Coseismic, dilational-fault and extension-fracture related pit chain formation in Iceland: Analog for pit chains on Mars

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ABSTRACT

Pit crater chains are common topographic features on Mars and several other planetary bodies, and a wide range of mechanisms has been proposed for their origin. Two rifting-related seismic events in 1975–1976 and 1978 along the Mid-Atlantic Ridge near the northern coast of Iceland, associated with the Krafla volcanic eruptions to the south, produced an array of pit chains in unconsolidated sediments overlying Holocene basalt flows. Fault scarps and extension fractures in basaltic lava flows are traceable laterally into overlying unconsolidated fluvial deposits, revealing contrasting deformation styles in the two mechanical layers. Map-scale structures in basalt with little or no sedimentary cover include (1) fault scarps, (2) extension fractures and fracture swarms, (3) faulted monoclines, (4) widened fractures with caverns, and (5) localized circular or elongate collapse pits. Where unconsolidated fluvial sand and gravel deposits >3 m thick cover the basaltic lava flows, structural geomorphic features are dominated by (1) grabens bounded by normal faults with ~1 m displacement, (2) cone- to bowl-shaped pit craters with depths up to 2.8 m, and (3) elongate troughs. Formation of these structures in fluvial sediment was triggered by reactivation of faults and extension fractures in the underlying basalt. Pit craters are readily explained by downward “draining” of poorly consolidated material into subterranean cavities produced by fault and extension fracture dilation in underlying cohesive material (basalt). High-resolution imagery on Mars shows geomorphic patterns that are directly analogous to these Icelandic pit chains, suggesting similar processes have occurred on Mars.

INTRODUCTION

Pit craters, pit chains, and troughs formed from pit chains are common geomorphic features on Mars (Banerdt et al., 1992; Davis et al., 1995; Wyrick et al., 2004). These features are also present on Earth (Okubo and Martel, 1998), the Moon (Head and Wilson, 1993), Venus (Bleamaster and Hansen, 2004), Phobos (Thomas, 1979; Horstman and Melosh, 1989), and Eros (Prockter et al., 2002; Buczkowski et al., 2008). Pit craters tend to be cone- to bowl-shaped collapse depressions, with circular to elliptical plan view shapes, and, in some cases, flat floors (e.g., Fig. 1). They most commonly occur in linear pit chains and are associated with fault or fracture networks in a diversity of extensional tectonic settings (Fig. 1).

There is general agreement that on Mars pit craters and pit chains form by surficial collapse into subterranean cavities. Wyrick et al. (2004) provided a detailed summary of the various pit crater–forming mechanisms. Briefly, these mechanisms include collapse into drained lava tube (Cushing et al., 2007), a propagating dike interacting with subsurface groundwater/cryosphere in a maar-type eruption (Mège and Masson, 1996, 1997; Mège, 1999; Montesi, 1999), collapse after a dike erupts in a Plinian-type eruption (Scott and Wilson, 2002; Scott et al., 2002), collapse into void formed by leakage of volatiles at the top of a dike (Wilson and Head, 2002), collapse of elongated magma reservoir (Mège et al., 2000, 2002, 2003), collapse into void formed by chemical dissolution of soluble rock (e.g., karst; Spencer and Fanale, 1990), collapse/drainage into extensional fractures (Tanaka and Golombek, 1989; Banerdt et al., 1992; Tanaka, 1997), and dilational normal faulting (Ferrill and Morris, 2003, a and b; Ferrill et al., 2004; Wyrick et al., 2004). Collapse may be a steady process, or it may be a sudden event triggered by reduction in pore fluid pressure due to water-table drop (Abelson et al., 2003), seismic shaking, fracture dilation, or dilational fault slip (Ferrill et al., 2004).

In this paper, we explore a system of fault- and fracture-related pit chains that formed in northern Iceland during rifting-related seismic events associated with magmatic activity further south along the Mid-Atlantic Ridge in the mid to late 1970s. We summarize pit characteristics as observed in the field, document depth and diameter relationships and shapes, provide an interpreted sequence of development, and compare the related geometries with pit chains on Mars. The geomorphic appearance and associations with faults and extension fractures in basalt flows are similar to numerous pit chains on Mars, providing valuable insights into pit chain formation on Mars.

