Watts 1974), then the transmission of a compressive stress large enough to raise the Rocky Mountains should have triggered the initiation of subduction beneath the east coast of North America. The geological history of the North and South American west coasts are largely devoid of west-subducting episodes (Coney et al. 1980; Dickinson 2006; Nelson & Colpron 2007; Ramos 2009); a westward slab pull contribution therefore seems implausible. Only the slab rollback configuration of the eastward subduction of oceanic lithosphere beneath the west coast of the Americas could have contributed to westward motion. Paradoxically, terrane accretion or shallow subduction phases, which are commonly associated with phases of compression and orogenesis (Kay & Copeland 2006; Nelson & Colpron 2007; Ramos 2009), should have inhibited or even reversed westward drift, yet westward drift of the Americas was largely oblivious to these shifts in the applied force (compression v. extension). Finally, much of the western coast of North America is defined by strike-slip fault systems and should not contribute to westward motion at all. Given the complete lack of a westward slab pull force, the long strike-slip plate boundaries, and the rough balance between compressional and extensional forces above east-directed subduction zones, it seems implausible to suggest that plate boundary forces are solely responsible for the westward drift of North America. An alternative view is that large-scale convective motions in the mantle push upon the deep, stiff, mantle keels of Precambrian craton-cored continents, and that this mantle traction force plays a major role in the westward drift of the American continents (Bokelmann 2002a, b; Liu & Bird 2002; Eaton & Frederiksen 2007). This model is applied to the indentation of Lakshmi Planum, and to shear displacements between Ovda and Thetis regiones in the Discussion.

Analogue modelling of contemporaneous folding and rifting resulting from underlying flow. Contemporaneous folding, conjugate strike-slip shearing and rifting resulting from underlying flow modelled by Ramberg (1967) using a high-acceleration centri-fuge showed that upwelling and downwelling of a ductile layer underlying a semi-brittle upper layer produces shear tractions that result in areas of tensile failure and separation (equivalent to rifts), and areas of localized shortening in which conjugate shear zones and folds were developed. In this model, horizontal flow (induced by a sinking weight) was symmetrical and the resulting geometry was also thus symmetrical, and there was no thickness variation of the upper, brittle—ductile ‘crust’. The effects of crustal thickness variations would be expected to enhance and localize areas of folding and shearing.

Discussion

Tectonic model for linked rifting, indentation and transcurrent faulting

The comparison between observations of Venus and plume- and mantle flow-related structures on Earth outlined above leads to the schematic tectonic interpretation for the western half of the study area in 2D and 3D in Figures 8 and 9, respectively. Rifting in Sedna Planitia (Fig. 8) is attributed to crustal extension on the northern flank of a zone of mantle upwelling, linking plumes and plume clusters. Extension and rifting is produced by tractions of mantle flowing out (horizontally) away from this zone of mantle upwelling. Horizontal mantle flow pushing against the deep keel to Lakshmi Planum drives the rigid planum into the surrounding area of initially thinner crust. A fold and thrust belt is developed ahead of Lakshmi Planum (Harris & Bédard 2014), accompanied by crustal thickening. A sinistral transpressional fold belt developed on the NW planum margin also results in crustal thickening, whilst no thickening occurs in this event on its NE margin, along which dextral trans-current displacement is interpreted by Harris & Bédard (2014). Where lateral flow away from the zone of mantle upwelling is not impeded by either the deep keel of Lakshmi Planum or the zone of mantle upwelling proposed by Mège & Ernst (2001) beneath the Bereghinya arachnoid cluster (Fig. 3a), the rift in Sedna Planitia is wider and the crust thinned more than where lateral flow is perturbed. Lateral variations in the degree of total extension are partitioned by NW-striking transfer faults.

The geometry of structures in Maxwell Montes (Keep & Hansen 1994), polyphase folding in Ovda Regio (Harris & Bédard 2014) and the change in displacement sense along the shear zone separating Ovda and Thetis regiones described above necessitate a change from north–south to approximately NE–SW to east–west shortening in the highland areas. Although the relative timing of events in these different areas remains to be established, the sequence of overprinting is the same. We suggest that this can be explained by the formation of a second set of north–south to NNE–SSW-trending rifts (e.g. Leda Planitia) linking plume centres, as shown in Figure 3a. In this second event, similar forces arising from mantle flow against the thicker crust of East Ishtar Terra formed north- to NW-trending folds during crustal underthrusting and extreme crustal thickening in Maxwell Montes on the eastern margin of Lakshmi Planum, as interpreted by Keep & Hansen (1994).

The structures in Maxwell Montes and the other fold and thrust belts surrounding Lakshmi Planum
imply crustal shortening, although the structural styles as described by Keep & Hansen (1994) and Harris & Bédard (2014) differ greatly. The difference reflects the initial mobility of Lakshmi Planum, leading to indentation and lateral escape about its NW, north and NE margins, whereas subsequent underthrusting against the eastern margin of Lakshmi Planum to create Maxwell Montes (as shown by Keep & Hansen 1994) reflects Lakshmi Planum’s subsequent immobility.

**Origin of features defined by gravity ‘worms’**

An intriguing outcome of this study is the identification of subparallel regional features from edges of horizontal gravity gradients in both the Sedna Planitia rift and across the whole northern part of the study area, including Ishtar Terra and for western Aphrodite Terra (Fig. 2). ‘Gravity worms’ commonly correspond to the margins of short-wavelength Bouguer anomalies (Fig. 2b) and thus act as markers that help identify transcurrent faults. Gravity worms have aided mapping of regional structures on Earth (e.g. Bierlein et al. 2006; Vos et al. 2006; Austin & Blenkinsop 2008; Heath et al. 2009; Harris & Bédard 2014), and the correspondence between transcurrent faults established from the deflection and displacement of ‘worms’ on the margins of Lakshmi Planum and shear zones interpreted from radar images validates their similar use in regional structural interpretation on Venus. The linear structures defined by ‘worms’ in Sedna Planitia resemble parallel normal faults and patterns of gravity ‘worms’ about mid-oceanic spreading ridges on Earth (Fig. 7), whereas the anastomosing, more concentric pattern of ‘worms’ over Guinevere Planitia, also interpreted as a rift, is the

![Fig. 9. Schematic, 3D ‘cartoon’ of indentation and lateral escape about Lakshmi Planum driven by tractions and push-force arising from horizontal mantle flow acting on its deep craton-like keel. A broad zone of mantle upwelling links mantle plumes (cf. Fig. 5 for the present-day Afar–East African rift system). Rifting on the flanks of this zone of upwelling is created through flow away from mantle upwelling. Plains volcanic material is rendered semi-transparent to reveal the underlying mantle interpretation. Bouguer gravity highs imply dense, mafic mantle underplating beneath rifts.](image-url)
same as observed over mantle plumes such as at Beta and Phoebe regions (see Fig. 3 for the location). Could gravity ‘worms’ in Venus’ rifts act as markers of faulting about a rift axis and be used in a similar fashion to seafloor magnetic anomalies on Earth? Further detailed comparisons between geological maps, radar and emissivity images, and ‘worms’ are, nevertheless, required to better understand their origin(s) and to determine whether some of Venus’ lowlands may have formed during symmetrical outpourings of magma about a rift axis similar to the formation of oceanic crust on Earth.

**Implications of fault/shear-zone reactivation**

In contrast to studies (discussed earlier) that recognize only limited strike-slip faulting on Venus, and that of McGuire et al. (1996), who suggested that faults are less likely to be reactivated on Venus compared with Earth, we show that large strike-slip displacements are not only widespread but that shear-zone reactivation with reversal of shear sense has occurred. Fault reactivation and inversion on Venus was also proposed by Kumar (2005) and Hansen (2006). Reactivation and reversal of displacement sense along regional transcurrent shear zones is common on Earth along crustal-scale transcurrent structures in Archaean granite–greenstone terrains (e.g. Mueller & Harris 1988; Mueller et al. 1988; Blewett et al. 2010; Leclerc et al. 2012; Harris & Bédard 2014). Multiple transcurrent (as well as normal and reverse) reactivation was documented along the Archaean–Cretaceous Darling Fault Zone on the western Yilgarn margin (summarized by Harris 1994a, b and Wilde et al. 1996) and in younger deformation zones (e.g. Palaeozoic–Tertiary transcurrent displacements on the Great Glen Fault in Scotland: Holgate 1969; Le Breton et al. 2013). Fault reactivation on Earth is attributed to fault-zone weakening (e.g. Handy et al. 2001; Rutter et al. 2001) largely due to the presence of water (e.g. Regenauer-Lieb & Yuen 2003 and references therein). Gurnis et al. (2000, p. 74) concluded that, on Earth, ‘old weak structures are reused by the convecting system because it takes less energy to reactivate a preexisting structure than it does to create an entirely new plate margin from pristine, intact lithosphere’. Whilst Gurnis et al. (2000) discussed fault reactivation on Earth in the context of plate tectonics, our results show that transcurrent fault formation and reactivation during changes in principal stresses can occur due solely to changes in the mantle flow field (probably due to changes in plume activity) without plate-tectonic-related stresses. The reactivation of transcurrent faults documented in our study and inversion of normal faults (e.g. Hansen 2006) show that regional faults/shear zones on Venus may be reactivated, similar to faults on Earth, despite the absence of surface water.

