Abstract: The Tharsis region of Mars is characterized by large volcanic and tectonic centres that have been active throughout Martian geological history, including distinct sets of graben that extend radially for distances of hundreds to thousands of kilometres. Formation of these graben has been attributed to crustal extension and/or dyke propagation. Physical analogue models using layered sand and liquid paraffin wax were constructed to test the magnitude and style of deformation in the host rock associated with dyke injection. A variety of igneous morphologies was produced, including dykes and plugs. Results suggest that, in the absence of pre-existing faults, vertical dykes do not produce significant deformation in the surrounding rock. Deformation associated with other magmatic intrusions produced primarily contractional features rather than extensional features, similar to previous numerical studies and terrestrial field investigations.

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The Tharsis region of Mars is characterized by large volcanic and tectonic centres that have been active throughout Martian geological history. Tectonic patterns (Fig. 1) correlate with at least five main episodes of activity concentrated around distinctive centres, dominated in the later stages by large volcanic provinces (Anderson et al. 2001). Many of these tectonic complexes exhibit distinct sets of graben that extend radially for distances of hundreds to thousands of kilometres (Carr 1974; Plescia & Saunders 1982; Scott & Tanaka 1986; Tanaka et al. 1991; Mège & Masson 1996; Anderson et al. 2001). Formation of these graben has been attributed to crustal extension (Plescia & Saunders 1982; Banerdt et al. 1992; Phillips et al. 2001) and/or dyke propagation (Mège & Masson 1996; Scott et al. 2002; Wilson & Head 2002; Schultz et al. 2004).

The dyke-induced graben formation hypothesis stems from both numerical (Rubin & Pollard 1998; Rubin 1992) and analogue modelling (Mastin & Pollard 1988) studies of terrestrial dyke intrusion. These models assumed slip along pre-existing faults to determine the extent of graben subsidence due to dyke intrusion. In contrast to these models, many dyke-intrusion models on Mars do not incorporate pre-existing faults and graben; rather, they rely upon dyke injection as a graben formation mechanism (Scott et al. 2002; Wilson & Head 2002; Head et al. 2003). The fundamental assumption of this interpretation is that the internal pressures within a dyke cause significant structural deformation in the surrounding host rock, specifically that a vertical dyke will allow a graben to form above the tip of the dyke.

In this study, we have constructed and analysed physical analogue models of magmatic injection as a primary mechanism for the production of graben on Mars. In particular, our models were designed to explore the extent to which magmatic injection, under varying emplacement conditions, will induce near-subsurface and surface deformation.

Methodology

A series of physical analogue models using layered sand and paraffin were constructed to test the magnitude and style of deformation associated with dyke injection. Physical analogue modelling techniques have been proven to provide robust simulations of a wide variety of tectonic and geological features and processes from global- or regional-scale crustal studies to outcrop and sub-metre-scale processes (e.g. Cadell 1888; Hubbert 1937, Ramberg 1963; Mulugeta 1988; Koyi 1997; Rahe et al. 1998; Wyrick et al. 2011; Byrne et al. 2013; Sims et al. 2013). Among the most important strengths of physical analogue modelling are: (1) the capability to model complex three-dimensional configurations; (2) the capacity to simulate discontinuous processes such as fracturing and faulting; and (3) the ability to document evolving deformation over time. analogue materials such as sand are selected to reproduce, at a small scale, the geometric and kinematic features of natural brittle deformation structures.

