Formation, erosion and exposure of Early Amazonian dikes, dike swarms and possible subglacial eruptions in the Elysium Rise/Utopia Basin Region, Mars

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A B S T R A C T

Hundreds of narrow, linear ridge segments are found in the transition zone between the Elysium Rise and the Utopia basin, occurring as both single and multiple ridges. The ridges are distinctive because of their very linear, steep-sided nature, their often sharp ridge crest (which sometimes is fractured), their association with stubby flows, their continuity over long distances and their cross-cutting of different terrain. The linear ridges are interpreted to be single dikes and dike swarms, either emplaced as normal dikes or as dikes emplaced subglacially feeding an explosive or effusive eruption. Five dike swarms are identified, having lengths ranging from 10–45 km and being between 1–7 km wide, while single ridges are up to 20 km long and 100–500 m wide. In the areas of dike swarms, crustal dilatation is estimated to vary from 15–60%. Dikes emplaced en echelon suggest that variations in the local stress field caused rotation during dike emplacement and dikes crosscutting flow units imply that dike emplacement can account for some of the observed linear fractures in the area. The ridges both modify and constrain Early Amazonian flows and flood plain deposits suggesting intense dike emplacement in the Early Amazonian. The association with different stages of inverted craters, as well as some features of ice-related origin (possible ice-cauldron and tindar-like features), indicate that the dikes may have been exposed due to eolian erosion and loss of volatile rich units subsequent to their emplacement.

1. Introduction

It has been known since the Mariner 9 mission that Mars exhibits the largest volcanic edifices known in the solar system (Carr, 1973), and these and related volcanic units provide very important information on martian thermal and geologic evolution. Dikes and dike swarms feeding and associated with these units are another important part of understanding these processes (Mége and Masson, 1996; Wilson and Head, 1994; 2002a,b). Furthermore, dike emplacement and configuration is governed by stress state, and thus their regional setting in relation to source regions is of crucial importance. Field and geodetic observations on Earth show that dike emplacement results in extensional near-surface stresses that can produce narrow, deep and v-shaped tension cracks, faulting, and linear, straight-walled, flat-floored grabens (Mastin and Pollard, 1988; Rubin and Pollard, 1988; Wilson and Head, 2002a). Since dikes rarely are exposed on a planet like Mars (with low erosion rates and minor uplift) these morphologies representing the near-surface manifestation of dike emplacement have been the main source for studying dike systems on Mars.

However, examples of dike outcrops in the form of positive linear features representing eroded and exposed dikes do exist, including a giant dike system 800 km north of Hellas Basin (Head et al., 2006), and observed dikes in the region of Tharsis (Mége and Masson, 1996; Wilson and Mouginis-Mark, 1999). The exposed dikes are characterized by being narrow, symmetrical and linear, low-relief ridges with no visible stratigraphy. They usually appear sharp-crested, crosscut different units, and their width and height remain virtually unchanged over long distances, (Mége, 1999; Wilson and Mouginis-Mark, 1999; Head et al., 2006).

No observations of eroded and exposed swarms of dikes have been reported to date and thus information on dike swarms is only known through mapping of graben and fractures. Ernst et al. (2001) and Wilson and Head (2002a,b) interpret several graben zones around Tharsis to be the surface manifestation of giant dike swarms reflecting plume-related dike intrusion complexes. These systems extend thousands of kilometers and thus appear to have very significant implications for martian geologic history, particularly in relation to the existing hypothesis regarding a global cryosphere and a sequestered groundwater system (Clifford, 1993; Clifford and Parker, 2001). Dike swarm activity has been proposed in the Elysium volcanic
province, consisting of circumferential troughs around Elysium Mons and a radiating pattern of fossae that mainly trends ESE–SE and NW defined by Elysium Fossae and Cerberus Fossae (Ernst et al., 2001).

Prior to the Mars Global Surveyor mission, the resolution of the available images was a problem for identification of dike systems, especially with respect to dike outcrop documentation. The Mars Express and Mars Reconnaissance Orbiter missions have now provided high resolution images on a regional scale with the High-Resolution Stereo Camera (HRSC) (resolution ~13 m/pixel), the Context Camera (CTX) (resolution of ~6 m/pixel), and HiRISE (0.5 m/pixel); with these data, detailed processes can be studied. Thus, it is now possible to distinguish between the variety of ridges that has been observed on the martian surface including inverted streams, eskers, thrust faults, dikes, fissures and möberg ridges. The importance of being able to distinguish the origin of these ridges is obvious and has significant implications for understanding their geologic context and history.

