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Volcanic features of New Mexico analogous to volcanic features on Mars

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4.1 Introduction

The arid climate, extensional rift setting, range in type and age of volcanic eruptions, and generally widespread and geologically youthful volcanism in New Mexico contribute to an environment rich in geologic processes and landforms analogous to many of those on Mars. Young (<5 Ma) volcanoes and associated volcanic rocks are more widely distributed throughout the state than in many other volcanic localities on the North American continent. All of the principal volcanic landforms occur including long lava flows, viscous domes, calderas, composite volcanoes, monogenetic scoria cones, small shield volcanoes, and numerous hydromagmatic vents. The morphologies, volcanic emplacement processes, and dissected structures, and the arid environment, result in many volcanic landforms analogous to those on Mars. These features provide some clues to the details of geologic processes responsible for their Martian counterparts that are uncommon in areas where volcanism is less abundant and where the environments are less arid.

The largest young caldera (Valles Caldera), largest young lava flows (McCartys and Carrizozo), abundance of Quaternary volcanic fields, volatile-rich magmatism, including non-juvenile (maars) and juvenile types (Shiprock-Narbona Pass), spring deposits, and one of the great modern rift valleys on Earth (Rio Grande rift) occur in an arid setting where annual precipitation is between 8 and 15 inches (20–40 cm) per year. Combined with arid dissection and eolian in-fill, these contribute to a landscape that mimics the appearance of many volcanic terrains on Mars. In addition to surficial geologic processes, the interaction between subsurface ground water

The Geology of Mars: Evidence from Earth-based Analogs, ed. Mary Chapman. Published by Cambridge University Press.

flow and emergence with the arid climate results in spring deposits that may be analogs for Martian groundwater circulation.

4.2 Distribution and characteristics of volcanism in New Mexico

New Mexico is divided into several broad geologic provinces: Rio Grande rift, Colorado Plateau, Eastern High Plains, Rocky Mountains, and Basin and Range. In New Mexico, volcanic landforms occur in all of these provinces (Figure 4.1). The most recent volcanism is associated with the Rio Grande rift and Colorado Plateau margins, whereas slightly older mid-Tertiary volcanism occurs within the Basin and Range, Rocky Mountains, and Colorado Plateau interior. Several dominantly basaltic and recent volcanic fields occur on the margins of the Rio Grande rift or within the rift interior: the Taos Plateau

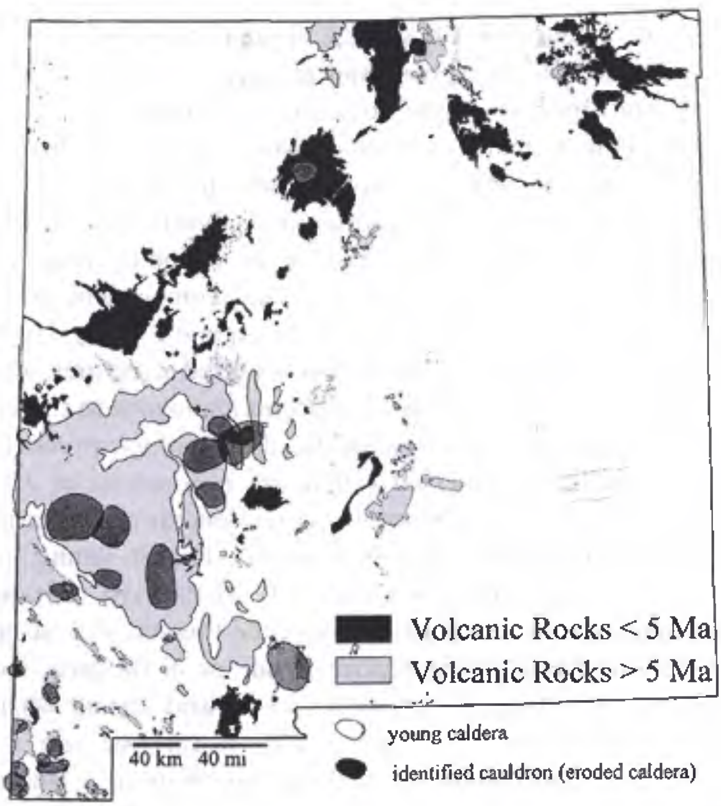

Figure 4.1. Distribution of late and middle Cenozoic volcanic rocks in New Mexico. The presence of a diverse range of volcano morphologies, the arid climate, and one of the few great continental rift valleys on Earth results in many volcanic landforms and processes that are analogous to those on Mars.

field, the Cerros del Rio field, the Jemez field, volcanoes within the Albuquerque basin part of the rift, and scattered fields and lava flows within the southern rift such as the Jornado del Muerto field, Carrizozo lava flow, and Engle (Elephant Butte) field. Several other volcanic fields, such as the Potrillo field and Palomas field, and isolated cones and flows, occur where the Rio Grande rift merges with the Basin and Range province. Eruptions within all of the late Cenozoic fields are widely dispersed in late Cenozoic time; ages of individual eruption within many of these volcanic fields cluster near 2 Ma, but range from 14 Ma to 0.03 Ma. Older, mid-Tertiary volcanism, associated with widespread silicic volcanism common throughout the Basin and Range province of the southwest, resulted in formation of many calderas that are now eroded, although their extensive sheets of ash flow tuffs are widespread and well exposed. Effusive and pyroclastic landforms within all of these volcanic areas have some bearing on understanding volcanic processes on Mars.

The younger volcanic fields around the margins of the Colorado Plateau in New Mexico are dominantly basaltic, but include large volcanic centers or isolated domes of more silicic magma, similar to other fields on the southern (Condit *et al.*, 1999) and southwestern (Best and Brimhall, 1974) margins of the Colorado Plateau. Most of the young New Mexico fields occur along a broad alignment known as the "Jemez zone" or "Jemez lineament" (Smith and Luedke, 1984). The Jemez zone includes the Red Hill, Zuni-Bandera (El Malpais), Mount Taylor, Jemez, Cerros del Rio, Ocaté, and Raton-Clayton fields. The Ocaté and Raton-Clayton fields are isolated from the Colorado Plateau margin and occur within the high plains of northeastern New Mexico. Although the Jemez zone has been described as a hot spot trace, and is roughly parallel to the Yellowstone hot spot track, ages throughout the Jemez zone are randomly distributed. The alignment of fields may instead represent a linear tectonically defined boundary between fundamentally different ancient lithosphere sections (McMillan *et al.*, 2000) with differing melting and magma emplacement properties. The Jemez field itself is the site of one of the largest young morphologically clear examples of an ash-flow caldera. It is an area where volcanism has occurred for over 13 Ma and has erupted basaltic, intermediate, and rhyolitic magma compositions. The development of large silicic calderas such as the Valles Caldera requires a significant, long-term melting anomaly in order to generate large magma chamber volumes associated with ash flow volcanism. The precise origin of the melting anomaly in the case of the Valles Caldera is unclear, but the location of the Jemez volcanic field at a point on the west margin of the Rio Grande rift where the rift steps east, suggests that the interaction between structures and the high regional geothermal gradients associated with the rift combined to generate a significant melt source and pathways for the melts into the upper crust (Self *et al.*, 1986).

Widespread volcanism in the Southwestern USA throughout the Cenozoic (Christiansen and Yeats, 1992) is attributed to high regional geothermal gradients and upwelling of mantle across the western USA following subduction of the East Pacific rise. Together with lithospheric extension and corresponding enhancement of magma ascent, the mantle melts generated by upwelling and heating resulted in volcanism both within the areas affected by lithospheric extension and within the interior of the Colorado Plateau. Volcanism in New Mexico may be categorized as "continental magmatism" and is distinct from that associated with plate margins. Although mid-Tertiary volcanism was voluminous and characterized by calc-alkalic affinities that include a variety of more silicic magma types, late Cenozoic magmas were largely alkali basaltic (Christiansen and McKee, 1978).

The regionally clustered large volcanoes of Mars have more in common with hot spot distributions controlled by broad upwelling of plumes (Crumpler and Revenaugh, 1997; Greeley *et al.*, 2000), such as the mechanism producing major volcanic provinces within the Southwestern USA, than they do to plate margin volcanism.

4.3 Mega morphology and outcrop scale morphology: scale-dependent preservation of volcanic morphology

The scale-dependent state of preservation of volcanic morphology on planetary surfaces in general is an important, but underappreciated aspect of volcanic analog studies. Many analog studies make use of relatively young and uneroded volcanic surfaces on Earth for comparison with Martian volcanic terrains. However, the great age and wide distribution of mantling deposits on Mars, combined with mechanical erosion by impact and environmental effects on rocky surfaces on Mars, likely result in significant degradation of primary volcanic landforms. Older volcanic terrains, such as those occurring in the arid environments in New Mexico, are better analogs for purposes of predicting the types of characteristics that occur in well-preserved but slightly degraded Martian volcanic terrains.

Primary volcanic features in New Mexico are preserved at several length scales and the degree of apparent preservaton of primary volcanic characteristics is often scale dependent. In other words, preserved morphologies and structures frequently appear youthful at scales exceeding 1 m (air photo resolutions), but may be soil-covered, rocky, and almost unrecognizable as volcanic landforms at outcrop (i.e., less than 1 m) scale (Figure 4.2). A similar state of preservation may characterize volcanic features on Mars. Volcanic features in excess of several hundred million to a billion years old on Mars may be usefully compared with primary morphologies of volcanic surfaces in New Mexico that are of the order of two million years old. In the following, we examine a few examples.

The general characteristics of young and unmodified lava flows are relatively well documented (e.g., Kilburn, 2000) from many studies. The particular morphologic characteristics present may vary from flow to flow due to differences in their emplacement conditions and composition and fundamental lava type (pahaoehoe or aa), but in general all recently erupted flows (less than 1000 to 10 000 years old) preserve millimeter- and centimeter-scale features of lava surfaces superimposed on larger-scale features such as tumuli, collapse depressions, channels, and individual flow margins (Elston *et al.*, 1976a). A survey of the surfaces of lava flows in New Mexico with reference to their individual ages identifies a progression with age in which progressively larger-scale features are degraded (Figure 4.3). Surface glass and centimeter-scale roughness characteristic of recently erupted flows are preserved up to tens of thousands of years. Meter-scale features, such as tumuli and larger structures only, are present after one to two hundred thousand years. At an age of one million years, few surface topographic features remain, although the individual flow margins are generally well preserved and are easily mapped in air photos or traced by ground traverses. At ages greater than about 5 million years, lava surfaces are generally flat and featureless in which even flow margins may be difficult to distinguish and the flow is frequently eroded and occurs as the caprock of isolated mesas.

The correlation between age and surface characteristics is not precise due to differences in the initial surface features and topographic roughness of individual flows, differences in the local environment, such as proximity to regional drainages, differences in local eolian deposition of silt, and differences in altitude and differences in global climate over the range of ages and corresponding variations in rainfall and vegetation at local and regional scales. Nonetheless, in New Mexico it is possible to infer an approximate age, to better than the closest order of magnitude, of many lava flows based on their surface preservation characteristics for a region as a whole.

