Does shallow dike intrusion and widening remain a possible mechanism for graben formation on Mars?

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ABSTRACT

Shallow dike intrusion and widening was proposed several decades ago as a cause of surface faulting and graben formation on Earth. This hypothesis was subsequently applied to the spectacular linear and/or radial graben systems visible on Mars. However, a recent study has suggested that shallow dike intrusion on Mars results in contractional folding and uplift adjacent to dike walls rather than extensional faulting and subsidence above the dike tip, even in the presence of concurrent regional extension. Here, discrete element numerical modeling is used to re-examine the typical style of deformation above the shallow tips of widening dikes on Mars. The dikes are embedded in a frictional, cohesive material representing the Martian crust. In the experiments presented here, subsidence and extensional faulting (graben formation) are produced above the dike tips, even with modest amounts of widening. For suggested depths to dike tips on Mars, an overlying graben is produced in all cases; no upright detachment-style folds are produced. Results indicate that dike widening does indeed remain a possible mechanism for graben formation on Mars. Implications for the interpretation of deformation associated with shallow dike intrusion on Earth and distant planetary surfaces are discussed.

INTRODUCTION

Shallow intrusion of magmatic dikes has long been associated with deformation at the Earth's surface. At a regional scale, dike intrusion has been shown to be intimately associated with extensional faulting in active rift settings (e.g., Belachew et al., 2013). On a more local scale, observational and geophysical data, together with analogue and numerical modeling studies, have supported the link between dike intrusion and faulting, graben formation, and limited uplift at the Earth's surface (e.g., Mastin and Pollard, 1988; Rubin, 1992; Rowland et al., 2007; Hollingsworth et al., 2013). This hypothesis has subsequently been applied to the spectacular linear and/or radial graben systems seen on both Mars and Venus (e.g., Scott et al., 2002; Wilson and Head, 2002; Grindrod et al., 2005; Pollard and Fletcher, 2005; Goudy and Schultz, 2005; cf. Fig. 1A). In the Tharsis region of Mars, the radial graben systems are characterized by a simple morphology: long narrow graben with pit craters, bounded by normal faults, with a downthrown flat floor unbroken by antithetic faults (Wyrick and Smart, 2009a; Fig. 1B). However, a recent discrete element study has suggested that this hypothesis is not sufficient to explain these features on Mars (Wyrick and Smart, 2009a), even in the presence of concurrent regional extension (Wyrick and Smart, 2009b). This assertion has been repeated in subsequent papers (Smart et al., 2011; Wyrick et al., 2015). Somewhat surprisingly, in these discrete element models, cover deformation took the form of uplift and contractional (detachment-style) folding adjacent to the dike walls rather than faulting and subsidence above the dike tip (cf. Pollard and Fletcher, 2005; Figs. 1A and 1C). Furthermore, these models required the growth of extremely wide, kilometric-scale dikes to produce significant deformation in the cover. These results seem to contradict physical, analytical, and boundary element modeling studies that predict a zone of horizontal stretching and associated faulting above the tip of a shallow, widening dike (e.g., Mastin and Pollard, 1988; Rubin, 1992; Pollard and Fletcher, 2005; Fig. 1A). The question then arises as to

