GRABEN MORPHOLOGY, DIKE EMPLACEMENT, AND TENSION FRACTURING IN THE THARSIS IGNEOUS PROVINCE OF MARS. D. Mège, Département de Géotectonique, ESA CNRS 7072, case 129, Université Pierre et Marie Curie, 75005 Paris, France, e-mail: dmege@lgs.jussieu.fr).

Introduction: The formation of many grabens on Mars is associated to geomorphologic processes resulting in graben deepening and widening. Material removal requires mode I opening in addition to normal faulting. Two mechanisms for material removal have been suggested to date, involving subsurface collapse in tension cracks underlying grabens at depth [1-3], and dike emplacement and interaction with subsurface volatiles [4-8]. In this paper, I review some of the geomorphologic, structural, and geodynamic arguments in favor of these mechanisms and some of the problems they pose.

Morphologies associated to grabens: They include pit crater chains, ovoid depressions resulting from pit coalescence, U-shaped troughs, spatter cones, lava flows at graben ends, and shallow flat-floored depressions [5-7]. Unlike other morphologic types, the latter are observed to be aligned with grabens, but are not necessarily bounded by them. They have morphology and dimensions akin to thermokarstic depressions on Earth [see 9]. Pit chains are found either within the troughs parallel to the fractures or superimposed on fractures, or present *en échelon* steps at low angle from main fracture trends. Many pits and pit chains are associated to local curved fractures (fig. 1c) similar to faults resulting from withdrawal of terrestrial magma chambers. Other grabens are located at the mouth of sapping channels (e. g. VO 610A17) or upstream from outflow channels [7].

Grabens and dike emplacement:

Positive points. (1) Many studies based on linear elastic fracture mechanics, experimental modeling and field work have shown that dike emplacement favors graben formation [e. g., 10, and refs. in 7].

(2) Pits resemble terrestrial pit craters attributed to pressure drop in dikes after magma removal. Association to local curved fractures in areas where pits formed strengthens this analogy. Some pits having shallower floors have been considered as maar analogs [11]. Spatter cones observed along grabens north of Alba Patera and in Tempe Terra also suggest that dikes underlie these fractures.

Interactions between dike emplacement and groundwater/permafrost can explain many kinds of morphologies. A model of dike-ice/water interaction in extensional regime has been proposed [7]. Dike rising to a volatile-rich level produces magma explosion if lithostatic pressure is 2-4 MPa, which may explain maar formation, local fracturing, and the style of spatter cone eruptions. Other morphologies are consistent with dike arrest at deeper level in the crust or other value of lithostatic pressure, generating thermal pressurization flow followed by hydrothermal flow. Distribution of such features in the whole Tharsis region suggests that dikes form giant swarms around the Tharsis central region. Dike swarm size suggests a mafic composition, and is similar to the size of giant mafic dike swarms observed around virtually all the terrestrial hotspots [12].

(3) Cumulated length of dike segments is similar to the length of the largest dike swarms on Earth (1000-2500 km [12]). Magma supply is the major factor governing duration of magma flow in dikes. Due to higher melting on Mars than on Earth for a given mantle temperature, dike swarms are expected to be even longer [7]. Linked graben segments on Mars are sometimes up to 2000 km long [13]. Consequently, dike swarms can provide a structural framework for such long grabens to develop.

(4) Magmatism associated to long-lasting thermal anomalies in the mantle on Earth systematically results in radial dike swarm emplacement, which is one of the key mechanisms of crustal growth and magma transfer to the surface. The role of radial dike swarm emplacement for crustal thickening at Tharsis and lava flow feeding can hardly be avoided.

Negative points. (1) Fracture systems and dikes form jointly in volcanic rifts on Earth. However, the influence of dike emplacement on the development of tectonic structures is negligible at scales larger than 1 m [14, 15]. Dilation of unusually large dykes is unlikely to produce huge grabens having dimensions of usual Martian grabens, both because of the sequence of volcano-tectonic events during dike emplacement [15, 7, 16], and because fracturing predicted by linear elastic fracture mechanics is impeded by cohesive stress at dike tip [17]. Influence of strength contrast between frozen dike and host rock may explain concentration of fractures on both upper sides of dikes. Ongoing quantitative analysis of strength contrast effects should help assessing this effect.

Grabens and tension fractures:

Positive points. (1) Grabens initiated at surface on Earth commonly result from tension fracture growth [e. g., 18]. Tension fracturing may also form graben-like structures even even if extension is not enough for shearing to occur [19, 20] (fig. 1a). In both cases, graben initiation at surface is observed when the topography is uplifted, due to magma reservoir bending or another mechanism. Tension fracturing may therefore be expected in central Tharsis areas, such as Uranius and Ulysses Fossae (fig. 1b) [21], and Syria Planum.

(2) The Griffiths failure criterion suggests that tension fractures on Mars transform into normal faults when they attain 1-2 km depth [21], but pore pressure may promote tension fracture propagation at greater depth [2].