Processes responsible for the degradation in the arid climate of New Mexico are largely mechanical weathering of the surfaces and airfall of silt derived from surrounding loose fines that compose many of the regional Mesozoic

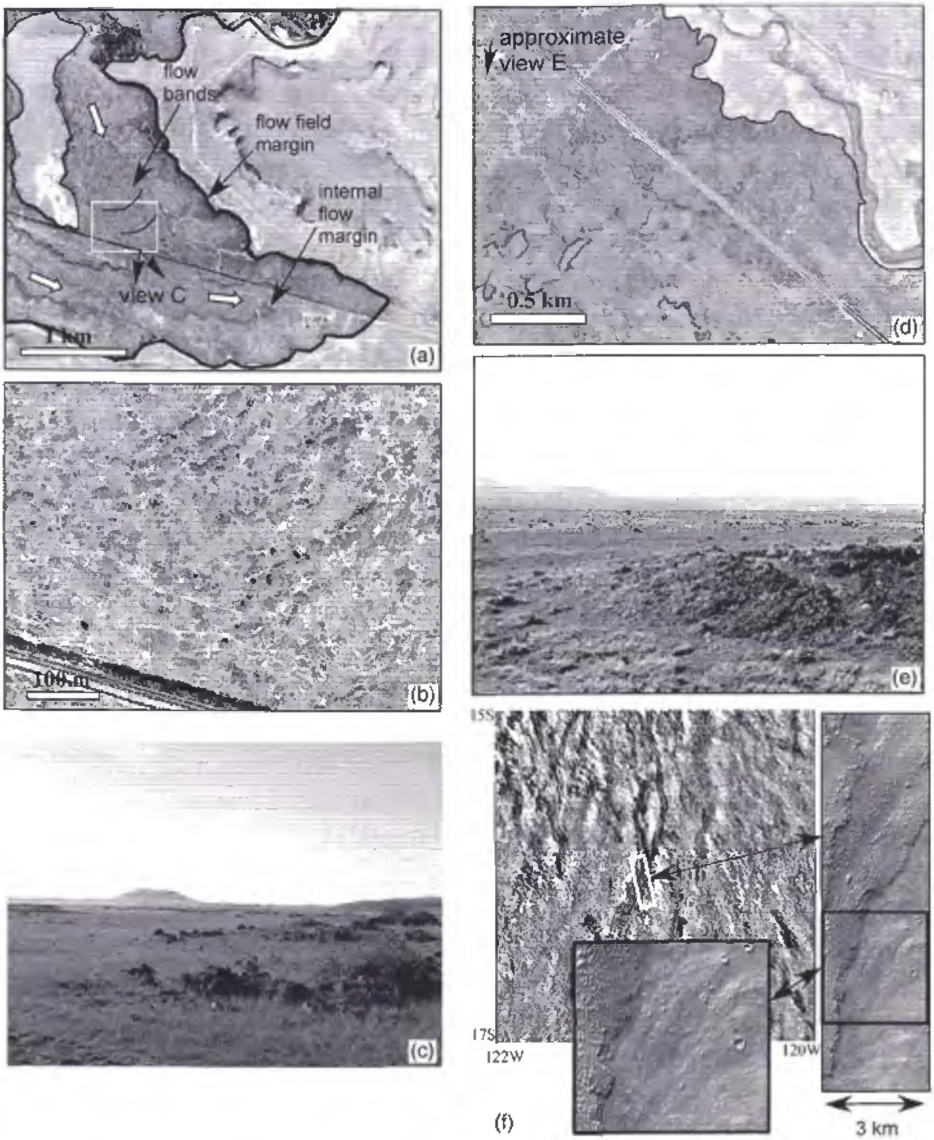

Figure 4.2. Examples of scale-dependent state of preservation in lava flows. (a–c) Sequence of progressively higher resolution images of a flow dated at <1.0 Ma. Flow margins and surface waves or bands are prominent in low-resolution images. At the surface outcrops are sparse and their relation to the flow surface structure is unclear. (d, e) Aerial photo of a flow dated at ~100 ka. Collapse depressions and tumuli are prominent, yet the surface appears as an undulating rubble sheet with low areas filled by fines; arrow in (d) indicates approximate direction of view shown in (e). (f) MOC image (FHA 01222) and corresponding Viking context of flows south of Arsia Mons. High-resolution perspective (inset) of these fresh-appearing flows shows that areas between relief features are smooth and appear mantled.

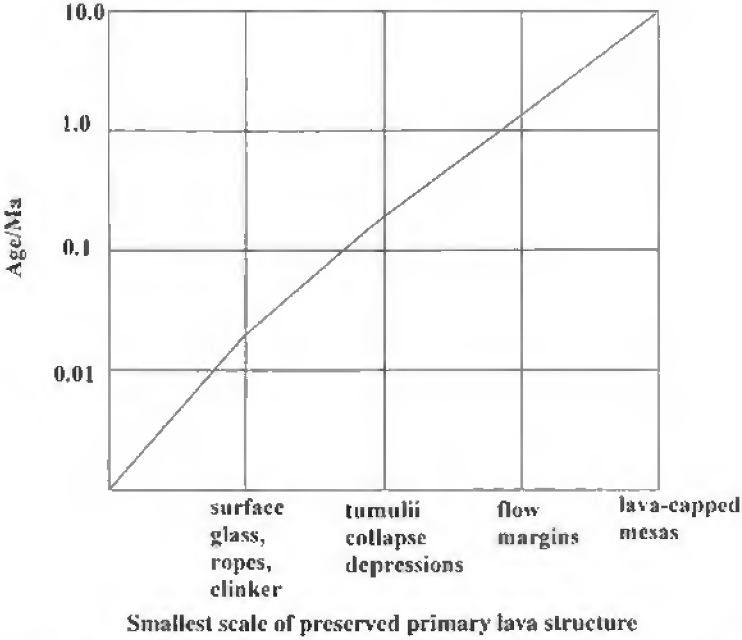

Figure 4.3. Proposed sequence of degradation on lava flow surfaces for New Mexico (after Elston *et al.*, 1976a). With increasing age, similar progressions of erosion on Mars will result in diminishing preservation of short-wavelength landforms. Lava flow margins and patterns of flow will be preserved much longer than detailed morphologic features characteristic of recent lava flows. Expectations of volcanological variety based on orbital images can thus be misleading.

sedimentary rocks. Low areas within a flow are gradually filled by spallation of surface glass (tachylite) and dislodged centimeter-scale fragments of surface clinker and fragmented glassy surfaces, and organic debris from sparse but widespread vegetation growing in cracks. Further infill occurs from airfall of silt. Relief features are in this way gradually lowered, the surfaces of low areas are raised, and the overall topographic roughness is smoothed. In the absence of significant rainfall and runoff that would carry accumulated silt away, alluvium accumulates in low areas of the flow surfaces to depths capable of burying many smaller-scale surface features. Despite overall weathering and degradation, a substantial component of the small-scale features may be preserved in low areas by these burial processes such that many small-scale features may actually be preserved even at great ages (>1 Ma) but are simply covered. Older flows are therefore not necessarily devoid of primary features, and detailed examination of outcrops and dissected exposures may still reveal characteristics of the primary surfaces.

Many of these or similar processes may have contributed to degradation of lava flow surfaces on Mars. Despite the relatively lower rates of weathering on Mars as compared with Earth, significant degradation of flows is predicted to have occurred over the large geologic times since most volcanic surfaces on Mars were emplaced. In the youngest lava flows, mantling by dust may be a more effective than direct ablative erosion. Based on the New Mexico analogies, most Martian lava flows may be expected to be less than pristine and to appear relatively degraded at outcrop scales, yet some characteristics of their original surfaces, including delicate surface textures, may be preserved beneath mantling deposits that have filled low areas on their surfaces; and larger-scale features such as tumuli, collapse depressions, and individual flow margins will still be visible.

4.4 Ash flows and calderas

Several large volcanic edifices and associated calderas on Mars, particularly the highland paterae (Greeley and Crown, 1990; Crown and Greeley, 1993) and several Tharsis (Gulick and Baker, 1990) and Elysium (Mouginis-Mark *et al.*, 1982) volcanoes have been compared with more explosive terrestrial volcanic centers. Radial deposits common to these volcanoes appear distinct from obvious lava flows associated with many shield volcanoes on Mars in that V-shaped valleys and flat inter-valley surfaces are consistent with erosion of more sheet-like and less digitate materials than lava flows (Figure 4.4).

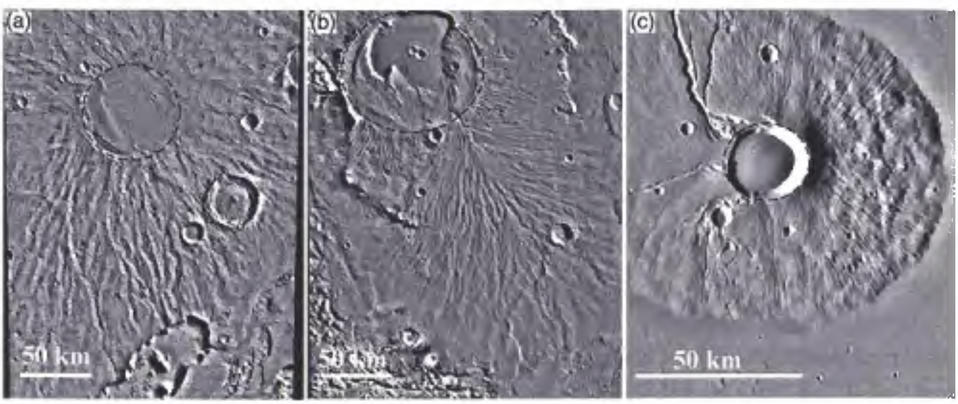

Figure 4.4. Examples of possible ash-flow type morphologies of Martian volcano flanks. (a) Hadriaca Patera. Shallow caldera and V-shaped valleys are analogous to the characteristics of many terrestrial ash-flow calderas and flows. The large valley to the south is a candidate for hydrothermal discharge. (b) Apollinaris Patera. (c) Ceraunius Tholus.

This characteristic has been compared with the morphology of radiating sheets of ash flow tuffs formed from pyroclastic flow mechanisms associated with many terrestrial explosive (plinian) volcanic centers (Reimers and Komar, 1979; Greeley and Crown, 1990; Gulick and Baker, 1990). Although terrestrial pyroclastic flows resulting in ash-flow tuffs are almost exclusively the result of silicic eruptions, on Mars the tendency for greater magma fragmentation (Wilson and Head, 1994) and the presence of geologic settings capable of delivering large volumes of volatiles to a high volume mafic eruption (Crown and Greeley, 1993) makes more tenable the suggestion that some deposits with ash-flow-like morphology may be mafic pyroclastic flows. The Valles Caldera, an almost circular, 20 km diameter caldera (Figure 4.5), bears many similarities to patera-type volcanoes of Mars in this respect. In diameter alone it is also comparable to the smaller Martian calderas (Crumpler *et al*., 1996; Mouginis-Mark and Rowland, Chapter 3, this volume).

The Valles Caldera is the type example of resurgent ash-flow calderas (Smith and Bailey, 1968). Eruptions of the Valles Caldera culminated with the emplacement of at least two stratigraphic members of a broad apron of ash flows, the Bandelier ash-flow tuff, during collapse of the caldera at about 1.1 Ma ago. The Bandelier ash-flow tuffs radiate outward from the caldera forming a broad apron of thick ash-flow tuff sheets. The ash-flow tuffs have been dissected subsequent to their emplacement resulting in a distinct radially patterned morphology of alternating V-shaped canyons and flat-topped interfluves (Figure 4.5d) analogous to the pattern of valleys surrounding highland paterae on Mars. Resurgent doming of the center of the Valles Caldera over the next several hundred thousand years following caldera formation resulted in uplift of the floor in a rounded central peak that exceeds the elevation of the caldera rim. The resurgent doming was followed by a series of extrusions of several rhyolite domes on the caldera floor along the collapse ring fracture and encircling the resurgent dome. The latest rhyolite dome eruptions occurred approximately 0.04 Ma. Resurgent doming in the Valles Caldera and subsequent extrusive dome formation is unlike the relatively flat-lying interiors of Martian paterae. This difference reflects the differing dynamics and shallow location of the associated Valles Caldera magma chamber and its rhyolitic composition as opposed to the likely mafic nature of Martian magmatism. However, the explosive characteristics of terrestrial rhyolite ash eruptions and gas-charged Martian mafic magmas may be comparable (Crown and Greeley, 1993).