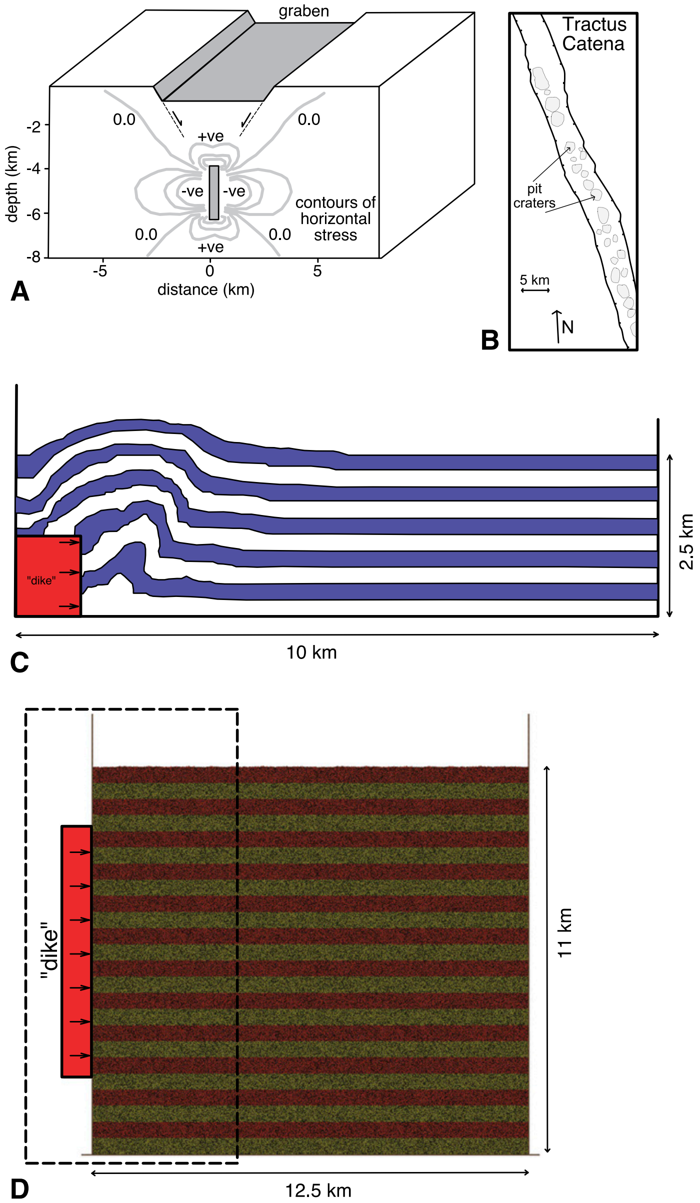

Figure 1. A: Schematic block diagram of dike overlain by graben, with horizontal stress caused by dike widening indicated on front face showing compressive stress adjacent to dike walls (–ve) and tensile stress near dike tips (+ve) (redrawn from Pollard and Fletcher, 2005). B: Line drawing of Tractus Catena graben on Mars (redrawn from Mège et al., 2003). C: Line drawing of standard model of Wyrick and Smart (2009b) at 1 km dike half-widening. D: Model setup and boundary conditions used in this study; dashed box indicates zoomed region shown in results (Figs. 2 and 3).

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why none of these features were produced in these numerical models. If correct, these models would have profound implications for the interpretation of tectonic features on both Earth and distant planetary surfaces, and as such are the catalyst for the present study.

Part of the answer as to why Wyrick and Smart's (2009a) results are distinct may lie in the experimental setup and boundary conditions used to simulate dike intrusion (cf. Fig. 1C). In the Wyrick and Smart (2009a) study, the shallow "dike" extended to the fixed base of the model. The cover modeled by the discrete elements was stated to be "unconsolidated regolith", however the coefficient of friction, density, and initial porosity of this material were unspecified. In their standard model this regolith is 2.5 km thick, in contrast to recent studies which suggest that regolith on Mars is perhaps only on the order of 10–100 m thick (e.g., Gilmore, 1999; Warner et al., 2014). Regardless of precise initial and boundary conditions, this setup created a basal décollement along which a rigid, dike-like indenter was pushed into unconsolidated material and above which upright, detachment-style folds formed (Fig. 1C). Any such model setup with a static base, or with a base that moves at a rate less than dike widening, will create a horizontal kinematic discontinuity. These boundary conditions are not compatible with those of previous analogue or numerical modeling studies: Mastin and Pollard (1988) simulated dike intrusion from the base of an analogue model, but the base moved outward at the same rate as dike widening and foam walls accommodated any lateral movement, whereas Rubin (1992) modeled dikes as planar cracks, with a specified stress or displacement boundary condition, embedded in an elastic half space.

In order to attempt to resolve these issues, this paper will employ a discrete element model to re-examine widening of shallow dikes and their effect upon a frictional, cohesive bedrock under Martian gravitational conditions. Boundary conditions will ensure that a basal kinematic discontinuity is not created and that the dikes are long relative to their final width. A comparison will be made with previous studies, and the viability of dike widening as a mechanism for graben formation on Mars reassessed.

MODELING METHODOLOGY AND BOUNDARY CONDITIONS

A series of discrete element numerical experiments were conducted in order to better understand cover deformation in frictional, cohesive materials, subject to boundary conditions that simulate deformation above and alongside a shallow, widening dike on Mars. Modeling of cover deformation to high strain is an ideal candidate for the application of the discrete element technique as it is well suited to studying problems in which discontinuities (shear zones, faults, fractures, etc.) are important. It allows deformation involving unlimited relative motions of individual elements and complex, abrupt boundary conditions (Cundall and Strack, 1979; Finch et al., 2004; Hardy, 2008, 2011, 2013; Thompson et al., 2010; Smart et al., 2011).