**Implications for mantle convection and tectonic regime of Venus**

The proposed causal link between mantle flow directed horizontally from a zone of mantle upwelling and the development of rifts, indentation tectonics, and strike-slip fault zones, agrees with Kohlstedt & Mackwell (2009) who, from an analysis of a likely rheological profile for Venus, inferred that ‘convection and lithospheric deformation will be strongly coupled’ (p. 418) and that ‘regional and planetary-scale tectonics will likely directly reflect underlying mantle processes such as convection’ (p. 419). Our evidence for lateral, ‘plate-like’ displacement due to mantle flow does not, however, indicate that plate tectonics occurs on Venus. Even in a purely stagnant lid regime (where, by definition, convective stress is less than lithospheric yield stress: Lenardic & Crowley 2012), the lid may still move passively but does not influence convection beneath it (Solomatov & Moresi 1997). Our interpretation for horizontal translation of terrains on Venus is consistent with recent research, based largely on numerical modeling, which suggests that Venus may be better considered as exhibiting intermediate ‘transient’ (Robin et al. 2007), ‘creeping stagnant lid’, or transitional (Solomatov & Moresi 1996) or ‘episodic’ (Turcotte 1993; 1995; Loddoch et al. 2006; Armann & Tackley 2012; Lenardic & Crowley 2012; Papuc & Davies 2012) convective regimes, transitioning from an earlier stagnant lid convective mode during progressive cooling (O’Neill 2013); that is, the opposite evolutionary trend to that proposed by van Thienen et al. (2004). Our proposed conceptual model shows some similarity with the ‘no subduction’ regime for the hot early Earth proposed by Sizova et al. (2010) from 2D numerical experiments, as argued for by Bédard et al. (2013) and for which there is recent geochemical support (Debaille et al. 2013). In this regime, horizontal movements of deformable plate fragments driven by mantle flow are accommodated by coexisting zones of shortening and rifting; the latter are also associated with thick mafic crust formation. This similarity supports the proposed analogy of Venus surface dynamics with Precambrian subduction-free geodynamics. The low elevations predicted in the subductionless models of Sizova et al. (2010) are, however, at apparent odds with the high topography present on Venus.

In tectonic models without subduction, lithospheric shortening is accommodated by either delamination (e.g. Turcotte 1989, 1995; Pysklywec et al.
of mantle lithosphere or through narrow zones of downwelling or ‘drips’ of basal lithospheric mantle into the asthenosphere (cf. West et al. 2009; Pysklywec et al. 2010; Sizova et al. 2010). A similar association between mountain belts and zones of symmetrical mantle downwelling was proposed before the advent of plate tectonic theory (Wilson 1961), and analogue models of Pysklywec et al. (2010) show that such a mechanism is plausible to accommodate folding of the upper crust without subduction.

Further detailed integration of the displacement history along interpreted regional faults with interpreted stratigraphic relationships is required to better constrain the sequence of regional tectonic events on Venus. The structures interpreted from gravity data in our study most probably represent deformation corridors and not discrete faults, and more detailed gravity data are required to more precisely map crustal- to lithospheric-scale faults. Mapping of present-day seismicity on Venus (proposed by Balint et al. 2009; Hunter et al. 2012), through wireless seismometers (Ponchak et al. 2012) or remote detection of seismic waves in the atmosphere (Garcia et al. 2005) or ionosphere (Lognonné et al. 2006; Lognonné 2009), is required to provide crucial missing information on whether regional faults interpreted in our study are still active.

Conclusions

Bouguer gravity, enhanced and visualized using modern geophysical software, combined with crustal thickness estimates, constitute important datasets to map regional crustal rift zones and faults on Venus. The high Bouguer gravity signature of the interpreted rifts on Venus is comparable to that of the North American Mid-Continent Rift interpreted to result from mantle upwelling. The surface expression of faulting does not provide a true indication of the scale of rifting, and rift-related extension is greater than previously proposed. Aerially extensive lava flows may mask early formed faults, such that visible faults record only the last stages of extension. Criteria for rifts on Venus must be revised to include the presence of long, straight Bouguer gravity highs; the full extent of rifts may thus not be portrayed in current maps that are based solely on structural interpretation of radar imagery.

In additional to local hotspot-like upwellings that may have a direct correlation with discrete volcanic centres and coronae, gravity data suggest the likelihood for an approximately 8000 km-long zone of sheet-like mantle upwelling formed by the coalescence of aligned, upwelling mantle plumes and plume clusters in Eistla Regio, similar to the coalescing and lateral flow of upwelling mantle plume in the Red Sea (but 3.5 times longer). This interpreted active volcanic zone above plumes is flanked by the Sedna and Guinevere rifts, which are characterized by crustal thinning and mafic underplating. Transcurrent shear displacements on Venus are concomitant with, and most probably compensate for, regional extension and rifting. Faults with transcurrent components of horizontal displacement that offset rifts differ from transcurrent faults formed during bulk shortening and indentation in Lakshmi Planum. Their origin compensates for differential extension between blocks where flow is hindered by the presence of either: (i) the deep keel of the adjacent Lakshmi Planum; or (ii) another zone of mantle upwelling (where narrower rifts develop) and blocks where underlying horizontal flow away from the zone of mantle upwelling is unhampered (and wider rifts develop). They show some similarities with transform faults on Earth but do not necessarily imply a central spreading axis. Changes in the locii of active rifting or variations in the amount of extension on orthogonal rifts are interpreted to have produced approximately 90° changes in principal horizontal stress orientations, leading to the reversal of shear sense on transcurrent shear zones separating Ovda and Thetis regions, refolded folds and underthrusting to produce Maxwell Montes on the eastern margin of the newly immobilized Lakshmi Planum.

On Earth, regional mantle flow and/or plume push acting against deep crustal keels (along with ‘pull’ from the related downwelling) contributes to the horizontal displacements of continents in addition to plate boundary forces. The Americas illustrate that continental blocks with the thickest keels are displaced further than terrains with no crustic keel (e.g. the Caribbean plate). Similarly, the displacement of Ishhtar Terra and the driving force for Himalayan–Indochina-like indentation and lateral escape, and lateral displacements between Ovda and Thetis regions, are attributed to mantle flow acting on their deep crustal keels, whereas terrains with thin crust are not displaced. We concur with previous studies that there is no evidence for subduction and Venusian plate tectonics similar to what is seen on the present-day Earth. The pattern of structures derived from gravity data, especially in the Sedna Planitia rift, however, raises the possibility for features similar to those formed in oceanic crust on Earth. We provide an updated view of Venusian tectonics where large, coherent displacements of its constituent terrains occur without true seafloor spreading or subduction. We surmise that this new perspective of Venus provides an analogue for the tectonics of the Archaean Earth.
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References

Allen, D. J., Braile, L. W., Hinze, W. J. & Mariano, J. 2006. Chapter 10: The Midcontinent rift system, U.S.A: A major Proterozoic continental rift. In: Olsen, K. H. (ed.) Continental Rifts: Evolution, Structure, Tectonics. Developments in Geotectonics, 25. Elsevier, Amsterdam, 375–407.

Alvarez, W. 2010. Protracted continental collisions argue for continental plates driven by basal traction. Earth and Planetary Science Letters, 296, 434–442.

Anderson, D. L. 1981. Plate tectonics on Venus. Geophysical Research Letters, 8, 309–311.

Anderson, D. L. 2000. The thermal state of the upper mantle; no role for mantle plumes. Geophysical Research Letters, 27, 3623–3626.

Anderson, D. L. 2013. The persistent mantle plume myth. Australian Journal of Earth Sciences, 60, 657–673.

Anderson, F. S. & Smrekar, S. E. 2006. Global mapping of crustal and lithospheric thickness on Venus. Journal of Geophysical Research: Planets, 111, E08006, http://dx.doi.org/10.1029/2004JE002395

Anguita, F., Fernandez, C. et al. 2006. Evidences for a Noachian-Hesperian orogeny in Mars. Icarus, 185, 331–357.

Annen, C., Blundy, J. D. & Sparks, R. S. J. 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. Journal of Petrology, 47, 505–539.

Ansan, V., Vergely, P. & Masson, P. 1996. Model of formation of Ishtar Terra, Venus. Planetary and Space Sciences, 44, 817–831.

Archibald, N. J., Boschetti, F. & Holden, D. J. 1999. Visualizing the geological ‘edges’ of US Gulf of Mexico structures. Offshore, 59(6), 74–76.

Arkani-Hamed, J. 1996. Analysis and interpretation of high-resolution topography and gravity of Ishtar Terra, Venus. Journal of Geophysical Research, 101, 4691–4710.

Armán, M. & Tackley, P. J. 2012. Simulating the thermochemical magmatic and tectonic evolution of Venus’s mantle and lithosphere: Two-dimensional models. Journal of Geophysical Research, 117, E12003, http://dx.doi.org/10.1029/2012JE004231

Artyushkov, E. V. 1973. Stresses in the lithosphere caused by crustal thickness inhomogeneities. Journal of Geophysical Research, 78, 7675–7708.

Austin, J. R. & Blinkinsop, T. G. 2008. The Cloncurry lineament: Geophysical and geological evidence for a deep crustal structure in the Eastern Succession of the Mount Isa Inlier. Precambrian Research, 163, 50–68.

Aydin, A. 2006. Failure modes of the lineaments on Jupiter’s moon, Europa: implications for the evolution of its icy crust. Journal of Structural Geology, 28, 2222–2236.

Balint, T., Cutts, J. et al. 2009. Technologies for Future Venus Exploration. White paper to the NRC Decadal Survey Inner Planets Sub-Panel, Venus Exploration Analysis Group, http://www.lpi.usra.edu/vexag/resources/decadal/TiborSBalint.pdf (accessed June 2013).

