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Eolian dunes and deposits in the western United States as analogs to wind-related features on Mars

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9.1 Introduction

Eolian processes produce distinctive features and deposits on planetary surfaces where the atmosphere is sufficiently dense to allow interactions between the wind and sediments on the surface (Greeley and Iversen, 1985). Arid and semi-arid regions on Earth contain abundant evidence of wind–surface interactions (e.g., Lancaster, 1995a; Thomas, 1997), and the Martian surface shows a diverse array of eolian features across the planet (e.g., Greeley *et al.*, 1992). The characteristics of several eolian localities (primarily sand dunes) in the western part of the United States have been used previously as analogs to features seen on Mars in data obtained from several spacecraft (e.g., Greeley *et al.*, 1978; Greeley and Iversen, 1987; Golombek *et al.*, 1995), yet the analog potential of other western eolian sites is relatively underutilized. Rather than attempting a comprehensive survey of all eolian features in the United States, this chapter will focus on several examples illustrative of a variety of dune forms and their potential applicability as analogs to eolian features observed on Mars. Dunes in the Great Plains, east of the Rocky Mountains, and all coastal dunes are excluded from this survey in order to concentrate on discrete sand accumulations in arid or semi-arid environments. Both traditional publications and selected internet sites (cited here as W#) are referenced throughout the text.

Eolian features in the western United States reflect varying climatic and drainage conditions that have directly contributed to the formation of the individual deposits. Cold conditions during the last glacial period gave way to warmer and more arid conditions during the ensuing interglacial

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(early Holocene) period (e.g., Spaulding, 1990; Hamblin and Christiansen, 1998), which in turn contributed directly to the development of numerous isolated sand deposits in North America (Smith, 1982; Tchakerian, 1997, W1). Both rivers and glacial pluvial lakes represent sources of sand-sized sediment that can be mobilized by the wind (see Kocurek and Lancaster, 1999); similar sand sources may exist on Mars (see Chapters 11, 12, and 13). Arid to semi-arid conditions in the western United States at present should not lead to an underestimation of the crucial role of water in the development of eolian deposits on Earth, and a similar caution is appropriate when analyzing eolian features on Mars. The current emphasis by NASA to "follow the water" in the design of the Mars Exploration Program and its associated spacecraft missions (W2) makes it particularly important to recognize the strong link between fluvial and lacustrine processes in generating the sand-sized sediments that subsequently are redistributed by the wind across the Martian surface.

Twenty-two sites throughout the western United States that possess significant eolian deposits were selected for discussion here, based on the abundance of eolian sediments, ease of access, and potential relevance for analog studies. Where applicable, nearby eolian deposits are mentioned along with the listed primary location. The sites are next discussed within the context of a simplified category basis, relating them to probable sediment sources and the conditions that may have contributed to their present location. The selected sites contain common types of sand deposits and associated dune forms, wind streaks, wind-eroded features, and large eolian ripples; this list is representative but by no means comprehensive. A review of the current view of eolian features on Mars emphasizes the new insights gained through the on-going Mars Global Surveyor (MGS) and Mars Odyssey spacecraft missions, including current working hypotheses derived from the new data. The similarities and differences between conditions on Earth and Mars as they relate to eolian features, along with prospects for study of eolian features from missions soon to be launched to Mars are presented in Section 9.5.

9.2 Selected eolian sediment locations

Twenty-two sites in the western United States (Figure 9.1) are briefly described below, chosen to illustrate the major types of dunes and associated eolian deposits. The selected sites are by no means the only eolian sediments present in the western United States, but they do represent the diversity of landforms developed by the interaction of the wind with sand-sized particles.

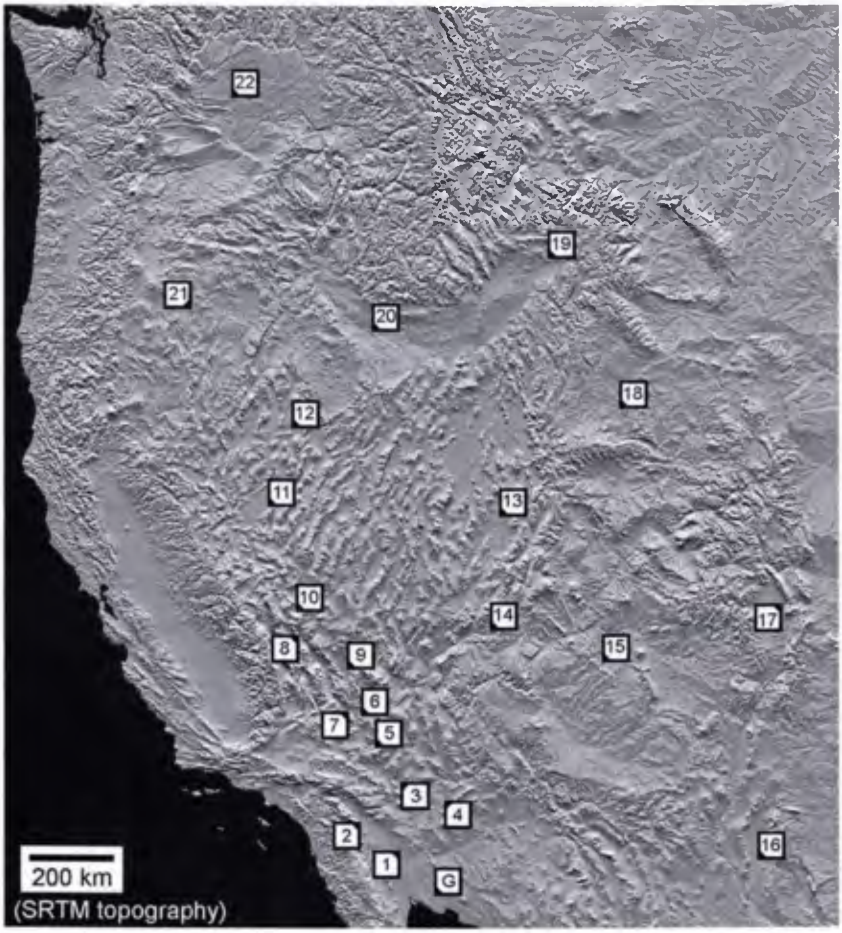

Figure 9.1. Map of eolian dune localities in the western United States discussed in this chapter. Numbers indicate the location of selected eolian sites discussed in the text, and listed in Table 12.1. G indicates the Gran Desierto in northern Mexico. Shaded relief base map uses data from the Shuttle Radar Topography Mission (SRTM) collected in February 2000, scaled to ~1 km/pixel horizontal resolution, obtained from one channel of an anaglyph product (W34). Area shown corresponds approximately to 32° to 48.5° N latitude, 103° to 125° W longitude, Mercator projection.