BACKGROUND

The Mid-Atlantic Ridge spreading center crosses Iceland generally from the northeast corner to the southwest corner of the island (Fig. 2, inset). In the northern half of Iceland, the spreading center trends NNE-SSW and is primarily represented by dip-slip normal faults and associated extension fractures (Ward, 1971; Sæmundsson, 1974; Brandsdottir and Einarssson, 1979; Einarssson, 1979, 1991; Sigmundsson, 2006). The youngest and most active part of this spreading center along the north coast defines a graben with surface geologic units consisting primarily of Holocene (postglacial) basalt and younger glacial outwash braided stream deposits of Jökulsá á...
Figure 1. Image showing pit chain, graben, and trough system of Phlegethon Catena, Mars. Brightly illuminated areas are dipping to the bottom, and dark shadowed areas are dipping to the top. Selected spot elevations in meters from Mars Orbiter Laser Altimeter Precision Experiment Data Record tracks are shown at black + symbols. Image credit: National Aeronautics and Space Administration/ Jet Propulsion Laboratory/Viking.

Figure 2. Geologic map of study area (from Jóhannesson and Saemundsson, 1998). Inset map of Iceland shows location of study area in the Mid-Atlantic Ridge spreading center (patterned area) in Iceland, and location of study area along the north coast. Distribution of earthquakes and ground ruptures associated with 1975–1976 and 1978 seismic events is after Sigurdsson (1980). The pink area indicates postglacial (Holocene) basaltic lava flows, and the light blue stippled area represents fluvial deposits.
Fjöllum (Figs. 2 and 3A; Jóhannesson and Sæmundsson, 1998).

The Krafla rifting episode of 1975–1984 occurred along the Mid-Atlantic Ridge, producing cumulative widening by as much as 8 m, centered over the Krafla magma reservoir (Tryggvason, 1984). Average widening of 5 m over an along-strike distance of 80–90 km occurred during the rifting episode, with widening in excess of 2 m off the north coast of Iceland, 70 km north of the maximum widening (Tryggvason, 1984). The Krafla rifting episode consisted of 20 discrete rifting events, each only affecting a portion of the overall system, causing reactivation of preexisting faults and fractures, and formation of new extension fractures. Two rifting-related seismic events occurred near the northern coast of Iceland in late 1975 and early 1976, and again in 1978 (Fig. 2). The first of these rifting and subsidence episodes began on 20 December 1975 (Björnsson et al., 1979; Sigurdsson, 1980; Tryggvason, 1984). The event continued into February 1976 (Sigurdsson, 1980) and was characterized by seismicity and deformation, including the reactivation of faults along existing surface traces and the formation of normal fault scarps, grabens, and pit craters in alluvium where surface ruptures were previously unmapped. Seismicity and ground-surface faulting and fracturing associated with the December 1975 through February 1976 event were concentrated 30–50 km north of the Krafla caldera center. Earthquake epicenters associated with the December 1975 through February 1976 event occurred offshore and extended in a relatively narrow band under the braided stream deposits exposed near the shoreline (Fig. 2).

The 1978 seismic sequence was farther south and showed some geographical overlap with the 1975–1976 earthquakes, occurring underneath the surface exposures of braided stream deposits and Holocene basaltic lava flows as illustrated in Figure 3. These seismic events were generally concurrent with the Krafla eruptions, dike intrusion, and magma chamber deflation to the south (Björnsson et al., 1979; Sigurdsson, 1980).

Although the seismic swarms during the middle to late 1970s exhibited a southward shift from 1975–1976 to 1978, the surface deformation for these two events geographically overlapped the earthquake distribution, in both cases extending further south from the map locations of the seismic swarms (Fig. 2). Fault slip associated with the seismic events near the northern coast produced surface deformation in Holocene basaltic lava flows and overlying modern braided stream deposits (Fig. 2). Surface ruptures with components of dilation and normal dip slip (Opheim and Gudmundsson, 1989; Angelier et al., 1997; Dauteuil et al., 2001; Tentler, 2005; Tentler and Temperley, 2007) have previously been documented by mapping heave and throw along fault traces in basalt flows. Angelier et al. (1997) calculated fault dips of 60°–75° at a depth of 1 km based on these displacement measures. To the north of the exposed basalt flows, a 1–1.25-km-wide and 12-km-long system of fault ruptures, fractures, and pit craters also formed in the fluvial plains of Jökulsá á Fjöllum (Sigurdsson, 1980). In the

