Chapter 3

SUBLACUSTRINE DEPOSITIONAL FANS IN SOUTHWEST MELAS CHASMA

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Abstract

Two depositional fan complexes have been identified on the floor of southwest Melas Chasma. The western fan complex is located near the center of an enclosed basin in southwest Melas Chasma and is composed of multiple lobes with dendritic finger-like terminations. These fans are very flat and have a morphology unlike any other fan that has been previously identified on Mars. Based on the morphologic similarity of the western fan complex to the Mississippi submarine fan complex, we suggest that it may be a deep subaqueous fan depositional system. There are numerous channels on the surface of the western fan complex and measurements of channel length, width, and sinuosity are consistent with channels observed on terrestrial submarine fans. The eastern Melas depositional fans are less well preserved and may be of deltaic or sublacustrine origin. Recognition of the fans supports earlier suggestions for the presence of a former lake in Melas Chasma and indicates that a significant body of water was present and stable at the surface of Mars for at least 10^2 to 10^4 years.

3.1 Introduction

Evidence for ancient lakes on Mars is based on multiple indirect criteria including constant-elevation contour lines inferred to be shorelines, the presence of flat-lying finely-layered deposits inferred to be lake-bottom sediments, terraced alluvial fans inferred to have formed in response to lake-level rise, and deltas with aggradational stratal geometries (Quantin et al. 2005; Lewis and Aharonson 2006; Grant et al. 2008; Kraal et al. 2008b). Direct evidence of a lacustrine environment requires observation of sedimentary deposits that could have formed only in fully submerged settings. The former presence of lakes, as well as the amount of time that they were stable on the surface, has important implications for the history and role of water on Mars (Baker 2001).

One area on Mars with possible evidence of a paleo-lake is Melas Chasma in Valles Marineris (Fig. 3.1). Dense, highly-organized valley networks have been identified in the topographic highs surrounding a basin in southwest Melas Chasma, hereafter referred to as Southern Melas Basin (Mangold et al. 2004). Since the heads of the valleys occur at different elevations, including near the tops of wall rock ridgelines, they have been interpreted to have been fed by precipitation (Mangold et al. 2004; Quantin et al. 2005). These valleys drain into a sub-circular closed depression within Southern Melas Basin, and this depression follows the -1800 m elevation contour (Quantin et al. 2005). Quantin et al (2005) suggest there may have been a body of standing water in the basin. The basin contains numerous light-toned flat-lying layers that can be traced over several kilometers. A set of strata that show clinoform geometries occurs in the northwest part of Southern

Melas Basin, and it has been suggested that this feature represents either a channel-levee complex or a delta complex (Dromart et al. 2007).

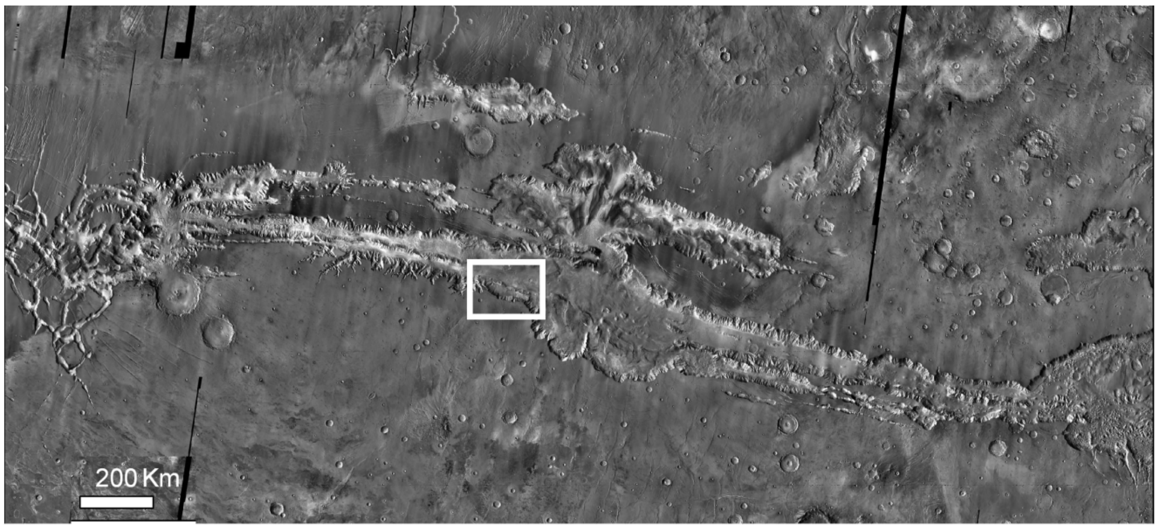

Figure 3.1 White box shows location of Southern Melas Basin within central Valles Mariners.

Channel-levee complexes are important components of deep-water depositional systems. Submarine fans are fed by turbidity currents that often flow down sinuous deep-water channels through laterally extensive channel-levee systems (Wynn et al. 2007). The channels are thought to avulse frequently with only one channel active at any given time (Damuth et al. 1983b; Damuth and Flood 1984; Wynn et al. 2007). Many studies have found similarities in the planform geometry of channels on upper and middle submarine fans and river channels (Flood and Damuth 1987; Clark et al. 1992), but with a lower occurrence of meander loop cutoffs and frequent avulsions in submarine channels as compared to subaerial channels (Kane et al. 2008). As the turbidity currents wane during flow events, deposition of lobes of sediment is common (Nelson et al. 1992). Cores through submarine fan deposits show clays with interbedded graded sand and silt beds with distorted layers arranged in discontinuous lenses (Nelson et al. 1992). These lenses of coarser material occur where channelized flows ‘freeze’ into dendritic patterns, depositing their sediment near the edges of depositional lobes (Nelson et al. 1992). ‘Freezing’ in sediment deposition occurs due to loss of pore fluid pressure or because of frictional grain resistance and cohesive grain interactions (Dasgupta 2003).

A fan was previously identified near the western margin of Southern Melas Basin, and it was suggested that it may be of deltaic origin (Quantin et al. 2005). We identify four fans in Southern Melas Basin, two in the western part of the basin and two in the eastern part of the basin. One of the western fans was considered part of the delta in the Quantin et al. (2005) analysis. We evaluate the potential origins for the two western fans which include submarine fan, delta, alluvial fan, or gully deposit. We compare the detailed morphology, basin position, and slope of each of the possibilities to those of the western Melas fans. Although many of the features of the fans are consistent with a deltaic origin, we propose that a sublacustrine origin is also consistent with the morphology and properties of the two western fans.

3.2 Geological Setting

The area of study in Southern Melas Basin is located within central Valles Marineris (Fig. 3.1). Surface features and materials in Melas Chasma have been studied using Mars Global Surveyor data (Pelkey and Jakosky 2002) and Mars Odyssey THermal

EMission Imaging System (THEMIS) data (Pelkey et al. 2003). These studies conclude that the recent surface in Melas Chasma has been dominated by eolian processes.

There is still much debate about how Valles Marineris formed, but mechanisms that have been suggested include structural collapse (Spencer and Fanale 1990; Schultz 1998; Rodriguez et al. 2006), tectonic rifting (Mege and Masson 1996; Schultz 1998; Peulvast et al. 2001) and gravity spreading due to loading of aerially-widespread salt deposits (Montgomery et al. 2008). The Valles Marineris canyon system is thought to have formed over several periods of tectonic activity spanning the late Noachian to late Hesperian or early Amazonian, and the material filling southwestern Melas Chasma is thought to be Hesperian to Amazonian in age based on impact crater-counting (Scott and Tanaka 1986; Pelkey and Jakosky 2002). Crater-counting of the material thought to compose the paleolake surface of Southern Melas Basin yields a complicated pattern with an age of 3 Gy followed by a period of resurfacing until 10 My (Quantin et al. 2005). The crater-size distribution of the valley networks indicates that they are younger than 3.5 Gy (Quantin et al 2005). Thus it is possible that the fluvial and lacustrine features in Southern Melas Basin date back to the beginning of the Valles Marineris system.

