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The Canyonlands model for planetary grabens: revised physical basis and implications

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15.1 Introduction

For more than a quarter of a century, the spectacular grabens of Canyonlands National Park, Utah, have provided planetologists with a fundamental analog for understanding what planetary grabens should look like and – more importantly – what may be implied about the depth variation of mechanical properties and horizontal extensional strain.

The seminal work on Canyonlands grabens was done by George McGill and coworkers in support of their investigations of the origin and kinematic significance of lunar and Martian straight rilles (McGill, 1971; McGill and Stromquist, 1975, 1979; Stromquist, 1976; Wise, 1976). McGill and Stromquist (1979) hoped to invert graben widths, assessed on an aerial or orbital image, for the depth of faulting (i.e., fault intersection depth). By equating this depth with stratigraphic layer thickness and assuming a symmetric graben geometry and plausible values of fault dip angles, grabens provided ready and seemingly reliable probes of the near-surface planetary stratigraphy and strain. Interestingly, the analog modeling of brittle-layer extension over a ductile (quasiplastic) substrate, appropriate to Canyonlands

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stratigraphy (McGill and Stromquist, 1975, 1979), anticipated the key role of faulting in triggering and mobilizing salt or shale diapirism at depth (Jackson and Vendeville, 1994; Jackson, 1995). Other observations and inferences made in the 1970s, including flexure of rock layers at ramps near graben terminations and incremental growth of fault slip (McGill and Stromquist, 1979), anticipated these fundamentally important ideas by at least a decade (Sibson, 1989; Peacock and Sanderson, 1991; Cowie and Scholz, 1992).

Kinematically, a symmetric graben geometry was thought to limit the type of structure beneath the graben to either a dilatant ("tension") crack or a décollement (for various rationales see Golombek, 1979; Golombek and McGill, 1983; Tanaka and Golombek, 1989; Banerdt *et al.*, 1992; Figure 15.1). These hypotheses are at variance with more recent (as well as some older) field, experimental, and theoretical investigations of developing grabens

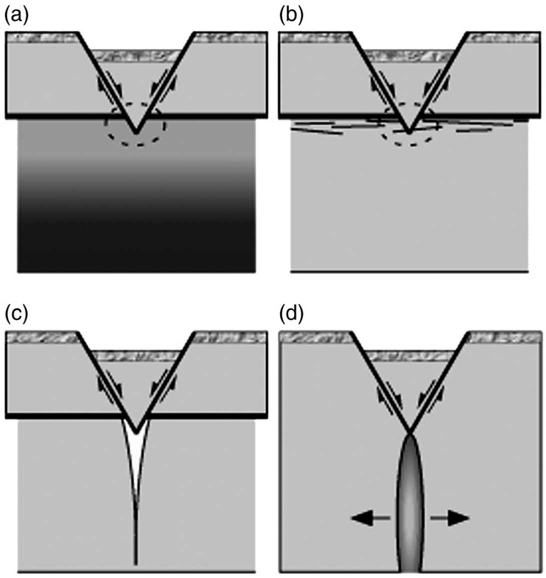

Figure 15.1. Previously proposed hypotheses for extrapolating planetary grabens to depth (after Tanaka *et al*. [1991]). (a) Faulting at bimaterial interface (e.g., brittle over quasiplastic rheology, megaregolith over basalt, dessicated ground over icy ground), (b) Faulted upper layer separated by sills or detachment zones from undeformed substrate, (c) Graben wedge falling into space-accommodating tensile crack in substrate, (d) Graben faults nucleated by dike dilation at depth. Dashed circles in (a) and (b) indicate areas of kinematic incompatibility; extension in (d) due to dike is subequal to that accommodated by superjacent graben. All these ideas imply a thin-skinned upper faulted layer that is uncoupled from subjacent strata.

(symmetric and asymmetric) on the Earth (see reviews by Schultz, 1992, 1999). The idea of ‘‘thin-skinned’’ extension, and the resulting problem of the mechanisms by which strain would then be accommodated at greater depths below the graben wedges, have motivated a variety of formulations of Tharsis tectonics (Tanaka *et al.*, 1991; Banerdt *et al.*, 1992; Thomas and Allemand, 1993).

Although reasonable when proposed, many of the initial ideas from Canyonlands faults, as applied to Mars and other planetary bodies, have not withstood the test of time. Substantial advances in understanding the kinematics of relay-ramps and systematic measurement of fault displacements over the past decades have led to more sophisticated approaches to graben geometry and development being commonplace today (Barnett *et al.*, 1987; Peacock and Sanderson, 1991, 1994; Odonne and Massonnat, 1992; Davison, 1994; Trudgill and Cartwright, 1994; Cartwright *et al.*, 1996; Moore and Schultz, 1999; Schultz, 1999, 2000). Nevertheless, it is still common to encounter papers from planetary researchers who attempt to map subsurface horizons using graben widths. We expect planetary grabens to look like those in Canyonlands and – despite the likely lack of thick, wet, evaporite sequences underlying large regions of post-Noachian Mars – to behave like them.

The purpose of this chapter is to propose a new model for planetary grabens, based on an improved understanding of Canyonlands graben analogs. The new ‘‘hourglass’’ model is derived from current concepts demonstrated by the field relations, kinematics, and mechanics of well-studied terrestrial faults and grabens. First, we review the salient aspects that motivated the original Canyonlands model for planetary grabens in the 1970s. After noting some important planetary applications and expansions to this hypothesis, we briefly review several new observations of Canyonlands grabens that require the present revision of this model. Last, we touch on some of the implications for extensional tectonics on the terrestrial planets and satellites.

15.2 Historical development of the model

The ‘‘simple’’ graben paradigm follows directly from an interpretation of the surface expression of the Canyonlands grabens. These interpretations were based on an understanding of fault kinematics and mechanics available in the 1970s. Because planetary grabens on Mars and elsewhere are, in many cases, still being interpreted by using this paradigm, a brief review of the origin and application of the original Canyonlands model will permit a clearer understanding of the changes that are needed to better interpret planetary grabens.