Smith (1982) provides an extensive treatment of sand dune locations throughout western North America (see also W1), and both McKee (1979) and Breed *et al.* (1979) present a global perspective of sand deposits derived from aircraft and spacecraft imaging. The reader interested in more detailed information about terrestrial sand deposits than what is provided below is encouraged to consult the references cited, as well as several excellent textbooks about eolian processes (e.g., Cooke and Warren, 1973; Greeley and Iversen, 1985; Pye and Tsoar, 1990; Lancaster, 1995a; Tchakerian, 1995; Thomas, 1997).

Use of off-highway vehicles (OHVs) at a site can be either a benefit (increased range of access) or a detriment (strong modification of original morphology), depending on the goals of the particular study. OHV accessibility is described below for many sites to aid the reader in identifying those sites where either the presence or absence of OHVs might prove critical to the potential investigation being envisioned. Locations within national or state parks can limit OHV access, but sometimes this does not include all of the deposits at a site. Websites maintained by the Bureau of Land Management (BLM) and other government-sponsored agencies usually include specific information about OHV use and restrictions.

The sites are arranged by the general physiographic providence in which they occur: the Mojave Desert, the Great Basin, the High Deserts, and locations in the Northwest. Each site description includes information on the general setting of the deposits, the principal dune type present, restrictions on use of the site, and an assessment with respect to four categories related to deposit emplacement conditions and sediment source (Table 9.1). Note that the existing literature is quite disparate among the sites discussed, with some having an extensive publication record while others have almost no citations. The following summaries are not intended to be exhaustive treatments of the eolian literature, but the references cited should point the reader to important publications from which a more detailed investigation can be carried out.

9.2.1 Mojave Desert

Algodones Dunes. The Algodones Dunes cover ~2600 km^2, making them one of the largest dune complexes in North America (Smith, 1978; W3). The Algodones Dunes primarily consist of barchanoid ridges (broad linear to sinuous sand accumulations) up to 90 m high with superposed barchan (crescentic, horns pointing downwind) undulations, both of which indicate that the main sand-driving winds here are to the southeast (Norris and Norris, 1961; McCoy *et al.*, 1967; Smith, 1978; Sharp, 1979; Kocurek and Nielson, 1986; Havholm and Kocurek, 1988; Sweet *et al.*, 1988). The dunes occur on the eastern margin of pluvial Lake Cahuilla, but detailed sedimentological studies indicate that the sand was derived from Colorado River sediments deposited in the basin that contained the lake rather than

Table 9.1. *Selected western United States eolian sites*

				Category of eolian feature			
		Name	Dune type	Topo-graphic	Pathway	Lake-related	River-related
Mojave Desert	1	Algodones	BR			X	
	2	Salton Sea	B			X	
	3	Bristol/Palen	–		X		
	4	Cactus Plain	TR				X
	5	Cady Mtns./Kelso	–	(x)	X		X
Great Basin	6	Dumont	TR				(x)
	7	Ibex	C	(x)			(x)
	8	Eureka	C	X		(x)	
	9	Big Dune	S			X	
	10	Clayton Valley	TR			X	
	11	Sand Mountain	TR	(x)	X	X	(x)
	12	Winnemucca	P		X	X	
	13	Little Sahara	TR			X	
	14	Coral Pink	BR	(x)			
High Deserts	15	Navajo	L	(x)			
	16	White Sands	BR			(x)	
	17	Great Sand Dunes	C	X			
	18	Killpecker	BR				
Northwest	19	St. Anthony	P		X		
	20	Bruneau	C	X			X
	21	Christmas Valley	P			(x)	
	22	Moses Lake	P				

B = barchan; BR = barchanoid ridge; C = complex; L = longitudinal; P = parabolic; S = star; TR = transverse ridge; X = significant aspect of site; (x) = secondary aspect of site.

from the surrounding mountains (Muhs *et al.*, 1995). North of California Highway 78, which crosses the dune complex, much of the dunes are a wilderness area with restricted access, but south of the highway and the very northern part of the dunes are designated as the Imperial Sand Dunes Recreational Area and are extensively used by OHVs.

Immediately south-southeast of the Algodones Dunes is the Gran Desierto (G in Figure 9.1), where ~5700 km^2 of northern Mexico is covered by sand as part of the Sonoran desert (Lancaster *et al.*, 1987; Lancaster and Blount, 1990; Lancaster, 1995a, b). The sand has accumulated into large (80 to >100 m relief) star dunes (three or more arms branching from a central deposit, formed under multiple wind regimes), crescentic dunes 5 to 20 m high that merge into complex crescentic mounds 10 to 80 m high (analogous to the hybrid forms present in the Algodones), as well as both linear and parabolic dunes and sand sheets along the margins (Lancaster, 1992, 1995b). Similar to the Algodones Dunes, sand in the Gran Desierto was transported to the region by the Colorado River where arid conditions allowed remobilization by the wind of the sand-sized sediments (Lancaster and Blount, 1990). OHVs are essential to access this broad sand deposit where only very limited logistical support is available in close proximity to the dunes.

Salton Sea Barchan Dunes. Barchans are crescent-shaped dunes whose horns point away from the primary wind direction (the opposite of the stabilized horns of parabolic dunes). Barchans form where the sand supply is less abundant than in other dune fields (McKee, 1979). The classic location in the United States for barchans is on the western side of the Salton Sea (Rempel, 1936; Norris, 1966; van de Kamp, 1973; Theilig *et al.*, 1978; Abbott, 1980). The barchans have been used to monitor dune migration over many decades (see Haff and Presti, 1995), confirming the inverse relationship noted between barchan slip face height and dune advance rate (Bagnold, 1941; Long and Sharp, 1964). The sand source is thought to be Lake Cahuilla sediments, similar to the nearby Algodones Dunes (site #1). Also nearby are longitudinal dunes that cover the southern portion of the Superstition Mountains, spawning barchans that migrate east toward the Salton Sea (Smith, 1982). The Salton Sea barchans are readily accessible from nearby highways but OHV use is restricted.

Bristol Trough/Palen. Sand accumulations in the southeastern Mojave Desert have morphologic indicators of eolian transport of sand across low drainage divides, resulting in two roughly parallel transport pathways through the Bristol Trough and through the Palen playa (Figure 9.2; Zimbelman *et al.*, 1995; W4). Sand deposits along these paths consist of a combination of sand sheets, sand ramps (see Lancaster and Tchakerian, 1996), and stabilized transverse ridges. Sediment studies show the sands are immature and geochemically distinct from the mature Colorado River sands (Zimbelman and Williams, 2002), with indications of varied local sediment sources (Pease and Tchakerian, 2003). OHV use is restricted throughout this portion of the eastern Mojave Desert, and local inquiries are required.

Cactus/LaPosa Plains. Stabilized transverse sand dunes of 1 to 3 m height and 100 to 200 m wavelength (Figure 9.3) cover the Cactus and LaPosa Plains east of the Colorado River (W5). The sand in the dunes has strong chemical affinities to sand from the Colorado River, unlike the Mojave sands west of the river (Muhs, 2002; Zimbelman and Williams, 2002).