There is some debate about the ages of materials on the floor of Valles Marineris, such as the interior layered deposits, which are distinct finely-layered materials located on the floors of troughs within Valles Mariners. There are many hypotheses suggested for their formation, many of which suggest they were deposited after the formation of Valles Marineris (Lucchitta 1990; Komatsu et al. 2004; Fueten et al. 2006; Okubo et al. 2008), but some suggest they are ancient materials exhumed from below the material forming the trough walls (Malin and Edgett 2000; Montgomery et al. 2008). It is possible that both of these hypotheses are true; for example, there could be large expanses of wall rock that predate the opening of Valles Marineris, but more local topographically enclosed basins may contain deposits that formed after the depression was formed. The age of the materials on the floor of Southern Melas Basin may in fact be older than their crater-counting ages suggest if they were recently uncovered by erosion (Malin and Edgett 2001; Hartmann 2005).

3.3 Methods

Structural attitudes were obtained using planar fits to bedding seen in a Digital Elevation Model (DEM) constructed using stereo Mars Reconnaissance Orbiter (MRO) High-Resolution Imaging Science Experiment (HiRISE) images (PSP_007087_1700, PSP_007667_1700). The DEM was constructed using the methods of Kirk et al. (2008), and the vertical precision of the DEM is ~0.2 m (resolution ~1 m). Linear segments were traced out along well-exposed layers. Only layers with some natural curvature in the horizontal direction were used in order to provide accurate constraints on the three-dimensional geometry of the layer. We employed the method presented in Squyres et al. (2007) and Lewis et al. (2008b), which uses principal component analysis to ensure the layers used are well fit by a plane.

Channels on the fans were identified using both images and the DEM. There are several ways to define a channel, but for this study two new channels are defined after each channel branch point. We define the main trunk channel as a first-order channel. When a first-order channel branches, the resulting channels are second-order channels. When a second order channel branches, the resulting channels are third order channels. Thus, the main trunk channel is a first order channel and the more distal channels are higher order. The width of each channel was measured at the beginning of each channel reach, and each width measurement has an uncertainty of about 1 m. The sinuosity of the channels was found by dividing the channel length, which is the length traced along the path of the channel, by the valley length, which is the straight-line distance from the beginning to the end of the channel (Schumm 1963).

To compare the channel patterns seen on the Melas fans against terrestrial depositional fans, we need to account for the different size of the systems. This was accomplished using non-dimensional parameters that included dimensionless width and length and sinuosity. The width of each channel was divided by the width of the main trunk channel, and length of each channel was divided by the length of the main trunk channel to make these parameters non-dimensional. The depth of each channel was measured from the DEM and has an uncertainty of ~1 m. The reported channel depths for the Melas fans are minimum estimates, since many of the channels have been at least partially filled in by eolian material and the channel levees may have been partially eroded. A minimum estimate of the channel gradient was calculated by finding the difference in elevation between the beginning and end of each channel and dividing by the length of the channel.

Ideally, the channels on the Melas fans would be compared to channels on terrestrial sublacustrine fans; however, images of the plan view morphology of terrestrial sublacustrine fans either have not been acquired or are not publicly available. Thus, the channel patterns on terrestrial sublacustrine fans could not be mapped and compared using the methods of this study. Bathymetric and seismic-reflection profiles across sublacustrine fans have been acquired and show that channels are present on sublacustrine fans (Normark and Dickson 1976b; Scholz and Rosendahl 1990; Back et al. 1998; Nelson et al. 1999).

The surface slope of the Mississippi submarine fan was found by superimposing the side-scan sonar image over the bathymetry (Gardner 2007). The slope was found by fitting a plane to a small area of the surface, similar to the methods used in Lewis et al. (2008b), and repeating this measurement for several areas on the fan. The values found were between 0.04° and 0.4° with an average of 0.08°, but there is an uncertainty of at least 0.04° in the measured values due to artifacts in the bathymetry. Despite the uncertainty, these values are close to the average seafloor slope of 0.06° reported for the Mississippi fan (Nelson et al. 1992; Schwab et al. 1996).

Fan lobes on the western Melas fans were identified and their thicknesses measured using the DEM. The lobe areas were measured, and their minimum volume calculated by multiplying lobe area by the thickness. These are all minimum estimates since some parts of the fans are obscured by overlying strata. The lobe areas and volumes were added to find the total area and volume of each fan.

3.4 Description of Fans used for Comparison

Channels identified and mapped on the Melas fans were compared to six terrestrial deep-water submarine fans (Brazos-Trinity Basin IV, Makassar, Mississippi, Pochnoi, Rhone, and Speculobe), two terrestrial deltas (Wax Lake and Lena), and one Martian delta (Eberswalde). These six terrestrial submarine fans were chosen because they were imaged at sufficient resolution to make a comparison, and we were able to obtain the data. The Brazos-Trinity Basin IV ponded apron is located in the northwestern Gulf of Mexico and is formed in the terminal basin of four linked intraslope basins (Table 3.1). The seafloor fan in Makassar Straits is a very low relief mud-rich fan located between the islands of Borneo and Sulawesi (Table 3.1). The Mississippi submarine fan is a large, mud-rich seafloor fan located in the Gulf of Mexico (Table 3.1) that was largely constructed during the Plio-Pleistocene (Wynn et al. 2007). The Pochnoi fan is located in the Aleutian Basin in the Bering Sea (Table 3.1), and it is thought to be a very young feature, possibly of late Pliocene-Quaternary age (Herman et al. 1996). The Rhone Neofan is part of the much larger Petit-Rhone Fan and formed from the most recent avulsion of the Rhone channel in the Gulf of Lion (Table 3.1). The Speculobe fan is a small sand-rich seafloor fan located in the Gulf of Cadiz offshore Spain (Table 3.1). As shown in Table 3.1, the six submarine fans chosen for comparison comprise the range of diversity seen on submarine fans (eg. mud-rich, sand-rich and mixed sediment; active and passive continental margin, basin floor and ponded fans).

Wax Lake Delta is a modern river-dominated bay head fan delta located at the mouth of the Wax Lake outlet, which is a man-made channel excavated in 1941 (Wellner et al 2005). The formation of this delta was tracked through time by images taken over the last thirty years. The Wax Lake Delta is a relatively young delta that has not had much human interference and thus appears in a natural state. The Lena delta is a river-dominated delta located at the Laptev Sea coast in northeast Siberia (Olariu and Bhattacharya 2006). The Eberswalde delta is located in Eberswalde crater near the western margin of the 65-km diameter crater (Wood 2006). It is an erosional remnant of a larger paleodeltaic deposit and has numerous bifurcating distributaries preserved in positive relief (Malin and Edgett 2003).

Fan	Location	Fan Type	Fan Area (km^2)	Water Depth (m)	Drainage Basin Area (km^2)*	Grain size	Tectonic State
BT Basin IV	27°20′N 94°24′W	ponded	128	1500	1.2×10^5	mixed	passive
Makassar	0°23′S 118°37′E	seafloor	2500	2400	7.5×10^4	mud	active
Mississippi	26°30′N 85°30′W	seafloor	300,000	3200	4.76×10^6	mud	passive
Pochnoi	54°35′N 173°56′W	seafloor	20,000	?	1.2×10^5	?	active
Rhone Neofan	41°45′N 4°54′E	seafloor	1430	2400	9.0×10^4	sand	passive
Speculobe	35°30′N 7°30′W	seafloor	48	1500	5.7×10^4	sand	active
Wax Lake Delta	29°30′N	delta	40	~0	?	-	passive

	91°26′W						
Lena Delta	72°13′N 126°9′E	delta	30,000	~0	2.5×10^6	-	active
Melas North	9°49′S 76°25′W	lacustrine	2.3	?	~500	?	?
Melas South	9°49′S 76°25′W	lacustrine	4.3	?	~500	?	?

Table 3.1 Characteristics of the submarine fans and deltas compared in this study. Grain size refers to the predominant grain size on the fan and the tectonic state refers to the margin on which the fan is developed. *The drainage basin area is based on the size of the drainage basin of the main river that ultimately feeds the fan.