2. Background

The Elysium region is the second largest volcanic province on Mars ascribed to Late Hesperian to Early Amazonian volcanic and tectonic activity; it consists of Elysium Mons and the two flank volcanoes, Albor Tholus to the south and Hecates Tholus to the north (Fig. 1) (Carr, 1973; Greeley and Guest, 1987; Tanaka et al., 1992, 2005). Utopia Basin borders the northern and western flank of Elysium Rise and several authors have found evidence for the presence of water (solid or liquid) based on morphologies such as fluidized crater ejecta, polygons, pingos, chaos, eskers and thumbprint terrain (Carr and Schaber, 1977; Rossbacher and Judson, 1981; Kargel and Strom, 1992; McGill and Hills, 1992; Cave, 1993; Kargel et al., 1995; De Pablo and Komatsu, 2007). Additionally, the Gamma Ray Spectrometer onboard Mars Odyssey discovered enhanced hydrogen levels suggesting that the near-surface is rich in H₂O ice (Boynton et al., 2002). The most extensive unit that occurs in Utopia Planitia is the Vastitas Borealis Formation (Tanaka et al., 2005), which is very smooth at 100 m and longer wavelengths (Kreslavsky and Head, 2000) and has been proposed to be a reworked sediment residue deposited from outflow channels (Kreslavsky and Head, 2002). Furthermore, on the basis of evidence for paleoshorelines, Parker et al. (1993) proposed that the northern lowlands, including Utopia Basin, was the site of large standing bodies of water. Based on MOLA data, Head et al. (1999) found evidence that contact 2 of Parker et al. (1993) was approximately an equipotential line (ca. −3760 m), supporting the ocean hypothesis. However, Parker’s proposed shorelines are controversial and Carr and Head (2003) found that many of the examples were related to other processes, and suggested that the outline of VBF might better represent the extent of a former ocean than the proposed shorelines; Kreslavsky and Head (2002) argued that a fast freeze-up of an ocean could explain why a clear coastal morphology has not developed. The transition between the Elysium Rise and Utopia is of special interest since volcanic activity and the deposits within Utopia Planitia may have interacted; this could shed light upon the existence and history of water in the region. Previous studies reveal that the area is very complex and several different landforms, interpreted to have formed from processes ranging from volcanic activity to glaciation, have been mapped.

Of special interest are the outflow-like channels and associated flow deposits originating from the NW flank of Elysium Rise and extending more than a thousand kilometers into Utopia Basin. They are of Early Amazonian age and thereby younger than the larger Hesperian-aged Chryse outflow channels (Tanaka et al., 1992). Some
of the flow deposits have been interpreted as evidence for mega-
lahars due to their lobate morphology, well-defined snout and close
association with channels; this has led to hypotheses that heat from
volcanic activity melted ground ice and thereby mobilized surface
and subsurface material (Christiansen and Greeley, 1981; Christiansen
and Hopler, 1986; Christiansen, 1989). Similar observations have been
made by Greeley and Guest (1987) and Tanaka et al. (1992), who
respectively interpreted the flows to be of volcanic origin modified by
fluvial and periglacial activity, or to be volcaniclastic material highly
fluidized by melt water. Studies by Russell and Head (2002)
supported the hypothesis of mega-lahar formation through observa-
tions of dendritic ridges along the margin of the flow deposits
interpreted to result from dewatering of the mega-lahars. Russell and
Head (2002, 2003) suggest that the discrepancy in source location
between lava flows and lahars reflects the hydrostatic-equilibrium in
the subsurface; their calculations imply that melted ground ice is not
sufficient to account for the enormous volumes of lahar deposits, thus
requiring a groundwater source.

Other evidence for ice-volcano interactions has been reported
(Head and Wilson, 2002, 2007), ranging from pseudocraters (Mou-
ginis-Mark, 1985), thermally distinct craters probably resulting from
interaction between a hot mudflow and ground ice (Morris and Mou-
ginis-Mark, 2006) and mud-like deposits near Hrad Vallis caused
by phreatomagmatic explosions due to dikes intruding an ice-rich
subsurface (Wilson and Mouginis-Mark, 2003). Moreover, subglacial
volcanic edifices like table mountains (Allen, 1979) and möberg ridges
have been reported, suggesting a minimum hypothetical ice thickness
of ~150 m (Chapman, 1994; Chapman et al., 2000). Mud volcanism
and sedimentary diapirism have also been proposed by Skinner and
Tanaka (2007) and Skinner and Tanaka (2001) based on observations
of fractured rises, elliptical mounds and depressions in the southern
Utopia highland-lowland boundary and the region of Galaxias Fossae.
Thus, because of the variety of suggested plausible geologic scenarios
in the area and because of new data from HRSC, CTX and HIRISE, an
area on the northern flanks of the Elysium Rise, in the region of Hrad
Vallis, was selected for studying landforms and processes in detail
(Figs. 1 and 2). The new data reveal hundreds of linear ridges, whose
geomorphic characteristics and origin have not been previously
analyzed. This work therefore evaluates the diagnostic characteristics
of these ridges, analyzes their stratigraphic relationships, and
evaluates the implications of their geologic context in the region of
Elysium.