The two-dimensional (2-D) numerical experiments reported here consider a 12.5-km-long by 11-km-deep section of the upper crust, subject to the lateral growth of a blind, dike-like structure (Fig. 1D). Many different models were run with dimensions and parameters similar to those described below. However, the specific experiments discussed herein are representative of the structural evolution typically observed in that they contain the reproducible, characteristic features seen in all models. The model represents the cover as a densely packed (initial porosity ~15%) assemblage of ~365,000 variably sized, circular elements. Element radii range from 6.25 m to 15.625 m (average radius 9.7 m) and their density is 2500 kg/m^3. The coefficient of friction of the assemblage is 0.78 (38°), with a cohesion of ~5 MPa. These values are chosen because the surface expression of faulting, and views of strata in canyons, on Mars suggest that they affect crustal materials (bedrock not regolith) that possess some strength/cohesion (cf. Ferrill et al., 2004; Smart et al., 2011), in contrast to the hypothesis that the Martian surface is so heavily damaged by impact cratering that it consists of cohesionless regolith. The assemblage properties used seek to represent a strong crustal material such as basalt which, given the scale of the elements, is weaker than typical laboratory-scale samples. The discrete elements obey Newton's equations of motion, are unbonded, and experience normal elastic repulsive and tangential Mohr-Coulomb frictional-cohesive contact interactions with their neighbors (including wall elements) under the influence of Martian gravity (see Finch et al. [2004] and Hardy [2011, 2013] for a full description of the modeling approach).

This assemblage is subject to displacement boundary conditions that simulate shallow dike widening in the Martian upper crust: a portion of the rigid left wall is progressively displaced toward the right into the cover (Fig. 1D). Long blade-like dikes are considered whose top and base both lie within the assembly in order to avoid any basal kinematic discontinuity. For simplicity and to compare with previous studies, a simple flat base and top are assumed, and dike height and width are considered to be independent. The modeled dike is assumed to have reached a neutral buoyancy level and thus does not rise vertically (cf. Wilson and Head, 2002). Computational time is reduced by considering only half of the symmetric problem (Fig. 1D). To compare with previous studies and lie within suggested geometric parameters for shallow dikes on Mars (cf. Scott et al., 2002; Wilson and Head, 2002), the tips of the dikes lie at between ~1.3 km and 3.3 km beneath the initial ground surface. The bases of the dikes lie at ~9.0 km depth, producing dike lengths of ~7.7–5.7 km. The dikes achieve a final half-width of 300 m and thus are very long in comparison to their width (cf. Wilson and Head, 2002).

EXPERIMENTAL RESULTS

Shown in Figure 2 is the progressive evolution of a typical dike-widening experiment, at 50, 150, and 300 m dike half-width. In this model the dike tip lies at ~1.7 km beneath the initial ground surface. This experiment is representative of the structural evolution typically observed in that it contains the reproducible, characteristic features seen in all models. A detailed zoom of the model is shown in order to highlight the pertinent features (the dashed box shown in Fig. 1D). The final widening represents ~2.5% shortening at the level of the dike. The geometry and the incremental shear strain and volumetric strain (both calculated over the previous 50 m of half-widening) are shown at each stage.

What can be seen is the clear development of extensional faults and subsidence above the dike tip with no evidence of upright detachment-style contractional folds (Fig. 2; cf. Figs. 1A and 1C). The structural evolution can be broken down into several distinct stages. With initial widening, there is a noticeable compaction (negative volume strain) adjacent to the dike walls and at some distance into the country rock (Fig. 2A). The magnitude of this compaction is not high, but it serves to accommodate some of the initial phase of dike widening. More compaction occurs at the base of the dike as a result of confinement and lack of normal faulting to accommodate strain. Two zones of localized deformation, at the upper and lower tips of the dike, also initiate at this stage. Although they have no expression geometrically, they are clearly expressed in the incremental shear strain plot (Fig. 2A). At the lower and upper dike tips subhorizontal shear faults develop, while extensional normal faults also develop at the upper dike tip. In the main, the normal faults are dilatational (positive volume strain). With continued dike widening (Fig. 2B) the extensional faults propagate to the surface and have a distinct topographic expression. The shear faults at both dike tips continue to develop, propagating laterally into the cover with numerous splays. Further volume strain (compaction) occurs adjacent to the dike wall, although it is now of limited magnitude. After 300 m of dike widening, there is a clear (half) graben at the surface with a width of ~1.3 km and a depth of ~220 m (Fig. 2C). In the bulk of the medium/cover dike widening is accommodated by faulting.