15.3 Grabens at Canyonlands National Park, Utah

The grabens occur within the Needles District of the Park and define an arcuate, northwest-trending system (McGill and Stromquist, 1979; Trudgill and Cartwright, 1994; Cartwright *et al.*, 1995; Schultz and Moore, 1996; Schultz-Ela and Walsh, 2002). The grabens range from ~100 m to 6 km in length and are generally spaced 700–1000 m apart. Widths at the surface range from <100 m to >400 m, with normal-fault displacements – defined here by the exposed stratigraphic offsets along the faults – varying from less than 25 m to more than 100 m (McGill and Stromquist, 1975; Cartwright *et al.*, 1995; Moore and Schultz, 1999).

Graben floors are mantled by Quaternary colluvial, aeolian, and alluvial sediments (Biggar and Adams, 1987) that produce a smooth, sub-horizontal surface. Previous work suggested that these sediments were negligibly thin (<10–15 m) in relation to the fault offsets (~100 m), implying that the present geomorphic surface mirrors the configuration of the structural graben floor (i.e., depth and attitude) (Cartwright and Mansfield, 1998).

The grabens deform a ~460 m thick section of clastic sedimentary rocks that overlie gypsum and other evaporites in the Paradox Formation (Lewis and Campbell, 1965; Condon, 1997). Down-dip sliding of the clastic sequence and/or flow of subjacent Paradox evaporites is thought to have initiated graben growth and related extension in the overlying rocks (e.g., Baker, 1933; Lewis and Campbell, 1965; McGill and Stromquist, 1975; Huntoon, 1982; Trudgill and Cartwright, 1994; Cartwright *et al.*, 1995; Schultz-Ela and Walsh, 2002; Walsh and Schultz-Ela, 2003).

Together, the faulted clastic sequence and the subjacent evaporites approximate a brittle-over-quasiplastic rheologic system that has two relevant attributes. First, the layered sequence prohibits fault development in the ductile substrate, leading to a special – and particular – tectonic setting for these structures. Second, the deformable substrate facilitates the accommodation of potential volumetric problems beneath the grabens by flow and growth of reactive salt diapirs (Jackson and Vendeville, 1994; Jackson, 1995; Moore and Schultz, 1999; Schultz-Ela and Walsh, 2002).

The geometric graben model that emerged from this body of work was based on several key observations. Graben walls at the surface were vertical to depths of ~100 m, implying that normal-fault slip occurred along preexisting subvertical joints (McGill and Stromquist, 1974, 1975, 1979). Where observed in crosscutting drainages (such as Lower Red Lake Canyon), graben faults steepened in average dip angle from vertical to ~70° below depths of ~100 m, leading to vertical gaps along graben walls as the graben wedge moved downward (McGill and Stromquist, 1975) along with inward rotation and failure of joint-bounded slabs. Normal faults having shallow and steep segments in particular layers, as a result of down-dip linkage of the individual joint and fault segments, are well documented in the literature (Gudmundsson, 1992; Gross *et al.*, 1997; Peacock, 2002; Wilkins and Gross, 2002; Ferrill and Morris, 2003; Soliva, 2004). The magnitude of vertical offset of Cedar Mesa sandstone caprock onto graben floors was taken to be subequal on both sides of the graben, leading to a symmetric graben configuration (McGill and Stromquist, 1974, 1979). Although asymmetric offsets were locally observed at the time (G.E. McGill, personal communication, May 1997), the symmetric graben model appeared more successful in accounting for the range of observations obtained, and it was consistent with physical experiments that simulated graben development (Stromquist, 1976; McGill and Stromquist, 1974, 1979).

Kinematically, the growth of two equal-displacement, conjugate normal faults that span the thickness of a brittle sequence was most easily interpreted as contemporaneous nucleation of both faults at depth, at the brittle–quasiplastic interface, and simultaneous upward propagation to the

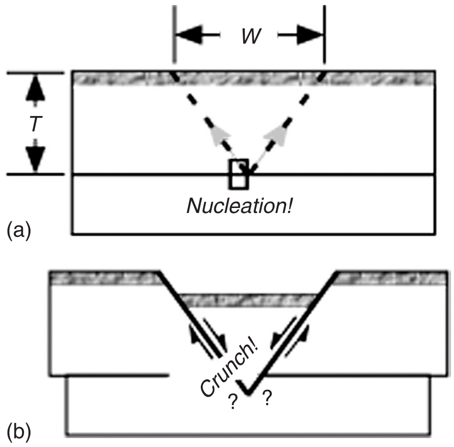

Figure 15.2. Kinematic sequence required by the original Canyonlands model for grabens. In (a), two conjugate fault surfaces nucleate simultaneously at the interface between the upper and lower layers, then propagate upward to the surface. Initial width of incipient graben W is taken to be proportional to faulted-layer thickness T. (b) Nonzero displacement along

surface (Golombek, 1979; Golombek and McGill, 1983; Golombek, 1985). This sequence, shown in Figure 15.2, implies that the incipient graben width at the surface is proportional, through an assumed (constant) value of fault dip angle, to the faulted-layer thickness (Figure 15.2). Continued extension and vertical offset would, however, necessarily lead to increasingly inaccurate relationships between width and thickness (Figure 15.2).

Horizontal extension of a layer that is accommodated by downward translation of a symmetric-graben wedge implies geometric (space) problems (Golombek, 1979; Golombek and McGill, 1983). In particular, the lower tip of the wedge must either deform internally, punch downward into quasiplastic rocks, or be truncated by a detachment surface at the interface (Golombek, 1979; Tanaka *et al.*, 1991; Figure 15.1) for horizontal extension to occur and accumulate. This geometric problem is circumvented in many terrestrial cases by the development of listric bounding faults and block rotations (Roberts and Yielding, 1994) for large-strain (and sufficiently deep) examples. Large horizontal displacements on planets other than the Earth that would produce listric faults and detachments are not typically observed, however (Okubo and Schultz, 2003, 2004). Alternatively, clay models reported by Cloos (1968) demonstrate how symmetric graben geometries can result from nucleation at depth of asymmetric faults that slip progressively with increasing horizontal strain, leading to internal deformations and a final symmetric graben geometry for relatively low-strain examples.