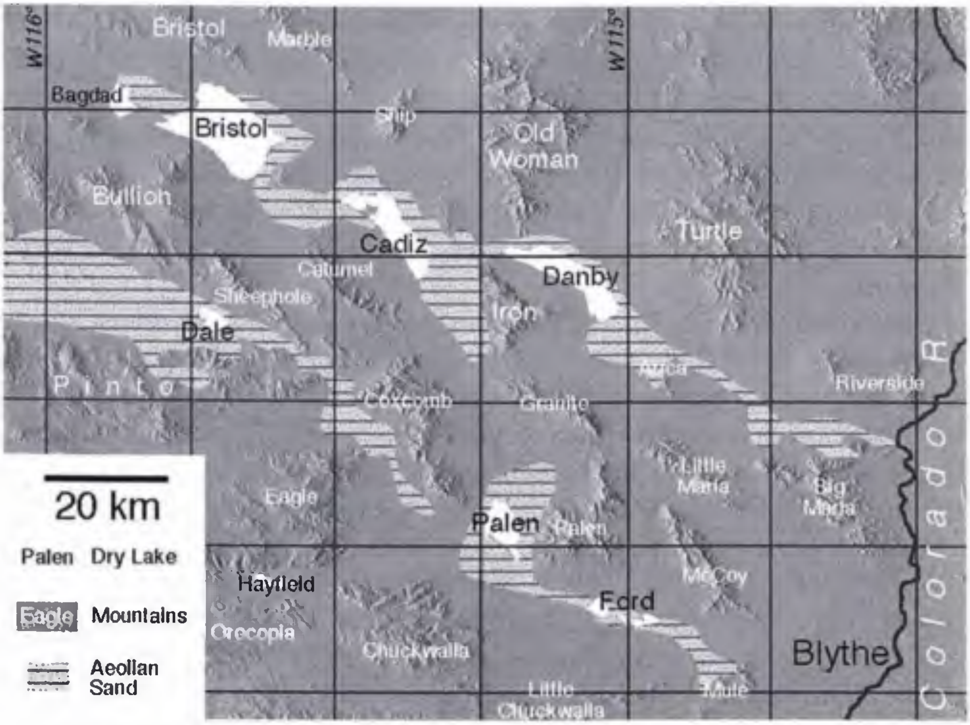

Figure 9.2. The Bristol trough and Palen transport paths. Lined pattern shows sand deposits that the wind has blown across several low topographic divides (modified from figure 9.1 of Zimbelman and Williams, 2002).

OHVs are permitted at some locations around the dunes; enquire locally for permission.

Cady Mountains/Kelso Dunes. Sand from the Mojave River has blown across portions of the Cady Mountains and forms thick ramps against the mountains on their western (windward) side (Lancaster and Tchakerian, 1996). Mojave River sand also exits out of Silver Lake playa through the Devil's Playground and into the 170 m tall transverse ridges of the Kelso Dunes (Sharp, 1966, 1978; Smith, 1982, 1984; Lancaster, 1993; W6; W7). Heavy mineral concentrations within the Kelso sands (MacDonald, 1970; Earl, 1981) led to commercial mining of the dunes for a short time. A variety of sand sheet deposits and stabilized transverse dunes populate these pathways, similar to the Bristol and Palen pathways (#3) discussed above. Thermal infrared remote sensing has proved to be a valuable tool for mapping and documenting the sand sources and transport pathways leading to the Kelso Dunes (Ramsey *et al.*, 1999). Restriction of both cattle grazing and OHV use has led to extensive stabilization of the dunes.

Figure 9.3. Oblique aerial photograph of stabilized transverse dunes on Cactus Plain near Parker, Arizona. The dunes are 2 to 3 m high with 100 to 200 m spacing. JRZ, 2/99.

The Devil's Playground and the Kelso Dunes are within the recently established Mojave National Preserve, restricting all OHV and cattle grazing activity in these areas, resulting in significant vegetation growth and dune stability over the last decade.

9.2.2 *Great Basin*

Dumont Dunes. A core of star and complex dunes up to 120 m tall occurs along a broad transverse ridge of sand, surrounded by smaller transverse and barchan dunes (Smith, 1982). Nielson and Kocurek (1987) provide an excellent overview of these dunes, including evidence supporting the possible origin of the dunes being concentrated at this location. This area is a major OHV site for southern California (W8), so very little detailed surface morphology remains undisturbed. Dune migration studies have been carried out, however, with recent aerial photography (W9).

Ibex Dunes. A small field of star dunes is located in the southeastern corner of Death Valley National Park (Figure 9.4). The highest of the dunes is ~50 m tall and the field extends ~3 km along the southwestern slope of the Saddle Peak Hills (Smith, 1982). Located within a Wilderness section of the park, no vehicular traffic is allowed within ~1.5 km of the dunes, making them among the most pristine but still accessible sand dunes in the United States.

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. (For a color vision of this figure, please refer to color plate section.)

Eureka Dunes. This complex dune mass includes small star dunes around a broad ridge of sand, the highest portion of which has 208 m of relief, making this the tallest dune complex in California (Smith, 1982). A plant found only on these dunes (Pavlik, 1980) makes the Eureka Dunes one of the most protected areas within Death Valley National Park, so that not only are OHVs restricted, but even walking on the dunes is only allowed along a designated trail (W10). Although not part of the Eureka Dunes, in nearby Panamint Valley are two star dune complexes, 50 to 60 m tall, surrounded by low transverse ridges, and the Stovepipe Wells star dunes rise to ~40 m above the floor of the center of Death Valley (Smith, 1982).

Big Dune. Big Dune is located in the Amargosa Desert of southwestern Nevada, and is a popular OHV site. Star dunes, with relief up to 80 m, are surrounded transverse ridges over an area of ~13 km^2, derived from nearby playa deposits (Swadley and Carr, 1987). The dune complex is misnamed in that total relief considerably less than the relief at Sand Mountain (#11), Eureka (#8), and Kelso (#5), but it is a locality where sand avalanches have been observed to emit audible acoustic energy (Trexler and Melhorn, 1986).

Clayton Valley. Also known as the Silver Peak dunes, sand is collected into a series of transverse dunes in the southern part of Clayton Valley, about 7 miles south of the Nevada town of Silver Peak (Trexler and Melhorn, 1986). These dunes were the site of a recent field study of sand grain deposition in the lee of transverse dunes (Nickling *et al*., 2002). The dune sand is of local origin, derived from deflation of playa and alluvial fan deposits that cover ~310 km^2 of Clayton Valley, comparable to the origin of the nearby Crescent Dunes, located northwest of Tonopah, Nevada (Trexler and Melhorn, 1986).