3. Geomorphology of linear ridges

Hundreds of narrow ridge segments, both multiple ridges and
single ridges, are observed within the study area as displayed on the IR
THEMIS mosaic (Fig. 2). Each ridge is linear with little to no curvature
and they are remarkably uniform in width and height. Their mean
orientation is 124°N with a circular variance of 0.012 and they are
subparallel to a number of linear features and extensional fractures
oriented NW–SE in the Elysium Region, which have been attributed to
flexural uplift (Hall et al., 1986; Head et al., 2001). In the following
sections, the physical characteristics of single and multiple ridge
segments are described with respect to ridge length, ridge width and
ridge geometry; the stratigraphic relationships are considered in the
following section.

3.1. Single ridges

Within the study area six occurrences of single ridges are
observed, consisting of a total of 23 single ridge segments; some
examples are shown on Fig. 3. The ridge segments are either single or
they are emplaced en echelon, separated by fractures or by edifices.
They are recognizable in HRSC data with a resolution of 12.5 m/pixel,
but more detailed characterization is possible using CTX imagery
(6 m/pixel). These data (Fig. 3) readily resolve the ridges and reveal
that single ridges generally have a sharply defined crest and are very
uniform in along- and across-strike character. They are up to ~19 km
long with a mean length of ~5770 m and their widths range from 13–
500 m, with an average of ~250 m (Fig. 5). Single MOLA profile
measurements show that individual ridges have heights varying
between ~5 and 30 m, but due to the narrow nature of the ridges with
respect to the shot spacing along the MOLA tracks there are large
uncertainties in these measurements.

Several individual ridges are emplaced en echelon (Fig. 3B and C).
The first example shows little displacement between the ridges;
segments are emplaced in a knobby textured unit and have a total
length of ~7 km. The second example (Fig. 3C) is more prominent,
consisting of several ridge segments with a total length of ~40 km. The
two longest segments are displaced dextrally with offsets of
approximately 750 m; the northernmost ridge segment curves
slightly towards the southern ridge segment in an area where a few
minor ridges also are exposed.

Another single ridge system (Fig. 3D) penetrates a lobate flow as a
fracture and continues as a ridge on the other side of the flow. The
flow unit is approximately 40–50 m thick and a fracture varying
between 130 m and 250 m in width is observed within the flow,
connecting the two ridge segments on each side of the flow
suggesting that the fracture is related to the ridge emplacement;
furthermore this is a very clear example of ridge that crosscuts
different units.

One of the largest single ridges is a sharp-crested ridge associated
with Galaxius Mons, a rough-textured mound with a central ridge,
which has been interpreted to be a möberg ridge (Chapman, 1994;
Chapman et al., 2000; Head and Wilson, 2002, 2007). The southern
crest of Galaxius Mons is a continuation of the southern segment and
extends further to the north as a 7 km long ridge on the other side of
Galaxius Mons (Fig. 3A, B).

3.2. Multiple ridges

Throughout the research area, systems of multiple ridges are
observed and four out of the five systems discovered are shown in
Fig. 4. These multiple ridge systems can only be identified in images
with resolution comparable to CTX or better and it is thus reasonable
to assume that increased CTX image coverage throughout the study
area will result in more discoveries of multiple ridge systems.

The ridge systems usually have a wedge-like shape, are ~10–45 km
long and ~1–7 km wide, and are broadest in the middle of their
transsects (Fig. 4). The individual ridges are generally smaller than the
single ridges documented above, having lengths ranging from ~47 m
to 13 km, and having an average length of ~1350 m. The individual
multiple ridges are also narrower than the single ridges, with an
average width of ~149 m, varying from 45 m to 341 m (Fig. 5). Some
of the multiple ridge systems may crosscut flow units, as shown in
Fig. 4B–C, where several ridges within each multiple ridge system are
observed. The multiple ridge system partly displayed in Fig. 4C is the
largest system observed in the study area, having a length of 45 km
and a width of 6–7 km. Its relation to the surrounding flow deposits is
difficult to resolve, whereas the multiple ridge system in Fig. 4B
clearly has modified the surrounding flow unit, which partly covers
the ridge system.