An alternative solution to the putative geometric incompatibility hypothesizes that a vertical "tension crack" could form directly beneath the symmetric graben and open to accommodate the lowering wedge (Golombek and McGill, 1983; Golombek, 1985). Space created by the crack would be invaded by the wedge (Figure 15.1). The crack would form in a subjacent layer, such as megaregolith, having hypothetical failure properties that would lead to jointing below the interface and faulting above (Golombek, 1985). This scenario has been applied to pit-crater chains and collapse depressions at Valles Marineris by Tanaka and Golombek (1989). However, the idea is at variance with typical rock-mass failure criteria (Hoek and Brown, 1980), that generally predict cracking at shallower depths than faulting (Schultz, 1992; Schultz and Zuber, 1994) and the implied volumetric balance between the wedge and subjacent void volume in the crack (Mège and Masson, 1996). This layer-cake scenario differs from cracking or faulting of individual intercalated units that later link up to form a "dilational fault" (Ferrill and Morris, 2003) having an average dip angle steeper than the optimal one for Coulomb frictional sliding alone (Gudmundsson, 1992; Gross *et al.*, 1997;

Peacock, 2002; Wilkins and Gross, 2002; Ferrill and Morris, 2003; Soliva, 2004). This "crack-below fault" conjecture – for the two-layer sequence (Figure 15.1) – is not considered robust for crustal-scale faults today.

Based on the echelon patterns of Martian pit-crater chains, Schultz (1989) originally suggested that these depressions may be the surface expression of dilatant hydrofractures at shallow depth, pressurized by either magma or groundwater. Other Martian grabens such as those in: (1) Tharsis (Wilson and Head, 2002; see Tanaka *et al.* (1991), Mège and Masson (1996) and Mège *et al.* (2003) for reviews and discussion), (2) the Valles Marineris system (Schonfeld, 1979; recently revived conceptually by McKenzie and Nimmo, 1999), (3) on the Moon (Head and Wilson, 1994), and (4) on Venus (Grosfils and Head, 1994; Ernst *et al.*, 1995) have also been proposed to extend as a result of dike dilation below. Planetary grabens associated with pit-crater chains might not be formed directly by regional crustal extension per se, but instead might nucleate and accumulate displacement in concert with local, inhomogeneous stresses associated with the free-surface interaction of near-surface dikes (Pollard *et al.*, 1983; Mastin and Pollard, 1988; Rubin and Pollard, 1988; Rubin, 1992; Mège and Masson, 1996; Mège *et al.*, 2003). Dike dilation and lateral propagation represent a balance between internal magma pressure and crustal stress state (Rubin, 1995; Fialko and Rubin, 1999), leading to an indirect relationship between crustal stress and graben strain. In this scenario (Figure 15.1), no stratigraphic or mechanical discontinuity is required, and the depth of faulting would be related to the details of dike emplacement (Mège and Masson, 1996; Wilson and Head, 2002). Schultz *et al.* (2004) recently inferred the existence of a dike below a Martian graben from MOLA topography.

15.4 Planetary implications of the symmetric graben model

One prominent and persistent byproduct of the Canyonlands model of graben faulting is the putative correlation of fault-intersection depth with the thickness of the megaregolith, or other mechanically distinct layer, on the Moon (Golombek, 1979; Golombek and McGill, 1983). The megaregolith is thought to be an intercalated sequence of laterally discontinuous ejecta deposits from impact craters and basins, along with lavas and sediments (Melosh, 1989, p. 197). Originally identified for the Moon (Hartmann, 1973; Squyres *et al.*, 1992), the putative Martian megaregolith is thought to attain cumulative thicknesses of perhaps 2 km (Fanale, 1976) and may comprise a substantial part of the older, Noachian terrains as impact-basin ejecta blankets (MacKinnon and Tanaka, 1989).

Patterned after the lunar stratigraphy, a layer-cake model of planets such as Mars was developed (MacKinnon and Tanaka, 1989; Squyres *et al*., 1992). The idea was that grabens would nucleate at the contact between basalts above and weaker, more plastically deforming megaregolith below, with graben widths directly indicating the thickness of the brittle basaltic layers (Wise, 1976). For Mars, this brittle-over-quasiplastic stratigraphic template (Davis and Golombek, 1990; Plescia, 1991; Banerdt *et al*., 1992) was expanded to include ice-rich layers (Soderblom and Wenner, 1978; Squyres and Carr, 1986; Squyres *et al*., 1992) as mechanical "discontinuities" (Golombek, 1985) or plastically deforming substrates that could lead to comparable graben-fault nucleation and geometric interpretations (Davis *et al*., 1995; Golombek *et al*., 1996). This general sequence – faulted basement, megaregolith, capping veneer of lava flows, ground ice, and/or sediments – has motivated many interpretations of Martian and planetary tectonics (Tanaka and Golombek, 1989; Allemand and Thomas, 1992; Thomas and Allemand, 1993).

The thin-skinned models discussed by Tanaka *et al*. (1991) all require either a brittle-over-quasiplastic layering (Figure 15.1) or a décollement (detachment) surface (Figure 15.1), both of which serve to decouple the faulted and extending upper carapace from everything below (Jackson and Vendeville, 1994). Thus, this paradigm for Martian extensional tectonics retains a clear heritage from the early ideas for the Moon and those developed for the grabens in Canyonlands. This simple two-layer scenario has been applied with varying success to icy satellites (Golombek and Banerdt, 1986; Pappalardo and Greeley, 1995) and to thermally induced rheologic stratification on Venus (Hansen and Willis, 1998; Ghent and Hansen, 1999; Ghent and Tibuleac, 2002).