Figure 3. (A) National Land Survey of Iceland (www.lmi.is) color infrared aerial photograph showing vegetated basalt flows with little or no sedimentary cover (red) and unconsolidated fluvial sediment (blue-gray). The prominent WNW- to ESE-trending road follows the contact between the basalt and fluvial deposits at the surface. Field photos of pit chain were taken on (B) 3 July 1976 (courtesy of George McGill) and (C) 11 August 2008. For reference to pit map presented later in this paper, the pit in foreground in B and C is pit 26. Note people standing in pit 31 for scale.
fluvial deposits of the Jökulsá plain, the normal fault system reactivated by the event produced a 1-km-wide graben that accommodated an estimated 1.5 m of horizontal extension and ~1 m of vertical throw. Pit craters, pit chains, and troughs that developed in the unconsolidated alluvium (Fig. 4A) can be traced southward along strike up the gentle northward dip into fault scarps and fractures in the underlying basaltic lava flows (Fig. 4B). These exposures provide the opportunity to study the structural style of coseismic deformation in the two contrasting mechanical layers (i.e., unconsolidated sediments versus basalt). Our attention was first drawn to pit craters associated with this seismic episode by George McGill, who provided a field photograph that he had taken on 3 July 1976 (Fig. 3B).

FIELD OBSERVATIONS AND DATA

Structures in Basalt

Structures in the basaltic lava flows include near-vertical normal fault scarps and extension fractures, a breached monoline, rock toppling and rockfall widening of fractures, and wedging of toppled rock blocks that has locally produced keystone arches and bridges across the tops of open fractures (Figs. 5 and 6). Fault scarp and fracture surfaces are composed of amalgamated cooling and tectonic extension fracture surfaces. Fault scarps are differentiated from extensional fractures by field evidence of vertical offset of layers. Monoclino development associated with normal faulting can be produced by a range of mechanisms (e.g., Ferrill et al., 2005). Synthetic dip (i.e., bedding or layering that dips in the same direction as the adjacent fault) has been widely observed in faulted basaltic lava flows associated with the Mid-Atlantic Ridge in Iceland (Grant and Kattenhorn, 2004; Tentler and Mazzoli, 2005), and interpreted to be related to fault-tip folding during upward fault propagation (Grant and Kattenhorn, 2004).

Stages in the progression of fracture development and collapse observed over along-strike distances of tens of meters include fracture initiation, fracture widening and local cave formation, pit formation localized by surface collapse into caves, and continued pit enlargement to form elongate collapsed fractures. Exploration revealed a cave in basalt associated with a dilational fault (Ferrill and Morris, 2003a, 2003b; Ferrill et al., 2004) that has 0.5 m of heave (dilating the fault) and 0.6 m of throw across a vertical fault segment. The cave has been enlarged by rock toppling and rockfall. The cave extends below the water table and upward to within 25 cm of the ground surface (see Figs. 6A and 7).

Structures in Sediments

As part of this effort, we were able to locate in the field the specific pits and fault scarps visible in George McGill’s 1976 photograph and found that the features are still clearly recognizable (Fig. 3C). The pits, fault scarps, and troughs are slightly degraded, and vegetation has become established in places. In addition, comparison of the 1976 and 2008 photographs (Figs. 3B and 3C) shows that the graben floor is lower with respect to the surrounding regional level, suggesting ~1 m additional fault throw and graben subsidence since 3 July 1976.

Aerial photographs from 5 September 1958, 2 September 1976, and 3 August 1984 (presented in Ferrill et al., 2004) show a progression, including (1) no visible pits and faintly visible lineaments in the alluvium in 1958, (2) well-developed pits and troughs in 1976, and (3) continued development and enlargement of pits, as well as erosion of a pit chain segment by a fluvial channel by 1984. A color infrared aerial photograph (Fig. 3) demonstrates establishment of vegetation, becoming pronounced by 1998.

Where unconsolidated fluvial sand and gravel deposits >3 m thick cover the basaltic lava flows, extensional features are dominated by normal faults and fractures (throws >1 m are common), grabens, pit craters, and elongate troughs (Figs. 8 and 9). We mapped the pit chain system that contains the pits in George McGill’s 1976 photograph (Fig. 3B) and refer to this...
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The pits tend to be approximately circular in plan view, and the most elongate pit that we mapped (pit 1) has a maximum long:short axis ratio of 2.1:1. Several of the mapped features are partially water filled where depressions extend below the local water table. For each pit, we measured the depth and diameter (in two orthogonal directions), and described the geometric shape of the pit (e.g., cone, bowl, cylinder). The pit craters are generally cone, bowl (approximated by segment of a sphere), or cone-bowl hybrid shapes, although we found one small pit with a cylindrical shape. Depths up to 2.77 m and diameters of as much as 10.16 m were measured. Pit craters are present in the absence of observable normal faults in a few places, but most of the pits we observed are within grabens or troughs. Saddles, narrow zones of intact graben floor between pits, are common. A positive correlation was found between depth and average pit diameter.