3.5 Results

3.5.1 Morphology

The western fan complex is located near the center of Southern Melas Basin and has two fans, each of which is composed of multiple lobes with dendritic finger-like terminations (Fig. 3.2). The lobes are elongated and the ‘fingers’ often branch off at high angles in the downstream direction (up to 90° to the overall transport direction). The mean

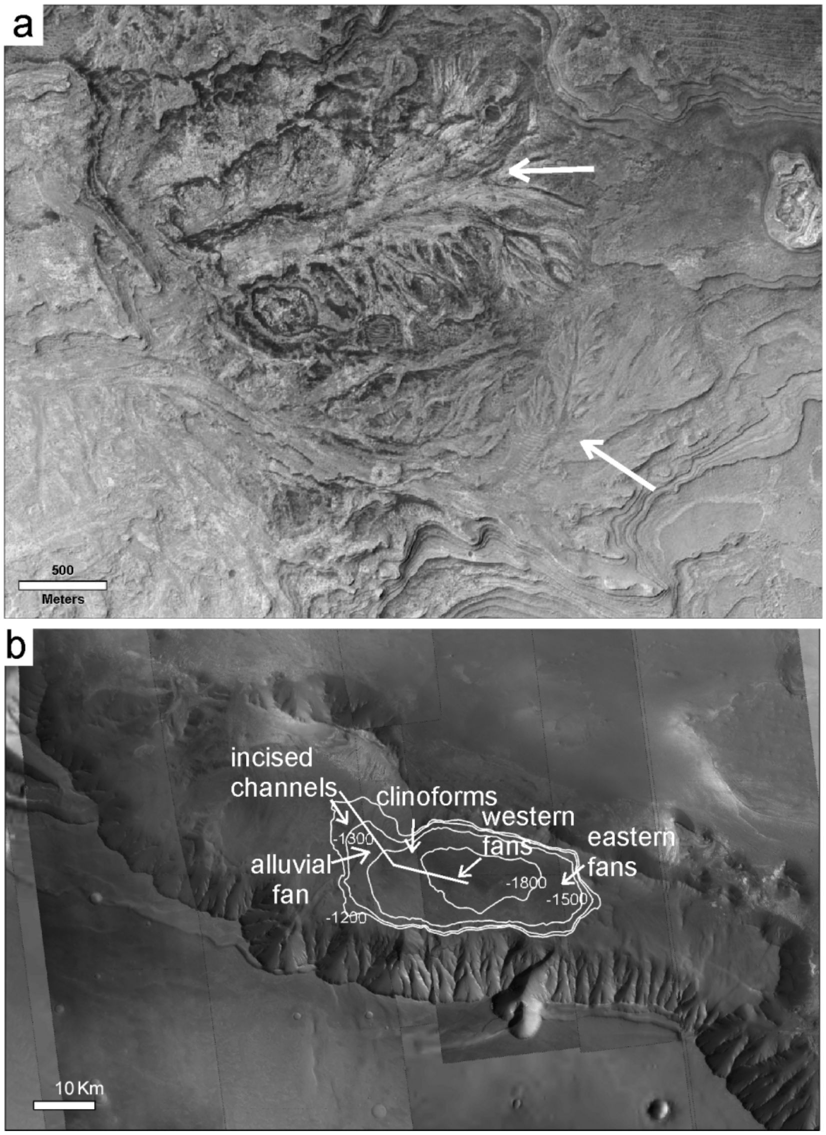

Figure 3.2 A.) Portion of HiRISE image PSP_007667_1700 with white arrows showing the location of the two putative western sublacustrine fans intercalated within the layers in Southern Melas Basin. B.) Mosaic of CTX images showing Southern Melas Basin where the putative sublacustrine fans occur. White line is actual topographic transect for schematic in Fig. 3.12.

branching angles for the fingers are 75 degrees while the median is 80 degrees. The surface of the fans in Southern Melas Basin is marked by numerous mildly sinuous

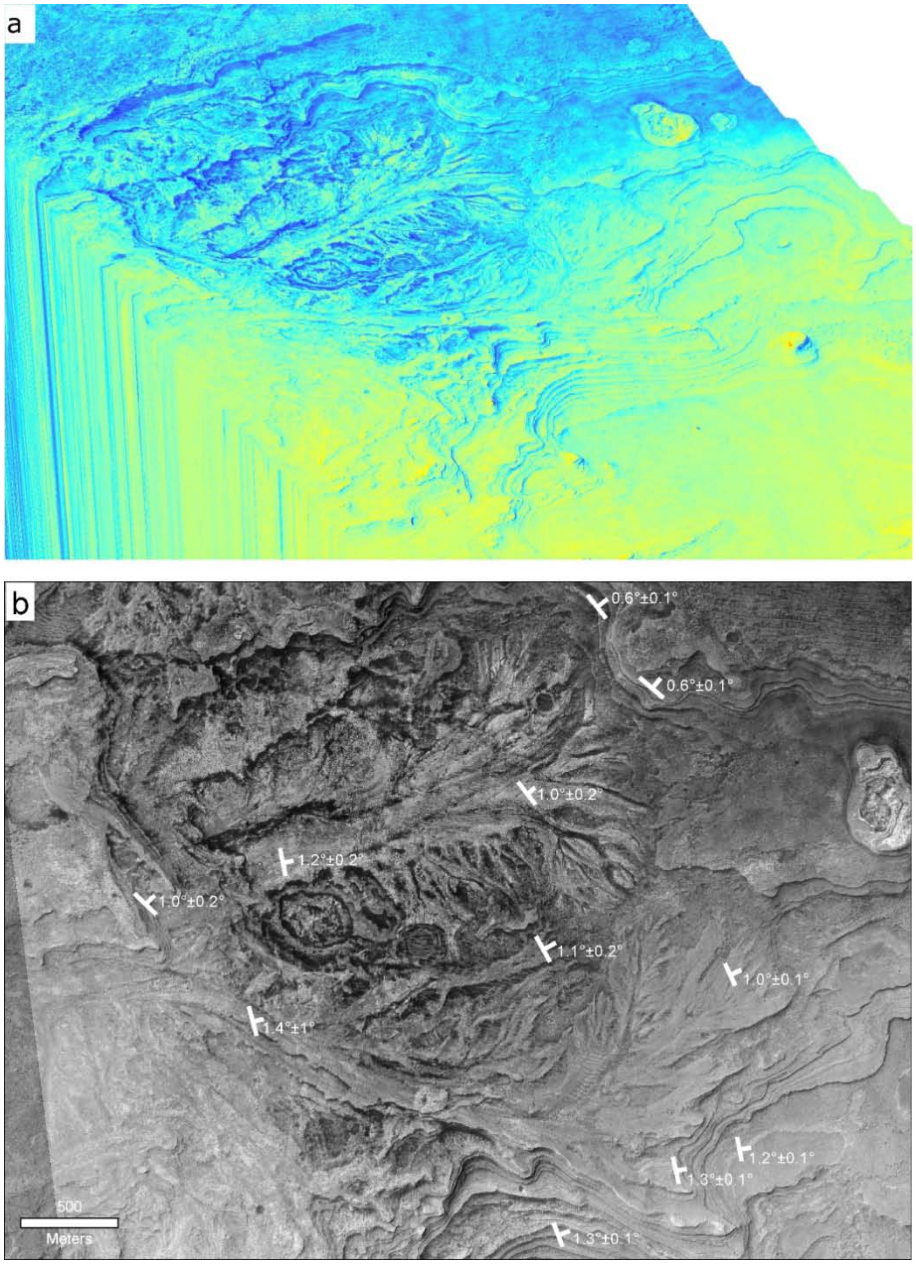

Figure 3.3. A.) Shaded relief perspective view of the western fans. The southern fan is topographically and stratigraphically above the northern fan. B.) Image of the fans showing the dips of the fan surfaces and layers. The main feeder channel of the southern fan is ~50 m above the basin plain.