Recent high-resolution images of Valles Marineris trough walls and other slope faces on Mars, from the Mars Global Surveyor spacecraft (Albee *et al*., 1998), have been unable, however, to identify either the megaregolith or its basal contact with the fractured bedrock below (McEwen *et al*., 1999; Williams *et al*., 2003). Previous searches using Viking data (Lucchitta *et al*., 1992) have also been unsuccessful in locating and demonstrating this contact. Ongoing analyses of high-resolution MOC images demonstrate the presence and regional extent of fine-scale layering on Mars (Williams *et al*., 2003), morphologically similar to terrestrial flood-basalt sequences with sedimentary interbeds. Sequences of individual layers ~5–10 m thick attain aggregate thicknesses exceeding 3–6 km in the Valles Marineris region (McEwen *et al*., 1999). These new observations of thinly layered sequences of strata in the Martian crust (Malin and Edgett, 2000) provide a firm basis for identifying Martian grabens in cross section by revealing offset markers and

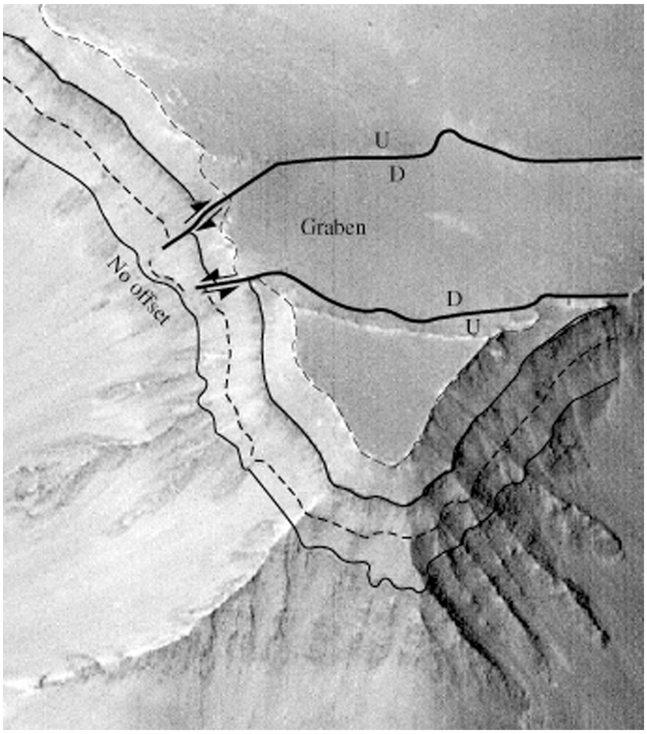

Figure 15.3. Map of a representative Martian graben showing offset of layers along slope and no offset of deeper layers (see McEwen *et al*. [1999] for discussion of this area and the layers). Normal separation of layers on slope exceeds the dip-slip offset due to the shallow slope angle. Part of MOC image 568174924.8003 P080-03 in eastern Coprates Chasma centered near 14.5°S, 55.8°W; graben width $\sim$ 1 km.

do not support assertions that Martian grabens must sole into a detachment, horizontal discontinuity, or change in stratigraphy, as illustrated in Figure 15.3.

The three-layer scenario is too simplistic to describe much Martian geology and stratigraphy (McEwen *et al*., 1999; Malin and Edgett, 2000). As a result, the original Canyonlands model may be of limited applicability to describe the three-dimensional deformation and strain in Martian terrains underlain by thick sequences of layered rocks (Hauber and Kronberg, 2001; Wilkins *et al*., 2002).

15.5 Canyonlands in the 1990s and beyond

Work on the Canyonlands grabens continued into the 1980s and 1990s by several researchers and agencies, mostly in support of candidate sites for high-level radioactive waste disposal (Woodward-Clyde Consultants, 1983) and petroleum exploration (Trudgill and Cartwright, 1994; Fossen, 1995). Drill cores became available that documented the stratigraphy of the Paradox Basin in many key places. Sedimentologic and stratigraphic work refined the interpretation of important units, such as the Cedar Mesa Sandstone (Loope, 1984) that caps several of the grabens (Lewis and Campbell, 1965; McGill and Stromquist, 1979), as well as the regional stratigraphy (Condon, 1997). Although no longer considered suitable (geologically or politically) for radioactive waste isolation, the Grabens area of Canyonlands National Park now provides a template – and scale model – for oil and gas fields associated with crustal rifting and graben-related structural and stratigraphic traps (Fossen, 1995). The Canyonlands grabens now also represent the type example of (normal) fault growth by segment linkage (Trudgill and Cartwright, 1994) as well as an important and widely cited data set for displacement-length scaling (Cartwright *et al*., 1995).

This continuing work by independent research groups has exploded the legend of symmetric, keystone-collapse grabens in Canyonlands (Table 15.1; Figure 15.4). For example, Trudgill and Cartwright (1994) and Cartwright *et al*. (1995, 1996) have demonstrated that the displacements along graben-bounding faults scale with the map lengths and that the displacement maxima are located near the fault-segment midpoints – just like on other examples of normal of faults (Dawers *et al*., 1993; Peacock and Sanderson, 1991, 1994; Soliva and Benedicto, 2004). This important and fundamental observation indicates that estimates of graben-floor depths, obtained by averaging several measurements made at arbitrary positions along the graben (Davis *et al*.,

Table 15.1. *Evolution of thought on graben mechanics*

Old	New
Symmetric grabens	Asymmetric grabens
Conjugate faults of equal offset	Opposing faults have unequal offset
Flat floors, shallow, and indefinitely long	Tilted floors, depth $= f$(length, position)
Strain independent of position	Strain dependent on along-strike position
Conjugate faults are synchronous	Sequential master-antithetic fault development
Faults grow upward from interface at depth	Subsurface interface/discontinuity not required
Rigid-block tectonics (wedge indentor)	Deforming blocks, variable slip on faults
Wedge crunch implies a crack, dike, or truncation at depth	Zero slip at wedge tip; fault networks at depth
Thin-skinned tectonics	Thick-skinned tectonics

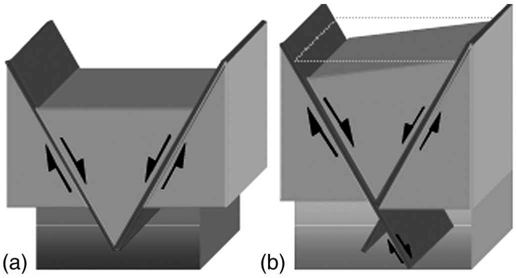

Figure 15.4. Comparison of symmetric "simple" graben (a) with asymmetric graben (b). Note variable offset along graben-bounding normal fault in (b). See text and Table 15.1 for discussion.