In the experiments described here, dry Oklahoma #1 sand sieved to 500 μm was used as an analogue for brittle upper crust. Dry sand behaves in a...
time-independent manner at the strain rates used in the experiments and its material properties and behaviour have been well documented (Cloos 1968; Weijermars 1986; Withjack & Jamison 1986; Krantz 1991). Shear testing of the sand yielded average cohesion values of 209 Pa and an average friction angle of 34°. These values scale to natural rock cohesion values of c. 27 MPa (Hubbert 1937; Schellart 2000). We chose a model/nature length ratio of $L^* = 5 \times 10^{-6}$, such that one centimetre in the model represents 2 km in nature. Faults produced in these analogue materials are geometrically and kinematically similar to those observed in terrestrial fault systems (Rahe et al. 1998; Wyrick et al. 2011; Sims et al. 2013). Although the absolute values of the principal stresses are not measurable, the experiments were set up so that the maximum principal compressive stress $\sigma_1$ was vertical and the relative magnitudes of the initial minimum principal stress $\sigma_3$ were controlled by varying boundary constraints.

These models were specifically designed to simulate deformation in the surrounding host rock in response to the injection of magma. Paraffin wax was used in these experiments as a magma analogue as it is capable of preserving the three-dimensional structure of the intrusive body relative to the surrounding host rock. The paraffin was kept liquid at 66 °C until injected into the overlying sand pack. An average of 300 cm³ of wax was injected in the experiments over 1–3 s before cooling and hardening. Rubber tubing (6.35 mm interior diameter) with a 20 cm-long slit parallel to the length of the tube along its uppermost edge was secured to the model base by aluminium plates such that its axis was parallel to the y-direction of the model rig (Fig. 2a). This configuration was designed to produce a linear injection into the overlying model. Layers of 1 cm-thick coloured sand were placed on top of the dyke model set-up. The total overlying sand thickness ranged from 6 to 10 cm in the models. The sand pack was cooled prior to injection of the liquid paraffin with solid carbon dioxide (dry ice) placed c. 2 cm above the sand pack for at least one hour. Once the sand was cooled, liquid paraffin was injected under pressure.
(1.0–1.8 bar or 15–26 psi) into the rubber tubing, which caused the paraffin to intrude upwards into the overlying sand layers where it cooled and solidified.

Three model configurations were used (Fig. 2) with some variation of parameters within each configuration. Figure 2a illustrates model configuration A with partially unconstrained sand pack. In this set-up, the sides of the sand pack parallel to the y-direction (in the model reference framework) were unconstrained and had a slope equal to the angle of repose of the sand used (c. 30°). The sand pack was composed of horizontal layers of coloured sand without mechanical differences between...
layers; the base of the sand pack was horizontal. Experiments were run with different sand pack thicknesses (6–10 cm) and with different widths in the x-direction (10–48 cm measured on the top of the sand pack). A second model configuration B, illustrated in Figure 2b, was used in a small number of runs; in this set-up, the sand pack was constrained in all four horizontal directions with no free faces except the top. Figure 2c illustrates the third model configuration C, which is the same as in Figure 2a but with slopes at the base of the sand pack directed away from the injection slit at 4–23.5°. A total of 22 models were run (Table 1).

Although the dynamic stress conditions within the sand pack during injection of the paraffin were not measured, the different model configurations were intended to influence the stress state into which the dykes were injected. Configurations A and C were intended to simulate either a near-hydrostatic stress state, or a weak normal faulting stress state with \( \sigma_3 \) directed in the x-direction within the model reference framework. Increasing sand pack thickness increased the vertical stress (maximum principal compressive stress \( \sigma_1 \)) and varying the (y-direction) width of the sand pack varied the magnitude of \( \sigma_3 \). Because of the fully enclosed sand pack, configuration B likely generated a reactive stress in the y-direction, resulting in a weak reverse-faulting stress state with \( \sigma_1 \) directed parallel to the y-axis.

After dyke injection, the models were wetted to allow for dissection. Models were typically sliced perpendicular to the dyke injection (x–z-plane in the reference framework of Fig. 2) at 1 cm intervals to determine the style and magnitude of deformation in the sand layers surrounding the paraffin injection (Fig. 2a). In some models, the paraffin structures were dissected at the same intervals as the sand pack; in others, the sand pack was carefully dissected around the wax to preserve the full 3D structure of the intact dyke. All models were photographed during experimentation and dissection to analyse deformation patterns.