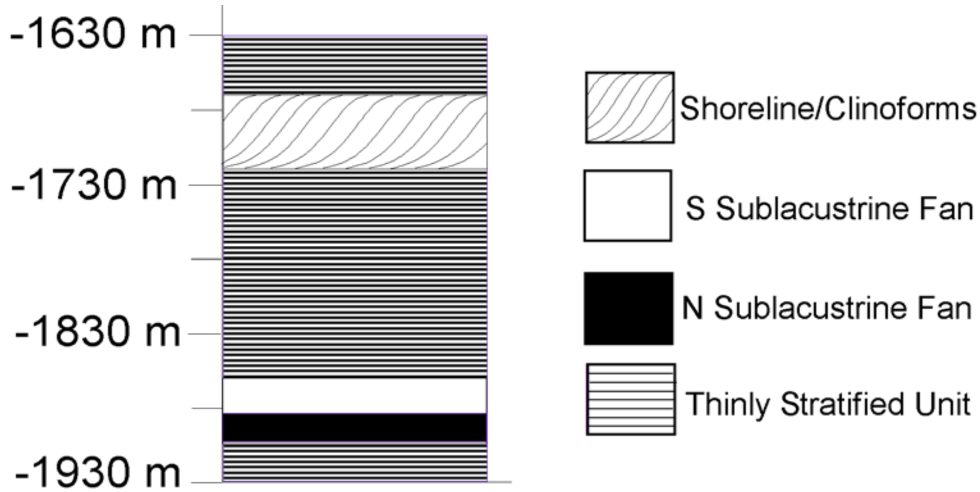

Figure 3.4. Stratigraphic column illustrating that the southern fan is located stratigraphically above the northern fan.

channels, and its average surface slope is ~1° (Fig. 3.3). The dips of the beds in the fans are also about 1° (Fig. 3.3). The fans have few craters, because they were probably buried beneath later sediments, which prevented small craters from forming on their surfaces. Subsequent exhumation has now exposed the surfaces of the fans. There are layered beds surrounding the fans, so the beds must have been joined in the past and then eroded back to expose the fans. The preservation of the channels, including a topographic signature, suggests the exhumed paleo-fan surface corresponds closely to the original fan surface.

The fans occupy different stratigraphic levels with the southern fan located stratigraphically above the northern fan, but both are located in the topographically lowest part of the basin (Fig. 3.4). The fans are surrounded by other layered material, and these beds are also relatively flat-lying with dips of between 0.6-1.4° (Fig. 3.3). The fans appear to be visible through an erosional window through the other layers.

Table 3.2 lists the characteristics of the western Melas fans, including slope, minimum area and volume, minimum length, mean and maximum channel depths, mean channel gradients, and channel sinuosity. Six lobes were identified on the northern fan and ten lobes on the southern fan (Fig. 3.5). The numbering of the lobes indicates the relative order that they formed in; parts of earlier formed lobes can be seen to be covered by later-formed lobes. Some of the later-formed lobes appear to have filled in the low areas surrounding earlier formed lobes. The channels identified on each fan are shown in Fig. 3.6.

Fan	Slope	Area (km^2)	Volume (km^3)	Length (km)	Channel depth (m)		Mean Channel Gradient (m/km)	Sinuosity
					Mean	Maximum		
Northern	1°	2.3	0.05	2.1	1	4	23	1.02
Southern	1°	4.3	0.10	1.3	1	2	32	1.02

Table 3.2 Characteristics of the western Melas fans.

There are two additional fans in the eastern part of Southern Melas Basin (Fig. 3.7a), but they are not as well-preserved as the western fans. They have an elongate branching morphology and are preserved in positive relief. The bulk of the fans appear to be composed of inverted channels (Fig. 3.7b), although there are a few channels on the surface of the southern fan which form topographic depressions. The channels composing the fans can be seen to migrate and cross-cut. The northern fan appears to have formed first (1 in Fig 3.7b); the main feeder channel switched south and built up a new channel system (2 in Fig. 3.7b). The main channel appears to have ultimately switched to the north as evidenced by the cross-cutting channel relatioonships (3 in Fig. 3.7b). There are several large and small impact craters on the surfaces of the fans. Since these fans are not as well-preserved as the western fans, this paper will focus on the western fans.

Figure 3.5 Outlines of the six lobes composing the northern fan and the ten lobes composing the southern fan are outlined in white.

The combination of low slope, channel branching geometry, presence of distinctive small-scale lobes, and position near the center rather than near the margin of a topographic basin show that the western fans are distinct from previously identified fluvial features on Mars.

Figure 3.6 Channels on the Melas fans are outlined by the solid white lines. Dashed lines show inferred positions of channels.

2.5.2 Mineralogy

The surfaces of the fans are covered in dust, which makes mineralogical detections difficult (Fig. 3.8a). However, MRO Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) spectra do show evidence for opaline silica (Fig. 3.8b,c) and jarosite (Fig.

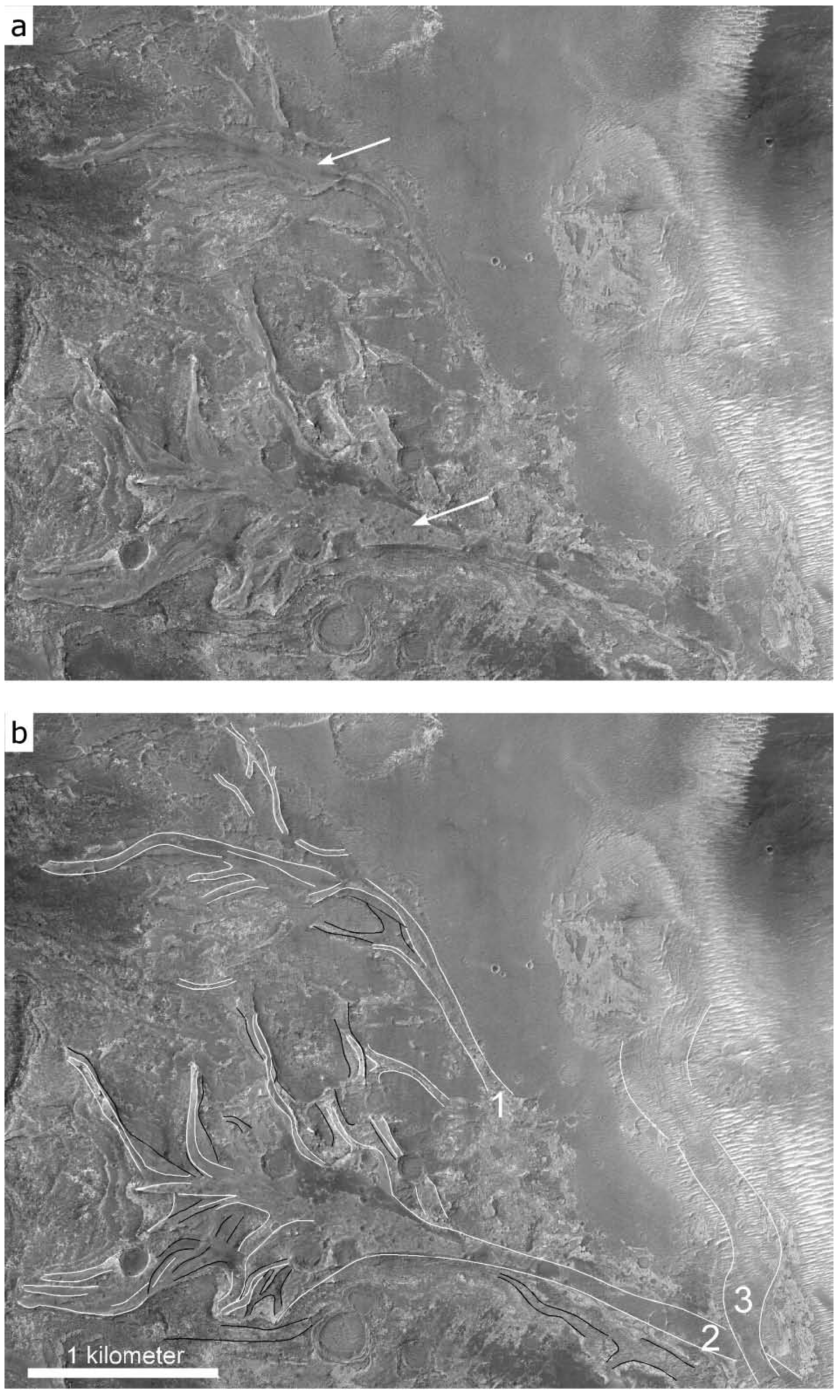

Figure 3.7. A.) Portion of HiRISE image PSP_007377_1700 with the white arrows showing the location of the eastern Melas fans. B.) White lines show outlines of channels. Black lines show an older generation of channels. The numbers refer to the relative ages of the channels based on cross-cutting relationships.