Sand Mountain. The largest dune in Nevada, with ~120 m of relief, is Sand Mountain (W11), consisting of a complex pattern of transverse ridges superposed on a terminal seif dune (Trexler and Melhorn, 1986), surrounded by transverse dunes that extend into the nearby hills (Figure 9.7). The sand at Sand Mountain has the distinctive properties that allow sand avalanches to produce audible sounds, and it has been the site of several investigations of this phenomenon (Criswell *et al*., 1975; Lindsay *et al*., 1976; Maloney, 1982; Trexler and Melhorn, 1986). Sand Mountain sediments are ultimately derived from materials deposited within nearby glacial Lake Lahontan (see Morrison, 1964, 1991; Benson *et al*., 1990), similar to the origin of several other Nevada

Figure 9.5. Great Sand Dunes National Monument, Colorado. The dune mass, more than 200 m tall, is trapped against the western margin of the lofty Sangre De Christo Mountains. JRZ,9/02.

dune sites like Big Dune (#9) and Clayton Valley (#10). Sand Mountain is a major OHV destination, so it is often difficult to find pristine sand surfaces, and increasingly difficult to find undisturbed slip faces for generating audible sounds.

Winnemucca. Dunes cover an area of ~900 km^2 north of Winnemucca, Nevada, as first described by Russell (1885). Stabilized parabolic dunes are the most common landform, but isolated barchans and transverse ridges occur scattered throughout the dune field. The dune morphologies and locations indicate sand transport has occurred to the east (Smith, 1975), crossing two mountain ranges that separate Paradise Valley, Silver State Valley, and Desert Valley; this leads to the dune field also being known as the Silver State Dune Complex (Eissmann, 1990; Epps *et al.*, 2000). The sand source ultimately was Lake Lahontan sediments (Morrison, 1964, 1991; Benson *et al.*, 1990; Epps *et al.*, 2000), as at Sand Mountain (#11). OHVs are allowed on portions of the dune field; enquire locally for permission.

Little Sahara Dunes. The largest field of active dunes in Utah is now a major OHV site (W12). Transverse ridges 100 to 200 m high are surmounted by active transverse dunes 5 to 15 m tall, all surrounded by stabilized parabolic dunes (Smith, 1982). Most of the sand comes from deposits left by the Sevier River, which used to flow into glacial Lake Bonneville (W13). A link was established between the beetle *Eusattus muricatus* found on the Little Sahara dunes and those found on dunes in Silver State Valley (Winnemucca, #12), many hundreds of kilometers to the west (Epps *et al.*, 2000) (see 12 and 13 in Figure 9.1).

Coral Pink Sand Dunes. Sand grains eroded from nearby Navajo sandstone outcrops provide the distinctive color of the barchanoid ridge dunes within the ~15 km^2 of this Utah state park (Ford and Gilman, 2000; W14; W15). Much of the dune field is still active, although some portions of the field have become fully stabilized by vegetation. OHVs are allowed on only selected portions of the dunes.

9.2.3 High Desert

Navajo Dunes. Longitudinal dunes (aligned parallel to the major wind direction) 2 to 9 m high and ~5 km long dominate a large portion of northern Arizona, along with isolated barchans, transverse dunes, and climbing and falling dunes (banked against bedrock obstacles) (Hack, 1941; Smith, 1982; Breed *et al.*, 1984; Billingsley, 1987; Stokes and Breed, 1993). The dune field includes the largest collection of longitudinal dunes in the western

United States, but any research effort in the area must be coordinated through the Navajo nation.

White Sands. Barchanoid ridges of very white sand make up a compositionally unique dune field in New Mexico. The whiteness of the sand results from being composed of gypsum (deflated from nearby Lake Lucero, but initially leached from rocks in the surrounding mountains), which accumulates through eolian processes into barchan-like dune forms (Murbarger, 1950; McKee, 1966; McKee and Douglass, 1971; McKee and Moiola, 1975; W16). Interaction of the gypsum sand grains with water results in some very unique modifications of the dune sedimentary structures (Simpson and Loope, 1985; Schenk and Fryberger, 1988). White Sands is now protected as a National Monument (W17), but the dunes are easily accessible by regular automobiles.

Great Sand Dunes. National Monument status also protects this large mass of sand trapped against the western margin of the Sangre De Christo Mountains of central Colorado (Figure 9.5; Wegemann, 1939; Johnson, 1967, 1968; Burford and Hutchinson, 1968; Freyberger *et al.*, 1979; Andrews, 1981; W18). The dunes are the tallest of the selected sites discussed here (215 m of relief), as well as at the highest elevation in the United States

Figure 9.6. Oblique aerial photograph of stabilized parabolic dunes near Moses Lake, Washington. The prevailing wind is from the lower left; parabolic dunes have horns stabilized by vegetation (a condition highly unlikely on Mars!) that point into the driving wind direction. Individual dunes are ~5 m tall and ~30 to 60 m wide. The dune sand has a large basaltic component. JRZ, 9/98.

(2400 m; USGS, 1982). Temporal changes in Landsat images of the dunes document movement of sand but reveal no systematic migration trends (Janke, 2002). However, satellite observations do document extensive dust plumes originating from Great Sand Dunes (figure 9.3 of Edgett, 2002).

Killpecker Dunes. The largest and most active dune field in Wyoming covers ~274 km^2 and extends over a length of ~100 km (Smith, 1982; W19). The dunes consist of barchanoid ridges, with some transverse ridges up to 45 m tall and parabolic dunes up to 15 m tall (Ahlbrandt, 1973, 1974a, b, 1975). The sand was derived from the Eocene Green River Formation instead of local glacio-fluvial deposits (Ahlbrandt, 1973, 1974a) and its mineralogical maturity is quite low, only slightly more mature than the sands in the Bristol pathway (#3) (Muhs, 2002). OHVs are allowed on the dunes not within designated Wilderness areas.

9.2.4 Northwest

St. Anthony Dunes. Both climbing and falling parabolic dunes cover much of the Juniper Buttes near the town of St. Anthony in eastern Idaho (Greeley, 1977; W20). The sand is most likely derived from local sediments washed into nearby Mud Lake and subsequently blown northeastward to form the dunes (Dort, 1959). A modern migration rate of 3 m per year has been documented for these dunes (Chadwick and Dalke, 1965). OHVs are allowed on the dunes.

Bruneau Dunes. The Bruneau Dunes have collected in an abandoned cut-off meander of the Snake River, carved into the basalts of the Snake River Plains, and they include the tallest single-structured sand dune (> 140 m relief) in North America (Murphy, 1973, 1975; W21). Basaltic (iron-rich) particles comprise 12% (by volume) of the sand grains in the Bruneau Dunes, likely derived from the surrounding basalts (Murphy, 1973). The Bruneau Dunes were proposed as analogs to features on Mars shortly after Mariner 9 first provided confirmation of sand dunes on Mars (Murphy and Greeley, 1972). OHVs are not allowed on the dunes, located within a state park preserve.