At geologically long time scales the radial ash sheets of the Valles Caldera appear easily eroded and less competent than lava flows because of the

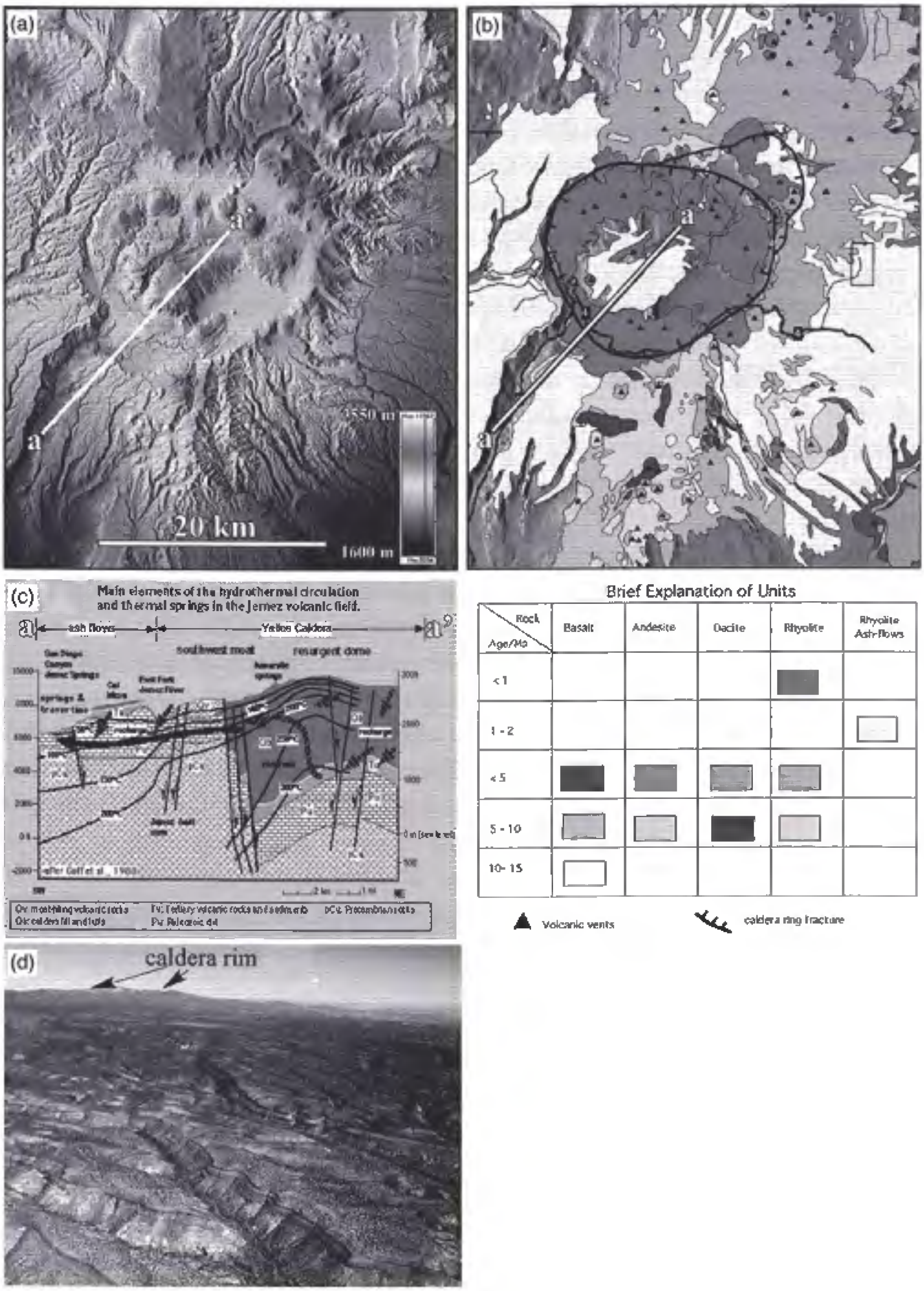

Figure 4.5. (a) Digital shaded relief map of the Valles Calderas, near Los Alamos, New Mexico. (b) Generalized geologic map of the Valles Caldera. After Luedke and Smith (1978) and Smith *et al.* (1970). (c) Schematic section (after Goff *et al.*, 1989) from the caldera center through

development of deep canyons with steep walls. However, the Bandelier ash-flow tuffs are in fact relatively competent rock formed from compaction and welding of ash at the time of emplacement. The combination of relatively low permeability and an underlying substrate and basal layers of loosely consolidated ash have contributed to fluvial runoff along general gradients directed outward from the caldera margins and corresponding rapid incision and valley wall retreat. Because of the impermeability, aqueous flow from the caldera interior tends to be directed along the base of the ash flow sheets further enhancing formation of springs along the base of the ash flows and enhanced erosion along the base of valley walls.

Many such springs around the margins of the ash sheets are anomalously warm due to deep penetration of water at its source in an area of high residual magmatic heat. These observations have significance in the context of current Mars exploration goals. If compaction and welding of mafic ash flows around explosive volcanic centers on Mars contributed to deposits with similar hydrologic properties, thermal springs may have been common in the valleys and distal reaches of the tuffs. Early in the history of caldera formation, any groundwater that emerged from the base of ash flow sheets around Martian paterae may have similarly inherited heat from the adjacent large volcanic centers, thus leading to numerous hot or thermal springs where the aquifer emerged in the valleys and edges of the ash flow sheets. These are the types of spring environments that are targets for investigation as potential sites for early pre-biotic and biotic processes (McKay and Stoker, 1989; Boston *et al.*, 1992). Thus, based on our understanding of an analogous caldera on Earth, the margins of radiating ash sheets around Martian paterae may be useful sites for concentrated investigations that seek sites of former thermal springs.

4.5 Large radial dikes

Radial fractures are a prominent characteristic of the Tharsis region of Mars (Figure 4.6a). Possible interpretations of the Tharsis pattern include

Caption for Figure 4.5. (cont.) the south margin and down the prominent valley on the southwest flank illustrating the principal characteristics of hydrothermal circulation and relationship to down-gradient springs and spring deposits. Similar circulation patterns may have existed shortly after formation of the highland paterae type calderas on Mars (see, for example, Figure 5.4a). (d) Oblique air photo of valleys cut into the extensive layered sheets of Bandelier ash flow tuffs that were erupted during caldera formation; view west from vicinity of the Rio Grande; note distance from the caldera rim. (For a color version of this figure, please refer to color plate section.)

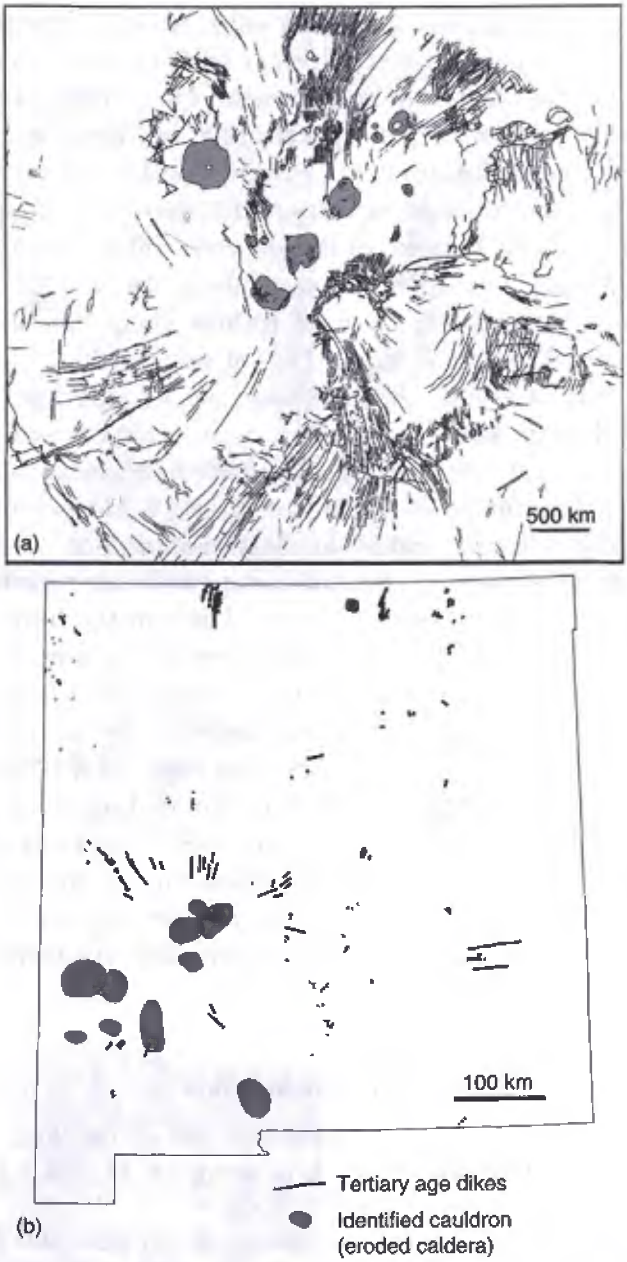

Figure 4.6. (a) Distribution of fractures radial to the Tharsis region of Mars (after Hamblin and Christiansen, 1990). (b) Distribution of mid-Tertiary mafic dikes in New Mexico. The pattern of dike orientations is generally radial to the central complex of mid-Tertiary ash flow calderas (the Mogollon volcanic province). Dike locations from Elston *et al.* (1976b) and New Mexico Bureau of Geology and Mineral Resources (2003).

strain associated with uplift (Banerdt *et al.*, 1992) and radial dikes associated with volcanism (Wilson and Head, 2002). Radiating fracture patterns interpreted as the surface expression of radial dikes occur on Venus, Mars, and Earth (Ernst *et al.*, 2001; Wilson and Head, 2002). Terrestrial examples may be up to several hundred to a thousand kilometers in overall diameter. Most examples are from older volcanic regions where erosion has been great enough to expose dikes and intrusions that were formerly at shallow depths within the crust. Some are associated with individual volcanoes, but the more intriguing examples radiate from large igneous provinces on Earth where magmatism was protracted and voluminous.

A potential example of the latter type occurs in association with the largest mid-Tertiary Mogollon magmatic province in New Mexico. A map of mid-Tertiary dike distribution in New Mexico (Figure 4.6; Elston *et al.*, 1976b) is similar to radial dike systems described from many igneous provinces on Earth. If all mid-Tertiary dikes in New Mexico are mapped, the distribution appears to radiate from a center located within the Datil-Mogollon ash-flow caldera volcanic complex (Elston *et al.*, 1976b), a cluster of silicic and intermediate composition ash-flow caldera of mid-Tertiary age.

Many stratigraphic, petrologic, chemical, and isotopic studies of the associated volcanic rocks of the Mogollon volcanic region suggest that the thermal source for production of many of the voluminous non-basaltic melts may have been extensive basaltic magmas injected into the lower crust at or slightly before the period of great ash-flow volcanism that occurred throughout the southwest in mid-Tertiary time. Many of the earliest eruptions were basalts and basaltic andesite, followed by development of many intrusions of magmas with mixed or intermediate compositions. Upward progression and mixing of renewed basaltic intrusions into previously melted crustal materials, and previously mixed magma volumes in the upper crust resulted in hybrid magmas across a broad range of compositions. Ultimately, these magmas developed as extensive plutons that fed overlying dominantly silicic centers and corresponding ash-flows and calderas. The volume of magma necessary for the development of such an extensive field of plutons was presumably large and resided in the lower crust as an extensive series of magma chambers of dominantly mafic composition. In many ways this is analogous to the situation envisoned for magmas within the Martian crust during emplacement of the Tharsis province (Wilson and Head, 2000).

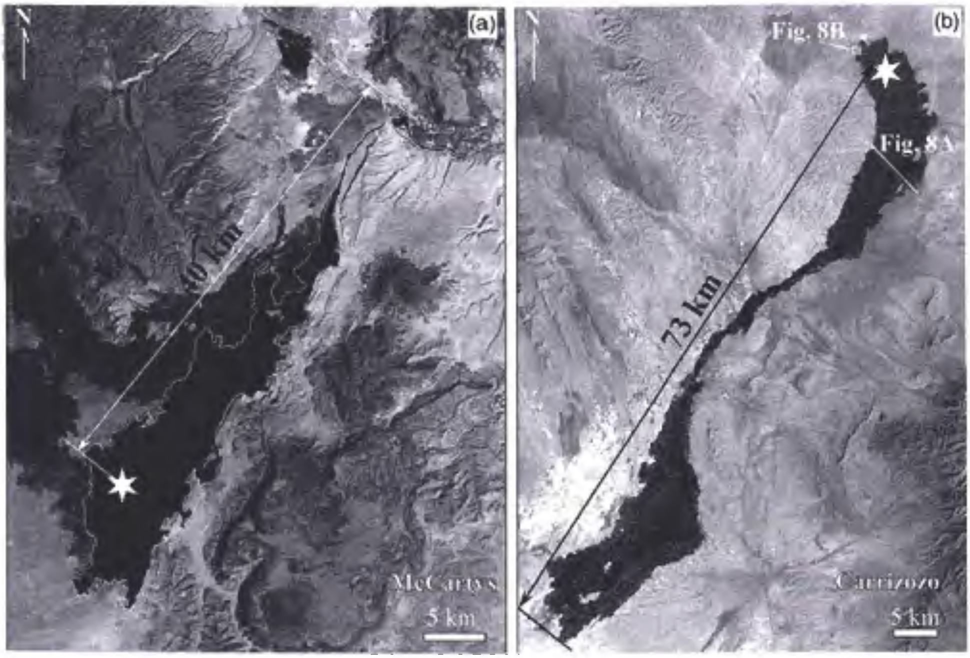

Figure 4.7. Two of the longest young lava flows in North America, the McCartys and Carrizozo flows, provide insights into possible emplacement mechanisms for large lava flows common on Mars. (a) McCartys lava flow (white outline), Grants, New Mexico. Older flows of differing age and surface brightness lie to the left (west). (b) Carrizozo lava flow. Location of two precison topographic traverse are shown as lines near the north source region and north central portions of the flow.