3.8b,d) in layers near the fans, similar to the mineral assemblages seen on the plains directly south of Melas Chasma (Milliken et al. 2008; Weitz et al. 2009). The opaline silica was detected in a small hill just to the east of the northern Melas fan and in bedded outcrops to the northeast of the fan (Fig. 3.8b). These latter exposures occur in strata that lie stratigraphically above the fans. The hydrated silica was identified by the presence of absorption bands centered near 2.21-2.26 μm due to the presence of Si-OH groups. The position and shape of a doublet band at 2.23 and 2.26 μm is most consistent with laboratory spectra of opal- A/CT (Fig. 3.8c). Hydrated silica can occur as primary sedimentary deposits (McLennan 2003), altered ash deposits, precipitation as pore-filling cements, or precipitation from shallow evaporating bodies of water (Milliken et al. 2008).

Mineral spectra that show a good spectral match to jarosite were detected in the clinoforms (Fig. 3.8b). The jarosite was identified based on bands at 1.85 and 1.93 μm and an OH-feature near 2.26 μm and is most consistent with Fe-deficient H_3O-bearing jarosite (Fig. 3.8d). H_3O-bearing jarosite is consistent with precipitation under low temperature acidic conditions (Milliken et al. 2008). Jarosite is not as soluble as other sulfates, such as Mg-sulfates, and could be transported by fluids if they were already saturated with S and Fe. It would depend on the composition of the transporting fluid and the amount of time the mineral was in contact with the fluid. The jarosite could also be diagenetic, and this cannot be ruled out since the CRISM data are too coarse to determine if the jarosite is cutting across bedding contacts. However, cementation is likely the most probable origin for the jarosite. The definitive sedimentary origin for the clinoforms implies that if this is a jarosite cement it would be of low temperature origin since the clinoforms are not a volcanic deposit. This provides a definitive constraint on paragenesis. The presence of

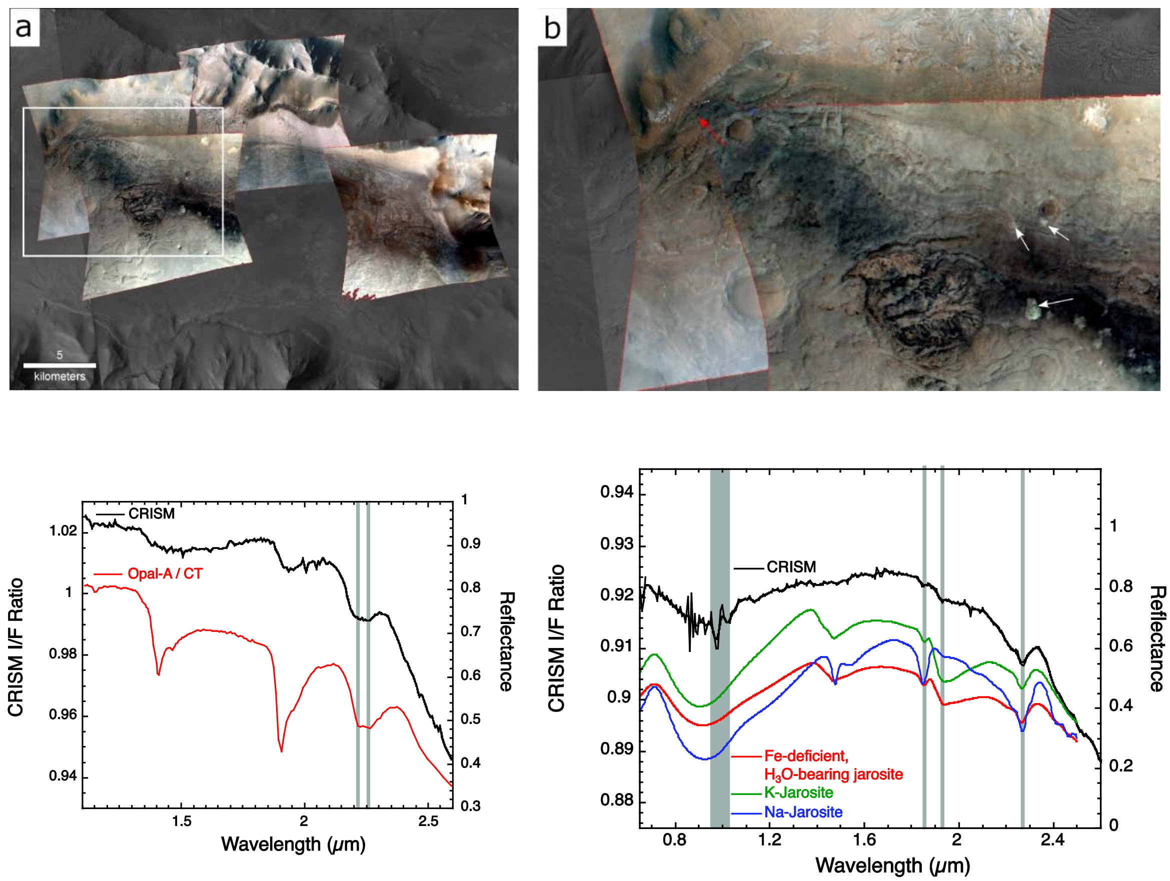

Figure 3.8 A.) CRISM targeted image overlain on a CTX mosaic of Southern Melas Basin. White box shows location of b. Light brown tones, such as on the eastern and western Melas fans, are indicative of dusty areas. B.) Close-up view of the area outlined in a. The white arrow shows the location of turquoise outcrops showing a good spectral match to opaline silica. Red arrow shows location of jarosite. C.) CRISM spectra (in black) of turquoise outcrops compared with library spectra of opaline silica A/CT (in red). Note good match of the double bands between 2.2 and 2.3 μm. D.) CRISM spectra (in black) of the clinoforms compared with library spectra of K-, Na- and H_30-bearing jarosite.

these hydrous minerals implies that water was present when they formed, possibly as a lake or as pore fluids in pre-existing sediments (Milliken et al. 2008).

3.6 Discussion

Because the western Melas fans are a newly identified class of fan-like features on Mars, we compare them to common depositional fans found on both Earth and Mars to evaluate the most likely process responsible for their formation.

3.6.1 Depositional Fan Comparisons

3.6.1.1 Alluvial Fans

Alluvial fans, both on Mars and on Earth, are cone-shaped deposits radiating from a dominant source channel. They typically develop near the base of topographic highlands, thus fringing basin margins. The Melas fans, however, occur near the center of a basin. Alluvial fans typically have relatively steep slopes; the average surface slope of alluvial fans on Mars based on our compilation of existing data is 2.5° (see Table 3.4) (Moore and Howard 2005; Kraal et al. 2008a). Alluvial fans on Earth have average slopes of 2-12° (Hashimoto et al. 2008; Blair and McPherson 1994b). Some authors have suggested that in humid areas alluvial fan formation is dominated by braided fluvial river processes and that these alluvial fans have more gentle slopes of 1° or less (Stanistreet and McCarthy 1993; Hashimoto et al. 2008). Other authors argue that these should not be classified as alluvial fans and are actually braided stream systems (Blair and McPherson 1994b). The slope of the Melas fans (~1°) does, however, overlap with the slopes of humid alluvial fans. This would indicate that if the fan was not of sublacustrine origin that it would have formed by alluvial processes that required continuous rather than flashy or sporadic discharge, consistent with a wetter climate.