Barnett, D. N., Nimmo, F. & McKenzie, D. 2000. Elastic thickness estimates for Venus using line of sight accelerations from Magellan Cycle 5. Icarus, 146, 404–419.

Barsukov, V. L., Basilevsky, A. T. et al. 1986. The geology and geomorphology of the Venus surface as revealed by the radar images obtained by Veneras 15 and 16. Journal of Geophysical Research: Solid Earth, 91, 378–398.

Basilevsky, A. T. & Head, J. W. III. 2000. Riffs and large volcanoes on Venus: global assessment of their age relations with regional plains. Journal of Geophysical Research: Planets, 105, 24 583–24 611.

Basilevsky, A. T. & Head, J. W. III. 2007. Beta Regio, Venus: evidence for uplift, rifting, and volcanism due to a mantle plume. Icarus, 192, 167–186.

Basilevsky, A. T., Shalynin, E. V. et al. 2012. Geologic interpretation of the near-infrared images of the surface taken by the Venus Monitoring Camera, Venus Express. Icarus, 217, 434–450.

Becker, J. J., Sandwell, D. T. et al. 2009. Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. Marine Geodesy, 32, 355–371.

Bédard, J. H., Harris, L. B. & Thurston, P. 2013. The hunting of the snArc. Precambrian Research, 229, 20–48.

Behn, M. D., Conrad, C. P. & Silver, P. G. 2004. Detection of upper mantle flow associated with the African Superplume. Earth and Planetary Science Letters, 224, 259–274.

Behrendt, J. C., Green, A. G. et al. 1988. Crustal structure of the Midcontinent rift system: results from GLIMPCE deep seismic reflection profiles. Geology, 16, 81–85.

Behrendt, J. C., Hutchinson, D. R., Lee, M. W., Thornber, C. R., Trehu, A., Cannon, W. F. & Green, A. G. 1990. Seismic reflection (GLIMPCE)
evidence of deep crustal and upper mantle intrusions and magmatic underplating associated with the Mid-continent Rift System of North America. Tectonophysics, 173, 617–626.

Bérthé, D., Choukroune, P., & Jegouzo, P. 1979. Orthogneiss, mylonite and noncoaxial deformation of granite: the example of the South American shear zone. Journal of Structural Geology, 1, 31–42.

Bierlein, F. P., Murphy, F. C., Weinberg, R. F. & Lees, T. 2006. Distribution of orogenic gold deposits in relation to fault zones and gravity gradients: targeting tools applied to the Eastern Goldfields, Yilgarn Craton, Western Australia. Mineralium Deposita, 41, 107–126.

Bindschadler, D. L., Schubert, G. & Kaula, W. M. 1992. Coldspots and hotspots: Global tectonics and mantle dynamics of Venus. Journal of Geophysical Research, 97, 13 495–13 532.

Bistacchi, N., Massironi, M. & Baggio, P. 2004. Large scale fault kinematic analysis in Noctis Labyrinthus (Mars). Planetary and Space Science, 52, 215–222.

Blakey, R. J. & Simpson, R. W. 1986. Approximating edges of source bodies from magnetic or gravity anomalies. Geophysics, 51, 1494–1498.

Bleamaster, R. S., III & Hansen, V. L. 2005. Geologic Map of the Ovda Regio Quadrangle (V-35), Venus. United States Geological Survey, Geologic Investigations Series, I-2808.

Blewett, R. S., Czarnota, K. & Henson, P. A. 2010. Structural-event framework for the eastern Yilgarn Craton, Western Australia, and its implications for orogenic gold. Precambrian Research, 183, 203–229.

Bobrov, A. M. & Baranov, A. A. 2011. Horizontal stresses in the mantle and in the moving continent for the model of two dimensional convection with varying viscosity. Physics of the Solid Earth, 47, 801–815.

Bokelmann, G. H. R. 2002a. Convection-driven motion of the North American craton: evidence from P-wave anisotropy. Geophysical Journal International, 148, 278–287.

Bokelmann, G. H. R. 2002b. Which forces drive North America? Geology, 30, 1027–1030.

Bondarenko, N. V., Head, J. W. & Ivanov, M. A. 2010. Present-day volcanism on Venus: Evidence from microwave radiometry. Geophysical Research Letters, 37, L23202, http://dx.doi.org/10.1029/2010GL045233

Borraccini, F., Di Achille, G., Ori, G. G. & Wezel, F. C. 2007. Tectonic evolution of the eastern margin of the Thaumasia Plateau (Mars) as inferred from detailed structural mapping and analysis. Journal of Geophysical Research, 112, E05005, http://dx.doi.org/10.1029/2006JE002866

Boschi, L., Becker, T. W. & Steinberger, B. 2007. Mantle plumes: Dynamic models and seismic images. Geochemistry, Geophysics, Geosystems, 8, Q10006, http://dx.doi.org/10.1029/2007GC001733

Brown, C. D. & Grimm, R. E. 1995. Tectonics of Artemis Chasma: a Venusian “plate” boundary. Icarus, 117, 219–249.

Bryan, W. B., Frey, F. A. & Thompson, G. 1977. Oldest Atlantic seafloor: mesozoic basaltts from western North Atlantic margin and eastern North America. Contributions to Mineralogy and Petrology, 64, 223–242.

Bunte, M. K., Williams, D. A., Greeley, R. & Jaeger, W. L. 2010. Geologic mapping of the Hi’iaka and Shamsuh regions of Io. Icarus, 207, 868–886.

Burke, K. & Cannon, J. M. 2014. Plume–plate interaction. Canadian Journal of Earth Sciences, 51, 208–221.

Burke, K. & Dewey, K. L. 1973. Plume generated triple junctions: key indicators in applying plate tectonics to old rocks. Journal of Geology, 81, 406–433.

Burov, E., Guillou-Frottier, L., d’Acremont, E., Le Pourhiet, L. & Cloetingh, S. 2007. Plume head–lithosphere interactions near intra-continental plate boundaries. Tectonophysics, 434, 15–38.

Camp, V. E. & Hanan, B. B. 2008. A plume-triggered delamination origin for the Columbia River Basalt Group. Geosphere, 4, 480–495.

Campbell, I. H. 2005. Large igneous provinces and the mantle plume hypothesis. Elements, 1, 265–269.

Cande, S. C. & Stegman, D. R. 2011. Indian and African plate motions driven by the push force of the Réunion plume head. Nature, 475, 47–52.

Catalán, M., Galindo-Zaldívar, J., Davila, J., Martos, Y. M., Maldonado, A., Gamboa, L. & Schreider, A. A. 2012. Initial stages of oceanic spreading in the Bransfield Rift from magnetic and gravity data analysis. Tectonophysics, 585, 102–112.

Chandler, V. W., McSwiggen, P. L., Morey, G. B., Henze, W. J. & Anderson, R. R. 1989. Interpretation of seismic reflection, gravity, and magnetic data across Middle Proterozoic Mid-Continental Rift System, northwestern Wisconsin, eastern Minnesota, and central Iowa. American Association of Petroleum Geologists Bulletin, 73, 261–275.

Chang, S.-J. & Van der Lee, S. 2011. Mantle plumes and associated flow beneath Arabia and East Africa. Earth and Planetary Science Letters, 302, 448–454.

Chetty, T. R. K., Venkataayudi, M. & Venkatsavispa, V. 2010. Structural architecture and a new tectonic perspective of Ovda Regio, Venus. Planetary and Space Science, 58, 1286–1297.

Cobbold, P. R. 2008. Horizontal compression and stress concentration at passive margins: causes, consequences, and episodicity. Paper presented at the 33rd International Geological Congress, Oslo, Norway, 6–14 August 2008, http://hal-insu.archives-ouvertes.fr/insu-00376344

Coney, P. J., Jones, D. L. & Monger, J. W. H. 1980. Cordilleran suspect terranes. Nature, 284, 329–333.

Connors, C. & Suppe, J. 2001. Constraints on magnitudes of extension on Venus from slope measurements. Journal of Geophysical Research, 106, 3237–3260.

Crumppler, L. S. & Head, J. W. III. 1988. Bilateral topographic symmetry patterns across Aphrodite Terra, Venus. Journal of Geophysical Research, 93, 301–312.

Crumppler, L. S., Head, J. W., III & Campbell, D. B. 1986. Orogenic belts on Venus. Geology, 14, 1031–1034.

Crumppler, L. S., Head, J. W., III & Harmon, J. K. 1987. Regional linear cross-strike discontinuities in western Aphrodite Terra, Venus. Geophysical Research Letters, 14, 607–610.

Crumppler, L. S., Head, J. W., III & Aubele, J. C. 1993. Relation of major volcanic center concentration on
Venus to global tectonic patterns. *Science*, 261, 591–595.

Darbyshe, F. A., White, R. S. & Prestley, K. F. 2000. Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study. *Earth and Planetary Science Letters*, 181, 409–428.

Debaille, V., O’Neill, C., Brandon, A. D., Haenecour, P., Yin, Q.-Z., Mattieli, N. & Treiman, A. H. 2013. Stagnant-lid tectonics in early Earth revealed by $^{143}$Nd variations in late Archean rocks. *Earth and Planetary Science Letters*, 373, 83–92.