4.6 Large lava flows and flow fields

The McCartys and Carrizozo lava flows (Figure 4.7) are two of the largest young lava flows in North America. The flows are unrelated and occur in widely separated areas of the state; however, both are compound, tube-fed pahoehoe type flows. Because of their great volume and youth they are exceptional analogs for large lava flows common on Mars and the other terrestrial planets (Zimbelman, 1998; Zimbelman and Johnston, 2001). For example, the overall planimetric shapes appear as though the flows are the result of a single fluid emplacement of lava, but in fact each developed from multiple overlapping segments and through branching tube arrangements. By understanding these and other details of the actual emplacement process, the actual factors controlling emplacement of large lava flows common on Mars may be better constrained.

The McCartys flow is the latest eruption in the extensive field of lava flows of the Zuni-Bandera field and is 48 km long from its small source vent to its terminus in the San Jose Valley near the present day route of interstate I-40 (Nichols, 1946; Maxwell, 1982, 1986; Thelig, 1990). The entire flow covers ~189 km^2, as outlined using satellite image data aided by published geologic mapping (Maxwell, 1986), a value smaller than the one reported by Nichols (1946). By assuming an average thickness of 23 m, Nichols (1946) estimated a total volume for the McCartys flow of 7.9 km^3. By comparison the somewhat less well-preserved 1783 flow of the Laki basaltic fissure eruption in Iceland (Thordarson and Self, 1993) is estimated to have a volume of 13 km^3. Basaltic glass (tachylite) is common throughout the surface of the McCartys flow which preserves a myriad of small-scale features resulting from plastic deformation of a fluid, hot silicate melt (Nichols, 1946). The flow surface is largely pahoehoe, although in many places the pahoehoe is broken up into jumbled plates that transition to a true a'a texture. The McCartys lava consists of tholeiitic basalt, initially considered to be undifferentiated (Renault, 1970). Subsequent extensive sampling and analysis revealed that the McCartys lavas are quartz-normative tholeiite with plagioclase phenocrysts within 4 km of the vent and olivine-normative tholeiite containing olivine phenocrysts at distances greater than 4 km (Carden and Laughlin, 1974). The detailed sample study also revealed considerable longitudinal variation in both major- and trace-element chemistry along the flow (Carden and Laughlin, 1974, table 1), but vertical chemical variations were found not to be significant. Likewise, a study of the vertical density and vesiculation along the length of the McCartys flow (Aubele *et al.*, 1988) indicated no significant variation with distance from the vent in the vesicularity. Cosmogenic and radiocarbon dating methods both give a young age of ~3000 yr for the McCartys flow, providing agreement within the analytical uncertainties of both methods (Laughlin *et al.*, 1994).

The Carrizozo flow is 75 km long from the vent area to the distal margin in the Tularosa Valley (Keszthelyi and Pieri, 1993; Zimbelman and Johnston, 2003). The entire flow covers ~330 km^2 to an estimated thickness of 10 to 15 m, for a total erupted volume of ~4.3 km^3 (Allen, 1951). The lava is intermediate in composition between alkalic and tholeiitic basalt and is consistent with the regional volcanism associated with the Rio Grande rift (Renault, 1970; Faris, 1980; Anthony *et al.*, 1998). Various researchers have distinguished between upper and lower Carrizozo flow units, separated by a narrow "neck" in the medial reach (e.g., Anthony *et al.*, 1998; Dunbar, 1999). Chemical analyses to date have measured small differences between the upper and lower lavas, although it is unclear whether the measurements are statistically significant. Cosmogenic (isotopic changes induced by exposure to high-energy particles) studies indicate exposure ages of 4800 yr (Anthony *et al.*, 1998) to 5200 yr (Dunbar, 1999) for the Carrizozo flow, well within the 1700 and 700 yr error estimates, respectively. These results make the Carrizozo flow the second youngest volcanism in New Mexico (Anthony *et al.*, 1998), after only the McCartys flow.

Recent Differential Global Positioning System (DGPS) data of both flows (Zimbelman and Johnston, 2003) have revealed new details about the relief and emplacement of these compound basaltic flows. A topographic transect across the Carrizozo flow along Highway 380, ~10 km down flow from the vent, supports the interpretation that multiple flow elements banked against earlier episodes to build the field from east to west (Figure 4.8a). The topographic data, with horizontal and vertical precision ~2 to 4 cm, show distinctive terracing along the flow margins in the proximal and distal portions of both flows (Figure. 4.8b), interpreted to be indicative of multiple episodes or scales of the local flow emplacement. The origin of these terraces is unclear but they may be associated with changes in local gradient that resulted in the fluid flow interiors exceeding the crustal strength during inflation of the flow and corresponding breakouts. Topographic measurements of the McCartys flow are consistent with results obtained for the Carrizozo flow, and help to constrain how the eruptions may have produced both flows. The dimensions of a very narrow neck on the McCartys flow, ~40 km down flow from the vent, provide strong constraints on the lava tube that must have fed the distal portions the flow, resulting in a maximum likely effusion rate of ~500 m^3/s. At Carrizozo, a single medial ridge along the narrow central portion of the flow can be interpreted as a lava tube similar to the McCartys flow neck, which suggests a maximum likely effusion rate of ~800 m^3/s. Both flows could have been emplaced at these rates within a period of a few months, or of the order of 20 years at sustained lower rates (Keszthelyi and Pieri, 1993).

4.7 Hydromagmatic volcanism

Evidence for fluvial and ice-related processes on Mars (Fanale *et al.*, 1986; Squyres and Carr, 1986; Squyres *et al.*, 1992; Clifford, 1993; Carr, 1996), together with widespread evidence for volcanoes at many scales, raises the possibility that the interaction between water and magma, or hydromagmatic eruptions, may have occurred on Mars (Frey and Jarosevich, 1982; Mouginis-Mark *et al.*, 1982; Mouginis-Mark, 1985; Squyres *et al.*, 1987; Mouginis-Mark *et al.*, 1992; Crown and Greeley, 1993; Fagents and

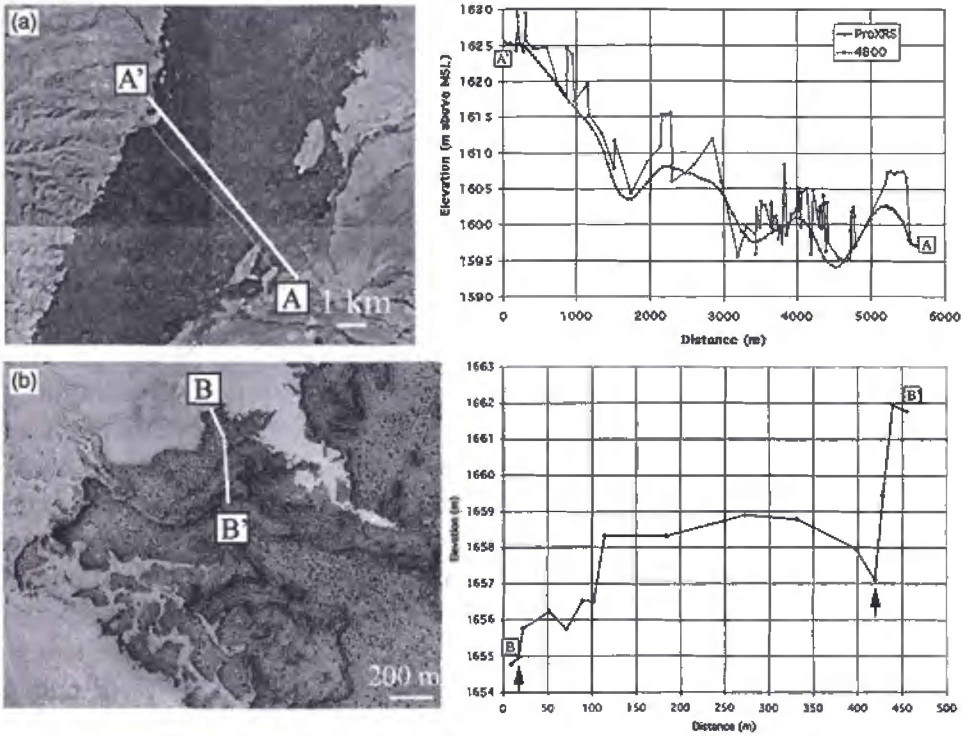

Figure 4.8. Precision topographic transects across portions of the Carrizozo lava flow; locations indicated on Figure 4.7(b). (a) DGPS data along US Highway 380, across the Carrizozo flow ~10 km down flow from the vent at Little Black Peak. A pronounced slope from the right (east) to left (west) is interpreted as the result of multiple flows banked against one another. (b) Terraced margin, NW corner of Carrizozo flow. Line shows location of DGPS profile. Left: Portion of USGS Digital Orthophoto data of Black Peak Quadrangle, New Mexico. Right: DGPS data along indicated traverse.

Thordarson, Chapter 6; Chapman and Smellie, Chapter 7, this volume). Hydromagmatic eruptions are a type of plinian to vulcanian eruption in which near-surface water is vaporized when magma ascends into the saturated layer. The rapid flashing of the water to vapor drives powerful explosive bursts (Sheridan and Wohletz, 1983; Wohletz, 1986) capable of fragmentation and deposition of significant quantities of both conduit wall rock and the magma itself. Landforms associated with magma–water interaction are common and distinctive on Earth, and if present on Mars should be detectable based on the predictable characteristics of deposits and structures associated with hydromagmatic eruptions. Relief on any hydromagmatic vents on Mars is likely to have been subdued over geologic time through mechanical weathering and gradual infilling of the crater floors with airfall dust. In addition, consideration of gravitational and environmental effects on rim ejecta morphology (McGetchin and Ullrich, 1973; Wilson and Head, 1994) insure that the morphology of hydromagmatic vents are likely to be somewhat different than modern, unweathered terrestrial counterparts. Therefore an understanding of the morphology of older and eroded examples on Earth may be important in identifying them on Mars. The abundance and wide range in age of hydromagmatic vents in New Mexico offers an excellent opportunity to explore the range of preservation characteristics.

Hydromagmatic landforms are relatively common in New Mexico because many of the eruptions occurred during the late Pleistocene when conditions were wetter throughout the Southwest. In addition, the association of volcanism with the Rio Grande rift, which confines one of the major water courses in New Mexico, the Rio Grande, has also resulted in numerous eruptions where water-saturated sediments were characteristic of the near-surface environment at the time of eruption. Because many eruptions in New Mexico have been dominantly monogenetic and basaltic, a common hydromagmatic feature is the maar (Aubele *et al.*, 1976). Maars are crater-form volcanic centers, generally on the order of a kilometer in diameter, typically developed with raised rims consisting of accidental materials and ash ejected during multiple violent steam-blast explosions (Lorenz, 1973). Subsequent to eruption most maars are occupied at least temporarily by ponded water and are thus sites of pluvial deposition, partial infilling, and back-wasting of the initially steep crater walls.