**Results**

Various dyke and plug geometries were produced during experimentation, similar to previously modelled magmatic intrusions (Galland *et al.* 2006, 2009; Mathieu *et al.* 2008). The paraffin wax injections preserved the detailed morphology of these intrusions. Although the purpose of these models was to characterize deformation associated with vertical dykes, the deformation styles associated

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Table 1. Model names, configurations and principal variables

| Model      | Configuration | Outward dip of base plates (°) | Sand pack thickness above injection site (cm) | Injection pressure (psi) | Sand pack width at top (cm) |
|------------|---------------|--------------------------------|---------------------------------------------|--------------------------|-----------------------------|
| 05JAN12    | B             | 0                              | 6                                           | 15                       | n/a                         |
| 24JAN12    | B             | 0                              | 10                                          | 15                       | n/a                         |
| 08FEB12    | A             | 0                              | 6                                           | 15                       | 22                          |
| 13FEB12    | A             | 0                              | 8                                           | 15                       | 10                          |
| 15FEB12    | A             | 0                              | 8                                           | 15                       | 25                          |
| 20FEB12    | A             | 0                              | 8                                           | 15                       | 18                          |
| 22FEB12    | A             | 0                              | 8                                           | 18                       | 18                          |
| 21AUG12    | A             | 0                              | 8                                           | 15                       | 18                          |
| 27AUG12    | A             | 0                              | 8                                           | 15                       | 18                          |
| 30NOV12    | A             | 0                              | 8                                           | 15                       | 18                          |
| 12MAR13a   | A             | 0                              | 6                                           | 20                       | 40                          |
| 12MAR13b   | A             | 0                              | 8                                           | 20                       | 28                          |
| 13MAR13a   | A             | 0                              | 6                                           | 22                       | 38                          |
| 13MAR13b   | A             | 0                              | 8                                           | 22                       | 28.5                        |
| 15MAR13    | C             | 4                              | 8                                           | 23                       | 38.5                        |
| 28MAR13a   | C             | 11                             | 8                                           | 23                       | 34                          |
| 28MAR13b   | C             | 11                             | 6                                           | 23                       | 29                          |
| 02APR13a   | C             | 11                             | 8                                           | 26                       | 16                          |
| 02APR13b   | C             | 22                             | 8                                           | 23                       | 14                          |
| 03APR13    | C             | 23.5                           | 8                                           | 23                       | 14                          |
| 04APR13    | C             | 10                             | 8                                           | 26                       | 17                          |
| 31MAY13    | A             | 0                              | 8                                           | 22                       | 45                          |

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with other intrusive geometries are presented here to inform future interpretations of surface structure.

Vertical paraffin dykes produced no discernible deformation or offset of sand layers, either ahead of or above the intrusion (Fig. 3a). Vertical dykes appeared more often with higher injection pressures of 1.5–1.8 bar (22–26 psi) and under model configurations A and C. Several vertical dykes produced cup formations along their strike. These cups formed near the surface, transporting the sand layers above both vertically and laterally, creating uplift and reverse faulting directly above the cup (Fig. 3b). Non-vertical dykes typically occurred in models with lower injection pressures of 1.0–1.4 bar (15–20 psi) under varying overburden and model configurations A, B and C. These dykes induced reverse motion in overlying layers, expressed either as reverse faults or folds (Fig. 4).