Dickinson, W. R. 2006. Geotectonic evolution of the Great Basin. *Geosphere*, 2, 353–368, http://dx.doi.org/10.1130/GES00054.1

Dureau, G., Harris, L. B. & Corriave, L. 2014. Tectonic reactivation of transverse basement structures in the Granville orogen of SW Quebec, Canada: insights from potential field data. *Precambrian Research*, 241, 61–84.

Eaton, D. W. & Frederiksen, A. 2007. Seismic evidence for convection-driven motion of the North American plate. *Nature*, 446, 428–431.

 Elliot, D. H. 2013. The geological and tectonic evolution of the Transantarctic Mountains: a review. In: Hamblin, M. J., Barker, P. F., Barrett, P. J., Bowman, V., Davies, B., Smellie, J. L. & Tranter, M. (eds) *Antarctic Palaeoenvironments and Earth-Surface Processes*. Geological Society, London, Special Publications, 381, 7–35.

Ernst, R. E. & Buchan, K. L. 2003. Recognizing mantle plumes in the geological record. *Annual Review of Earth and Planetary Sciences*, 31, 469–523.

Ernst, R. E. & Desnoyers, D. W. 2004. Lessons from Venus for understanding mantle plumes on Earth. *Physics of the Earth and Planetary Interiors*, 146, 195–229.

Ernst, R. E., Head, J. W., Parfitt, E., Grosfils, E. & Wilson, L. 1995. Giant radiating dyke swarms on Earth and Venus. *Earth Science Reviews*, 39, 1–58.

Ernst, R. E., Desnoyers, D. W., Head, J. W. & Grosfils, E. B. 2003. Graben–fissure systems in Guinevere Planitia and Beta Regio (264°–312°E, 24°–60°N), Venus, and implications for regional stratigraphy and mantle plumes. *Icarus*, 164, 282–316.

Ernst, R. E., Buchan, K. L. & Desnoyers, D. W. 2007. Plumes and plume clusters on earth and venus: evidence from Large Igneous Provinces (LIPs). In: Yuen, D. A., Maruyama, S., Karato, S.-I. & Windley, B. F. (eds) *Superplumes: Beyond Plate Tectonics*. Springer, Dordrecht, 537–562.

Facenna, C. & Becker, T. W. 2010. Shaping mobile belts by small-scale convection. *Nature*, 465, 602–605.

Facenna, C., Becker, T. W., Conrad, C. P. & Hussus, L. 2013. Mountain building and mantle dynamics. *Tectonics*, 32, 80–93, http://dx.doi.org/10.1029/2012TC003176

Fernández, C., Anguita, F., Ruiz, J., Romeo, I., Martín-Herrero, Á. I., Rodríguez, A. & Pimentel, C. 2010. Structural evolution of Lavinia Planitia, Venus: implications for the tectonics of the lowland plains. *Icarus*, 206, 210–228.

Forsyth, D. & Uyeda, S. 1975. On the relative importance of the driving forces of plate motion. *Geophysical Journal International*, 43, 163–200.

Foster, A. & Nimmo, F. 1996. Comparisons between the rift systems of East Africa, Earth and Beta Regio, Venus. *Earth and Planetary Science Letters*, 143, 183–195.

Fouger, G. L. 2010. *Plates vs Plumes: A Geological Controversy*. Wiley-Blackwell, Chichester.

French, S., Lekic, V. & Romanowicz, B. 2013. Waveform tomography reveals channeled flow at the base of the oceanic asthenosphere. *Science*, 342, 227–230.

Fretzdorf, S., Worthington, T. J., Haase, K. M., Hekinian, R., Franz, L., Keller, R. A. & Stoffers, P. 2004. Magmatism in the Bransfield Basin: Rifting of the South Shetland Arc? *Journal of Geophysical Research*, 109, B12208, http://dx.doi.org/10.1029/2004JB003046

Gait, A. D., Lowman, J. P. & Gable, C. W. 2008. Time-dependence in 3D mantle convection models featuring evolving plates: the effect of lower mantle viscosity. *Journal of Geophysical Research*, 113, B08409, http://dx.doi.org/10.1029/2007JB005538

Garcia, R., Lognonné, P. & Bonnin, X. 2005. Detecting atmospheric perturbations produced by Venus quakes. *Geophysical Research Letters*, 32, L16205, http://dx.doi.org/10.1029/2005GL023558

Ghosh, A., Becker, T. W. & Humphreys, E. D. 2013. Dynamics of the North American continent. *Geophysical Journal International*, 194, 651–669, http://dx.doi.org/10.1093/gji/ggt151

Gilmore, M. S., Collins, G. C., Ivanov, M. A., Marangeli, L. & Head, J. W. III, 1998. Style and sequence of extensional structures in tessera terrain, Venus. *Journal of Geophysical Research: Planets*, 103, 16813–16840.

Glen, R. A., Korsch, R. J., Hegarty, R., Saeed, A., Poudjom Diomani, Y., Costelloe, R. D. & Belousova, E. 2013. Geodynamic significance of the boundary between the Thomson Orogen and the Lachlan Orogen, northwestern New South Wales and implications for Tasmanian tectonics. *Australian Journal of Earth Sciences*, 60, 371–412.

Glukhovskiy, M. Z., Vloraev, V. M. & Kuz’min, M. I. 1995. Hot belt in the early Earth and its evolution. *Geotectonics*, 28, 367–379.

Grimm, E. A. 1998. What do we really know about the heat flow of Venus (or anyplace else we can’t stick with probes?). *The Leading Edge*, 1998, 1544–1546.

Gripp, A. E. & Gordon, R. G. 2002. Young tracks of hotspots and current plate velocities. *Geophysical Journal International*, 150, 321–361.

Grosfils, E. B. & Head, J. W. 1994. The global distribution of giant radiating dike swarms on Venus: implications for the global stress state. *Geophysical Research Letters*, 21, 701–704.

Guillou-Frottier, L., Burov, E., Cloetingh, S., Le Goff, E., Deschamps, Y., Huet, B. & Bouchot, V. 2012. Plume-induced dynamic instabilities near crustal blocks: Implications for P–T–t paths and metallogeny. *Global and Planetary Change*, 90–91, 37–50.

Gupta, S., Zhao, D. & Rai, S. S. 2009. Seismic imaging of the upper mantle under the Erebus hotspot in Antarctica. *Gondwana Research*, 16, 109–118.

Gurnis, M., Zhong, S. & Totti, J. 2000. On the competing roles of fault reactivation and brittle failure in generating plate tectonics from mantle convection.
Handy, M. R., Mulch, R., Rosenau, M. & Rosenberg, C. R. 2001. The role of transient sheared zones as melt conduits and reactors and as agents of weakening in the continental crust. In: Holdsworth, R. E., Strachan, R. A., Magloughlin, J. F. & Knipe, R. J. (eds) The Nature and Significance of Fault Zone Weakening, Geological Society, London, Special Publications, 186, 303–330.

Hanajlic, K. & Kenjerel, S. 2006. RANS-based very large eddy simulation of thermal and magnetic convection at extreme conditions. Journal of Applied Mechanics, 73, 430–440.

Hansen, V. L. 1992. Non-coaxial deformation on Venus. In: Proceedings of the 23rd Lunar and Planetary Science Conference, March 16–20, 1992, Houston, Texas. Lunar and Planetary Institute, Houston, TX, 479–480.

Hansen, V. L. 2006. Geologic constraints on crustal plateau surface histories, Venus: the lava pond and bolide impact hypotheses. Journal of Geophysical Research, 111, E11010, http://dx.doi.org/10.1029/2006JE002714

Hansen, V. L. 2007. LIPs on Venus. Chemical Geology, 241, 354–374.

Hansen, V. L. & Olive, A. 2010. Artemis, Venus: the largest tectonomagmatic feature in the solar system? Geology, 38, 467–470.

Hansen, V. L. & Willis, J. J. 1996. Structural analysis of a sampling of tesserae: implications for Venus geodynamics. Icarus, 123, 296–312.

Hansen, V. L., Willis, J. J. & Banerdt, W. B. 1997. Tectonic overview and synthesis. In: Bouger, S. W., Hunten, D. M. & Phillips, R. J. (eds) Venus II: Geology, Geophysics, Atmosphere, and Solar Wind Environment. University of Arizona Press, Tucson, AZ, 797–844.

Harris, L. B. 1994a. Neoproterozoic sinistral displacement along the Darling Mobile Belt, Western Australia. Journal of the Geological Society, London, 151, 901–904.

Harris, L. B. 1994b. Structural and tectonic synthesis for the Perth Basin, Western Australia. Journal of Petroleum Geology, 17, 129–156.

Harris, L. B. & Bédard, J. H. 2014. Chapter 9. Crustal evolution and deformation in a non-plate tectonic Archaean Earth: Comparisons with Venus. In: Dilek, Y. & Furnes, H. (eds) Evolution of Archaean Crust and Early Life. Modern Approaches in Solid Earth Sciences, 7. Springer, Berlin, 215–288.

Harris, L. B., Byrne, D. R., Wetherly, S. & Beeeson, J. 2004. Analogue modelling of structures developed above single and multiple mantle plumes: applications to brittle crustal deformation on Earth and Venus. In: Bertotti, G., Butter, S., Ruffo, P. & Schreurs, G. (eds) GeoMod 2004 – From Mountains to Sedimentary Basins: Modelling and Testing Geological Processes. Bollettino di Geofisica teorica ed applicata, 45(Suppl. 1), 301–303.