On Mars, because of the prevalence of small impact craters, the ability to distinguish between small craters of hydromagmatic origin and small craters of impact origin will be critical if maars are to be identified on Mars at all. Several studies of maar craters in New Mexico have helped to define the physical characteristics of these volcanic craters. Relatively youthful and morphologically typical maars occur within the Zuni-Bandera volcanic region, the Potrillo volcanic field, and within the Mount Taylor volcanic field.

The Zuni Salt Lake maar (Figure 4.9a; Cummings, 1968) is an excellent example. In size and age (1.5 to 2 km and 0.024 Ma) (Bradbury, 1966) and in its arid Colorado Plateau setting, it is comparable to Meteor Crater (1.3 km and 0.08 Ma), making it an exceptional model for comparison and discrimination of the morphology of both types of crater. Zuni Salt Lake also illustrates the type of characteristics that are most useful in determining the volcanic origin of maars as compared with impact craters. The most prominent difference is the relatively shallow relief of the maar floor,

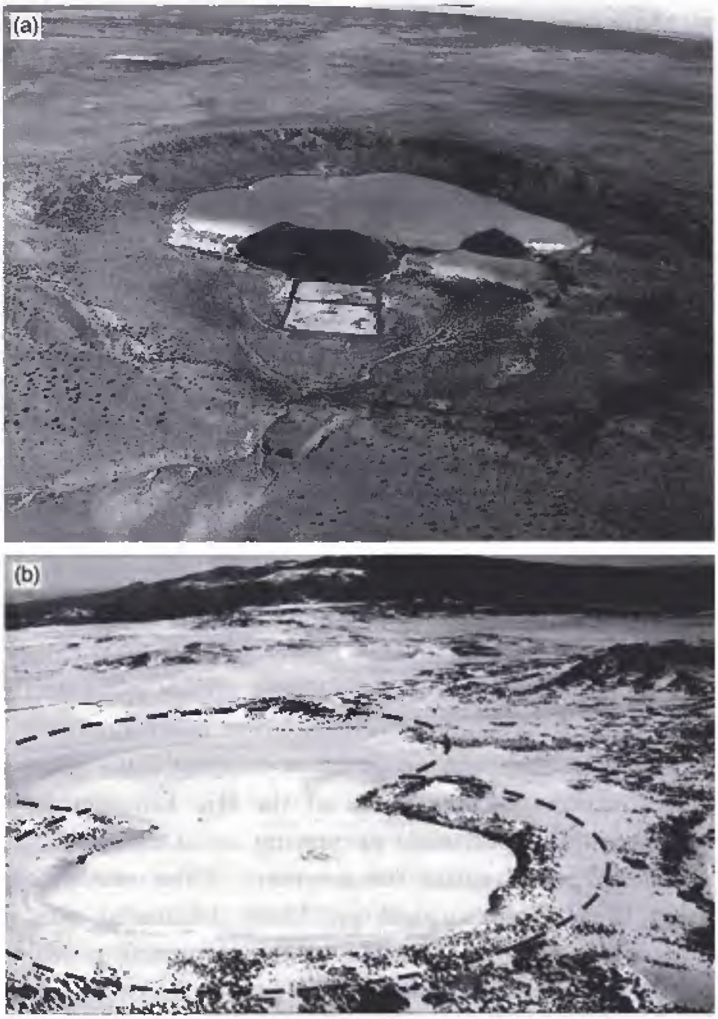

Figure 4.9. Although dry now, many volcanic vents in New Mexico were emplaced during the extended pluvial periods of the late Cenozoic in New Mexico. Centers of former hydromagmatic eruptions are common in New Mexico. Similarly, volcanism during the early wetter geologic past of Mars may have resulted in analogous landforms. (a) Zuni Salt Lake maar, Quemado, New Mexico. (b) Laguna de Alejandro maars, Mount Taylor field, San Mateo, New Mexico.

approximately 60 m from rim to floor, compared with Meteor Crater (200 m). The original depth is estimated as only slightly deeper considering that the base of the interior scoria cones appear not to have been buried. Erosion of the loosely consolidated rim ejecta and the long-term presence of an interior saline lake have resulted in flattening of the floor and retreat of the crater walls. More distinctive is the presence of two small scoria cones on the floor. Clear evidence of association with interior volcanic features together with the layered and easily eroded rim deposits such as this is a salient characteristic that would distinguish Martian hydromagmatic craters from those of impact origin.

Maars within the Mount Taylor field (Crumpler, 1980a, b) are of interest because of their great age and location in an area where dissection has been minimal. The eruptions that formed the maars of the Mount Taylor field occurred approximately 2 million years ago within a volcanic field that is dominated by scoria cones and extensive alkali basalt flows. Several are elongated or overlap along distinct fissure lines (Figure 4.9b). Almost all are a least 1 km in diameter and were occupied for extensive time by interior lakes. Because of the great thickness of basaltic rocks in the field, the rims consist largely of accidental blocks of underlying basalt and trachytic rocks in a matrix of tuff breccia and comminuted sandstone from the deep substrate. These maars are now situated on an extensive volcanic plateau that is essentially a 2 million year old surface isolated 300 m above the surrounding deserts. Because of their subdued, yet otherwise preserved form, they may be somewhat better examples of the state of preservation to be expected for small hydromagmatic centers on Mars where relief has been "softened" yet dissection has been minimal.

A few maars within volcanic fields of the Rio Grande rift have been dissected by canyon erosion, while preserving some characteristics of their surface expression, thus revealing the geometry of the interior deposits and its relationship to surface morphology. These are useful sites for understanding the complex internal dynamics of maar formation. Montoso maar in the Cerros del Rio field (Aubele, 1978) is an example in the middle Rio Grande rift and lies on the margins of a deep side canyon cut into the walls of a narrow gorge (White Rock Canyon) cut by the Rio Grande. Here a side canyon has completely cut into the relatively soft interior of a maar, exposing layers of inward-dipping ash and tuff breccias, several subsidence faults, and interior basaltic intrusions, yet rim ejecta typical of maars, consisting of accidental blocks of basalt, sandstone, and tuffs mixed with juvenile ash and palagonite, is preserved on the top of the canyon walls.

Maars in the Potrillo field (Hoffer, 1976) include the irregular-shaped Potrillo maar and Hunt's Hole, a deep maar with numerous ultramafic blocks in the rim ejecta. Portrillo maar illustrates the fact that not all maars are circular but can have complexly scalloped margins resulting from transient explosions appearing at different locations across the interior of the active vent.

4.8 Tertiary Colorado Plateau volcanism

Because of the relatively great crustal thickness (Bills and Ferrari, 1978) and potentially more iron-rich mafic and ultramafic mantle melt compositions of Mars (McGetchin and Smyth, 1978; Treiman, 1986; Bertka and Holloway, 1989; Longhi, 1990), erupted melts and eruption processes are potentially different from those on Earth. One consequence of this is the possibility of the eruption of high-fluidity melts and the inclusion of mantle volatiles leading to explosive eruptions with pelean and vulcanian characteristics (Wilson and Head, 1994). Such eruptions would be more explosive and compositionally distinct from common mafic eruptions on Earth. One problem with identifying this type of volcanic vent on Mars is the near absence of information about the morphology of the vents that they would produce. For this reason, volcanic styles on Earth that appear to have resulted from unusual volatile rich mafic eruptions are of potential importance in understanding some eruption processes on Mars.

Volcanism in the interior of the Colorado Plateau, represented by the mid-Tertiary Navajo volcanic field (Williams, 1936; Semken, 2001), is an example of a type of volcanism which has not been observed in the historic record. The Navajo volcanic field consists of approximately 80 eroded volcanic centers of Oligocene to Miocene age distributed throughout the Four Corners region, now preserved as volcanic necks or eroded depressions. They are characterized by unusual compositions, evidence for vulcanian eruption, and association with large sub-circular depressions. These eruption centers are also unusual in that they have occurred in a region of stable and thick lithosphere in the near absence of strong extensional stresses leading to the conclusion that magma was deep-seated and ascended by volatile-aided processes uncommon in most modern volcanic regions.

Many of these eruption centers consist of unusually mafic to ultramafic compositions. The exposures of the conduits from which they erupted are composed almost entirely of tuff breccias of highly comminuted mafic rocks suggesting extremely explosive emplacement styles and deep mantle sources (Delaney and Pollard, 1981). Inferred surface characteristics based on the overwhelming abundance of tuff breccia imply a vent that was perhaps similar to maars although possibly driven by juvenile volatiles more than near-surface hydromagmatic processes. Because most of these centers are deeply eroded, their value from a morphological standpoint is limited. However, at least one example of the near-surface characteristics of these volcanic vents remains in the form of an unusual crater-shaped depression (Narbona Pass volcano; Figure 4.10) on the summit of the Chuska Mountains

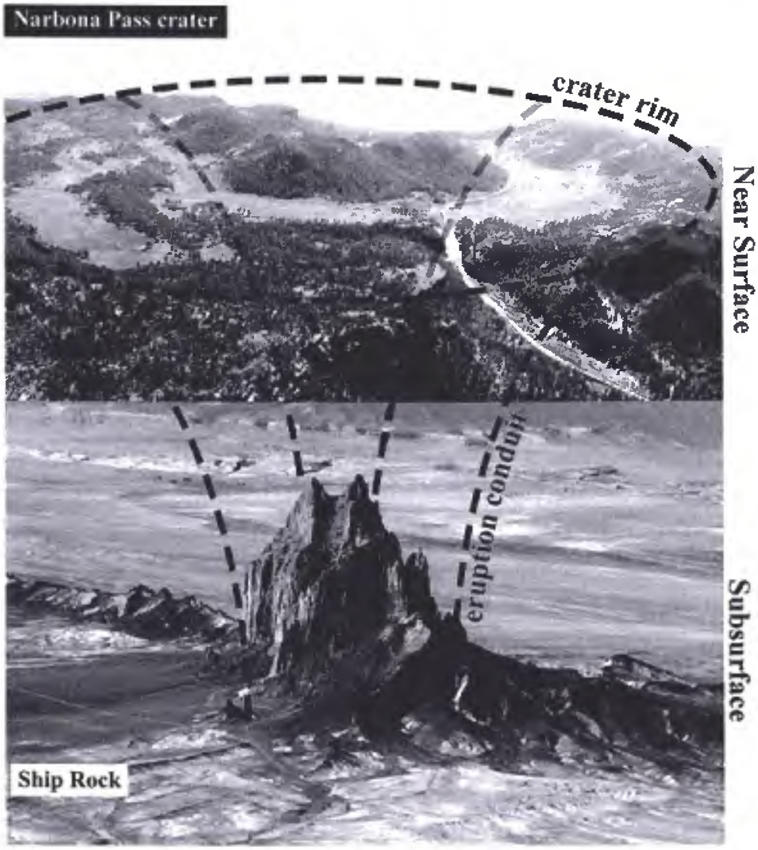

Figure 4.10. Comparison of Ship Rock and Narbona Pass volcano, Chuska Mountains, between Gallup and Shiprock, New Mexico. Ship Rock is interpreted (Semken, 2001) to be the near-surface conduit fill for a former hydromagmatic volcano. The surface expression of the former Ship Rock volcanic vent may have appeared similar to the Narbona Pass crater. The Narbona Pass crater is preserved because it is perched on the summit of an elevated plateau, the Chuska Mountains, which is an erosional remnant of a formerly thicker section of sediments within the central Colorado Plateau.

of western New Mexico (Ehrenberg, 1978; Semken, 2001). Narbona Pass volcano is a nearly circular depression 3 km in diameter. The absence of significant volcanic materials in the areas outside the depression leads to the conclusion that at least some vertical erosion of what is essentially a Tertiary surface has occurred since its emplacement. Within the depression there are several intrusions of basaltic composition as well as horizontal trachyte flows surrounded by tuff breccias analogous to that in other Navajo field volcanic necks. The relatively large size compared with modern hydromagmatic craters (maars) attest to the fact that the original vent was substantial.