Plug formation at the model base led to the translation of overlying material vertically, producing reverse faulting at the plug margins (Fig. 5a). A few complex morphologies were formed, such as a plug that developed vertical dykes at its margins. Dissection of this model suggested that reverse faulting developed above the plug first; feeder dykes at the plug margin then created steep anticlines on either side of the intrusion (Fig. 5b). The first appearance of a reverse fault occurred c. 1 cm ahead of the leading edge of the rising plug. Immediately above the leading edge of the plug, a topographic high formed and the deformed subsurface layers indicate the development of an anticline. Further along the dyke, reverse faults developed nearly to the surface and became slightly asymmetrical as the plug became more cup-like in geometry along strike. The main paraffin plug developed two distinct smaller vertical dykes at the margins that produced anticlines above the dyke tips. The uppermost layers developed folds above the width of the dyke that translated to the surface as symmetrical topographic highs of c. 0.4 cm on the sides of the dykes. It should be noted however that the region above the plug and dyke tips did not drop below the regional model elevation.
Many of the paraffin dykes in the models developed en echelon branching segments at or near their tip lines (Fig. 6). These branches typically formed c. 30° rotated from the dyke plane. In one model where the horizontal stresses were inferred to be close in magnitude (i.e. $\sigma_2 \approx \sigma_3$; model configuration C), a fairly symmetrical spiral plug was formed with branching segments rotated c. 30° from the spiralling edge of the plug.

**Discussion**

Vertical paraffin dykes in our models – without a significant dip or base plug – produced no discernible deformation, either at the surface or in the subsurface. This result is consistent with previous numerical studies and field investigations of arrested dykes (Gudmundsson 2003; Geshi et al. 2010). Dykes in the models that transitioned to cup formation in the near surface may be reflections of near-surface effects similar to terrestrial non-feeder dykes (Geshi et al. 2010).

Non-vertical dykes produced reverse faulting and folds. In our models, surface deformation above and around the paraffin dykes primarily took the form of anticlines and reverse faults (i.e. contractional features) rather than graben and normal faults (i.e. extensional features). Our models suggest that, for cases of a non-vertical dyke, the shallower the dip the more likely reverse motion above and along the dyke injection surface is to occur. Previous numerically modelling efforts have examined the role of a widening subsurface dyke in the absence of regional extension and under various configurations of mechanically layered stratigraphy (Gudmundsson & Loetveit 2005; Wyrick & Smart 2009). Their results suggested that deformation was accommodated primarily by contractional fold development or reverse faulting on existing graben. The results of our models suggest dyke injection would produce reverse motion on pre-existing faults, similar to terrestrial examples of dyke-induced reverse faulting in graben (Gudmundsson et al. 2008)

**Fig. 5.** (a) Paraffin plug formation translates overlying material vertically, producing reverse faulting at the plug margins. Model configuration as in Figure 2b, with paraffin injection at 1.0 bar (15 psi) into 6 cm of sand overburden. (b) Further dissection of this model suggested that reverse faulting developed above the plug first, and then feeder dykes at the plug margin created steep anticlines on either sides of the intrusion.

Many of the paraffin dykes in the models developed en echelon branching segments at or near their tip lines (Fig. 6). These branches typically formed c. 30° from the dyke plane. In one model where the horizontal stresses were inferred to be close in magnitude (i.e. $\sigma_2 \approx \sigma_3$; model configuration C), a fairly symmetrical spiral plug was formed with branching segments rotated c. 30° from the spiralling edge of the plug.

**Fig. 6.** (a) Paraffin model of dyke intrusion showing rotated en echelon branching segments. These branches typically formed c. 30° from the dyke plane. (b) In cross-section, these branching segments appeared as en echelon sill-like bodies.
Various intrusion types were produced during experimentation, including dykes, cups and plugs. Many of the paraffin dykes produced bladed ‘branches’ that formed at c. 30° to the main dyke plane. However, in cross-section these branches often appeared as separate horizontal en echelon intrusion bodies rather than the edges of a much larger subvertical igneous structure. At Martian scales, these en echelon segments would likely be mapped as separate dykes in satellite imagery rather than belonging to a larger parent dyke. Estimates of the stress conditions of dyke emplacement based on the orientation of these en echelon branches may be missing the larger in situ stress state for the parent dyke.