A typical multiple ridge system characterized by a wedge shaped
zone of ridges (Fig. 4D) is about two kilometers wide at its maximum
width and is characterized by ridges that occasionally crosscut each
other, producing a braided appearance. This ridge system appears to
be emplaced in a degraded unit surrounded by flat-topped mesas,
which cover up some of the ridges. The longest ridge is ~6 km long
and ~150 m wide and the distances between the ridges vary between
60 and 500 m with an average of ~100 m.
Fig. 2. Research area displaying identified ridges, fractures and other linear features. Had Vallis is situated in the western part, Galaxias Fossae bound the area to the north, and Galaxias Chaos is located east of the study area. A) THEMIS day IR mosaic displaying linear features in the research area; B) Topographic map derived from MOLA digital elevation model. The contour interval is 50 m and the MOLA elevations range from $-4800$ m to $-3500$ m.
Fig. 3. Four examples of single ridges. The sun illumination is from lower left corner on all images. A) Research area displaying the locations of Fig. 3B–E on a THEMIS IR mosaic. B) Two sharp-crested ridge segments, which are partly fractured and emplaced en echelon in a knobby-textured unit. The ridge segments are 3.4 km and 4.8 km long and 200–300 m wide and associated with a linear mound (P03_002134_2148). C) Single ridge segments emplaced en echelon merging into eroded terrain to the north. The total length of the ridge segments is ~40 km. The northernmost ridge segment curves slightly towards the southernmost segment, a characteristic common for intersecting dikes (Pollard, 1987) (P06_003268_2158). D) A single ridge penetrates a flow as a fracture and continues as a ridge on the other side of the flow. The size of the ridge segment north of the flow is 5 km long and 200–250 m wide, while the ridge south of flow is ~60–80 m wide and wedges out twice, ~400 m and ~2.5 km away from the southern edge of the flow. The flow is approximately 40–50 m high (P01_002345_2140). E) A linear ridge, 400 m wide and ~14 km long, emplaced in a knobby-textured unit. The ridge is associated with a mound and the ridge crest is aligned with ridge of the linear mound (P03_002134_2157).
Fig. 4. Four examples of multiple ridges. The sun illumination is from the lower left corner on all the images. A) Research area displaying the locations of Fig. 4 B–E on THEMIS IR. B) Multiple ridge system consisting of 6–8 ridges and a surrounding flow and partly superposed irregular hills. The ridges are up to 5 km long and occur in a 1 km broad zone (P03_002345_2148). C) A closer look at the largest observed multiple ridge system, which is emplaced in a flow deposit; the dikes are occasionally cross-cutting each other (P02_001989_2150). D) The easternmost multiple ridge system and its relation to the surrounding mesas. The zone with multiple ridges is ~1.2 km wide and narrows to ~200 m where it wedges out; the distance between the ridges is approximately 100 m (P03_002279_2161). E) A section of HiRISE image PSP_006591_2165 showing properties of the multiple ridges in the westernmost part of the research area. Some of the ridges have a very distinct, symmetric fracture on top of the ridge crest (white arrows) and four stubby flows (black arrows) emerge from the northernmost ridge.
In the westernmost part of the study area, HiRISE imagery reveals that some of the multiple ridge systems have a distinct, symmetric fracture on the crest of the ridge, with a width of ~40 m (see Fig. 4E; marked with white arrows). This indicates that the ridge material is competent, and not loose, poorly consolidated material. Moreover, short stubby flows (indicated by black arrows) with well defined steep lobate flow fronts appear to originate from the northernmost ridge in Fig. 4E; these have lengths varying from 130 m to 350 m and widths ranging from 350 to 500 m.

4. Stratigraphic relationships

As documented above, the ridges crosscut different units, and both single ridges and multiple ridges crosscut flow units, as seen in Figs. 3D, 4B and C. Fig. 6A and B show an enlarged image of the stratigraphic relationships seen on Fig. 4B. The ridges, marked with red, are surrounded by an orange-colored flow unit; fractures along the contact between the ridges and the flows (marked with a dashed brown line) are also observed. The ridges are at the same time partly covered by irregular hills, which extend to the south. The modification of the flow, shown by the fracturing along the flow-ridge contact, as well as by the contact between the flow and the irregular hills, indicates that the flow unit was the first unit to be emplaced. The stratigraphic relationship between the ridges and the irregular hills is ambiguous, they might be erosional remnants, but the distinct contact between the surrounding flow unit tentatively suggest that the two units are genetically related and could have been emplaced simultaneously. Tanaka et al. (1992, 2005) mapped the flows that the ridges crosscut as Early Amazonian, and thus the formation of the ridges is interpreted to be Early Amazonian or younger based on this relationship.