Hashimoto, G. L., Roos-Serote, M., Sugita, S., Gilmore, M. S., Kamp, L. W., Carlson, R. W. & Baines, K. H. 2008. Felsic highland crust on Venus suggested by Galileo near-infrared mapping spectrometer data. Journal of Geophysical Research, 113, E00B24, http://dx.doi.org/10.1029/2008JE003134

Head, J. W., Vorder Bruegge, R. W. & Crumpler, L. S. 1990. Venus orogenic belt environments: architecture and origin. Geophysical Research Letters, 17, 1337–1340.

Head, J. W., Crumpler, L. S., Aubele, J. C., Guest, J. E. & Saunders, R. S. 1992. Venus volcanism: Classification of volcanic features and structures, associations, and global distribution from Magellan Data. Journal of Geophysical Research, 97, 13 153–13 198.

Head, J. W., Hurwitz, D. M., Ivanov, M. A., Basilevsky, A. T. & Kumar, P. S. 2008. Geological mapping of Fortuna Tessera (V–2): Venus and Earth’s Archean process comparisons. In: Abstracts of the Annual Meeting of Planetary Geologic Mappers, Flagstaff, AZ, June 2008. NASA, Washington, DC, 463, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080 40988.pdf

Heaman, L. M., Easton, R. M., Hart, T. R., Hollings, P., MacDonald, C. A. & Smyk, M. 2007. Further refinement to the timing of Mesoproterozoic magmatism, Lake Nipigon region, Ontario. Canadian Journal of Earth Sciences, 44, 1055–1086.

Heath, P., Dhu, T., Reed, G. & Fairclough, M. 2009. Geophysical modelling of the Gawler Province, SA – interpreting geophysics with geology. Exploration Geophysics, 40, 342–351.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfiess, D. & Müller, B. 2008. The World Stress Map Database Release 2008, http://dx.doi.org/10.1594/GFZ.WSM.Rel2008

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfiess, D. & Müller, B. 2010. Global crustal stress pattern based on the World Stress Map database release 2008. Tectonophysics, 482, 3–15.

Helbert, J., Müller, N., Kostama, P., Marinangeli, L., Piccioni, G. & Drossart, P. 2008. Surface brightness variations seen by VIRTIS on Venus Express and implications for the evolution of the Lada Terra region, Venus. Geophysical Research Letters, 35, L12101.

Henson, P. A., Blewett, R. S., Roy, I. G., Miller, J. McL., & Czarnota, K. 2010. 4D architecture and tectonic evolution of the Laverton region, eastern Yilgarn Craton, Western Australia. Precambrian Research, 183, 338–355.

Herrick, R. R. & Phillips, R. J. 1992. Geological correlations with the interior density structure of Venus. Journal of Geophysical Research, 97, 16 017–16 034.

Hinz, W. J., Allen, D. J., Braile, L. W. & Mariano, J. 1997. The Midcontinent Rift System: a major Proterozoic continental rift. In: Ojakangas, R. W., Dickas, A. B. & Green, J. C. (eds) Middle Proterozoic to Cambrian Rifting, Central North America. Geological Society of America Special Papers, 312, 7–35.

Holgate, N. 1969. Palaeozoic and Tertiary transient movements on the Great Glen Fault. Scottish Journal of Geology, 5, 97–139.
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Hoogenboom, T. & Houseman, G. A. 2005. Rayleigh Taylor instability as a mechanism for corona formation on Venus. Icarus, 180, 292–307.

Hooper, P. R., Camp, V. E., Reidel, S. P. & Ross, M. E. 2007. The origin of the Columbia River flood basalt province: Plume versus nonplume models. In: Fougerer, G. R. & Jurdy, D. M. (eds) Plates, Plumes and Planetary Processes. Geological Society of America Special Papers, 430, 635–668.

Hoppa, G., Tufts, B. R., Greenberg, R. & Geissler, P. 1999. Strike-slip faults on Europa: global shear patterns driven by tidal stress. Icarus, 141, 287–298.

Horowitz, F. G., Strykowski, G. et al. 2000. Earthworms; ‘multiscale’ edges in the EGM96 global gravity field. SEG Technical Program Expanded Abstracts, 19, 414–417, http://dx.doi.org/10.1190/1.1816801

Howarth, G. H., Barry, P. H. et al. 2014. Superplume metasomatism: evidence from Siberian mantle xenoliths. Lithos, 184–187, 209–224.

Hunter, G. W., Ponchak, G. E. et al. 2012. Development of a high temperature Venus seismometer and extreme environment testing chamber. Paper presented at the International Workshop on Instrumentation for Planetary Missions, http://www.lpi.usra.edu/meetings/ipm2012/pdf/1133.pdf

Hurwitz, D. M. & Head, J. W. 2012. Geologic Map of the Snegurochka Planitia Quadrangle (V–1), Venus. Pamphlet to accompany United States Geological Survey, Geologic Investigations Map, 3178, http://pubs.usgs.gov/sim/3178/sim3178_pamphlet.pdf (accessed June 2013).

Husson, L. 2012. Trench migration and upper plate strain over a convecting mantle. Physics of the Earth and Planetary Interiors, 212–213, 32–43.

Husson, L., Conrad, C. P. & Facenna, C. 2012. Plate motions, Andean orogeny, and volcanism above the South Atlantic convection cell. Earth and Planetary Science Letters, 317, 126–135.

Ivanov, M. A. & Head, J. W. 2008. Formation and evolution of Lakshmi Planum, Venus: assessment of models using observations from geological mapping. Planetary and Space Science, 56, 1949–1966.

Ivanov, M. A. & Head, J. W. 2010a. Geologic Map of the Lakshmi Planum Quadrangle (V-7), Venus. United States Geological Survey, Geologic Investigations Map, 3116.

Ivanov, M. A. & Head, J. W. 2010b. Geologic Map of the Lakshmi Planum Quadrangle (V–7), Venus. Scientific Investigations Map 3116, Atlas of Venus: Lakshmi Planum Quadrangle (V–7). Pamphlet to accompany United States Geological Survey, Geologic Investigations Map, 3116.

Ivanov, M. A. & Head, J. W. 2010c. The Lada Terra rise and Quetzalpantitlán Corona: a region of long-lived mantle upwelling and recent volcanic activity on Venus. Planetary and Space Science, 58, 1880–1894.

Ivanov, M. A. & Head, J. W. 2011. Global geological map of Venus. Planetary and Space Science, 59, 1559–1600.

Ivanov, M. A. & Head, J. W. 2013. The history of volcanism on Venus. Planetary and Space Science, 84, 66–92.

James, P. B., Zuber, M. T. & Phillips, R. J. 2013. Crustal thickness and support of topography on Venus. Journal of Geophysical Research: Planets, 118, 859–875, http://dx.doi.org/10.1029/2012JE004237

Johannesson, H. & Sæmundsson, K. 2009. Geological Map of Iceland. Tectonics, Revised edition, scale: 1:600 000. Icelandic Institute of Natural History, Gardabaer.

Jull, M. G. & Arkani-Hamed, J. 1995. The implications of basalt in the formation and evolution of mountains on Venus. Physics of Earth and Planetary Interiors, 89, 163–175.

Kattenhorn, S. A. 2004. Strike-slip fault evolution on Europa: evidence from tailcrack geometries. Icarus, 172, 582–602.

Kattenhorn, S. A. & Marshall, S. T. 2006. Fault-induced perturbed stress fields and associated tensile and compressive deformation at fault tips in the ice shell of Europa: implications for fault mechanics. Journal of Structural Geology, 28, 2204–2221.

Kaula, W. M. 1996. Regional gravity fields on Venus from tracking of Magellan cycles 5 and 6. Journal of Geophysical Research, 101, 4683–4690.

Kaula, W. M. & Phillips, R. J. 1981. Quantitative tests for plate tectonics on Venus. Geophysical Research Letters, 8, 1187–1190.

Kaula, W. M., Bindschadler, D. L., Grimm, R. E., Hansen, V. L., Roberts, K. M. & Smrekar, S. E. 1992. Styles of deformation in Ishtar Terra and their implications. Journal of Geophysical Research: Planets, 97, 16 085–16 120.

Kay, S. M. & Copeland, P. 2006. Early to middle Miocene backarc magmas of the Neuquén Basin: geochemical consequences of slab shallowing and the westward drift of South America. In: Kay, S. M. & Ramos, V. A. (eds) Evolution of an Andean Margin: A Tectonic and Magmatic View from the Andes to the Neuquén Basin (35°–39°S Lat.). Geological Society of America Special Papers, 407, 185–213.

Keep, M. & Hansen, V. L. 1994. Structural history of Maxwell Montes, Venus: implications for Venusian mountain belt formation. Journal of Geophysical Research, 99, 26 015–26 028.

Kelbert, A., Egbert, G. D. & deGroot-Hedlin, C. 2012. Crust and upper mantle electrical conductivity beneath the Yellowstone hotspot track. Geology, 40, 447–450.

Kerr, R. A. 1994. A new portrait of Venus: thick-skinned and deceptively. Science, 263, 59–76.

Kiefer, W. S. & Hager, B. H. 1991. Mantle downwelling and crustal convergence. A model for Ishtar Terra, Venus. Journal of Geophysical Research, 96, 20 967–20 980.

Kiefer, W. S. & Peterson, K. 2003. Mantle and crustal structure in Phoebe Regio and Devana Chasma, Venus. Geophysical Research Letters, 30, 1005, http://dx.doi.org/10.1029/2002GL015762

Kiselev, A. I., Ernst, R. E., Yarmolyuk, V. V. & Egorov, K. N. 2012. Radiating rifts and dyke swarms of the middle Paleozoic Yakutsk plume of eastern Siberian craton. Journal of Asian Earth Sciences, 45, 1–16.
Koenig, E. & Aydin, A. 1998. Evidence for large-scale strike-slip faulting on Venus. Geology, 26, 551–554.