1995), are only marginally informative because they ignore the fundamental position-dependence of these depth values (Schultz and Fori, 1996). The work also demonstrates the necessity of identifying the fault-segmentation lengths appropriate to the observed surface displacements (Schultz, 1997; Wilkins *et al.*, 2002), rather than just mapping the aggregate length of an echelon graben array.

Detailed structural and topographic mapping (Schultz and Moore, 1996; Moore and Schultz, 1999; McGill *et al.*, 2000) has demonstrated that the grabens are characteristically asymmetric, rather than the simple, symmetric, keystone-collapse wedges previously thought. Characteristics of asymmetric graben geometry in cross section include (Schultz and Moore, 1996; Moore and Schultz, 1999):

(1) Significant differences in the amount of stratigraphic offset across graben. These differential offsets, indicating master and antithetic faults, are documented in grabens that vary widely in size (Devils Pocket, Devils Lane, Cyclone Canyon, Red Lake Canyon; Moore and Schultz, 1999).
(2) Distinct map pattern of graben bounding faults. The fault having greater stratigraphic offset (master fault) is continuous along the graben's length, whereas that of the facing graben wall (antithetic fault) is discontinuous, segmented, and echelon.
(3) Rollover anticlines formed adjacent to the antithetic fault are related to the translation of strata down the master fault, resulting in local flexure (Higgs *et al.*, 1991). The widths of preexisting joints that parallel the graben (see Figure 15.5) also differ considerably across a graben: greater widths (individual joint openings of perhaps several meters) on the antithetic side are associated with increased surface area and bending of the jointed rocks along the upper, outer surface of the rollover anticline.

Figure 15.5. Aerial view of Devils Pocket graben in Canyonlands National Park (photo by Matt Soby, looking north) showing echelon, segmented geometry of grabens, and stratigraphic offsets of preexisting Needles topography. Jeep trail on graben floor for scale.

(4) Footwall uplift and gentle flexure, perhaps tens of meters in amplitude, occurs adjacent to the master fault; it decreases both along strike toward the fault terminations and across strike away from the fault trace. The pre-existing joints are closed in the footwall area.
(5) Seismic refraction and gravity results (Grosfils *et al.*, 2003) demonstrate substantial floor tilt in northern Devils Lane graben, down toward the master fault and deeper (>65 m) in the center of the graben than near the ends (~ 15 m). The graben floor is best described as "spoon-shaped," or deepest in the center and tilted down toward the master fault, beneath the overlying sedimentary wedge.

These attributes, either individually or together, are definitive indicators of asymmetric cross-sectional geometry.

Construction of balanced cross sections (Moore and Schultz, 1999; Grosfils *et al.*, 2003), as well as field observation of grabens exposed in cross section (McGill *et al.*, 2000), suggest that the graben faults do not necessarily intersect at the base of the brittle layer – as previously postulated – but at perhaps only two-thirds to three-quarters of the layer thickness (see also parallel conclusions by Schultz-Ela and Walsh, 2002). The intersection depths and fault geometries are sensitive to the layer properties, curvature of the layer in cross section, and other parameters (Schultz-Ela and Walsh, 2002). Thus, graben widths measured at the planetary surface do not provide a reliable measure of the thickness of the faulted layer (see discussion of lunar graben widths below).

Independent mechanical modeling of graben nucleation during down-dip extension of the faulted sequence by Schultz-Ela and Walsh (2002), using a finite-element simulation that incorporates strain-softening and fault nucleation processes (Schultz-Ela *et al*., 1993), is consistent with the field results reported by Moore and Schultz (1999) and McGill *et al*. (2000). They found that grabens nucleated with asymmetric geometries and had bounding faults that intersected well above the base of the brittle layer. Reactive salt diapirs (Vendeville and Jackson, 1992; Jackson, 1995) continued down from the graben wedge and "hourglass" fault geometries (Figure 15.4) were produced (see also the pioneering analog models of McGill and Stromquist, 1979, and the work of Nicol *et al*., 1995). Graben formation in this layered mechanical system is more complex than the symmetric-graben model can accommodate, leading to a poor correlation between graben width, depth of faulting, and faulted-layer thickness (Schultz-Ela and Walsh, 2002).

Recent seismic refraction and gravity experiments carried out in Canyonlands grabens demonstrate that a thick sedimentary wedge exceeding 70 m in thickness overlies the structural floor in at least one graben (northern Devils Lanei; Grosfils *et al*., 2003). This finding indicates that the exposed stratigraphic offsets along the graben-bounding faults are minimum values and that the attitude of the graben floor (strictly speaking, the attitude of the surficial sediments at the ground surface) does not necessarily contain information about the degree of horizontality of the buried structural floor (Moore *et al*., 1997; Moore and Schultz, 1999; Grosfils *et al*., 2003; Figure 15.4).

15.6 The new hourglass model for grabens and implications for planetary faulting

Recognition of systematically varying (nonconstant) displacements on graben-bounding normal faults, both along-strike and down-dip, since the original 1970s-era Canyonlands model, as summarized in this chapter, motivates a revised model for planetary grabens. In this section we first redefine a graben, following current usage, highlighting useful observables in planetary data sets. Then we briefly examine some implications of the new "hourglass" model – as viewed in cross section – for the Moon, Venus, and Mars.

A graben can be defined as a pair of parallel, non-coplanar normal faults, that dip toward each other, that completely overlap with small cross-strike separations relative to their lengths. Grabens commonly exhibit a greater amount of vertical stratigraphic offset (throw) on one (master) fault than on the other (antithetic) fault. Such asymmetric grabens (Gibbs, 1984; Rosendahl, 1987; Groshong, 1989; Jackson and White, 1989) can display a rich assemblage of topographic features (Davison, 1994) such as footwall uplift (Weissel and Karner, 1989), hangingwall subsidence (Gudmundsson and Bäckström, 1991), and rollover anticlines (Moore and Schultz, 1999). These topographic elements increase in amplitude from zero at the graben terminations to maximum values near the middle regions of the fault, tracking the shape of the displacement distribution (Dawers *et al.*, 1993; Dawers and Anders, 1995; Davies *et al.*, 1997) and location of maximum offset, $D_{\max}$ (Barnett *et al.*, 1987; Pollard and Segall, 1987; Walsh and Watterson, 1987; Bürgmann *et al.*, 1994; Soliva and Benedicto, 2004).