Because of the association with a relatively uncommon magma type and unusual conduit characteristics, the Narbona volcano is likely to be one of the more unusual volcanoes in the terrestrial record and relates to a type potentially present on Mars, dating from early Noachian time when explosive volcanism may have been more common. In this respect, not all maar-like features on Mars may have formed from interaction with near-surface volatiles. Juvenile volatiles from a primitive volatile-rich Martian mantle also could have played an important part in possible explosive volcanism on Mars. Centers such as the Narbona Pass volcano, and other eroded centers of the Colorado Plateau, may be among the few terrestrial examples of this type of volcanism.

4.9 Spring deposit cones

Deposits associated with natural springs are another form of endogenic geologic process that can be similar, in both their mechanisms of formation and their resultant landforms, to volcanic vents and volcanic terrains. In New Mexico, these deposits create a variety of morphologies including large sheets and ledges and conical edifices surmounted by summit "craters" and fissures (Figure 4.11) that strongly mimic volcanic vents. Some of the New Mexico spring deposits are associated with hydrothermal circulation. Others are the result of natural ground water flow in an arid environment. Both are conditions that may have counterparts on Mars.

In New Mexico, spring deposits occur where a significant vertical discontinuity interrupts the groundwater flow and causes the water to emerge at the surface (Figure 4.12). (See Figure 4.4 for another example of thermal spring deposits associated with the Valles Caldera.) Spring deposits are particularly common in association with high-angle faults, such as the marginal fault zones of the Rio Grande rift, which act as high hydraulic conductivity conduits for aquifers confined by overlying aquitards and aquicludes. Faults on the margins of basins and other discontinuous structures, such as anticlines, where aquifers are brought in contact with less permeable rocks or where an aquifer is abruptly terminated within existing topographic slopes by recent faulting are also common sites of spring deposits. Spring deposits are common in New Mexico, therefore, because they are associated with tectonically active or formerly active areas and both evaporation rates and mineral content of spring water are high. These controls on spring formation mean that spring deposits mimic many of the characteristics of volcanic vents: most importantly, they occur in association with linear structures and faults, and they form volcano-like deposits.

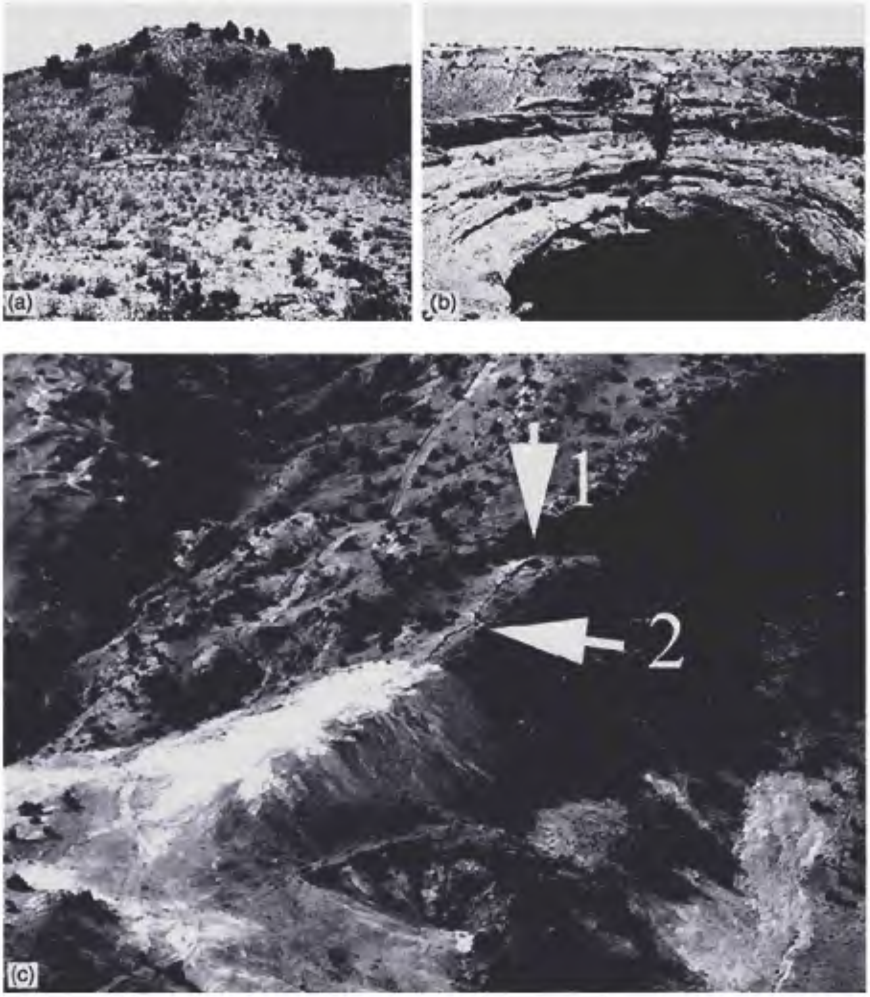

Figure 4.11. Constructional edifices at spring emergence sites may emulate volcanoes, including conical forms, summit craters, and fissured mounds. (a) Conical spring mound; and (b) Summit "crater" on edifice shown in (a). Spring deposits are developed along the axis of a prominent anticline. San Ysidro, New Mexico. (c) Fissured mound. Note crater near far end (arrow 1) and graben along apex (arrow 2). San Ysidro, New Mexico.

The upper few kilometers of the Martian crust are likely to be highly fractured (Fanale, 1976; Carr, 1979) and thus permeable to fluid flow and aquifer development (Clifford, 1993). If water is present in the subsurface as a fluid, it will accumulate within the permeable zone and, under the force of gravity, water will flow in the substrate from topographically high regions towards regions of discharge in topographically low regions. At that point

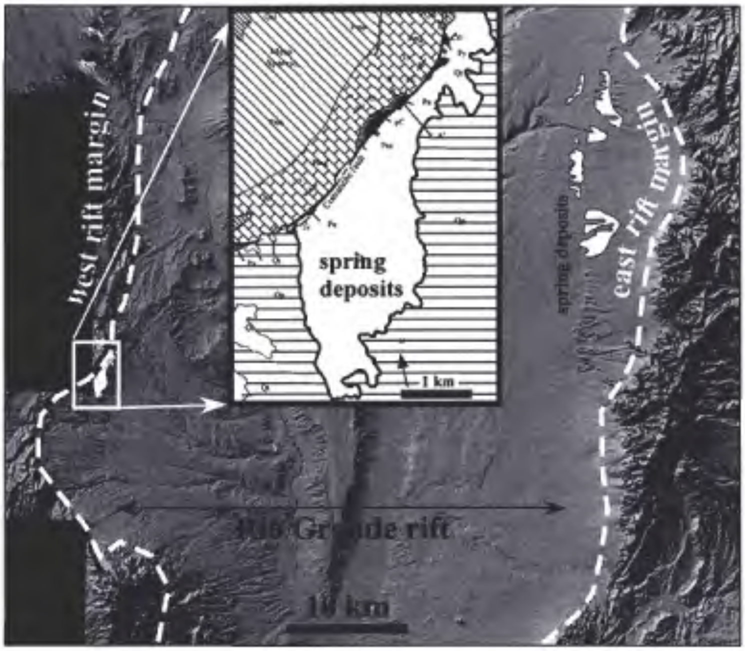

Figure 4.12. Springs are commonly located along the trace of significant regional faults. In this case, springs have developed along the western boundary fault of the Rio Grande rift near Belen, New Mexico. Continuous discharge, high mineral content of the spring waters, and the arid environment have resulted in the accumulation of significant deposits.

it is either discharged or accumulated in the subsurface. The gradient on the upper surface of the water-saturated region defines the top of the water table (Hubbert, 1953; Freeze and Cherry, 1979). The flow is controlled by the relief on the water table, or the potentiometric surface, which is generally a subdued reflection of the surface topography. At the largest scales, we may expect that water in a Martian aquifer of regional extent will flow from high elevations, such as the highlands to lowlands or local basins. There are many physical features over the surface of Mars that are similar to the morphologies typical of terrestrial spring mounds. For example, large areas of pitted mounds, generally interpreted as hydromagmatic (e.g., "pseudocraters"; Frey and Jarosevich, 1982) or ice-related phenomena (pingos), bear many of the characteristics of summit-pitted spring mounds (Figure 4.13a). Other anomalous mounds in apparently non-volcanic terrain on Mars occur in young basins or around basin margins (Figure 4.13b).

The influence of environment of formation on spring deposition, such as ambient pressure and temperature, is unknown, as are the chemical

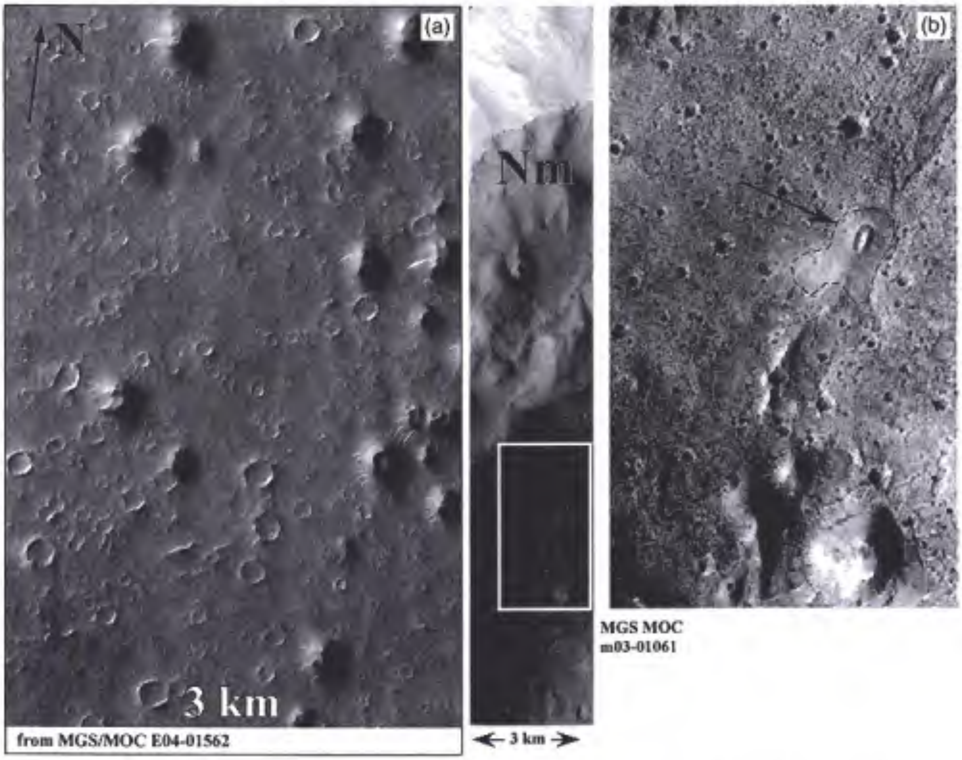

Figure 4.13. (a) Pitted mounds within the Isidis basin. (b) Isolated cratered mound within the highland–lowland transition zone. Down-gradient from an area of abundant valley networks.

compositions of materials that might comprise spring deposition environments on Mars. The corresponding deposits may reflect differences in their detailed environment and composition; however, they must form by a similar mechanism and with similar associations to major tectonic features. Spring deposits formed from carbonates appear relatively unlikely on Mars because there is as yet little evidence for extensive carbonate in the surface. Nonetheless many minerals are soluble in water and will respond similarly to dissolution, transportation, and deposition during desiccation. The abundance of dissolvable compounds in the Martian crust must be great. Given the deeply brecciated nature likely for the highlands and the widespread distribution of atmospherically transported volatiles and dust, including volcanic and impact-generated aerosols, the crust is likely to be liberally mixed with compounds that are unstable in water. Sulfur, sulfides, and related iron-rich materials may be important water-soluble materials that could constitute spring deposits on Mars.