Another observation that can constrain the timing of the emplacement of the ridges is the structural relationship between the linear features observed within the study area and the easternmost flood plain deposit (Tanaka et al., 1992). A sketch map of the observed linear features (black lines) and the flood plain deposit (grey unit) is displayed on Fig. 6C and D. The deposit seems to be controlled by the ridges, because the linear features are aligned along the edges of the deposit and the deposit itself has an angular shape, suggesting that the topography was there beforehand, and that the flow followed this.
Fig. 6. Stratigraphic relationships. The sun illumination is from the lower left corner. A and B) Multiple ridge system (red lines) crosscutting and modifying a flow unit (orange) and partly covered by irregular hills (light yellow). Modification due to fractures in the flow is observed along the contact between the ridges and the flow as well as between the irregular hills and the flow. C and D) The relationship between the linear features observed within the study area and the easternmost flood plain deposit. The outline of the flood plain deposit suggests that it is structurally controlled by the linear features that are aligned along the edges of the flood plain deposit. E) Context map and sketch map of a characteristic knobby-textured unit, called eroded unit, and its close association with observed ridges. F) The knobby-textured unit shows different stages of inverted craters progressing from normal bowl shaped craters (black arrows) to knobs with a crater bowl on top (red arrow) and to circular knobs (yellow arrows).
Fig. 6 (continued).
topography. Since the flood plain deposit, like the observed flow unit mentioned above, are interpreted to be Early Amazonian in age (Tanaka et al., 1992, 2005), it seems most likely that the ridge emplacement occurred within the same epoch.

Several ridges crosscut a distinct knobby-textured unit; the extent and the characteristics of this unit, called eroded unit are displayed in Fig. 6E, and F and are also observed in the Fig. 3B, D and E. The sketch map (Fig. 6E) shows the areal extent of this unit and its relation to the linear ridges and other linear features in the area. Different stages of inverted craters exist in the area (Fig. 6E; location outlined by red box on Fig. 6E) ranging from large normal craters marked by black arrows, to knobs with a crater bowl on the top (red) and end up as knobs (yellow), which gives the unit its knobby texture. This pitted cone to knob relationship has been described and discussed on the basis of observations from the Medusae Fossae Formation by Schultz and Lutz (1988), Schultz (2002) and Kerber and Head (2007) and is interpreted to be the result of wind erosion of a friable unit, where the strongly eroded unit caused the erosion of units has taken place in the area making it plausible that the ridges have been exposed by similar processes, as proposed for the ridges interpreted to be dikes in the Huygens–Hellas region (Head et al., 2006).

5. Origin of linear ridges

Several different geologic processes can produce ridge-like landforms, including eskers (e.g., Head and Pratt, 2001), inverted stream beds (Ruff and Greeley, 1990; Burr et al., 2009), faults (e.g., Watters, 1993), moberg ridges (e.g., Chapman, 1994) and dikes (e.g., Ernst and Barager, 1992; Ernst et al., 1995; Wilson and Head, 1994, 2002a; Head et al., 2006). We compare these candidate origins with the diagnostic geomorphic characteristics described above in order to assess the origin of the linear ridges observed in the transition zone between Elysium Rise and Utopia Basin.

The very uniform and linear nature of the observed ridges in the study area, their parallel orientation and the crosscutting relationships with other units, exclude landforms such as eskers (Head and Pratt, 2001) and inverted stream channels (Ruff and Greeley, 1990; Burr et al., 2009). The ridges are not likely to be related to faulting, as faults usually do not exhibit symmetric ridges (e.g., Watters, 1993) or stubby flow-like features originating from the ridges as observed (Fig. 4E).