Depocenters along faults and grabens are closely associated with the position of maximum depth, or maximum displacement, along the faults (Gibbs, 1990; Roberts and Yielding, 1994; Gupta *et al.*, 1998; Gawthorpe and Leeder, 2000; Gupta and Cowie, 2000; McLeod *et al.*, 2000; Grosfils *et al.*, 2003). These depocenters normally occur near fault midpoints and, with time, shift toward the stepover of echelon or interacting faults as linkage begins (Morley *et al.*, 1990; Morley, 1999). Each fault in a planetary graben has its own maximum displacement, and depocenter, created prior to linkage and its incorporation into the observed graben (for examples from Mars see Schultz, 1995; Wilkins and Schultz, 2003). Although deposition of dust and other aeolian sediments in Martian grabens may partly fill and thus obscure the original structural topography within the graben (i.e., its tilted floor), the uplifted topography outside the graben remains, mirroring in reverse the topography within the graben itself. In addition, the depocenters will serve to collect any hydrothermal (or other) fluids that migrate into the graben, either along its faults or from surrounding rock units. The segmented geometry of planetary normal faults (Schultz, 1991, 1995, 1997, 1999; Schultz and Fori, 1996; Wilkins and Schultz, 2003) provides ready clues to the best locations of depositional sinks within grabens (Figure 15.7).

15.6.1 Lunar grabens revisited

The new thinking about planetary grabens summarized in this chapter provides a renewed impetus to investigate lunar grabens – the place where planetary structural geology largely began. In this section we discuss two main issues: map-view geometry and its implications, and the venerable relationship (or lack of one) between graben width and depth of faulting.

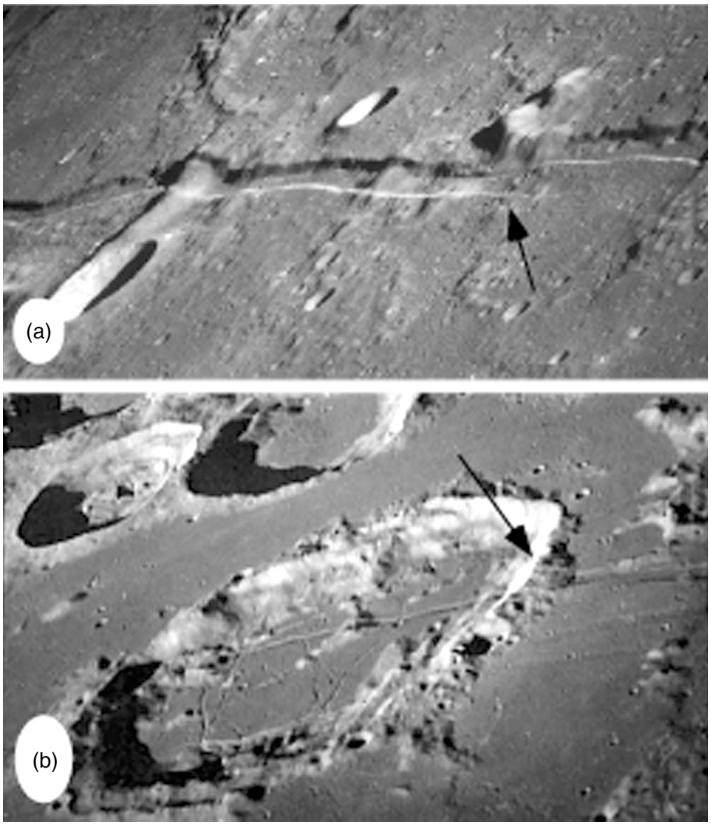

Figure 15.6. Examples of lunar grabens that demonstrate key geometric and mechanical characteristics. (a) Echelon graben (Rima Ariadaeus) traversing lunar plains materials. Note change in graben width over the ridge, and ramp with change of asymmetry sense at stepover (arrow). Part of AS10–31–4645 (H). (b) Grabens traversing basaltic lava flows in Mare Fecunditatus and rim (arrow) and interior fill of crater Goclenius. Note ramps and echelon segmentation of grabens on mare and continuity along strike through all three geologic units. Part of AS8–13–2225 (H).

Several typical lunar grabens are shown in Figure 15.6. These grabens, photographed by Apollo 8 and Apollo 10 astronauts before 1970, provide spectacular and unusually informative examples of normal fault growth and development that, with hindsight, we can readily interpret. A clear echelon stepover is recorded in Figure 15.6 along Rima Ariadaeus. One can see how the central fault changes its sense of dip direction (“polarity”) as the graben steps to the left. The graben changes width as it crosses the non-mare ridge near the large crater: in addition to evidence for non-vertical fault dip angles (McGill, 1971), continuous fault traces across basalt, non-mare ridges, and crater wall and floor materials all demonstrate that the graben is not confined to a thin sequence of mare fill material (basalt), but has propagated along-strike into a different lithologic and stratigraphic sequence (Schultz and Zuber, 1994).

A similar paradoxical example is found in Figure 15.6, where grabens transect mare basalts outside of the large central-peak crater Goclenius, the crater rim, and interior fill within the crater. Using the classic Canyonlands model, these spatial relationships are impossible, because: (a) the grabens must be symmetric (violated by the first example, Figure 15.6, where the outer fault extends farther along-strike than the inner one); (b) the grabens must be confined to the ''megaregolith'' (Golombek, 1979) and thus cannot propagate across different lithologies (Figures 15.6a and 15.6b); and (c) although the graben width in Figure 15.6a is constant at the step, the offset increases from zero at the graben tip, down its ramp, toward a larger value far from the step – an impossible situation if the depth of faulting scales only with the width of the graben (Golombek, 1979; Golombek and McGill, 1983; and many others). These examples suggest that the classic Canyonlands model is inadequate at best at explaining the spatial relationships that we find along typical lunar grabens.