The origins of Tharsis-radial graben have been debated for many years (e.g. Plescia & Saunders 1982; Banerdt et al. 1992; Mège & Masson 1996; Wilson & Head 2002). The Tharsis radial graben systems are characterized by the ‘simple graben’ morphology: long narrow graben bounded by normal faults, with down-dropped flat floors unbroken by anticlinal faults. To gain a better understanding of the role and extent of dyke-induced deformation on Mars, physical analogue experiments were performed to document deformation in response to magmatic intrusion. Modelling of magmatic dyke intrusion did not produce the hypothesized extensional graben formation; instead, magma intrusion was primarily characterized by contractional strain patterns. The primary result was surface deformation in the form of contractional folds producing uplift at the surface (i.e. bounding anticlines with a synclinal trough) rather than extensional graben over the dyke tip producing subsidence (i.e. bounded by normal faults with a down-dropped floor).

It should be noted that although the models reported here were performed with homogeneous sand layers, Mars probably has a layered, heterogeneous crust. The role of mechanical stratigraphy in fault and dyke development has been investigated by several researchers (e.g. Gudmundsson 2003; Schöpfer et al. 2007a, b; Wyrick & Smart 2009) and likely plays a role in the development of the Tharsis radial graben. Our homogeneous analogue model results produced deformation patterns similar to numerical model results that do incorporate mechanical stratigraphy, however (Gudmundsson 2003; Wyrick & Smart 2009).

Both dyke emplacement and normal faulting occur in extensional environments (Anderson 1951), so distinguishing the relative roles of each in deforming the near-surface crust is difficult. This study suggests that a vertical dyke intrusion alone does not produce significant deformation in the near surface; vertical dykes in the analogue models produced no resolvable deformation above or ahead of their propagation. This result is similar to terrestrial field evidence of arrested dykes without graben and normal faults ahead of their tips (Gudmundsson 2003). If the dyke dip is not vertical, folding and contractional faulting develop adjacent to and above the dyke. The type of contractional deformation found in the models is not associated with the Tharsis radial graben systems, suggesting that dyke intrusion was not the primary deformation driver.

An alternative interpretation is that the dykes have intruded into pre-existing faults and fractures that provide paths of least resistance through the host rock. These pre-existing faults would also be subject to the same regional stress environment that would favour dyke formation (Anderson 1951). Many of these faults and fault segments would likely have a high slip tendency, with the potential to be more dilatant (Morris et al. 1996; Ferrill & Morris 2003). This condition favours fluid flow (Ferrill & Morris 2003) and likely influences the emplacement pathways of an intruding dyke. Further injection of magma likely produces displacement along these faults in the form of a contractional reverse-fault slip (Gudmundsson et al. 2008). Together, these investigations suggest a more passive role in dyke emplacement rather than the active graben-producing hypothesis.

The dyke-induced graben hypothesis has been widely used to interpret underlying dykes and dyke swarms and to help understand the magmatic history of the Tharsis region. This study suggests that the Tharsis-radial graben were not formed primarily in response to magmatic dyke intrusion. Instead, the graben (and their fault segments) likely predate dyke emplacement. These pre-existing faults would have responded to the same regional extensional stress environment predicted for dyke emplacement, with some fault segments becoming dilatant and influencing the emplacement pathway of the magma. It is likely that many of the graben in the Tharsis region are underlain (filled) as dykes. The graben alone are not evidence of an underlying dyke, however; additional evidence such as lava flows, cinder cones and gravity anomalies are required to accurately interpret sub-surface magmatic intrusions. Understanding the dynamic interaction between magmatic activity and the structural response of the host rock is crucial for understanding the volcanic and tectonic history of Mars and has implications for astrobiological research at past and present geothermally active sites. Our results from this project provide constraints on the relative contributions of dyke- and fault-related deformation in the Tharsis region and contribute to the evolving debate regarding the timing and sources of stress for Tharsis (cf. Mège & Masson 1996; Dimitrova et al. 2006).
These results are consistent with terrestrial field examples and are probably applicable to other planetary bodies, such as the Moon (Head & Wilson 1993) and Venus (Ernst et al. 2001), where dyke-induced graben formation has been inferred.

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