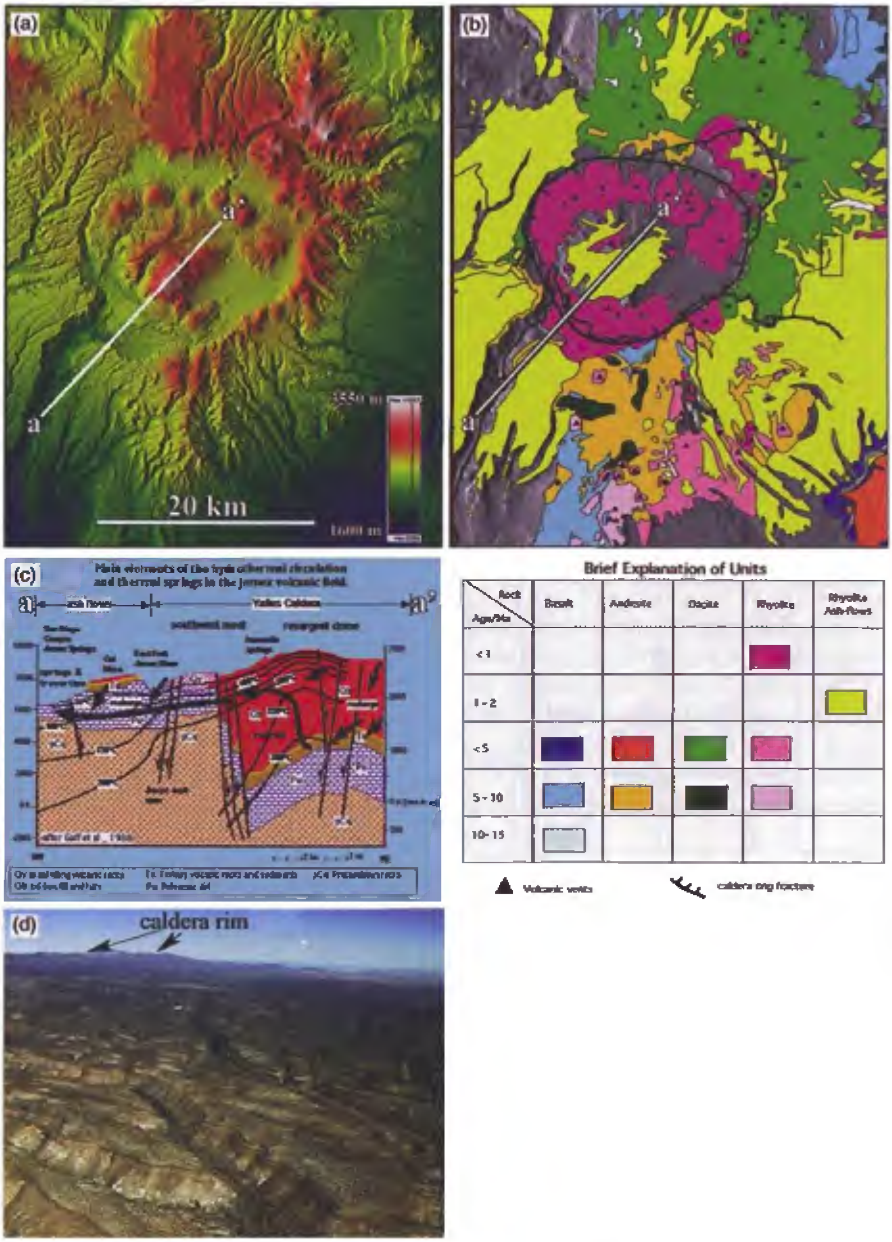

Figure 4.5. (a) Digital shaded relief map of the Valles Calderas, near Los Alamos, New Mexico. (b) Generalized geologic map of the Valles Caldera. After Luedke and Smith (1978) and Smith *et al.* (1970). (c) Schematic section (after Goff *et al.*, 1989) from the caldera center through the south margin and down the prominent valley on the southwest flank illustrating the principal characteristics of hydrothermal circulation and relationship to down-gradient springs and spring deposits. Similar circulation patterns may have existed shortly after formation of the highland paterae type calderas on Mars (see, for example, Figure 4.4a). (d) Oblique air photo of valleys cut into the extensive layered sheets of Bandelier ash flow tuffs that were erupted during caldera formation; view west from vicinity of the Rio Grande; note distance from the caldera rim.

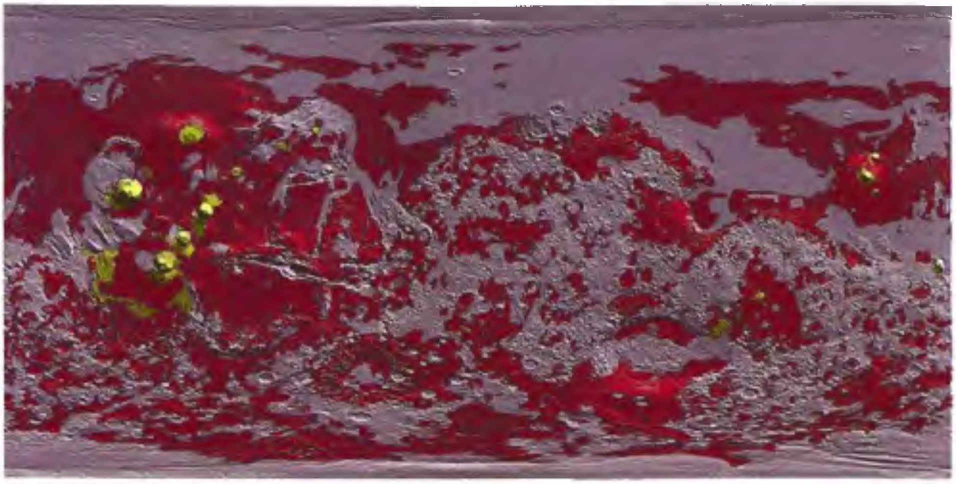

Figure 5.1. Distribution of possible flood lavas on the surface of Mars. Simplified from global maps (Scott and Carr, 1978; Scott and Tanaka, 1986; Tanaka and Scott, 1987; Greeley and Guest, 1987) and placed over MOLA global shaded relief topographic map. Areas in red have been either mapped as flood lavas or as likely to contain modified flood lavas. Yellow shows other primarily volcanic units. All remaining materials are shown in light blue. The red areas cover 47% of the surface of Mars, which is marginally

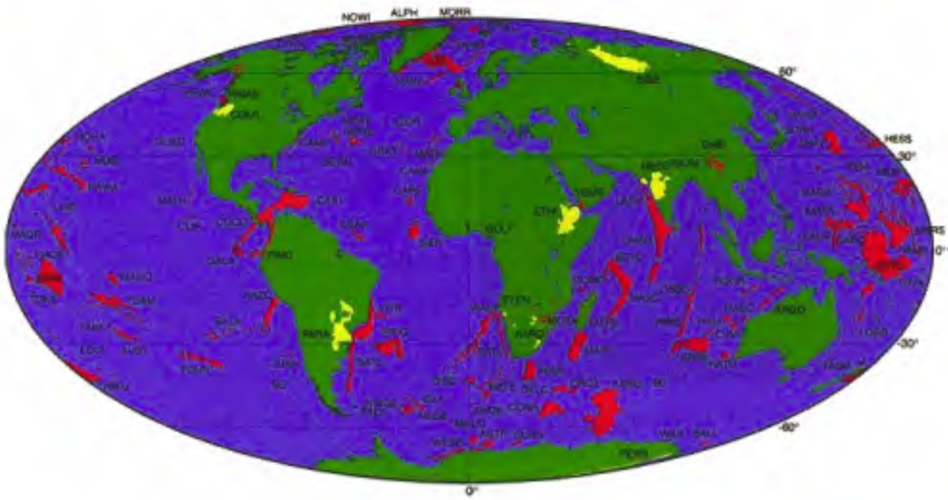

Figure 5.5. Map of Recent (≤250 Ma) Large Igneous Provinces (LIPs) on Earth. Well-preserved continental flood basalt provinces listed in Table 5.2 are depicted in yellow, other LIPs in red. While recent LIPs only cover a few percent of Earth's surface, it is important to note that this only represents a few percent of Earth's geologic history. Map after Coffin and Eldholm (1994). Abbreviated names listed in full in Coffin and Eldholm (1994).

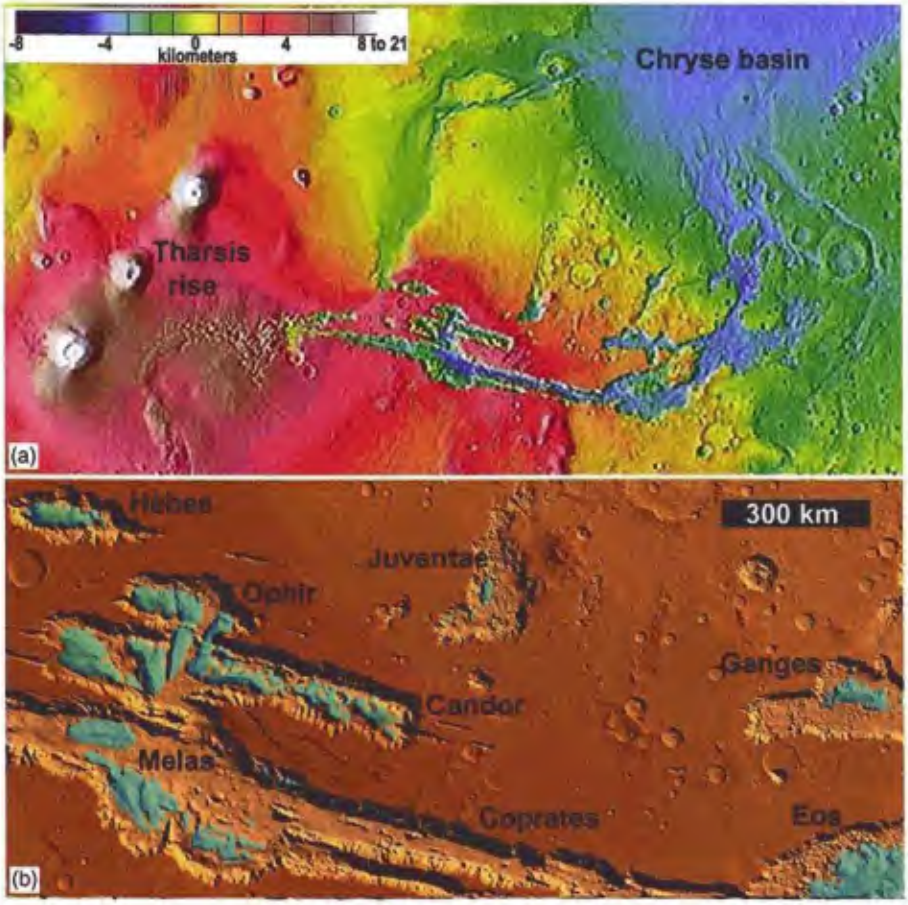

Figure 7.1. The 3000 km long canyon of Valles Marineris, Mars. (a) MOLA (Mars Observer Laser Altimeter) topographic view showing volcanoes of the Tharsis rise, on the west, Valles Marineris canyons (center) and large-scale catastrophic flood channels that drain into Chryse basin from Valles Marineris, on the east. (b) MOLA-derived three-dimensional enlarged view of central and east Valles Marineris showing interior layered deposits in blue. Note topographic lows in central Melas and Juventae Chasma, and high partial wall separating Candor Chasma from Melas Chasma.

Figure 9.4. Oblique view of a star dune in the Ibex Dunes, California. The star dune is ~30 m tall. The dark patches at the base of the dune consist of dark pebbles and granules derived from the nearby mountains, some of which have accumulated into large ripples of 2 to 8 m wavelength, over a sand substrate, possibly analogous to some ripple-like features on Mars (see Figure 9.8). JRZ, 2/03.