The processes observed to act on alluvial fans are debris flows, sheet floods, and shallow braided streams (Schumm 1977; Blair and McPherson 1994b; Harvey et al. 2005). The channels on the Melas fans are distinct and moderately sinuous, not braided. The Melas fans also have distinct depositional lobes from individual flows. Debris flow-dominated alluvial fans could be expected to have lobate deposits, but these typically have boulder-laced snouts (Whipple and Dunne 1992). The Melas fans do not show evidence for large boulders at the scale of HiRISE images (~25 cm/pixel). Also, debris flow-dominated fans typically have slopes above 5° while the Melas fans have much lower slopes (Harvey 1984; Wells and Harvey 1987; Blair and McPherson 1994a). Furthermore, the high branching angles of the lobes in the Melas fans are not seen in subaerial debris-flow dominated fans.

3.6.1.2 Gully Deposits

Gully deposits that have been identified on Mars have lobe-shaped terminations but are developed on steep rather than gentle slopes. The average slope on which gullies are developed is 27° based on over 200 measurements from recent studies (Malin et al. 2006; Dickson et al. 2007; Heldmann et al. 2007). These elongate deposits are thought to form by dry mass wasting on steep slopes or perhaps by liquid water flows (Pelletier et al. 2008). The flows typically originated from a small region, and the flows did not diverge widely to create complex branching networks as seen in the Melas fans.

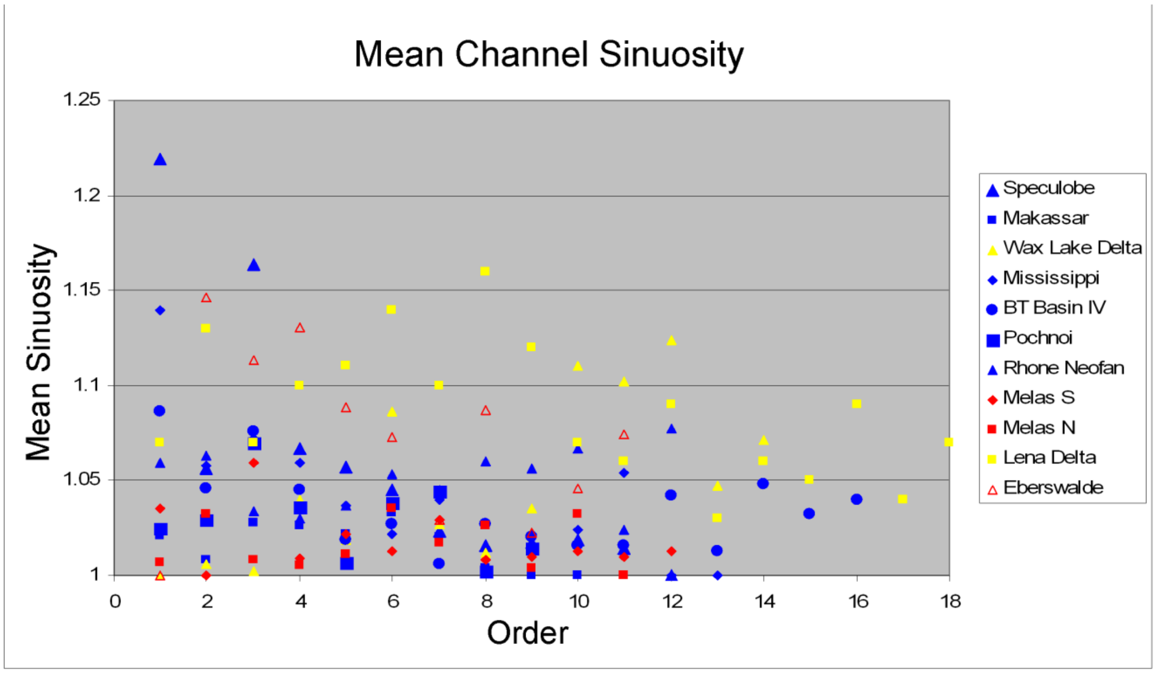

Figure 3.9. Plot showing how mean channel sinuosity changes down-fan (i.e. for increasing order) for six terrestrial submarine fans, two terrestrial deltas, and the two western Melas fans. Sinuosities were measured for channels on the distal portions of the terrestrial submarine fans.

3.6.1.3 Deltas

Deltas are partially subaerial masses of sediment deposited near where a river enters a standing body of water. The Eberswalde delta on Mars has a low surface slope that averages 2° (Lewis and Aharonson 2006), and many meandering and sinuous channels, scroll bars and branching terminations (Wood 2006). Terrestrial deltas also commonly have low surface slopes (<1°) and can show lobate stacking patterns from lobe buildup and switching (Coleman and Wright 1975). Delta channels show a range of sinuosities and can be meandering and sinuous (Wood 2006) or mildly sinuous (Fig. 3.9). The western Melas fans show low surface slopes and mildly sinuous channels (sinuosity of 1.02), which both fall within the range of values common for deltas (Table 3.3, Fig. 3.9). The Eberswalde delta is located at the margin of its crater, similar to terrestrial deltas which are located near the margins of basins. Jezero crater delta, southeast of Nili Fossae on Mars, is also located at the margin of its crater (Ehlmann et al. 2008). However, the western Melas fans are found near the center of the basin. The delta channels also have low branching angles, and its lobes do not lead into the high-angle fingers seen in the Melas fans.

Feature	Basin Position	Slope	Shape	Channels
Alluvial Fan	Margin	2.5°	Cone-shaped	Braided
Gully Deposit	Wall	27°	Elongate lobes	-
Delta	Margin	2.1°* <1°**	Fan-shaped, lobes	Sinuous, meandering, mildly sinuous
Submarine Fan	Center	≤1°	Elongate branching lobes, fingers	Mildly sinuous
Melas W. Fans	Center	~1°	Elongate branching lobes, fingers	Mildly sinuous

Table 3.3 Depositional fan characteristics. *This is the average slope reported for the Eberswalde Delta (Lewis and Aharonson 2006). **This is the average slope value for terrestrial deltas.

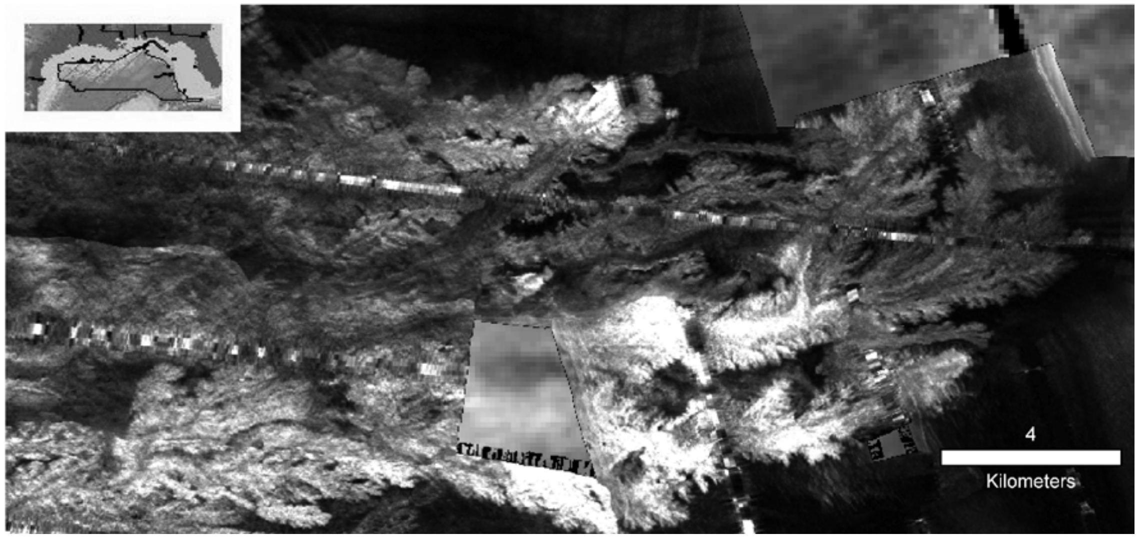

Figure 3.10 SeaMARC IA Side-scan sonar image of the Mississippi submarine fan showing the elongated nature of the lobes and the fingers that branch off at high angle (USGS). Inset shows location of the side-scan sonar image. High backscatter areas are composed of clay facies with interbedded sand and silts, whereas low backscatter areas are composed of clay facies with no siliciclastic sands or silts (Nelson et al. 1992).