Christmas Valley. Southern central Oregon was the site of several lakes during the last glaciation; the demise of Lake Chewaucan led to sand accumulations at Christmas Valley (W22), while other isolated lakes led to sand-sized sediments in (now dry) Alkali Lake and Alvord Valley (Orr and Orr, 2000, p.88). The dunes are primarily parabolic, possessing long horns stabilized by vegetation that connect to an active crescentic main body,

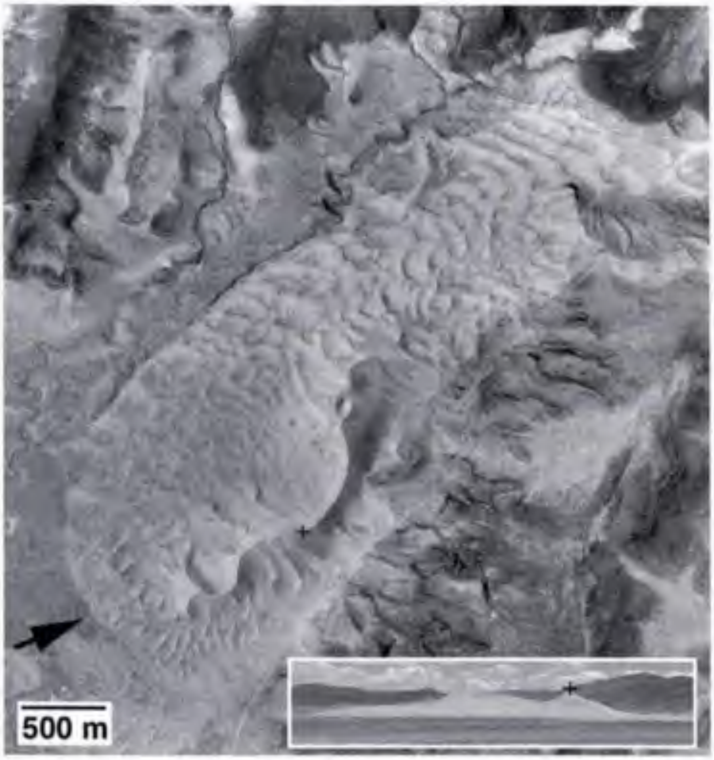

Figure 9.7. Sand Mountain, Nevada. A sinuous transverse ridge contains the highest portions of the dune complex, with transverse ridge dunes extending into the surrounding mountains. Inset shows a horizontal view, looking in the direction of the black arrow; "+" marks the same high point in both views. Portion of digital orthophoto mosaic of the Four Mile quadrangle. Inset, JRZ, 4/03.

and the sand is essentially basaltic in composition (Edgett, 1994). OHVs are permitted on these dunes.

Moses Lake Dunes. A broad field of stabilized parabolic dunes (Figure 9.6) is found southwest of the Moses Lake (Washington) city limits (W23), portions of which are flooded by water from the Potholes Reservoir. The dune sand consists of significant amounts of basalt and granodiorite fragments, as well as clay weathering products; all of these components can be detected remotely using hyperspectral mapping techniques similar to those provided by recent spacecraft instruments (Bandfield *et al.*, 2002). Basalt and granodiorite outcrops within the Channeled Scablands, caused by massive floods from glacial Lake Missoula (e.g., Baker, 1973; Alt, 2001), are the likely source of the sand and not nearby Columbia River (Bandfield *et al.*, 2002). The Juniper Dunes Wilderness is a similar nearby collection of stabilized parabolic dunes, south of Moses Lake, but the Juniper Dunes lack the potential fluvial–eolian interactions of the Moses Lake dunes. OHVs are permitted on most of the Moses Lake dune field, although some dunes are on private land requiring local approval for access.

9.3 A process-based view of the deposits

Regional sand transport by the wind can be semi-independent of topography, unlike water transport which must at all times go downhill. In most places on Earth, the geomorphic effects of running water mask those of wind; however, in some desert regions, the interaction between eolian transport and topography can be clearly seen. Sand can be transported between basins over considerable distances, surmounting substantial topographic barriers without significant obstruction of sand movement (Zimbelman *et al.*, 1995). Pathways of active eolian sands result, and may extend many for many tens of kilometers. Sand will form ramps at topographic barriers along such a sand pathway (see Lancaster and Tchakerian, 1996); Table 9.1 includes two sites (#3 and #5) in such transport pathways.

Layering and/or soil horizons in those ramps provide dates and other clues to the changing climate prevailing while the ramps were created. For example, interbasin transport of sand from the Dale Dry Lake area of Pinto Valley eastward via Clarks Pass to Palen Dry Lake (site #3) has built a ramp incised by drainage from the mountains at the margin of the valley. Layers and soil horizons within the ramp can be correlated to Holocene variations in the level of Dale Lake (Tchakerian, 1991; Lancaster and Tchakerian, 1996). A similar sand ramp has been built by the wind at Soldier Pass along the Mojave River, part of the Devil's Playground regional sand transport path that feeds sediments into the Kelso Dunes (#5). Quarrying activities have revealed layering similar to that at Clarks Pass (Rendell and Sheffer, 1996). The nearby Bristol Trough (#3) contains a sand pathway connecting Bristol, Cadiz, Danby, and Rice Valleys (Figure 9.2; Zimbelman *et al.*, 1995).

Once sand ramps are fully developed, sand motion over the topographic barrier proceeds apace, at least in theory. The Bristol Trough and Palen sand paths (#3) in California are examples where geomorphic evidence clearly indicates that some interbasin transport of sand has occurred (Zimbelman *et al.*, 1995). Chemical studies of samples from along transport paths confirm the geomorphic observations (Zimbelman and Williams, 2002); however, detailed analysis also shows that local contribution of sediments can be important (Pease and Tchakerian, 2003).

The other end-member case is when sand transport between basins does not occur, probably due to some combination of weak or multi-directional winds, vigorous destruction of sand ramps by running water, and steep boundaries between basins. Wind may trap sand near such a topographic barrier, producing a trapped dune mass. Overland flow of water down the steep gradient of the topographic obstruction may assist the trapping process. Examples include Great Sand Dunes in Colorado (#17) and the Eureka Dunes in California (#8). In the case of the former, prevailing winds transport sediments from the Rio Grande drainage across the San Luis Valley to the front of the Sangre de Christo Mountains. The wind is funneled up steep Medano and Mosca Passes, but the gradient is too steep and stream action from those passes is too vigorous for sand ramps to form. Similarly for the latter, prevailing northwesterly winds trap eolian sediments in a pocket in the Last Chance Range, but a ramp has not formed, presumably because of a combination of wind regime and stream action.

The intermediate case is a topographic barrier that is sufficiently large to cause a significant obstruction to sand flow and the formation of a large dune mass, but not so large that all interbasin flow is prevented. An example is Sand Mountain (#11) east of Fallon, Nevada, where sand from pluvial Lake Lahontan has blown against the mountains east of Fallon. The sand transport path surmounts the Blow Sand Mountains to the southwest, and the Sand Mountain dune complex extends over the topographic trap, but much of the sand in motion resides at Sand Mountain.