A further set of experiments on dike widening is shown in Figure 3. All parameters are identical to the experiment shown in Figure 2, however the depth to the dike tip is now varied (~3.3, 2.3, and 1.3 km). The depth to the dike base is not varied and all dikes are embedded within the cover. The geometry and incremental shear strain at 300 m widening are shown. It can be seen that a similar final geometry is produced in all cases—i.e., a

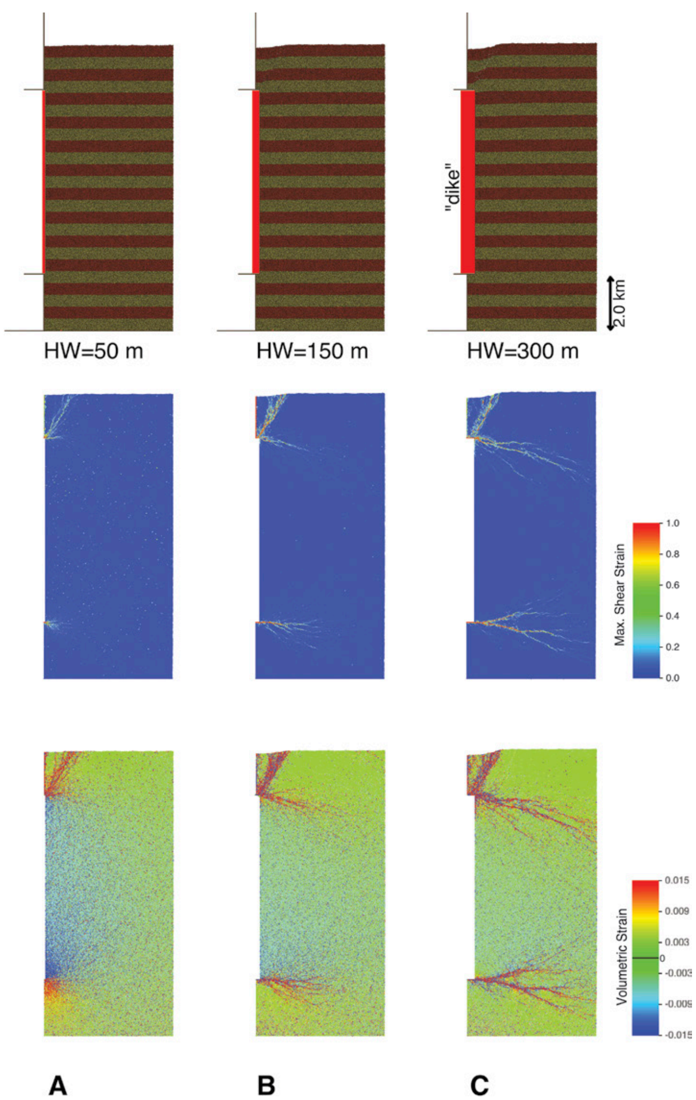

Figure 2. Progressive evolution of dike widening experiment at (A) 50, (B) 150, and (C) 300 m dike half-width (HW). Top row: Geometry; colored layers serve as strain markers and have no mechanical significance. Middle row: Maximum shear strain calculated over previous 50 m of dike widening. Bottom row: Volumetric strain calculated over previous 50 m of dike widening; blue denotes contraction, red denotes dilation. No vertical exaggeration.