Kohlstedt, D. L. & Mackwell, S. J. 2009. Chapter 9. Strength and deformation of planetary lithospheres. In: Watters, T. R. & Schultz, R. A. (eds) Planetary Tectonics. Cambridge University Press, Cambridge.

Konopliv, A. S. & Siogren, W. L. 1996. Venus Gravity Handbook. Technical Report 96–2. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Konopliv, A. S., Banerdt, W. B. & Siogren, W. L. 1999. Venus gravity: 180th degree and order model. Icarus, 139, 3–18.

Kozak, R. C. & Schaber, G. G. 1989. New evidence for global tectonic zones on Venus. Geophysical Research Letters, 16, 175–178.

Krasilnikov, A. S., Kostama, V.-P., Aittoni, M., Guseva, E. N. & Cherchakova, O. S. 2012. Relationship of coronae, regional plains and rift zones on Venus. Planetary and Space Science, 68, 56–75.

Kumar, P. S. 2005. An alternative kinematic interpretation of Thetis Boundary Shear Zone, Venus: evidence for strike-slip ductile duplexes. Geophysical Research, 110, E07001, http://dx.doi.org/10.1029/2004JE002387

Kyle, P. R., Moore, J. A. & Thirlwall, M. F. 1992. Petrologic evolution of anoroclaschal phonolite lavas at Mount Erebus, Ross Island, Antarctica. Journal of Petrology, 33, 649–675.

Lakdawalla, E. 2012. Isotasy, gravity, and the Moon: an explainer of the first results of the GRAIL mission. The Planetary Society, http://www.planetary.org/blogs/emily-lakdawalla/2012/12110923-grail-results.html (accessed May 2013).

Lancaster, M. G., Guest, J. E. & Magee, K. P. 1995. Great lava flow fields on Venus. Icarus, 118, 69–86.

Lawyer, L. A., Keller, R. A., Fisk, M. R. & Strelin, J. A. 1995. Bransfield Strait; Antarctic Peninsula. Active extension behind a dead arc. In: Taylor, B. (ed.) Backarc Basins: Tectonics and Magmatism. Plenum Press, New York, 315–343.

Le Breton, E., Cobbold, P. R., Dauteuil, O. & Lewis, G. 2012. Variation in amount and direction of sea-floor spreading along the North East Atlantic Ocean and resulting deformation of the continental margin of North West Europe. Tectonics, 31, TC5006, http://dx.doi.org/10.1029/2011TC003087

Le Breton, E., Cobbold, P. R. & Zanella, A. 2013. Cenozoic reactivation of the Great Glen Fault, Scotland: additional evidence and possible causes. Journal of the Geological Society, London, 170, 403–415.

Leclerc, F., Harris, L. B., Bédard, J. H., van Breeman, O. & Goulet, N. 2012. Structural and stratigraphic controls on magmatic, volcanogenic, and syn-tectonic mineralization in the Chapaís-Chibougamau mining camp, northeastern Abitibi, Canada. Economic Geology, 107, 963–989.

Lencard, A. & Crowley, J. W. 2012. On the notion of well-defined tectonic regimes for terrestrial planets in this solar system and others. The Astrophysical Journal, 755(2), 132.

Lithgow-Bertelloni, C. & Silver, P. G. 1998. Dynamic topography, plate driving forces and the African super-swell. Nature, 395, 269–272.

Liu, Z. & Bird, P. 2002. North America plate is driven westward by lower mantle flow. Geophysical Research Letters, 29(24), 17–1–17–4.

Loddochi, A., Stein, C. & Hansen, U. 2006. Temporal variations in the convective style of planetary mantles. Earth and Planetary Science Letters, 251, 79–89.

Lognonné, P. 2009. Seismic waves from atmospheric sources and atmospheric/ionospheric signatures of seismic waves. In: Infrasound Monitoring for Atmospheric Studies, 2009, 281–304.

Lognonné, P., Garcia, R., Crespòn, F., Occhipinti, G., Kherani, A. & Arti-lambin, J. 2006. Seismic waves in the ionosphere. Europhysics News, 37, 11–14.

Magee, K. P. & Head, J. W. 2001. Large flow fields on Venus: Implications for plumes, rift associations, and resurfacing. In: Ernst, R. E. & Buchan, K. L. (eds) Mantle Plumes: Their Identification Through Time. Geophysical Society of America Special Papers, 352, 81–101.

Marinangeli, L. & Gilmore, M. S. 2000. Geologic evolution of the Akna Montes–Atropos Tessera region, Venus. Journal of Geophysical Research: Planets, 105, 12 053–12 075.

Markov, M. S. 1986. Structural Ensembles of the North Belt of Venus Deformations and Possible Mechanisms of their Formation. NASA TM–88511, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19870005708/1987005708.pdf. (Translation of Sreukturnyje Ansambli i Severnogo Poyasa Deformatsiy na Venereyi. Vosmohynek Mekhanizmy Ikh Obrazovaniya. Geotektonika, 21, 77–87, 1986.)

Markov, M. S., Smirnov, Yu. B. & Dobzhinetskaya, L. F. 1989. Tectonics of the Venus and the early Precambrian. Earth, Moon, and Planets, 45, 101–113.

Marone, F., Van der Lee, S. & Giardini, D. 2004. Threedimensional upper-mantle S-velocity model for the Eurasia–Africa plate boundary region. Geophysical Journal International, 158, 109–130.

Massironi, M., Di Achille, G. et al. 2012. Strike-slip kinematics on Mercury: Evidences and implications. In: Proceedings of the 43rd Lunar and Planetary Science Conference, March 19–23, 2012, The Woodlands, Texas. Lunar and Planetary Institute, Houston, TX, 1924, http://www.lpi.usra.edu/meetings/lpsc2012/pdf/1924.pdf

Massironi, M., Di Achille, G. et al. 2014. Lateral ramps and strike-slip kinematics on Mercury. In: Platz, T., Massironi, M., Byrne, P. K. & Hiesinger, H. (eds) Volcanism and Tectonism Across the Inner Solar System. Geological Society, London, Special Publications, 401. First published online June 5, 2014, http://dx.doi.org/10.1144/SP401.16

May, P. R. 1971. Pattern of Triassic-Jurassic diabase dikes around the North Atlantic in the context of predrift positions of the continents. Geological Society of America Bulletin, 82, 1285–7292.

Mc Gill, G. E. 1983. The Geology of Venus. Episodes, 1983, 10–17.

Mc Gill, G. E., Stofan, E. R. & Smrekar, S. E. 2010. Venus tectonics. In: Watters, T. R. & Schultz,
R. A. (eds) Planetary Tectonics. Cambridge University Press, Cambridge, 81–120.

McGuire, J. C., Davis, D. M. & Consolmagno, G. J. 1996. Crossing fractures and the strength of Venus crustal rocks. Lunar and Planetary Science, 27, 847–848.

Mège, D. & Ernst, R. E. 2001. Contractional effects of mantle plumes on Earth, Mars, and Venus. In: Ernst, R. E. & Buchanan, K. L. (eds) Mantle Plumes: Their Identification Through Time. Geological Society of America Special Papers, 352, 103–140.

Meringo, M., Keller, G. R., Stein, S. & Stein, C. 2013. Variations in Mid-Continent Rift magma volumes consistent with micropaleo evolution. Geophysical Research Letters, 40, dx.doi.org/10.1002/grl.50295.

Miller, J. D. Jr. 2007. The Midcontinent Rift in the Lake Superior region: A 1.1 Ga large igneous province. In: LIP of the Month. Large Igneous Provinces Commission, International Association of Volcanology and Chemistry of the Earth’s Interior, http://www.largeigneousprovinces.org/07no/a (accessed May 2013).

Montelli, R., Nolet, G., Dahlen, F. A. & Masters, G. 2006. A catalogue of deep mantle plumes: new results from finite-frequency tomography. Geochemistry, Geophysics, Geosystems, 7, Q11007, dx.doi.org/10.1029/2006GC001248.

Montesi, L. G. J. 2013. Fabric development as the key for forming ductile shear zones and enabling plate tectonics. Journal of Structural Geology, 50, 254–266.

Moore, E. M., Yikilmaz, M. B. & Kellogg, L. H. 2013. Tectonics: 50 years after the revolution. In: Bickford, M. E. (ed.) The Web of Geological Sciences: Advances, Impacts, and Interactions. Geological Society of America Special Papers, 500, 321–369.

Moresi, L. & Solomatov, V. 1998. Mantle convection with a brittle lithosphere: thoughts on the global tectonic styles of the Earth and Venus. Geophysical Journal International, 133, 669–682.

Morgan, P. 1983. Hot spot heat loss and tectonic style on Venus and in the Earth’s Archean. American Journal of Science, 14, 515–516.

Morgan, W. J. 1971. Convection plumes in the lower mantle. Nature, 230, 42–43.

Mouthereau, F., Lacombe, O. & Vergés, J. 2012. Building the Zagros collisional orogen: timing, strain distribution and the dynamics of Arabia/Eurasia plate convergence. Tectonophysics, 532–535, 27–60.