3.6.1.4 Submarine Fans

The morphology of the Melas fans compares favorably with depositional features formed on the Mississippi submarine fan (Figs. 3.2, 3.10). The distal Mississippi submarine fan also has a lobate morphology with finger-like dendritic terminations, elongated lobes, and splays that branch off of the main deposit at high angles (up to 90°). The distal Mississippi submarine fan also has low relief mildly-sinuous channels and is very flat, with a surface slope of ~0.08° based on our analysis of existing bathymetric data (Gardner 2007). Although the slope of the Melas fans (~1°) is somewhat higher than that of the Mississippi fan, it is possible that slight differential erosion of the surface of the

Melas fans could cause an increase in the slope. If the surfaces of the Melas fans were not an exact bedding plane, measured surface slopes would be higher than the true slope.

Submarine fans are densely channelized distributary systems and the distal Mississippi fan is composed of depositional lobes whose beds consist of graded sand and silt (Nelson et al. 1992). The detailed structure of these lobes shows a "finger-like" or high branching angle dendritic backscatter pattern in sidescan sonar which correlates to the sand-silt beds formed by abrupt deposition of channelized flows to form small lobes at their distal reaches (Fig. 3.10; Nelson et al. 1992; Klaucke et al. 2004). These finger-like lobes are commonly oriented at high angles to the channels which delivered the sediment to the lobes (except for the cluster of termination lobes). Similar finger-shaped deposits have been observed on the Monterey Fan and in the distal areas of Permian submarine fans preserved in the Tanqua Karoo basin, South Africa (van der Werff and Johnson 2003; Klaucke et al. 2004). The relatively abrupt terminations associated with the finger-like lobes are characteristic of sediment-gravity flow deposits. Full preservation of these lobes on subaerial fans is unlikely due to subsequent reworking and sediment transport by flowing water (Whipple and Dunne 1992). The unmodified preservation of sediment-gravity flow deposits such as those observed in Southern Melas Basin is consistent with accumulation in the distal reaches of a subaqueous fan. The channels present on distal submarine fans are mildly sinuous (<1.3), and the channels on the Melas fans show similar sinuosities (Fig. 3.9). These measurements show the channels on the Melas fans have properties that are consistent with channels on submarine fans.

The Melas fans are located near the center of the basin in the current topographically lowest area, which could be the result of subsequent erosion of the basin or the original depositional setting. Many submarine fans also occur on basin plains in the topographic lows of the basin, but this may not necessarily correspond to the center of the basin. For example, the Mississippi submarine fan is located at ~3300 m water depth and is over 500 km away from the Mississippi Canyon on a very low gradient surface (Schwab et al. 1996). It is bounded to the east by the Florida escarpment (Schwab et al. 1996). Although the Mississippi submarine fan is not located in the center of the Gulf of Mexico, it is located on the basin plain in a depositional low. Sublacustrine fans are also found in the deepest areas of lakes (Normark and Dickson 1976a). They typically occur on the basin plains near the centers of their lakes, such as in Lake Baikal, Siberia (Nelson et al. 1999) and Lakes Malawi and Tanganyika, east Africa (Scholz and Rosendahl 1990). Thus, the current basin position of the Melas fans is similar to that of terrestrial sublacustrine fans.

3.6.2 Formation of the Melas Western Fans

Based on their morphological similarity to the Mississippi submarine fan, the western Melas fans could be interpreted as sublacustrine fans. Sublacustrine fans commonly occur in deep lakes on Earth and form important depositional systems that commonly are fed by density underflows originating from regional drainage systems (Nelson et al. 1999). Turbidity current experiments in the laboratory have produced subaqueous fan deposits that are channelized with mildly sinuous, low-relief channels (Yu et al. 2006). Thickness maps of these deposits show finger-shaped deposits that resemble the distal stretches of submarine fans.

In contrast to the small size of the Melas fans, the overall area and volume of the Mississippi submarine fan is 3×10^5 km^2 and 2.9×10^5 km^3, and the fan is 600 km long (Wynn et al. 2007). The much larger size of the Mississippi fan is expected since the size of a submarine fan is as much a function of sediment flux as its duration, and the Mississippi drains a large part of the North American continent. For Melas Chasma, the sediment flux must have been much smaller due to the small size of the catchment area which would have yielded the sediments which formed the fan. Terrestrial submarine fans comparable in size to the Melas fans do exist, such as the upper fan in Brazos-Trinity Basin IV and the Pochnoi fan (Kenyon and Millington 1995; Beaubouef et al. 2003), but they have not been imaged in as much detail as the Mississippi fan so their small-scale morphology cannot be compared.

The properties of the channels on the Melas fans (i.e. channel length, width, and sinuosity) are also consistent with the values measured for terrestrial submarine fans and deltas (Fig. 3.9, 3.11). The mean sinuosity of the channels on the six distal terrestrial submarine fans is low overall. Sinuosity ranges from 1.0 to 1.3 but the majority of the submarine fans have channels with a sinuosity less than 1.1. The Melas fan channels also have low sinuosity with most values below 1.05. The relationship between mean channel length and mean channel width for submarine fans and deltas roughly follows a power law distribution (Fig. 3.11). The channels on the Melas fans follow a similar trend. The steepness of the power law trend does not appear to correlate with the dominant grain size present on the fan, the water depth of the fan, fan size, margin type or drainage basin size. It is possible that a combination of these factors determines how quickly or slowly the channel width decrease for a given decrease in channel length. We have not yet identified a good quantitative measure of channel properties that is able to distinguish between the submarine channels formed on submarine fans and the subaerial channels formed on deltas.

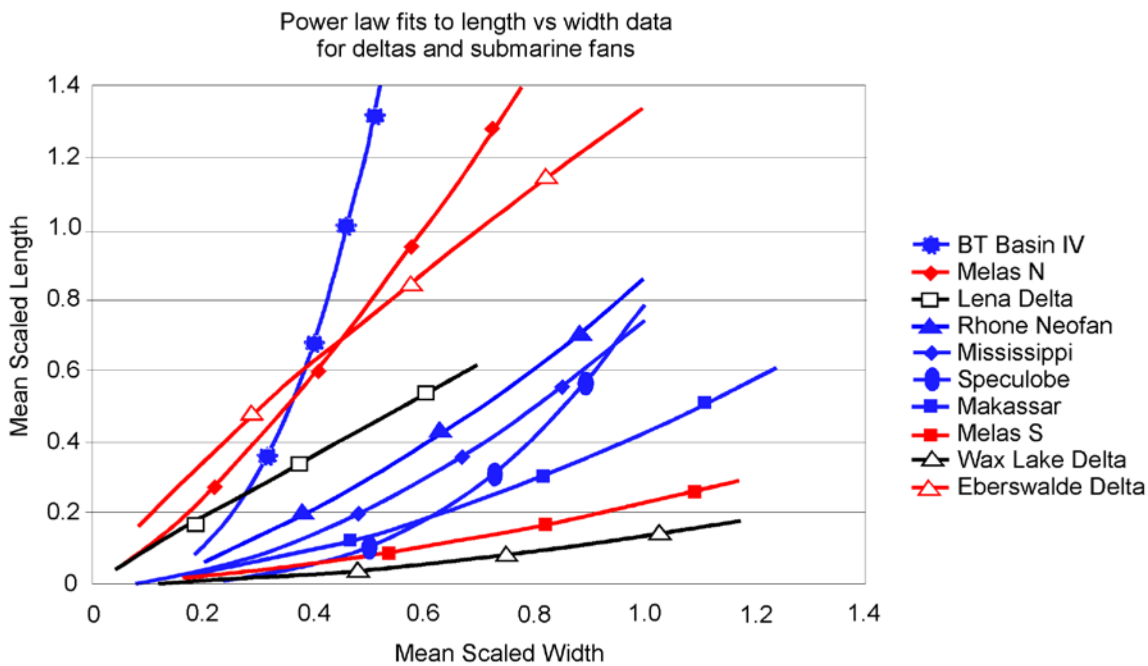

Figure 3.11 Plot showing power law fits to mean scaled channel length versus mean scaled channel width data. Fits for six terrestrial submarine fans, two terrestrial deltas, one Martian delta, and the two western Melas fans are plotted. This plot shows that the channel widths and lengths for the Melas fans fall within the typical range of values seen for terrestrial submarine fans and deltas.