The width of lunar (or other) grabens is not a reliable indicator of the depth of faulting, for several reasons discussed in this section. Theoretical work has suggested that many grabens may grow as their bounding normal faults nucleate at the surface and propagate downward (Melosh and Williams, 1989; Schultz-Ela and Walsh, 2002; Walsh and Schultz-Ela, 2003), rather than up from a common horizon (McGill and Stromquist, 1974; Golombek, 1979; Golombek and McGill, 1983). Slip along the first (usually master) fault changes the stress state in its vicinity, leading to nucleation and growth of a second normal fault nearby; the second fault grows into an antithetic configuration in order to compensate for rotations of the faulted layer due to the first fault (Reches, 1978, 1983; Aydin and Reches, 1982; Krantz, 1988, 1989; Melosh and Williams, 1989), leading to a graben. The flexural rigidity of the faulted layer thus determines the point of nucleation of the second, antithetic fault (Turcotte and Schubert, 1982; Buck, 1988), and therefore, the initial graben width. Because flexural rigidity depends on layer properties (principally Young's modulus) in addition to layer thickness, initial graben spacing is sensitive to the lithology of the faulted layer. The flexural rigidity term is influenced by (and thus dependent on) the degree of homogeneity (i.e., layering) of the faulted crust and by the presence of the fault itself (Buck, 1988); Schultz-Ela and Walsh (2002) found that flow patterns in the subjacent salt layer also influenced initial graben width in Canyonlands.

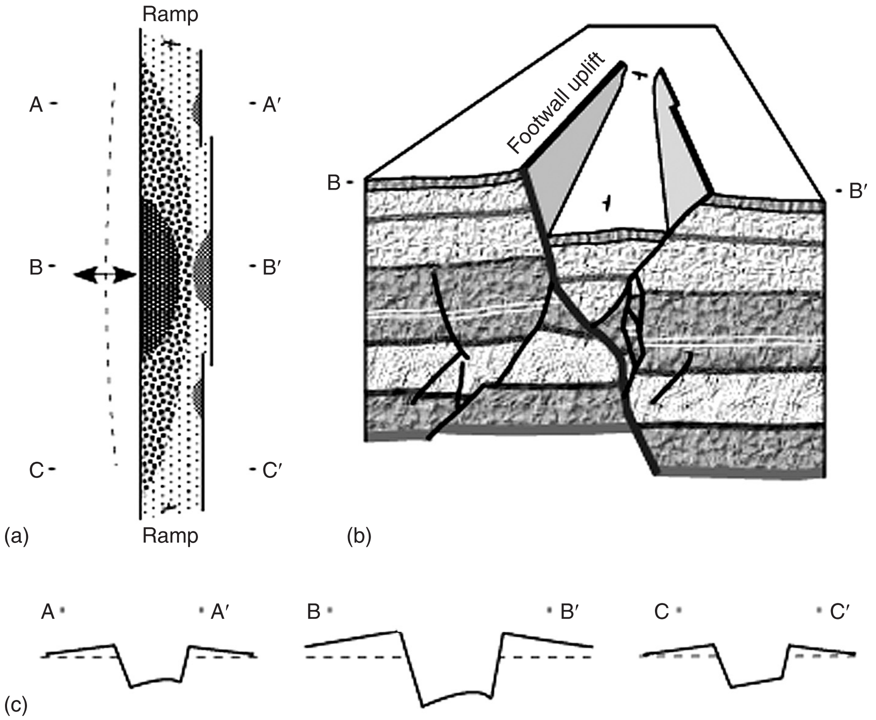

Figure 15.7. (a) Map view sketch of representative planetary graben emphasizing topography of graben floor (shaded); footwall uplift anticline shown by arrow on dashed curve. Locations of section lines A–A′, B–B′, and C–C′ as indicated. (b) Hypothetical cross sectional view of Martian graben along B–B′, showing the "hourglass" model for surface-breaking Martian grabens (constructed after Watterson *et al.* [1998]; the fault sets shown can retrodeform using dip-slip offsets). Note that volumetric changes associated with the fault intersection region are accommodated by nucleation and growth of additional small faults and by block rotations during horizontal extension, along with development of the inverted graben below. (c) Schematic topographic cross sections of the graben shown in (a).

In addition, graben widths change with ongoing extension of the faulted layer. Extension of a layer containing a graben necessarily leads to a progressively widening graben (Figure 15.2; Walsh and Schultz-Ela, 2003). However, continued extension can also lead to growth of new faults outside the graben (Jackson and Vendeville, 1994) as well as new faults within it (as a response to a reactive diapir at depth; Walsh and Schultz-Ela, 2003), so that increasing extensional strains lead to increasing graben widths and/or more complex patterns of graben-bounding faults.

Because the stratigraphic offset within a graben varies with position along the structure (Figure 15.7), a simple relationship between width and depth of faulting cannot, and does not, exist. Field and theoretical research on normal faults suggests that the faults are approximately semi-elliptical or triangular in cross section, with the depth of faulting being maximum near the fault's midpoint (at the semi-minor axis of the ellipse) and minimum (close to zero) at the fault's tips (Barnett *et al.*, 1987; Peacock and Sanderson, 1991, 1994; Davison, 1994; Willemse, 1997; Cartwright and Mansfield, 1998; Crider and Pollard, 1998; Kattenhorn *et al.*, 2000; Manighetti *et al.*, 2001; Crider, 2001; Figure 15.7). The relationship between fault length at the planetary surface and the maximum depth of faulting thus depends, in part, on the factors that control the fault shape (Nicol *et al.*, 1996; Benedicto *et al.*, 2003) along with processes that lead to fault nucleation and growth (Schultz-Ela and Walsh, 2002). As a result, other methods such as explicit mechanical modeling of topography above a planetary fault (Ma and Kusznir, 1992, 1993; Willemse, 1997; Cohen, 1999; Schultz and Lin, 2001; Schultz and Watters, 2001; Watters *et al.*, 2002; Schultz, 2003; Wilkins and Schultz, 2003; Okubo and Schultz, 2004; Schultz *et al.*, 2004) provide more reliable estimates of depth of faulting than graben width alone.