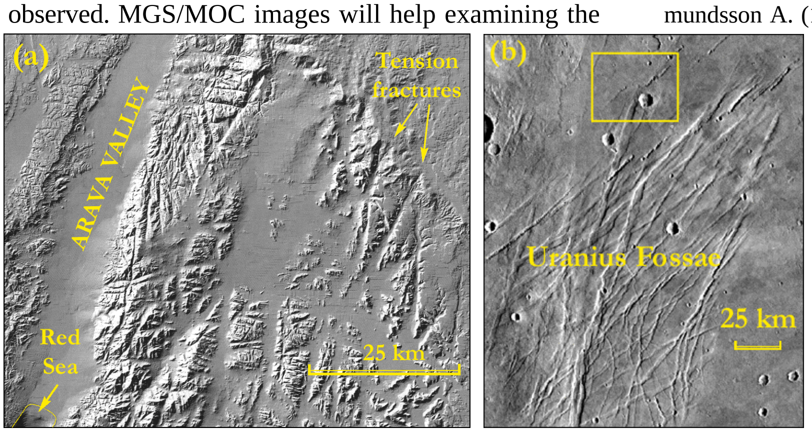
Negative points. (1) The variety of trough morphologies observed on Mars attributed to collapse of subsurface material appears not to have been reported on Earth, even in case of subsurface water circulation.

(2) Terrestrial evidence in Iceland suggests that tension fractures in volcanic regions actually change to normal faults at few hundred meters depth [e. g., 22, 16], as predicted by the Griffith criterion. Normal faulting accommodates strain until several km depth, where tensile regime prevails again. However, that tensile regime is due to magmatic fluids, and results in dyke opening [16]. In this scheme, tension fractures form structurally above the shear domain, unlike in the Martian model published in [2], and the shallowest dikes may still be involved in geomorphologic evolution of graben areas.

Conclusion: Structural, geomorphologic, and geodynamic evidence suggest that both dikes and tension fractures should play a key role the evolution of many graben areas in the Tharsis region. Tension fractures are expected to prefigure early stages of graben initiation at surface, but dike emplacement better explains graben length and the variety of graben morphologies observed. MGS/MOC images will help examining the relationships between graben location and dike emplacement. Despite the absence of regional context at the MOC resolution scale, at least 15 individual images from the aerobreaking and science phasing orbits in 1997 and 1998 display possible dikes segments [23]. More images are necessary to confirm these interpretations and examine their relations with grabens.

References:

[1] Battistini R. (1985) *in* J. Klinger et al. (eds.), *Ices in the Solar System*, Reidel, NATO ASI Ser, 156, 607-617. [2] Tanaka K. L. and Golombek M. P. (1989) *Proc. 19th LPSC*, 383-396. [3] Tanaka, K. L. et al. (1991) JGR 96, 15-17-15633. [4] Schultz R. A. (1988) *NASA TM* 4130, 539-540. [5] Mège D. (1994) *Ph.D. thesis*, Université Paris-Sud, Orsay, France, 384 p. [6] Davis, P. A. et al. (1995) *Icarus*, 114, 403-422. [7] Mège D. and Masson P. (1996) *Planet. Space Sci., 44*, 1499-1546. [8] Montési, L. G. J. (1999) *in* R. E. Ernst and K. L. Buchan (eds.), *GSA Spec. Pap.*, submitted. [9] Costard F. M. and Kargel J. S. (1995) *Icarus*, 114, 93-112. [10] Pollard D. D. et al. (1983) *Tectonophysics*, 94, 541-584. [11] McGetchin T. R. and Ulrich G. W. (1973) *JGR*, 78, 1833-1853. [12] Ernst R. E. et al. (1995) *in* G. Baer and A. Heimann (eds), *Physics and chemistry of dykes*, Balkema, 3-21. [13] Schultz R. A. (1999) *Tectonophysics*, submitted. [14] Bonafede M. and Olivieri M. (1995) *Geophys. J. Int*., 123, 639-652. [15] Gundmundsson A. (1995) *in* G. Baer and A. Heimann (eds), *Physics and chemistry of dykes*, Balkema, 23-34. [16] Angelier J. et al. (1997) *J. Struct. Geol*., 19, 673-685. [17] Rubin A. M. (1995) *JGR*, 100, 5911-5929. [18] Opheim J. A. and Gudmundsson A. (1989) *GSAB*, 101, 1608-1622. [19] Nur A. (1982) *J. Struct. Geol.*, 4, 31-40. [20] Gudmundsson A. (1987) *Tectonophysics*, 139, 295-308. [21] Mège D. and Masson P. (1997) *LPSC* XXVIII, 931-932. [22] Gudmundsson A. (1992) *Terra Nova*, 4, 464-471. [23] Mège D. (1999) *5th Int. Conf. on Mars* (this volume).



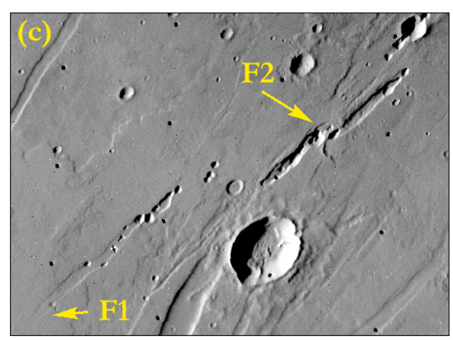


Figure 1: (a) Tension cracks east of the Gulf of Aqaba uplift (Israel DEM, Hall J. K., 1994, Geol. Survey of Israel), and **(b)** possible analogs at Uranius Fossae, northeastern Tharsis province (NASA-JPL MDIM, CD-Rom VO_2007). **(c)** Enlargement of box in (b) displaying segments from the Tharsis radial grabens (NASA-JPL, VO 626A42). Some graben ends display waning vertical fault offsets (F1), typical of terrestrial grabens, whereas other graben ends display curved segments linking the two border faults (F2), suggesting analogy with caldeira processes and magma withdrawal underneath. North toward the top.