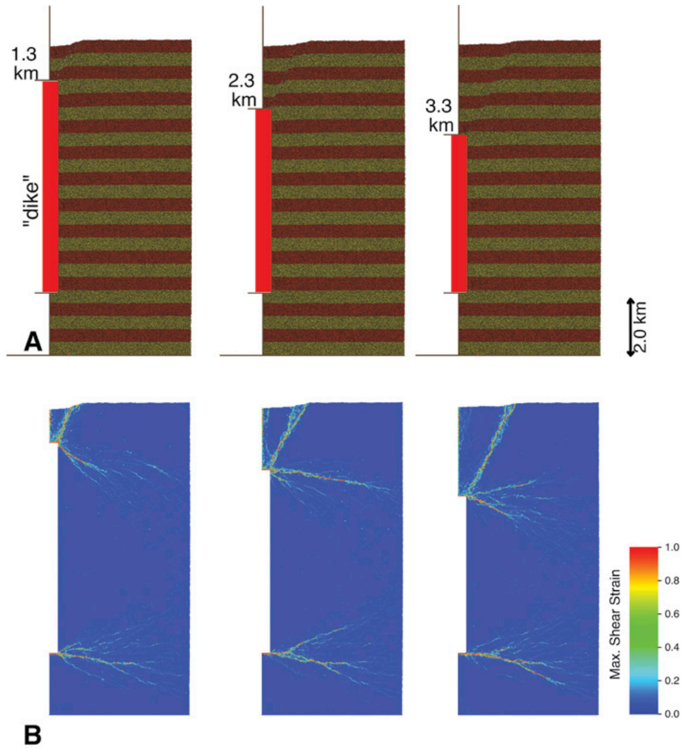

Figure 3. Three dike experiments shown at 300 m dike half-width. In these models, all parameters are identical those in to Figure 2; however, depth of dike tip is varied (~3.3, 2.3, and 1.3 km). A: Geometry; colored layers serve as strain markers and have no mechanical significance. B: Maximum shear strain calculated over previous 50 m of dike widening. No vertical exaggeration.

simple normal fault/graben above the upper dike tip whose width increases with depth to tip. As the dip of the graben-bounding fault remains approximately constant between experiments (~65°), this widening results from simple geometric considerations. The depth of the graben decreases with increasing depth to dike tip. This is because for a constant depth to dike base, the area of material displaced by widening decreases progressively with deeper dike tips; thus, there is less subsidence required on normal faults to accommodate it. The surface expression of these graben is quite simple, with simple flat bases and planar footwalls with limited uplift.

DISCUSSION AND CONCLUSIONS

The results presented here demonstrate that extensional faulting and subsidence can indeed be produced above a shallow, widening dike tip on Mars (or Earth), in agreement with previous analogue, analytical, and outcrop studies (Mastin and Pollard, 1988; Rubin, 1992: Figs. 2 and 3). Minor thickening is produced adjacent to dike walls, rather than upright detachment-style contractional folds. This thickening is accommodated by both tectonic compaction and faulting. For the suggested range of depths to dike tip on Mars (Wilson and Head, 2002), an overlying graben is produced in all cases (Figs. 2 and 3). Furthermore, kilometric-scale widening of dikes is not needed to produce this surface deformation; even modest amounts of widening seem sufficient (hundreds of meters; cf. Fig. 2).

These results are in contrast to the standard model of Wyrick and Smart (2009a) where upright contractional folds were formed adjacent to dike walls and a final half-width of 1.0 km was necessary to produce significant deformation (cf. Fig. 1C). The key difference in the experiments presented here are that (1) no basal décollement or discontinuity is imposed, as the widening dike is embedded within the cover material, and (2) the cover is formed of cohesive, frictional bedrock rather than unconsolidated regolith, consistent with recent observations of the surface expression of faulting, and views of strata in canyons, on Mars (cf. Ferrill et al., 2004; Smart et al., 2011). In the Wyrick and Smart (2009a) study, some investigation was made of dike widening under various configurations of mechanical layered stratigraphy, but regolith was still the dominant cover material.

The inclusion of stronger layers within the regolith did produce some subsidence above the dike tip and fracturing and/or faulting within the strong layers, but results were still dominated by upright, detachment-style folds. Taken together, it seems that the combination of a basal kinematic discontinuity and a thick, unconsolidated regolith led to the creation of detachment folds and minimal extensional faulting. The experiments presented here, in agreement with physical and boundary element models, show that when numerically modeling dike intrusion, the basal boundary condition and the nature of the material considered are of key importance.

The results presented here have important implications for interpretation of surface faulting both on distant planetary surfaces and on Earth. Firstly, they suggest that shallow dike widening still remains a viable mechanism for the creation of linear/radial graben systems such as those seen in the Tharsis region of Mars. While it is not the only possible mechanism, this study has shown that it cannot be ruled out. Secondly, it is clear that concurrent regional extension is not necessary for such graben to form, although its presence will clearly enhance their development. Thirdly, the results simulate the finite, irreversible deformation associated with dike intrusion and widening. The surface expression of these graben is simple: flat downthrown graben floors, bounded by normal faults and with minimal footwall uplift. A key feature is the occurrence of substantial tectonic compaction during the early stages of dike widening. This highlights the importance of including such volumetric deformation in numerical models in order to correctly predict the system response, particularly at early stages. While such compaction may not occur in all crustal rocks, layer-parallel shortening is a common feature of deformation and not just a numerical artifact.

Finally, the model presented here clearly does not include all processes active during dike intrusion and widening (e.g., ductile deformation, heat transfer, fluid flow). It could also be improved by more realistic blade-like dike geometries, the use of pressure rather than kinematic boundary conditions, variable mechanical stratigraphy, and extension to 3-D; these are topics of ongoing research.

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