In general, many of the characteristics of the ridges are consistent with near-surface characteristics of dikes and dike swarms (e.g., Ernst and Barager, 1992; Ernst et al., 1995; Wilson and Head, 1994, 2002a; Head et al., 2006; Shean et al., 2005; Kadish et al., 2008; Wilson and Head, 2009). These include the linear nature of the ridges, their symmetric profiles, summit features, often en echelon character, sometimes crosscutting nature, parallel development, associated flow-like features, and their relation to near-surface units. When magma-filled cracks (dikes) are emplaced from depth, they rise to the near-surface along most of their length, and the top of the dike can stall within a few meters to a few hundred meters of the surface (Wilson and Head, 1988; Head et al., 1996), the depth depending on stress levels and orientations, local crustal density distribution, magma overpressurization levels, and gas content and exsolution patterns (e.g., Mastin and Pollard, 1988; Rubin, 1992). A small portion of the dike often breaches the surface and creates a short duration eruption, such as a "curtain of fire" (linear Hawaiian-style eruption), or a longer duration eruption producing a larger vent and edifice (e.g., Wilson and Head, 1988). Eruptions do not occur along most of the length of single dikes; eruptions are typically sustained along the widest portion of the dike (Wilson and Head, 1988), and the dike remains below the surface and solidifies in the shallow subsurface. Removal of the topmost layers by erosion can expose the shallow dike, as in the famous Ship Rock, New Mexico, USA, example (see Fig. 2 in Head et al., 2006). Thus, in most cases, we interpret the ridges to be shallow dikes that have been exposed by erosion and removal of thin near-surface units.

Some of the ridges, or portions of the ridges, could be moberg ridges or dikes emplaced in ice-rich deposits or sub-glacially (e.g., Chapman, 1994), such as the examples of subglacial volcanic intrusions and eruptions in the Tharsis Montes tropical mountain glaciers (Head and Wilson, 2002, 2006; Shean et al., 2005; Kadish et al., 2008). In the future, more detailed local studies are required to distinguish among individual specific examples. Nonetheless, subglacial dike emplacement, and moberg ridge formation, could help to explain why the ridges are now exposed. Ice-rich material would be very easily removed as a function of changing climate conditions, perhaps helping to explain why this area is characterized by so many exposed dikes and dike swarms. Allen (1979) suggested that intrusions and eruptions into a mixed unit of rock and ice would generate landforms similar to subglacial volcanic edifices. Furthermore, we see evidence that features formed in association with some examples (Fig. 7) are similar to those associated with well-known subglacial eruptions such as those at the Gjálp and Grímsvötn structures underlying the Icelandic Vatnajökull ice cap. Vatnajökull covers ~8100 km² in south-central Iceland and has a mean thickness of 380 m (Björnsson and Pálsson, 2008). The Gjálp subglacial eruption of 1996 was very well monitored (Gudmundsson et al., 2004); the eruption melted through 600–750 m of overlying ice to the surface, forming a 7×8 km wide depression (an "ice cauldron" characterized by nested concentric faults), and tephra darkened the area surrounding the vent. The most significant activity, however was subglacial; the eruption created a central subglacial ridge, or tindar, 6 km long and up to 500 m high. Grímsvötn represents a large (15–20 km diameter) subglacial edifice with three calderas, and is the most active volcano in Iceland, having erupted at least 70 times in the last 1100 years (Björnsson and Gudmundsson, 1993). Subglacial melting causes similar types of "ice cauldrons" and tephra-covered ice surfaces, as well as phreatomagmatic craters, and glacial and subglacial lakes, during many of these eruptions (Gudmundsson, 2005). The array of features shown in Fig. 7 suggest that similar subglacial-like eruptions might have occurred in the Elysium Volcanic Province; in addition to the exposed parallel ridges (Fig. 7, 1–3), a complex circular to oval structure, surrounded by nested concentric faults (Fig. 7, 4 and inset) and several complex linear ridge segments (Fig. 7, 5) are exposed within the deposit. We interpret these examples to be the remnants of dike-fed eruptions beneath an ice-rich unit.

The morphologic characteristics of the stubby flows emanating from some ridges (Fig. 4E) might also support this interpretation because subaerial flows generally extend much further downslope than they spread laterally (Wilson and Head, 1994). Theoretical predictions (Wilson and Head, 2002b) and observations (Head and Wilson, 2002) show that shallow subsurface and subglacial sills can readily form. The observed flow width/length ratio of the example in Fig. 4B is only ~1–2; this may indicate that the flows were emplaced as sills, either subglacially or in a substrate readily removed by later eolian erosion. Moreover, the stratigraphic relationship between the observed flow units and the ridges (Figs. 3D and 4B, C) is easily explained if the ridges are dikes and thus during the intrusions have fractured the overlying flow unit. The irregular hills unit might also be related to the emplacement process, and one option is that the emplacement of the ridges into the flow unit caused explosive activity producing cones of tephra material around the ridges.