Both interbasin sand transport and the formation of dune masses trapped by topography require an ultimate source of the sand supply. On Earth, that source is typically one or more of the following: a paleo-lake, a paleo-river, erosion of local sandstone outcrops, paleo-flood deposits, and volcanic deposits. Each terrestrial source type is potentially analogous to sand deposits on Mars.

Tectonic activity has produced many enclosed drainage basins throughout much of the western United States. During the last glacial epoch, many pluvial lakes formed in those basins. Some were small and occupied but a single basin; others filled many interconnected basins with very large bodies of water (e.g., lakes Bonneville and Lahontan). Rivers and streams feeding these lakes supplied large quantities of sand, and when the lakes dried up with the changing of the climate, that sand was then available for mobilization by the wind. The sand supply is not renewed unless the lake returns, and the subsequent transport of lacustrine sands diminishes with time as a consequence. The Algodones Dunes (#1) are composed of sand collected in Lake Cahuilla, a precursor to the modern Salton Sea. The barchan dunes on the west side of the Salton Sea (#2) similarly were derived from paleo-shoreline sediments, and the dunes at Sand Mountain (#11) and north of Winnemucca (#12) are formed from sands from pluvial Lake Lahontan.

Some lake-related dunefields were associated with temporary accumulations of runoff rather than a pluvial lake that might have persisted for many centuries. In many cases, wind deflates part of the playa surface to form lunette dunes, unusually high in silt content (parna) (44 to 61 wt.% clay fraction for dunes in Grass Valley, Nevada; Greeley and Williams, 1994). Not enough sand was delivered to the parent playa to generate a large dune or dunefield. The dunes of Alkali Lake, Christmas Valley (#21), Big Dune (#9), St. Anthony (#19), and Moses Lake (#22) may include examples of this type.

Rivers and streams can, in some cases, provide sufficient sands to build dunes, without a significant lake having been present. Examples include the sand of the Devil's Playground/Kelso Dunes and Cady Mountains pathways (#5), related to the Mojave River, and the Dumont (#6) and Ibex (#7) Dunes (California) are related to the Amargosa River. The sands of the Great Sand Dunes National Monument (#17) come from the Rio Grande and its tributaries, and the transverse dunes of the Cactus and La Posa Plains (#4) in western Arizona are built of sands derived from the Colorado River (Zimbelman and Williams, 2002). The large-scale floods that formed the Channeled Scablands of Washington State produced large sand deposits that are the source of some of the dunes in the Pacific Northwest (e.g., #22). In some cases, the massive floods eroded volcanic materials into the size range amenable to subsequent eolian transport into dunes and pathways.

In a few cases, the primary source of the sand is local erosion of sandstone outcrops or older alluvium; overland water flow plays only a minor role in the sand source. The beautifully colored sands of the Coral Pink Sand Dunes (#14) in southern Utah are derived from local erosion of the Navajo Sandstone deposits that ring the valley in which the dunes reside. The sands of the Killpecker Dunes (#18) in Wyoming are derived from the erosion of the Laney Member of the Eocene-age Green River Formation, which underlies the dune area (Smith, 1982). The dunes of the Cactus and La Posa Plains of Arizona (#4), the Algodones Dunes (#1) of California, and the Gran Desierto (G in Fig. 12.1) are composed of sand transported by the Colorado River; however, those sands may have resided in local alluvial deposits in between the time they were transported by the river and freed to form the present-day dunes.

9.4 A post-MGS perspective of eolian deposits on Mars

Eolian features were first clearly documented on Mars in images taken by the Mariner 9 spacecraft, and the Viking orbiters revealed details of the global distribution of sand and dust around the planet (see reviews in Greeley and Iversen, 1985; Greeley *et al.*, 1992). The instruments on the MGS spacecraft (see MGS at W2) are providing data that continue to produce revisions to many of the Viking-based concepts for Mars (see Chapter 1). In particular, the 2 to 6 m/pixel images from the Mars Orbiter Camera (MOC; W24) on MGS provide views of eolian features that are comparable to aerial photographs of Earth (Malin *et al.*, 1998; Edgett and Malin, 2000; Malin and Edgett, 2001; Edgett, 2002). The MOC images have not revealed "new"

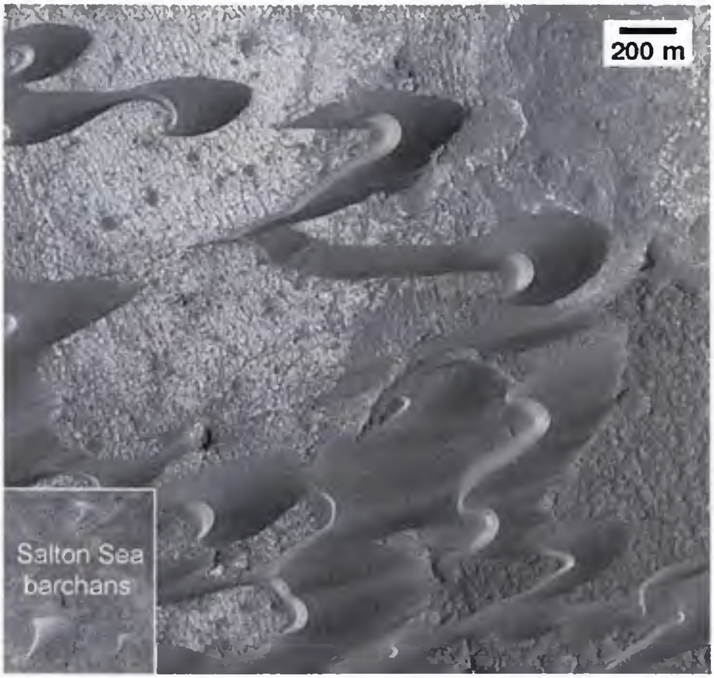

Figure 9.8. Large barchans and barchanoid ridges on the floor of the caldera of Nili Patera, Mars. Prevailing wind was from the upper right; barchans have horns that point away from the prevailing wind direction. Slip faces on the downwind side of individual dunes indicates the dunes are ~70 m tall. TES data indicate the dark sands are basaltic in composition. Portion of MOC image E03-02016, centered at 8.8° N, 292.9° W, 3.22 m/pixel, NASA/JPL/MSSS (W25). Inset (lower left) shows three of the Salton Sea barchans (2) at the same scale as the Mars barchans, rotated here 180° to match the orientation of the Martian features; scaled subset of a US Geological Survey Digital Orthophoto Mosaic.

eolian features as much as they have clarified the perception of specific details for Martian sand dunes and dust deposits, including instances of eolian deposition and erosion that are comparable in scale to features on Earth, a change from the Viking view (Edgett and Malin, 2000). Comparison of MOC and the best Viking and Mariner 9 images have yet to reveal any observable movement of dune-forms on Mars (Zimbelman, 2000; Malin and Edgett, 2001). Classification of Martian dunes is now becoming feasible, although barchans (Figure 9.8; W25) and transverse dunes are still by far the most abundant Martian dune forms (Malin and Edgett, 2001). Martian dune assemblages include an enormous erg (sand sea) surrounding the north polar cap, covering ~680 000 km^2 between 75° and 80° N (Tsoar *et al.*, 1979). Numerous sand deposits are trapped within large impact craters in the southern hemisphere, the largest deposits in the craters Kaiser, Proctor, and Rabe between 42° to 48° S and 320° to 345° W (Greeley *et al.*, 1992), potentially analogous to topographically trapped sand on Earth (Table 9.1).