Golombek (1979) used the original Canyonlands model to infer the depth to megaregolith on the Moon. He assumed constant fault dips and faults that meet at (and therefore originated at) the upper surface of the buried megaregolith. Using the revised model in this chapter, the flexural rigidity of the faulted layer and its substrate jointly determine the initial graben width. As a result, the grabens may crudely map out the thickness of the faulted layer as Golombek suggested, but for different physical reasons and with larger uncertainties than previously estimated (dependence of width and fault dip on strain magnitude and layer properties). In particular, the requirement for graben-bounding faults to meet precisely at a point at the megaregolith's upper surface is relaxed. Similarly, layer thicknesses obtained by using this method for Mars (Banerdt *et al.*, 1992; Golombek *et al.*, 1996), Venus (Ghent and Hansen, 1999), and elsewhere (Golombek and Banerdt, 1986) may provide useful estimates (and again, on different physical grounds) but with larger uncertainties as discussed in this section.

15.6.2 Implications for grabens on Venus

On Venus, the current absence of high spatial- and vertical-resolution topography data makes it difficult to estimate the depth of faulting (or D_{max}). However, the general abundance of distributed deformation at the surface, including numerous grabens, provides a rich dataset for assessing graben properties. For example, complex sequences of intersecting graben sets

(Radunitsa Labyrinthus; Kortz *et al.*, 2003), provide interesting new opportunities to study fault set interactions and thus to evaluate the behavior of faulting at depth.

Distributed sets of "tensile-fracture ribbons" and "shear-fracture ribbons" (i.e., grabens), identified as some of the earliest-formed structural elements in many tessera terrains, are interpreted as deformation accommodated within a thin brittle layer overlying a ductile substrate (Hansen and Willis, 1998; Hansen *et al.*, 2000). While "tensile-fracture ribbons" represent a different style of deformation, mechanically, as noted by Hansen *et al.* (2000), "shear-fracture ribbon" formation is thought to be closely analogous to the style of deformation observed in Canyonlands. The thickness of the thin brittle layer is estimated using various methods, for instance using radargrammetric calculations to measure visible fault topography at point locations and by employing layer instability theory (Ghent and Tibuleac, 2002), to relate dominant ribbon spacing to the thickness of the deformed layer. Improved mechanical fault models should, however, provide a powerful way to augment the approaches used to date. For "shear-fracture ribbons" with lengths ranging from tens to ~170 km (Hansen and Willis, 1998), the topographic offset should vary as a function of position along an individual structure, leading to the appropriate "spoon shaped" along-strike topographic profile of the graben floor – the preservation of which is a reasonable possibility in the absence of younger lava embayment because both erosion and sedimentation rates are thought to be extremely low on Venus. As our ability to determine surface topography around the "shear-fracture ribbons" improves for specific structures, mechanical modeling can provide additional insight into the expected extent of subsurface faulting as a function of position along the bounding faults, yielding new estimates for brittle layer thickness at the time the faults were forming.

15.6.3 Martian grabens and Tharsis tectonics

Planetary megaregoliths (consisting of impact-crater ejecta and other poorly consolidated materials) were previously thought to be significantly weaker than an overlying basaltic sequence (Golombek and McGill, 1983; Golombek, 1985; Allemand and Thomas, 1992; Davis *et al.*, 1995; Golombek *et al.*, 1996). However, recent experimental work suggests that this assumption is not correct. Terrestrial deposits considered analogous to Martian megaregolith consist of highly angular clasts (Grant and Schultz, 1993; Urrita-Fucugauchi *et al.*, 1996). Non-indurated materials composed of angular clasts can be as strong as other crustal rocks, such as basaltic lava flows, regardless of clast size and sorting (Mair *et al*., 2002). The presence of water ice in the Martian subsurface can, however, lead to a mechanical stratigraphy with horizons of reduced strength (as inferred for wrinkle ridges by Mangold *et al*., 1998, and Okubo and Schultz, 2004), but this phenomenon cannot provide a Canyonlands-type brittle-over-plastic sequence without extraordinarily large (i.e., a kilometer or more), and conjectural, thicknesses of ice. Thus, the Martian megaregolith cannot be considered to be a mechanically weak layer or a potential site for detachment horizons (Okubo and Schultz, 2003) without independent and compelling evidence to the contrary.

The assumption of weak megaregolith beneath a basaltic caprock sequence was central to the formation of narrow, closely spaced Tharsis-radial graben swarms (Wise *et al*., 1979, 1982). Systematic mapping shows that these grabens developed simultaneously on Tharsis and on its periphery coeval with or younger than wrinkle ridges (Scott and Tanaka, 1986; Banerdt and Golombek, 1990; Tanaka *et al*., 1991). Okubo and Schultz (2003) showed that the assumption of a weak Martian megaregolith was inconsistent with the vergence directions of the thrust faults that underlie, and control the formation of, wrinkle ridges. Therefore, the presence of a weak megaregolith appears incompatible with the formation of both wrinkle ridges and grabens in Tharsis (and beyond) that require regional shearing along mid-crustal detachments in weak megaregolith. Instead, scenarios such as dike-induced graben formation (Rubin and Pollard, 1988; Rubin, 1992) and normal faulting down to the brittle-quasiplastic transition (Wilkins and Schultz, 2003) are suggested. Thus, Tharsis grabens most likely reflect lithosphere-scale thick-skinned deformation, rather than thin-skinned deformation above a weak Martian megaregolith (Okubo and Schultz, 2003).

15.7 Conclusions

The classic Canyonlands model of planetary grabens, formulated in the 1970s, has been supplanted by new concepts and understanding of fault and graben development. The Canyonlands-based stratigraphic model of "brittle over ductile" is not supported by recent laboratory investigations of megaregolith analogs and by observations of Martian crustal sections. An "hourglass" geometric model for planetary grabens is in better accord with current understanding of these structures than the former symmetric undeformable wedge. Instead, the revised graben model and the current literature on the map-view development of terrestrial normal faults and grabens, provides an improved basis for mapping and interpreting graben arrays on the Moon, Mars, Venus, and elsewhere.

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