Pit volume was calculated based on the mean diameter and the appropriate equation based on the geometric shape. Pit volume increases with increasing average diameter, similar to the conclusion from analysis of Martian pit craters. The Martian pits, with diameters measured in kilometers, are several orders of magnitude larger than the pits of McGill pit chain, where diameters are measured in meters.

Figure 6. Field photographs (locations shown in Figure 5) showing tectonic cave and collapse pit (A, B), and dilational faults (C, D). Oval in A shows person in dilational segment for scale. Fault dilation (heave) is approximately 0.5 m in part C and approximately 2 m in part D. Upthrown and downthrown blocks are indicated by U and D in parts C and D.

Figure 7. (A) Cross-sectional sketch of tectonic cave associated with dilational fault segment shown in Figure 6A. Note that cave has collapsed to form a pit along strike, seen in foreground in Figures 6A and 6B. (B) Schematic illustration of dilation of steep fault segment produced by slip along less steeply dipping fault segment below.
Figure 8. Map of McGill pit and trough system. Yellow arrows indicate directions of view for photographs in Figures 9A and 9B. Pit numbers correspond to data provided in Table 1.

Figure 9. Field photographs (locations shown in Figure 8) of key elements of pits and troughs in the fluvial deposits overlying the faults and fractures in basalt. (A) Pit 18 (foreground) is approximately 8 meters wide. (B) Trough ranges from 8 to 10 meters wide.

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is that whereas Mars pits shown in Figure 7 of Wyrick et al. (2004) were assumed to have conical shapes, field observations indicate that non-conical pits are more common than conical pits in the McGill pit chain.

**INTERPRETATION**

We interpret that pit craters developed in basalt by collapse into caverns formed by fracture widening, and in sediments by draining of unconsolidated material downward into fault- or fracture-related voids in the underlying basalt. Similar “tectonic caves” were previously described by Opheim and Gudmundsson (1989). In their description, Opheim and Gudmundsson (1989) primarily attributed tectonic caves to tension fractures, although the photograph that they included as figure 12 in their paper appears to show several (3–4) meters of vertical offset (throw) across the fracture (fissure) with the tectonic cave, which is consistent with a dilational fault origin. In sediments, troughs appear to be produced by a combination of graben formation and pit crater amalgamation. A sequence of development from pit crater chain (or pit chain within graben) to trough to open extension fracture (fissure) occurs with increasing dilational fault displacement or fracture width, and will likely vary as a function of sedimentary cover thickness. This field-based study demonstrates that pit craters are readily explained by movement of poorly consolidated material downward into subterranean cavities produced by coseismic fault and extension fracture dilation in underlying cohesive material (basalt).

**DISCUSSION**

 Faults along the Iceland rift have dilational displacement (Gudmundsson, 1987; Angelier et al., 1997; Grant and Kattenhorn, 2004; Tentler and Mazzoli, 2005), and extensional fractures and dilational faults together accommodate extension in the upper crust. This same extension has been interpreted to be accommodated by dike intrusion at depth (Angelier et al., 1997; Dauteuil et al., 2001). Fault and extension fracture networks have been carefully examined and quantified, leading to well-founded interpretations of refracted fault profiles that are near vertical at the ground surface and less steep at depth (Angelier et al., 1997; Dauteuil et al., 2001). Sliding on the less-steep segments at depth has caused dilational slip in the uppermost crust in basaltic lava flows exposed at the ground surface (Opheim and Gudmundsson, 1989; Angelier et al., 1997; Dauteuil et al., 2001). Similar observations of dilational faulting, monoclinal folding with fissuring, and

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**Figure 10.** (A) Average pit diameter versus depth and (B) average pit diameter versus volume for 38 pits in McGill chain, along with reference curves for a hemispherical bowl and cones with 15°, 30°, and 45° slopes.
related pit chain formation have been described in Afar (Rowland et al., 2007), formed during a rifting and volcanic episode in 2005 (Wright et al., 2006; Ebinger et al., 2010).

These pit chain and trough systems in Iceland are remarkably similar to many pit chains and troughs that are clearly visible in high-resolution surface imagery on the surface of Mars (Fig. 1). Similar geomorphologic features of Martian pit chains include the conical to bowl shapes of pits, occurrence associated with normal faults and within grabens, and saddles in graben floors between pits. In addition, the Martian crust is mechanically layered (e.g., McEwen et al., 1999), and includes volcanic rock as well as unconsolidated layers of volcanic and sedimentary origin.