MOC images are providing tests of hypotheses for the growth and development of dune fields trapped within craters like Proctor (e.g., Fenton *et al.*, 2002; Williams *et al.*, 2003).

While the thin Martian atmosphere can clearly set sand in motion when winds are sufficiently strong, once the sand falls within a topographic depression with steep walls (like a crater or valley), it is effectively trapped. Some material is blown away from the trapped sediments (Edgett, 2002), but MOC images have yet to reveal sufficient sand to form sand ramps or climbing dunes, as occur along terrestrial transport pathways. MOC images have revealed abundant eolian transverse ridges over much of the Martian surface, with wavelengths of tens to one hundred meters (Figure 9.9; W26; W27); these features could either be small dunes or large ripples, which form by different transport mechanisms (Malin *et al.*, 1998; Malin and Edgett, 2001; Zimbelman and Wilson, 2002). Large eolian ripples on Earth have wavelengths of several to tens of meters and heights of 0.3 to 2 m and always involve a bimodal particle distribution of sand and granules to pebbles (Williams *et al.*, 2002); efforts are underway to test whether the smallest Martian transverse ridges are more likely ripples or dunes (Wilson *et al.*, 2003).

MGS includes non-imaging instruments that also have greatly altered the Viking view of Mars, most notably its topography and the composition of its surface materials. The Mars Orbiter Laser Altimeter (MOLA; W28) has measured topography to a vertical precision of better than 1 m over spatial scales of hundreds of meters, providing the first quantitative assessment of regional and local slopes across the entire planet (Smith *et al.*, 1999).

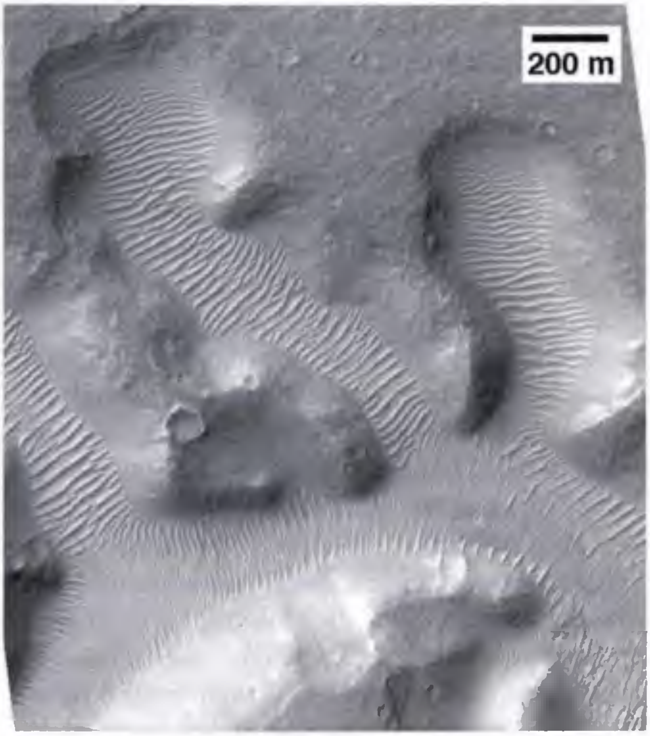

Figure 9.9. Transverse ripple-like features confined to the floor of Nirgal Vallis, Mars. Features have wavelengths of 30 to 100 m, and could be formed by either dune or ripple processes. Portion of MOC image E02-02651, centered at 27.8° S, 43.3° W, 2.8 m/pixel, NASA/JPL/MSSS (W26).

Unfortunately, MOLA does not resolve individual dunes, except for some exceptional transverse ridges in the northern erg, and thus will not provide morphometric information on Martian dune masses. In spite of this, MOLA has established precise control for the slopes across which sand is transported by the wind. The Thermal Emission Spectrometer (TES; W29) on MGS has provided compositional constraints for Martian surface materials over areas as small as 3 by 3 km (Christensen *et al.*, 1998, 2001). TES spectra have revealed two distinct volcanic compositions abundant on the Martian surface: a typical basaltic composition and a slightly more chemically evolved basaltic andesite composition (Bandfield *et al.*, 2000) that is comparable to several rocks at the Mars Pathfinder landing site (Golombek *et al.*, 1999). The TES basalt component has a high concentration in Syrtis Major (Bandfield *et al.*, 2000; Ruff and Christensen, 2002), a classic low-albedo feature that includes large barchan dunes (Figure 9.8). The presence of basaltic dunes on Mars increases the importance of studies of basaltic sand dunes on Earth, like those at Moses Lake (#22) (e.g., Bandfield *et al.*, 2002). TIMS data (Ramsey *et al.*, 1999) have been used to document the transport of specific compositions of sand at the Kelso Dunes (#5), but it is not yet clear how severely the dust on Mars will interfere with a similar analysis of Martian sediments. TES has thus far failed to detect much quartz, the most common sand component on Earth, even in regions that contain abundant dunes (Christensen *et al.*, 2001). Edgett and Lancaster (1993) discuss the role of composition for many sand deposits, particularly those derived from volcanic products.

MGS data have also intensified the investigation of hypothesized oceans and isolated lakes on Mars, first proposed based on analysis of Viking images (e.g., Parker *et al.*, 1989; Baker *et al.*, 1991; Forsythe and Zimbelman, 1995; Edgett and Parker, 1997). The ocean hypothesis continues to be controversial, with MOLA data providing topographic evidence in support of at least one northern ocean level (Head *et al.*, 1998) but with inconclusive MOC evidence of diagnostic shoreline morphologies (Malin and Edgett, 2001). Detailed topography using Differential Global Positioning System surveys of shorelines from glacial Lake Lahontan (Nevada), when scaled for gravity and the shallow slopes of the northern lowlands of Mars, compare very well with MOLA topography across one hypothesized shoreline on Mars (Zimbelman *et al.*, 2004); additional field data are being collected to test this correlation further. MOLA data revealed the presence of large lakes ponded within the southern highlands, one of which helps to explain the origin of Ma'adim Vallis at a kilometer-wide channel that empties into Gusev crater (Irwin *et al.*, 2002). Water has played a crucial role throughout Martian history (e.g., Carr, 1996), but the lack of a recently active hydrosphere on Mars is a substantial difference from the environment of all sand deposits on Earth, and this situation must be considered during analog eolian field investigations.