There are several possible mechanisms to expose the dikes and the dike swarms by eroding more than 5–30 m of overlying material that appears to cover the full height of the dikes. As revealed by the stratigraphy, the knobby-textured unit shows evidence of eolian erosion due to the existence of inverted craters, and several ridges are...
Fig. 7. Exposed parallel ridges, just north of the multiple ridge system shown in Fig. 4B (1–3), together with a circular to oval structure and surrounding nested concentric features (4 and inset), and elongated ridge segments in depressions (5) (P03_002345_2148). The features show many similarities to sub-glacial eruptions in Iceland. The sun illumination is from the lower left corner.
exposed in these areas. However, since the mound displayed on Fig. 3E has been interpreted as a moberg ridge (Chapman, 1994; Chapman et al., 2000) another option is that the dikes were emplaced in an ice-rich deposit or subglacially and that the exposure was a result of the sublimation of ice.

6. Emplacement of linear ridges and implications

From observations on Earth and Venus it is known that dike swarms may contain thousands of very narrow dike segments, some of which reach the surface locally. These segments can range from radial to a central source, to parallel to each other, from discontinuous to continuous, and are sometimes emplaced en echelon, depending on the stress field. These characteristics fit the described systems of multiple ridges very well.

Dike swarms are indicators of the stress field, and the orientations of the dikes are of great interest in assessing regional tectonics (e.g. Grousels and Head, 1994). Dike swarms often occur in a radial pattern close to the magma body (Krassimikow and Head, 2003), indicating random dike propagation in response to individual overpressurization events (e.g. Parfitt and Head, 1993) in a regionally homogenous stress field. Further away, the regional stress field can produce unidirectional trends aligned with the regional maximum of horizontal stresses. Moreover, the local near-surface stress field may deviate from that at depth, resulting in en echelon emplacement and segmentation of dikes by spatial or temporal rotation of the remote principal stresses (Pollard et al., 1982; Pollard, 1987; Ernst et al., 1995).

The dikes and dike swarms in the research area (the transition zone between the Elysium Rise and the Utopia basin) have a unidirectional orientation of ~124°N. Since the dikes and dike swarms are unidirectional, trending NW to SE, it seems reasonable that the regional stress fields are governing the dike emplacement; the proximity of the Elysium Volcanic Province suggest that this province is at least partly responsible. All of the dike swarms have a geometry similar to that which Ernst et al. (2001) have characterized as subparallel dikes in a narrow zone. Several examples of braided ridges might imply repeated activation of the same dike over relatively short times. The dikes emplaced en echelon are slightly overlapping and especially in the case of Fig. 3C the overlapping dikes respond to the presence of each other, resulting in converging curving dikes. A further example of intersecting dike swarms is seen in Fig. 7, where a NW–SE-trending parallel ridge complex (arrow 1) sweeps slightly northward (arrow 2) and is cross cut by a separate set of NW-trending parallel ridges (arrow 3).

Important parameters for measuring the sizes of dike swarms are the areal extent of the swarm (excluding areas of very sparse dike coverage) and the maximum length of the swarm. Table 1 lists these parameters for each of the observed dike swarms. On Earth, swarms related to volcanic edifices are generally less than a hundred kilometers long (Ernst et al., 1995) and from Table 1 it is clear that all observed dike swarms in the study area are much shorter than this value and that these dike swarms are broadly similar to those on Earth. This relationship is consistent with the generation of near-surface extensional stresses in the overlying substrate as the dike is intruded to shallow depth; the portion of the substrate remaining (the flow) preserves the fracture, while the adjacent slightly deeper areas that have had the substrate removed preserve the ridged top of the dike. This relationship between fracture development and dike emplacement can plausibly explain some of the linear fractures observed within the study area and therefore the example from Fig. 3D is used to calculate whether the extension from the dike emplacement can account for the fracture width. The measured fracture width is ~180 m, and this width is approximately equal to the total horizontal extension, which is estimated to be around 2/3 of the average dike width. Thus, the mean dike width should be around 270 m (Head and Wilson, 1993) and this estimate fits well with the measured maximum dike width in front of the flow (230 m to 270 m). The dimension of the dike can therefore account for the observed fracture and this strengthens the interpretation that the linear fractures within the study area are also related to dike emplacement.

The dike-induced dilatation in the area of a dike swarm can be obtained by projecting the dikes onto a line perpendicular to the envelope of the dike swarm and dividing the cumulative dike width by the length of the profile onto which the dikes are projected (Gudmundsson, 1990). Fig. 8 displays the five dike swarms and the locations of the profiles used for calculating the dike-induced dilatation. Table 1 shows the calculations for each profile starting with the easternmost profile (number 1) and ending with the westernmost dike swarm (number 5). The lengths of the profiles are defined by the outermost dike segments and the dilatation has been calculated for the broadest cross section of each dike swarm profile. The calculated dike induced dilatation varies significantly from ~15 to 60%, reflecting the fact that the density of dikes in each swarm varies, and generally the dike-induced dilatation diminishes as the distance from the Elysium Rise increases.