Although the pit craters analyzed in Iceland are small (generally <10 m diameter), they are excellent geometric analogs for pit craters observed on Mars. As discussed by Ferrill et al. (2004, p. 11), possible explanations for the occurrence of large pit craters on Mars include: (1) thickness of low-cohesion surface material (i.e., regolith); (2) depth extent of the dilational fault segment that creates the subsurface void (due to differences in gravity); and (3) Martian pit craters representing cumulative volume over a number of faulting events, whereas on Earth, pit volume often represents a single event (because of the different erosion rates on both planets). The small size of the Icelandic pit craters is likely controlled by the small magnitude of extensional deformation (dilation) and possibly by the small thickness of unconsolidated surficial deposits. As discussed by Ferrill et al. (2002, 2004), the lower gravitational acceleration on Mars relative to Earth, a factor of 2.64 difference, should result in dilational normal faulting through a much thicker crustal section on Mars (upper 5 km; Ferrill et al., 2004) compared with Earth (upper 1–2 km; Ferrill and Morris, 2003a, 2003b). The greater depth of dilational faulting allows for larger subsurface volume (void space) increases, which in turn should lead to larger pit crater chains expressed at the surface on Mars. This large subsurface volume on Mars could, similar to the dilational faults, extension fractures, and tectonic caves observed in Iceland, also provide potentially large and porous reservoirs important for water or water ice storage on Mars.

Many researchers have interpreted pit craters and pit crater chains on Mars as surface manifestations of either lava tubes (e.g., Cushing et al., 2007) or dikes (e.g., Wilson and Head, 2002; see summary by Wyrick et al., 2004). The pit chains that we studied near the north coast of Iceland appear to have been produced by dilational fault and extension fracture origins rather than by lava tube collapse or near-surface dike intrusion. While emplacement of dikes and sills is interpreted to have occurred at deeper crustal levels and south of our study area in Iceland during the Krafla event (see Sigìmundsson, 2006, and references therein), our field observations suggest that there was no direct involvement of dike intrusion in this area during the Krafla eruptions to the south, the low confining pressure and near-surface water table coupled with heat from the dike would likely have led to phreatic (steam) eruption (e.g., Germanovich and Lowell, 1995) or related steam release activity, and we have found no reports of these processes in the study area during the rift events in 1975–1976 and 1978. These observations do not however imply that the dilational faulting and extension fracturing are unrelated to dike intrusion—normal faulting, extension fracturing, and dike intrusion all accommodate plate-scale crustal extension and occur together in Iceland to accommodate plate motion associated with the Mid-Atlantic Ridge spreading center (Fig. 12). Recent modeling work of Wyrick and Smart (2009), however, has demonstrated that dike intrusion alone is a mechanically unrealistic mechanism for creating pit chains. Magma pressure within a widening dike produces contractional deformation normal to the plane of the dike, which likely suppresses dilation and therefore inhibits the formation of open fractures (Wyrick and Smart, 2009).

As noted before by Ferrill et al. (2004), pit craters on Mars appear to be some of the youngest features on the Martian landscape, postdating all other structures and, in some cases, showing apparently pristine form with no evidence of significant morphologic degradation or sediment infilling. By analogy with the structures in Iceland, the youngest pits on Mars show evidence of being recently active, and would be consistent with active faulting and potentially Marsquake activity. Martian pits have revealed no direct evidence of in situ water or water ice in pit floors. Importantly, however, these pits provide windows into the subsurface, in many cases penetrating several kilometers (Wyrick et al., 2004) below the surrounding landscape. Pit craters are likely centered over partially filled dilational faults and extension fractures that could potentially be reservoirs for water ice at relatively shallow depths.
CONCLUSIONS

Pit craters along the Mid-Atlantic Ridge spreading center in northern Iceland formed in basalt by collapse into caverns formed by fracture widening during rifting-related seismic events in 1975–1976 and 1978. Fault scarps and extension fractures in basaltic lava flows can be traced laterally into overlying unconsolidated fluvial deposits, revealing contrasting deformation styles in the two mechanical layers. Map-scale structures in basalt with little or no sedimentary cover include (1) fault scarps, (2) extension fractures, and (3) locally developed gentle synclinal hanging-wall dip away from the related normal fault. Stages in the progressive development observed over along-strike distances of tens of meters include narrow fractures and fracture swarms, widened fractures with fossil相关内容 includes (v) 837-8441, doi:10.1029/1991GB002025.

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