9.5 Discussion

The ubiquitous nature of eolian features on Mars has been revealed by spacecraft missions with progressively more capable remote sensors: Mariner 9, Viking, Mars Global Surveyor, and Mars Odyssey. Mars is obviously enough like Earth to support a similarity in eolian processes and products; however, the Martian eolian environment is sufficiently different to account for significant differences between the two planets.

Mars is like the Earth when it comes to eolian transport in general, sediment sources, bedform formation, and interbasin sediment transport.

The basic process of eolian transport, especially by saltation, is the same on both planets, as are the features produced by saltating sand. Fluvial processes on both planets create and transport sediment later subject to wind action. Viking and MOC data show abundant examples of eolian materials trapped by Martian topography. Many craters contain fields of barchans/barchanoid ridges that cover significant portions of their floors (e.g., Rabe and Proctor craters). Valleys such as Nirgal Vallis (Figure 9.9) also trap considerable quantities of eolian sediments.

But Mars is not like the Earth in other ways. The thin atmosphere of Mars, its surface geologic history, and lack of an active, terrestrial-style, hydrologic cycle affects the source and evolution of eolian sediments, the details of the sediment transportation process, and the location and durability of the resulting bedforms. The thinness of the Martian atmosphere requires wind speeds an order of magnitude larger than on Earth to initiate and sustain eolian transport (Greeley *et al.*, 1982, 1985). Viking and Pathfinder observations suggest that winds capable of moving loose sediments are rare. The rocks at the Viking landing sites show some evidence of eolian sandblasting (Binder *et al.*, 1977; Mutch *et al.*, 1977), and many rocks at Pathfinder show considerable sculpting by wind-borne sand (Bridges *et al.*, 1999; Greeley *et al.*, 2002). The crater populations of these sites indicate that they are relatively old, from the Hesperian (middle) period of Martian history (Scott and Tanaka, 1986). Calculations of potential eolian abrasion rates at those sites show that only a very small amount of the abrasion that potentially could have occurred has, in fact, actually occurred. The most likely explanations are: competent sand-sized material is very scarce on Mars, sand-sized sediments are there in abundance, but its motion is inhibited by some mechanism; or the surfaces we have landed on to date have been buried (protected from abrasion) for a substantial proportion of their existence (Greeley *et al.*, 1982, 1985).

Sand-sized material must be abundant in the Martian surface environment, as evidenced by the presence of ergs, dunefields, isolated dunes, and large-wavelength bedforms, all of which require saltation for their formation (by terrestrial analogy), which in turn implies particle sizes in the few hundred micrometer diameter range. The Algodones Dunes (#1) show a mix of many dune types (longitudinal, transverse, and barchan), and parts of it strongly resemble dune fields imaged by MOC, for example, the dunes within Proctor crater.

Just how mobile the sand-sized material is, however, is less easy to determine from orbital images. Comparisons of Viking and MOC images of dunes, for example, show zero movement to within the spatial resolution of the Viking images (8 m/pixel, Zimbelman, 2000; 17 m/pixel, figure 40 of Malin and Edgett, 2001) over periods of 10 Mars years (20 Earth years). Further, there are numerous examples where large-wavelength bedform features, which by terrestrial analogy should be highly mobile, have persisted in their positions long enough to have been subject to impact cratering and be overriden by debris flows and channel deposits, events that should have obliterated bedforms composed of loose sand.

Neither theory nor observation has revealed widespread granitic rocks on the surface of Mars. (Bandfield *et al.*, (2004) note that the Thermal Emission System (TES) on the Mars Odyssey Spacecraft recently detected only local outcrops of granite-like material in the central peaks of two impact craters.) Consequently, particulate materials are more likely to be composed of basalt rather than quartz. Erosion of basalt by fluvial/eolian processes could be the source of much of the sand-sized sediments seen on the Martian surface, which would make the dunes at Christmas (#21) and Moses (#22) lakes particularly good analogs (Edgett, 1994; Bandfield *et al.*, 2002).

Another consequence of the difference in terrestrial and Martian surface environments is that Mars does not have parabolic dunes analogous to those at Alkali Lake, Christmas Valley (#21), Juniper Flats, Moses Lake (#22), St. Anthony (#19), and Winnemucca (#12). Parabolic dunes like these owe their distinctive shape in large part to the stabilization of part of the sand mass by vegetation, which of course is not present on Mars. However, perhaps other agents (thick dust cover?) may stabilize Martian dunes within the dusty low thermal inertia regions of Mars (Zimbelman, 2000).

Recent ideas of Martian gullies notwithstanding (e.g., Christensen, 2003), lakes and streams are unlikely to have played a significant role in the formation of the eolian bedforms that are nearly ubiquitous in MOC images. However, postulated oceans, paleo-lakes, and the emplacement of dendritic drainage patterns in ancient terrains (see Chapters 1 and 13), could have been an older source of at least some of the sediments now residing in dunes and ripple-like bedforms. Large outflow channels on Mars are analogous to (and larger than) the flooding caused by breaching of glacial dams like that which created the Channeled Scablands (see Chapter 12). Outflow channels may have produced significant quantities of eolian material, much of which has been blowing around the Martian surface for a long time (see Chapters 11 and 12).

New data from current and future Mars missions should help to refine the strength of some of the analog sites discussed above. The Mars Odyssey spacecraft (W30) now in orbit includes the Thermal Emission Imaging

System (THEMIS; W31), a camera that shows the Martian surface at both thermal infrared and visual wavelengths. THEMIS images have already led to new hypotheses about features such as the enigmatic gullies (Christensen, 2003), and the capability is just as great for similar advances for eolian features. The Mars Exploration Rovers (MER) are providing detailed imaging and compositional information from two new landing sites on Mars; while not specifically targeted at eolian features, new insights have been gained for wind-blown materials and eolian deposits (W32; Greeley *et al.*, 2005). The 2005 Mars Reconnaissance Orbiter should provide sub-meter-scale images, which will likely change many of our current ideas about the Martian surface and provide new opportunities for investigating analog eolian sites here on Earth (W33).

9.6 Summary

Twenty locations in the western United States are discussed as potential analog sites for eolian features and deposits on Mars. The sites represent sand that is topographically trapped (a common occurrence on Mars), sand deposits along transport pathways (potentially present on Mars, but not reported to date), and sand that is derived from either lake or river sediments (again potentially present on Mars, but not specifically identified as such), although not all eolian sediments remain confined to topographic traps (Edgett, 2002). MGS data have greatly improved the level of detail available for Martian eolian features. On-going MGS and MER data collection, combined with prospects from future missions to Mars, holds great potential for more specific analog studies of eolian features and deposits in the future.

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