Mueller, A. & Harris, L. B. 1988. Application of wrench tectonic models to mineralized structures in the Golden Mile, Kalgoorlie. In: Ho, S. E. & Groves, D. I. (eds) Recent Advances in the Understanding of Precambrian Gold Deposits. University of Western Australia Geology Department and University Extension, University of Western Australia Publications, 11, 97–108.

Mueller, A., Harris, L. B. & Lungan, A. 1988. Structural control of greenstone-hosted gold mineralization by transient shearing: a new interpretation of the Golden Mile district, Kalgoorlie, Western Australia. Ore Geology Reviews, 3, 359–387.

Mueller, N., Helbert, J., Hashimoto, G. L., Tsang, C. C. C., Erard, S., Piccioni, G. & Drossart, P. 2008. Venus surface thermal emission at 1 µm in VIRTIS imaging observations: evidence for variation of crust and mantle differentiation conditions. Journal of Geophysical Research, 113, E00B17.

Nelson, J. & Colpron, M. 2007. Tectonics and metallogeny of the British Columbia, Yukon and Alaskan Cordiller, 1.8 Ga to the present. In: Goodfellow, W. D. (ed.) Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods. Geological Association of Canada, Special Publications, 8, 755–791.

Nikolaeva, O., Ivanov, M. & Borozdin, V. 1992. Evidence on the crustal dichotomy (of Venus). In: Venus Geology, Geochemistry, and Geophysics—Research Results from the USSR (A 92-39726 16-91). University of Arizona Press, Tucson, AZ, 129–139.

Nimmo, F. & McKenzie, D. 1998. Volcanism and tectonics on Venus. Annual Review of Earth and Planetary Sciences, 26, 23–51.

Okubo, C. H. & Schultz, R. A. 2006. Variability in Early Amazonian Tharsis stress state based on wrinkle ridges and strike-slip faulting. Journal of Structural Geology, 28, 2169–2181.

O’Neill, C. 2013. Tectonothermal evolution of solid bodies: terrestrial planets, exoplanets and moons. Australian Journal of Earth Sciences, 59, 189–198.

O’Rourke, J. G. & Korenaga, J. 2012. Terrestrial planet evolution in the stagnant-lid regime: size effects and the formation of self-stabilizing crust. Icarus, 221, 1043–1060.

Orth, C. P. & Solomatov, V. S. 2012. Constraints on the Venusian crustal thickness variations in the isostatic stagnant lid approximation. Geochemistry, Geophysics, Geosystems, 13, Q11012, dx.doi.org/10.1029/2012GC004377.

Pappalardo, R. T. & Collins, G. C. 2005. Extensional tectonics on Ganymede as recorded by strained craters. Journal of Structural Geology, 27, 827–838.

Papuc, A. M. & Davies, G. F. 2012. Transient mantle layering and the episodic behaviour of Venus due to the ‘basalt barrier’ mechanism. Icarus, 217, 499–509.

Patthoff, D. A. & Kattenhorn, S. A. 2011. A fracture history on Enceladus provides evidence for a global ocean. Geophysical Research Letters, 38, L18201, dx.doi.org/10.1029/2011GL048387.

Pavlis, N. K., Holmes, S. A., Kenyon, S. C. & Factor, J. K. 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). Journal of Geophysical Research: Solid Earth, 117, B04406, dx.doi.org/10.1029/2011Jb008916.

Phillips, R. J. & Hansen, V. L. 1994. Tectonic and magmatic evolution of Venus. Annual Review of Earth and Planetary Sciences, 22, 597–654.

Phillips, R. J. & Hansen, V. L. 1998. Geological evolution of Venus: rises, plains, plumes, and plateaus. Science, 279, 1492–1497.

Phillips, R. J., Kaula, W. M., McGill, G. E. & Malin, M. C. 1981. Tectonics and evolution of Venus. Science, 212, 879–887.

Phillips, R. J., Grimm, R. E. & Malin, M. C. 1991. Hot-spot evolution and the global tectonics of Venus. Science, 252, 651–658.

Pirajno, F. 2000. Ore Deposits and Mantle Plumes. Kluwer Academic, Dordrecht.
Piraino, F. 2007. Mantle plumes, associated intraplate tectono-magmatic processes and ore systems. Episodes, 30, 6–19.

Pohn, H. A. & Schaber, G. G. 1992. Indenter type deformation on Venus as evidence for large-scale tectonic slip, and multiple strike-slip events as a mechanism for producing tesselated terrain. In: Proceedings of the 23rd Lunar and Planetary Science Conference, March 16–20, 1992, Houston, Texas. Lunar and Planetary Institute, Houston, TX, 1095, www.lpi.usra.edu/meetings/lpsc1992/pdf/1539.pdf.

Ponchak, G. E., Scardelletti, M. C. et al. 2012. High temperature, wireless seismometer sensor for Venus. In: Wireless Sensors and Sensor Networks (WiSNet), 2012 IEEE Topical Conference, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/2012004170_201204292.pdf.

Pronin, A. A. & Stofan, E. R. 1990. Coronae on Venus: morphology, classification, and distribution. Icarus, 87, 452–474.

Price, M. H., Watson, G., Suppe, J. & Branckman, C. 1996. Dating volcanism and rifting on Venus using impact crater densities. Journal of Geophysical Research: Planets, 101, 4657–4671.

Pykslywec, R. N., Gogus, O., Percival, J., Cruden, A. R. & Beaumont, C. 2010. Insights from geo-dynamical modeling on possible fates of continental mantle lithosphere: collision, removal, and overturn. Canadian Journal of Earth Sciences, 47, 541–563.

Raitala, J. 1994. Main fault tectonics of Meshkenet Tesser on Venus. Earth, Moon and Planets, 65, 55–70.

Raitala, J. 1996. Chocolate tablet aspects of tectonics of Meshkenet Tessera on Venus. Earth, Moon and Planets, 74, 191–214.

Ramberg, H. 1967. Gravity, Deformation and the Earth’s Crust as Studied by Centrifuge Models. Academic Press, London.

Ramos, V. A. 2009. Anatomy and global context of the Andes: main geologic features and the Andean orogenic cycle. In: Kay, S. M., Ramos, V. A. & Dickinson, W. R. (eds) Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision. Geological Society of America, Memoirs, 204, 31–65.

Regenauer-Lieb, K. & Yuen, D. A. 2003. Modeling shear zones in geological and planetary sciences: solid and fluid-thermal mechanical approaches. Earth Science Reviews, 63, 295–349.

Richard, P. D., Naylor, M. A. & Koopman, A. 1995. Experimental models of strike-slip tectonics. Petroleum Geoscience, 1, 71–80.

Riedel, W. 1929. Zur mechanik geologischer brucherscheinungen. Zentral-blatt fur Mineralogie, Geologie und Palaeontologie B, 354–368.

Robin, C. M. I., Jellinek, M., Thayalan, V. & Lenardić, A. 2007. Transient mantle convection on Venus: the paradoxical coexistence of highlands and coronae in the BAT region. Earth and Planetary Science Letters, 256, 100–119.

Romeo, I., Capote, R. & Anguita, F. 2005. Tectonic and kinematic study of a strike-slip zone along the southern margin of Central Ovda Regio, Venus: geodynamical implications for crustal plateau formation and evolution. Icarus, 175, 320–334.

Rummel, R. 2005. Gravity and topography of moon and planets. Earth, Moon, and Planets, 94, 103–111.

Rutter, E. H., Holdsworth, R. E. & Knipe, R. J. 2001. The nature and tectonic significance of fault-zone weakening: an introduction. In: Holdsworth, R. E., Strachan, R. A., Magloughlin, J. F. & Knipe, R. J. (eds) The Nature and Tectonic Significance of Fault Zone Weakening. Geological Society, London, Special Publications, 186, 1–11.

Sandwell, D. T. 1992. Antarctic marine gravity field from high-density satellite altimetry. Geophysical Journal International, 109, 437–448.

Saunders, A. D., England, R. W., Reichow, M. K. & White, R. V. 2005. A mantle plume origin for the Siberian traps: uplift and extension in the West Siberian Basin, Russia. Lithos, 79, 407–424.

Schubert, G., Masters, G., Olson, P. & Tackley, P. 2014. Superplumes or plume clusters? Physics of the Earth and Planetary Interiors, 146, 147–162.

Schultz, R. A. 1989. Strike-slip faulting of ridged plains near Valles Marineris, Mars. Nature, 341, 424–426.

Schultz, R. A. 1999. Understanding the process of faulting: selected challenges and opportunities at the edge of the 21st century. Journal of Structural Geology, 21, 985–993.

Schultz, R. A., Hauber, E., Kattenhorn, S. A., Okubo, C. H. & Watters, T. R. 2010. Interpretation and analysis of planetary structures. Journal of Structural Geology, 32, 855–875.

Searle, M. P. 2006. Role of the Red River Shear zone, Yunnan and Vietnam, in the continental extrusion of SE Asia. Journal of the Geological Society, London, 163, 1025–1036.

Seiff, A., Schofield, J. T., Kliore, A. J., Taylor, F. W. & Limaye, S. S. 1985. Models of the structure of the atmosphere of Venus from the surface to 100 kilometers altitude. Advances in Space Research, 5, 3–58.

Sen, G. & Chandrasekharam, D. 2011. Chapter 2. Deccan Traps flood basalt province: An evaluation of the thermochemical plume model. In: Ray, J., Sen, G. & Ghosh, B. (eds) Topics in Igneous Petrology. Springer, London, 29–53.