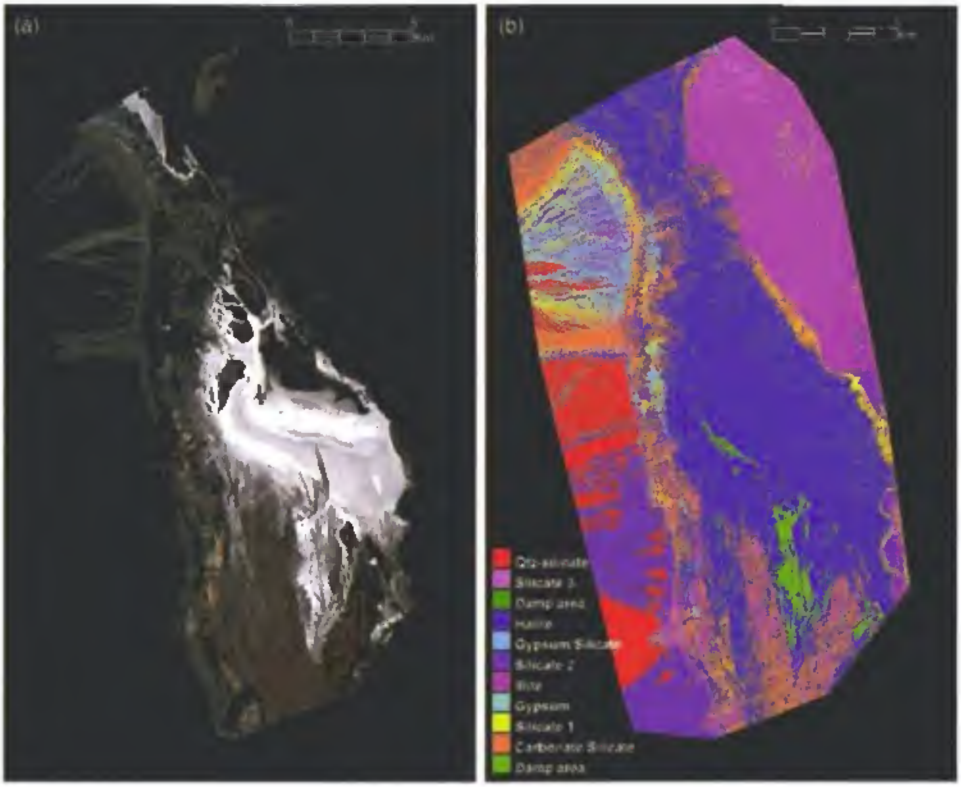

Figure 13.12. MASTER views of Badwater Basin, Death Valley, California. (a) Approximate true color image created using the MASTER 0.654, 0.542, and 0.460 μm reflectance bands. (b) Spectral classification map of MASTER thermal infrared bands.

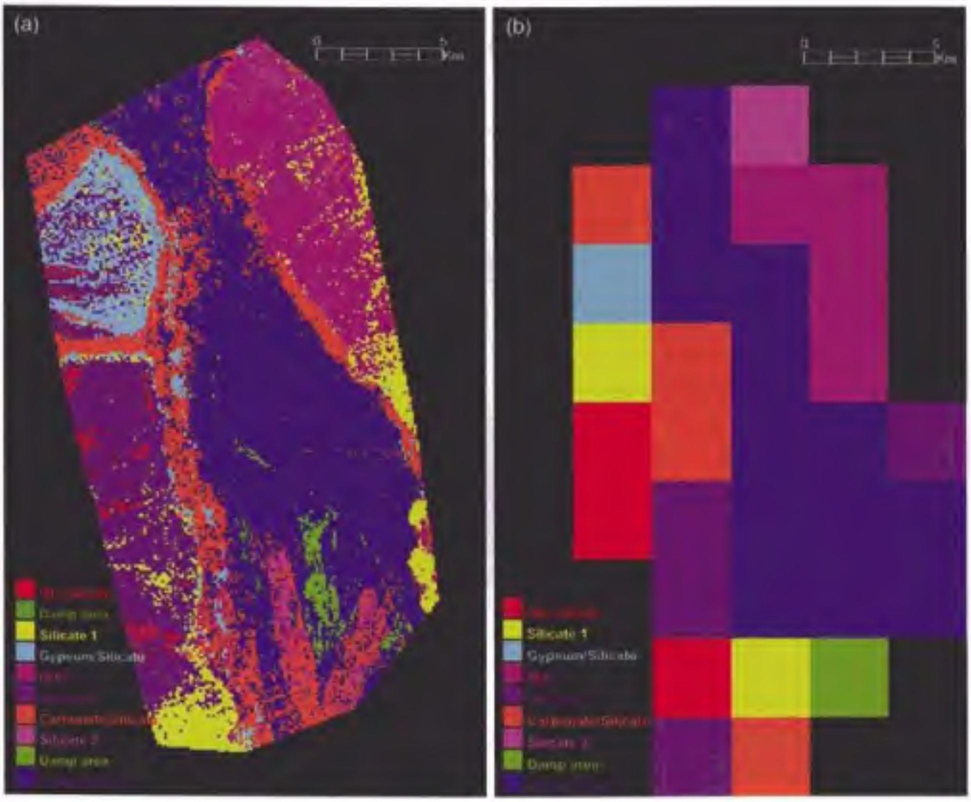

Figure 13.13. The effects of spatial resolution on spectral classification mapping of Badwater Basin. (a) MASTER thermal infrared emissivity data were degraded to the 100 m/pixel spatial resolution of the THEMIS instrument and then spectrally classified as in Figure 13.12b. (b) The same data were degraded to 3 km spatial resolution (approximately equal to TES resolution) and then spectrally classified. Spectral endmembers used to classify the TES-resolution data were taken from THEMIS-resolution data because there were insufficient pixels available at TES resolution to provide useful endmembers. Note that the typical spatial/spectral evaporite patterns on the western margin of the basin are clearly visible at THEMIS resolution, but are lost at TES resolution.

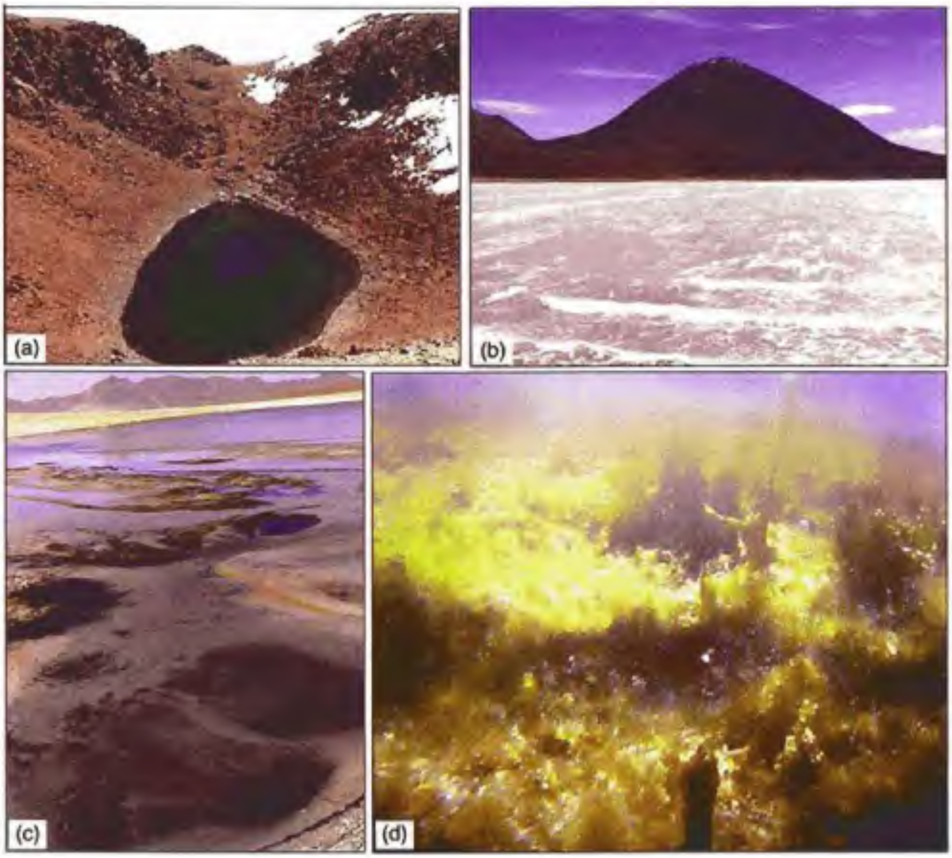

Figure 14.2. (a) Licancabur lake 100 m below the summit rim. Paleoshorelines are visible. The lake currently ~100 × 90 m and possibly up to 10 m deep, may have reached 65 m and ~200 m in diameter at its peak. (b) Laguna Verde with Licancabur in the background. (c) Hydrothermal springs in Laguna Blanca and algal mat. (d) Oxygen producing algae in the "Thermales" hot spring. Algae abound in the +36 °C water. Credit photographs: Brian H. Grigsby and Nathalie A. Cabrol.

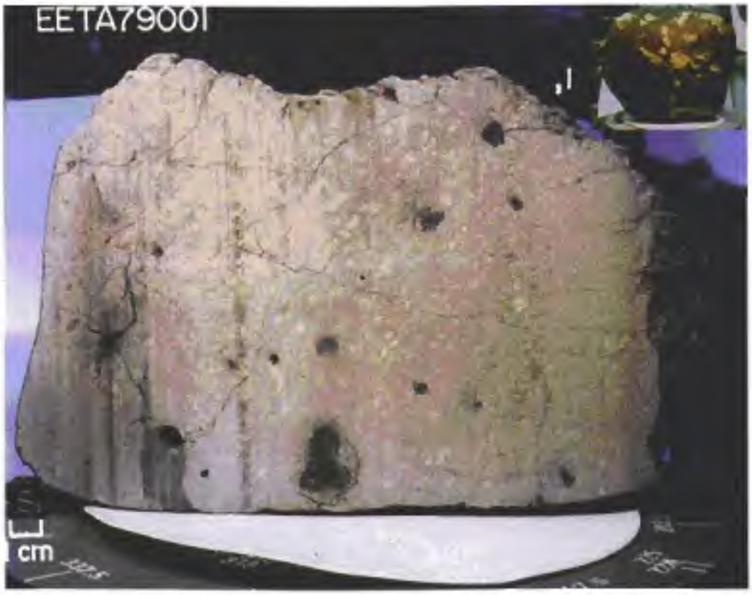

Figure 16.1. The Martian meteorite EETA 79001 was found in Elephant Moraine, Antarctica in 1979. This meteorite is a basaltic rock of the Shergottite class of Martian meteorites. The inset shows the original sample with its fusion crust, while the larger image shows a sawn face and the igneous texture. The dark areas on the cut face are impact melt pockets that contain trapped Martian atmosphere whose composition is the strongest evidence for a Martian origin for this meteorite.

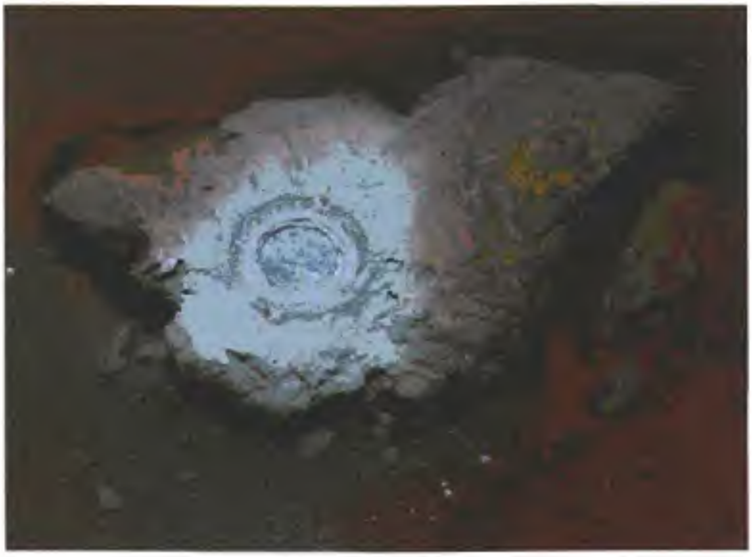

Figure 16.2. The Mars Exploration Rover Opportunity studied a rock dubbed 'Bounce' as shown in this false-color composite taken on sol 68. The 40 cm long rock was drilled to a depth of 7 mm by the rover's rock abrasion tool. The chemical composition of this sample measured by the Rover's Alpha Particle X-ray Spectrometer is nearly identical to the Martian meteorite EETA 79001 illustrated in Figure 16.1.

Acknowledgments

The results in this discussion were supported in part by National Aeronautics and Space Administration Grants NAG5 9785 and NAG5 12850 (LSC) from the Mars Data Analysis Program and Mars Fundamental Research Program, and NAG5-4164 and NAG5-10375 (JRZ) from the Planetary Geology and Geophysics Program.

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