We can also use the morphometric characteristics of the linear ridges interpreted to be dike swarms to estimate effusion rates, in a manner similar to that employed by Head et al. (2006). A key issue distinguishes dikes that intrude without breaking through to the surface and those that produce a significant erupted volume (Wilson and Head, 2009). If eruptions took place through dikes ~200 m wide, magma flow speeds could be up to ~20 m/s and volume fluxes up to ~5000 m³/s per meter of active fissure (Head et al., 2006). However, when a dike erupts to the surface, much of the excess pressure holding the dike open is relaxed as the pressure gradient driving magma flow.

<table>
<thead>
<tr>
<th>Swarm number</th>
<th>Length (km)</th>
<th>Geometry</th>
<th>Areal extent (km²)</th>
<th>Cumulative dike width (m)</th>
<th>Profile width (m)</th>
<th>Dike dilatation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.4</td>
<td>Subparallel dikes in a narrow zones</td>
<td>19.7</td>
<td>1329</td>
<td>2294</td>
<td>58</td>
</tr>
<tr>
<td>2</td>
<td>41.3</td>
<td>Subparallel dikes in a narrow zones</td>
<td>24.5</td>
<td>866</td>
<td>1378</td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>72.4</td>
<td>Subparallel dikes in a narrow zones</td>
<td>199.3</td>
<td>3456</td>
<td>7605</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>53.6</td>
<td>Subparallel dikes in a narrow zones</td>
<td>39.3</td>
<td>440</td>
<td>1476</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>30.5</td>
<td>Subparallel dikes in a narrow zones</td>
<td>74.9</td>
<td>1166</td>
<td>7352</td>
<td>16</td>
</tr>
</tbody>
</table>

For each system the length, the areal extent, and the cumulative dike width along a profile (see Fig. 8 for exact location) have been measured and the dike-induced dilatation has been calculated.
Fig. 8. Map of the location of multiple ridge systems interpreted to be dike swarms. The red boxes show the locations of panels B–F and encompass the five observed dike swarms. For each dike swarm the profiles perpendicular to the envelope of the swarm is marked with a black line. The pink lines represent the measured dike width along the profile and these data are used for the calculated dike dilatation displayed in Table 1. The sun illumination is from the lower left corner on all images.
develops (Wilson and Head, 2009). Active fissures up to 20–30 km long, corresponding to the eruption of the larger lengths of single dikes observed, would correspond to the eruption of magmas with ~0.2–0.3 mass% volatiles rising at speeds in the range 1–2 m/s through dikes with sub-surface widths of ~2 m, leading to total lava volume fluxes in the range 10^4–10^5 m^3/s. These effusion rates are more than an order of magnitude greater than values in the range 1000–3000 m^3/s found to be implied by the lengths (up to 200 km) and thicknesses (~50 m) of flows on the flanks of Elysium Mons (Norman, 2003). Thus, depending on the slope of the surface onto which they were emplaced, we infer that magma erupted from the dikes studied here could readily have produced lava flow units up to at least a few hundred km long.

7. Conclusions

Hundreds of narrow, linear ridge segments with an orientation of ~124° N are found in the transition zone between the Elysium Rise and the Utopia Basin. Five multiple ridge systems are identified, having lengths ranging from 10–45 km and widths ranging between 1 and 7 km; lengths of single ridges range up to ~20 km and widths vary between 10 and 500 m. The linear ridges are interpreted to be eroded and exposed dikes, with some possibly emplaced subglacially to produce mohor ridges and tindars. The finding of different stages of inverted craters indicates that significant local erosion of units has taken place, making it plausible that shallow-intruded dikes have been exposed by erosion and possible volcanic loss. The stratigraphic relationships show both modifications of Early Amazonian flows by dike emplacement as well as Early Amazonian flood plain deposits that have partly been constrained in their emplacement by the exposed dikes. We interpret these relationships to mean that intensive dike emplacement modified the transition between the Elysium Rise and the Utopia Basin during this period. Calculation of dike-induced dilatation shows that 15–60% extension perpendicular to the dike swarm envelope may have occurred in the area due to this activity. Dike widths suggest that local eruption of magmas with ~0.2–0.3 mass% volatiles rising at speeds in the range 1–2 m/s would lead to total lava volume fluxes in the range 10^4–10^5 m^3/s, readily able to produce flow units up to several hundred km long.

References

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