Šengör, A. M. C. & Natal’in, B. A. 2001. Rifts of the world. In: Ernst, R. E. & Buchan, K. L. (eds) Mantle Plumes: Their Identification Through Time. Geological Society of America Special Papers, 352, 389–482.

Shellnutt, J. G. 2013. Petrological modeling of basaltic rocks from Venus: a case for the presence of silicic rocks. Journal of Geophysical Research: Planets, 118, 1350–1364.

Simons, M., Hager, B. H. & Solomon, S. C. 1994. Global Variations in the geoid/topography admittance of Venus. Science, 264, 798–803.

Simons, M., Solomon, S. C. & Hager, B. H. 1997. Localization of gravity and topography: constraints on the tectonics and mantle dynamics of Venus. Geophysical Journal International, 131, 24–44.

Sizova, E., Gerya, T., Brown, M. & Perchuk, L. L. 2010. Subduction styles in the Precambrian: insight from numerical experiments. Lithos, 116, 209–229.

Sleep, N. H. 1994. Martian plate tectonics. Journal of Geophysical Research, 99, 5639–5655.
Environment, Geology, Geophysics, Atmosphere, and Solar Wind

Hunten, D. M. & Head, J. W. 1987. Geology of the southern Ishtar Terra/Guinevere and Sedna Planitiae region on Venus. Earth, Moon, and Planets, 38, 183–207.

Stofan, E. R., Sharpston, V. L., Schubert, G., Baer, G., Bindschadler, D. L., Janes, D. M. & Squyres, S. W. 1992. Global distribution and characteristics of coronae and related features on Venus: implications for origin and relation to mantle processes. Journal of Geophysical Research: Planets, 97, 13 347–13 378.

Storey, B. C., Leat, P. T., Weaver, S. D., Pankhurst, R. J., Bradshaw, J. D. & Kelley, S. 1999. Mantle plumes and Antarctica-New Zealand rifting; evidence from mid-Cretaceous maﬁc dykes. Journal of the Geological Society, London, 156, 659–671.

Strom, R. G., Schaber, G. G. & Dawson, D. D. 1994. The global resurfacing of Venus. Journal of Geophysical Research, 99, 10 899–10 926.

Stuud, D., Ernst, R. E. & Samson, C. 2011. Radiating graben–fissure systems in the Ulfrun Regio area, Venus. Icarus, 215, 279–291.

Sukhanov, A. L. & Pronin, A. A. 1988. Spreading features on Venus (abstract). In: Proceedings of the 19th Lunar and Planetary Science Conference, March 14–18, 1988, Houston, Texas. Lunar and Planetary Institute, Houston, TX, 1147–1148.

Sullivan, K. & Head, J. W. 1984. Geology of the Venus Lowlands: Guinevere and Sedna Planitia. In: Proceedings of the 15th Lunar and Planetary Science Conference, March 12–16, 1984, Houston, Texas. Lunar and Planetary Institute, Houston, TX, 836–837.

Suppe, J. & Connors, C. 1992. Critical Taper Wedge Mechanics of Fold-and-Thrust Belts on Venus: initial Results From Magellan. Journal of Geophysical Research, 97, 13 545–13 561.

Sylvestre, A. G. 1988. Strike-slip faults. Geological Society of America Bulletin, 100, 1666–1703.

Tanaka, K. L., Moore, H. J. et al. 1994. The Venus Geologic Mappers Handbook, 2nd edn. United States Geological Survey, Open–File Report 94–438.

Tanaka, K. L., Anderson, R. et al. 2010. Planetary structural mapping. In: Watters, T. A. & Schultz, R. A. (eds) Planetary Tectonics. Cambridge Planetary Science, 11. Cambridge University Press, Cambridge, 351–396.

Tanaka, K. L., Skinner, J. A. Jr. & Hare, T. M. 2011. Planetary Geologic Mapping Handbook—2011. United States Geological Survey, Astrogeology Science Center, Flagstaff, AZ.

Tchalenko, J. S. 1968. The evolution of kink-bands and the development of compression textures in sheared clays. Tectonophysics, 6, 159–174.
Van Kranendonk, J. S. 1970. Similarities between shear-zones of different magnitudes. *Geological Society of America Bulletin*, 81, 1625–1640.

Thomas, M. D. & Teskey, D. J. 1994. An interpretation of gravity anomalies over the Midcontinent rift, Lake Superior, constrained by GLIMPCE seismic and aeromagnetic data. *Canadian Journal of Earth Sciences*, 31, 682–697.

Tuckwell, G. W. & Ghail, R. C. 2003. A 400-km-scale strike-slip zone near the boundary of Thetis Regio, Venus. *Earth and Planetary Science Letters*, 211, 45–45.

Turcotte, D. L., Greenberg, R., Hoppa, G. V. & Geissler, P. 1999. Astypalaea Linea: a San Andreas-sized strike-slip fault on Europa. *Icarus*, 141, 53–64.

Turcotte, D. L. 1989. A heat pipe mechanism for volcanism and tectonics on Venus. *Journal of Geophysical Research: Solid Earth*, 94, 2779–2785.

Turcotte, D. L. 1993. An episodic hypothesis for Venusian tectonics. *Journal of Geophysical Research: Planets*, 98, 17061–17068.

Turcotte, D. L. 1995. How does Venus lose heat? *Journal of Geophysical Research*, 100, 16961–16940.

van Hinsbergen, D. J. J., Steinberger, B., Doubrovine, P. & Gassmoller, R. 2011. Acceleration and deceleration of India – Asia convergence since the Cretaceous: roles of mantle plumes and continental collision. *Journal of Geophysical Research*, 116, B06101.

Van Kranendonk, M. J. 2010. Two types of Archaean continental plume and plate tectonics on early Earth. *American Journal of Science*, 310, 1187–1209.

van Thienen, P., Vlaar, N. J. & van den Berg, A. P. 2004. Plate tectonics on the terrestrial planets. *Physics of the Earth and Planetary Interiors*, 142, 61–74.

Veizolainen, A. V., Solomatov, V. S., Head, J. W., Basilevsky, A. T. & Moresi, L.-N. 2003. Timing of formation of Beta Regio and its geodynamical implications. *Journal of Geophysical Research*, 108, 5002, http://dx.doi.org/10.1029/2002JE001889

Violay, M. E. S., Gibert, B., Mainprice, D., Evans, B., Pezard, P. A., Flovenz, O. G. & Asmundsson, R. 2010. The brittle ductile transition in experimentally deformed basalt under oceanic crust conditions: evidence for presence of permeable reservoirs at supercritical temperatures and pressures in the Icelandic crust. Paper presented at the World Geothermal Congress 2010, Bali, Indonesia, 25–29 April 2010.

Vörder Bruegge, R. W., Head, J. W. & Campbell, D. B. 1990. Orogeny and large-scale strike-slip faulting on Venus: tectonic evolution of Maxwell Montes. *Journal of Geophysical Research*, 95, 8357–8381.

Vos, I. M. A., Bierlein, F. P., Barlow, M. A. & Betts, P. G. 2006. Resolving the nature and geometry of major fault systems from geophysical and structural analysis: the Palmerville Fault in NE Queensland, Australia. *Journal of Structural Geology*, 28, 2097–2108.

Watters, T. R. 1992. A system of tectonic features common to Earth, Mars, and Venus. *Geology*, 20, 609–612.

Watters, T. R. & Schultz, R. A. 2009. Planetary tectonics: introduction. In: Watters, T. R. & Schultz, R. A. (eds) *Planetary Tectonics*. Cambridge University Press, Cambridge.

West, J. D., Fouch, M. J., Roth, J. B. & Elkins-Tanton, L. T. 2009. Vertical mantle flow associated with a lithospheric drip beneath the Great Basin. *Nature Geoscience*, 2, 439–444.

Westaway, R. 1993. Forces associated with mantle plumes. *Earth and Planetary Science Letters*, 119, 331–348.

Wiegert, M. A. 2007. The gravity and topography of the terrestrial planets. *Treatise on Geophysics*, 10, 165–206.

Wilcox, R. E., Harding, T. P. & Seely, D. R. 1973. Basic wrench tectonics. *American Association of Petroleum Geologists Bulletin*, 57, 74–96.

Wilde, S. A., Middleton, M. F. & Evans, B. J. 1996. Terrane accretion in the southwestern Yilgarn Craton: evidence from a deep seismic crustal profile. *Precambrian Research*, 78, 179–196.

Willbold, M., Hegner, E., Stracke, A. & Rocholl, A. 2009. Continental geochemical signatures in dacies from Iceland and implications for models of early Archaean crust formation. *Earth and Planetary Science Letters*, 279, 44–52.

Willis, J. J. & Hansen, V. L. 1996. Conjugate shear fractures at “Ki Corona”, southeast Parga Chasma, Venus. *American Journal of Science*, 27, 1443–1444.

Wilson, J. T. 1961. Continental and oceanic differentiation. *Nature*, 192, 125–128.

Wilson, J. T. 1973. Mantle plumes and plate motions. In: Irving, E. (ed.) *Mechanisms of Plate Tectonics. Tectonophysics*, 19, 149–164.

Yin, A. 2012. Structural analysis of the Valles Marineris fault zone: Possible evidence for large-scale strike-slip faulting on Mars. *Lithosphere*, 4, 286–330.

Yin, A. & Taylor, M. H. 2011. Mechanics of V-shaped conjugate strike-slip faults and the corresponding continuum mode of continental deformation. *Geological Society of America Bulletin*, 123, 1798–1821.