Terrestrial submarine fans typically have only one active main channel at a time (Damuth et al. 1983b; Wynn et al. 2007). Each channel is eventually abandoned, probably by avulsion, and a new channel is formed nearby. This may have been the case for the Melas fans as well. The northern fan was deposited first since it is located stratigraphically and topographically below the southern fan. Eventually, its feeder channel was abandoned, and the channel may have avulsed to a new course further south. This could have resulted in the deposition of the southern fan.

Many features of the Melas fans are also shared with deltas. However, based on detailed morphologic comparisons of the lobes as well as basin location, the Melas fans appear more similar to terrestrial submarine fans than to either terrestrial or Martian deltas.

3.6.3 Discriminating Between Deltas and Submarine Fans

Analysis of plan-view morphology and slopes provides broad constraints on interpretations of depositional fans, but does not uniquely constrain their origin. Morphology alone points to a sublacustrine origin, however, a deltaic origin cannot be excluded. The observed facies, as well as their stacking pattern, allows us to discriminate conclusively whether deposits were formed as part of a delta or a submarine fan.

Since most of the information necessary to distinguish different sedimentary facies is small-scale, orbital images do not provide the necessary resolution. Views of the deposit in cross-section that expose details at the centimeter to decimeter scale would be required to provide definitive evidence of sublacustrine sediment transport via turbidity currents. Obtaining this kind of data would require rover images, similar to those taken at Meridiani

Planum by the Mars Exploration Rover *Opportunity* (Grotzinger et al. 2005; Metz et al. 2009a) and at Gusev crater by Spirit (Lewis et al. 2008b).

Distinctive features that could be observed in a deltaic environment, but would not be expected in a submarine fan environment include point bar deposits, floodplain deposits, paleosols and mudcracks (MacNaughton et al. 1997). Submarine fans are largely composed of the deposits of turbidity currents. However, turbidity currents can also occur in the distal delta front and in prodeltas, and so the presence of these deposits alone is not diagnostic (Mutti et al. 2003; Pattison 2005). Distinguishing a prodelta from a submarine fan may require examination of the fan architecture. The study of detailed facies transitions and stacking patterns may be necessary to distinguish between submarine fans and distal deltaic facies.

3.6.4 Timescales

In an effort to obtain the most conservative estimate of fan formation time, we have calculated minimum durations. This calculation assumes a continuous sediment accumulation rate, but it is known from Earth that sedimentation is characteristically discontinuous in time, and that discontinuities are the rule not the exception (Sadler 1981). Minimum formation time can be constrained using several approaches; analyses of formation times for subaerial deposits of roughly comparable volume on Mars (Jerolmack et al. 2004; Kraal et al. 2008b), estimates of subaqueous fan formation on Earth provided by age dating fan deposits, and quantitative estimates of how long turbidity currents would have taken to deposit the fans.

The well-studied terrestrial deposit of the Brazos-Trinity fan in Basin IV is somewhat larger in size than the Melas fan and formed in no more than ~35,000 years (Behrmann et al. 2006; Mallarino et al. 2006). This measure is similar to ~17,000 years of sediment deposition leading to development of several submarine fans in the California Borderland (Covault et al. 2007). Together these examples constrain a millennial-scale estimate for the minimum time that water must have been present in Southern Melas Basin. This estimate includes within it intervals of non-deposition. Deposits which span longer time intervals have the opportunity to incorporate more and longer hiatuses (Sadler 1981). Removing this inactivity would shorten the formation time and duration for standing water in Melas basin.

Theoretical analyses of primarily subaerial fan deposition on Mars assuming no intermittency in construction place minimum formation times at the decadal to century scale (Jerolmack et al. 2004; Kraal et al. 2008b). Comparison of formation times between these relatively proximal depositional systems and the distal fan of Southern Melas Basin is reasonable because of differences in the efficiency with which these systems trap sediment. Proximal subaerial systems have more sediment moving through them but also have relatively low trapping efficiencies for this detritus (Trimble 1981; Allison et al. 1998; Goodbred and Kuehl 1998; Walling et al. 1999), while distal subaqueous fans are viewed as efficient sediment traps.

Formation times for the Melas fans were also estimated by calculating how long subaqueous turbidity currents would need to flow in order to deposit the volume of material observed to compose the visible part of the fans. To estimate how long each lobe takes to form, we need to know the rate of sediment transport (Q_s). Fluid discharge through the channels is given by

$$Q_w = uBH \tag{1}$$

where u is the mean flow velocity, B is the channel width and H is the channel depth. Channel width and minimum depth (see discussion in the *Methods* section) can be measured from the Melas DEM. The flow velocity can be found by the Chezy flow resistance relation

$$u = (\tau_a^* RgD\alpha_r^2)^{1/2} \tag{2}$$

where τ_a^* is the dimensionless formative shear stress, R is the submerged specific density of grains ($R = \frac{\rho_s}{\rho} - 1$, where ρ_s is the sediment density and ρ is the fluid density), g is Martian gravity (g = 3.7 m/s^2), D is the grain diameter, and α_r is the resistance coefficient for flow in a channel. In order to determine the values of these parameters, a grain size and composition must be assumed. We assumed sand sized quartz grains (D=0.3 mm) which leads to τ_a^* =1.8, R=1.65, and α_r =15 for active, mobile bed conditions (Parker et al. 1998). This yields a flow velocity of 0.8 m/s which is reasonable for turbidity currents. The characteristic velocity of turbidity currents can be related to the buoyancy flux by

$$B_f = RguhBC \tag{3}$$

where B_f is the buoyancy flux, h is the flow thickness, and C is the concentration of sediment in the turbidity current. Britter and Linden (1980) related the buoyancy flux per unit width to the velocity of the current by

$$u_{front} = \Omega \left[\frac{B_f}{B} \right]^{1/3} \tag{4}$$

where u_{front} is the velocity of the head of the turbidity current and Ω is a proportionality factor. The densimetric Froude number is given by

$$Fr_{densimetric}{}^2 = \frac{u_{front}{}^2}{RghC} \tag{5}$$

(Middleton 1993), and can be related to Ω by

$$Fr_{densimetric}{}^2 \cong \Omega^3 = \frac{u_{front}{}^2}{RghC}. \tag{6}$$

For bed slopes between 0-10°, Ω^3 is between 1-1.5 (Britter and Lindon 1980). Since the slope of the southern Melas fan is ~1°, Ω^3 and hence the densimetric Froude number should equal ~1. In the case of small slopes, the front velocity of the turbidity current is the same as the characteristic velocity, so $u_{front}=u$ (Britter and Linden 1980). We can calculate the rate of sediment transport by

$$Q_s = Cu_{front}hB. \tag{7}$$

Typical sediment concentrations in turbidity currents range from 1-10%, and we assume a sediment concentration of 1% (Middleton 1993).

The timescale of formation is given by

$$t_{eq} = (1-\lambda)V / Q_s \tag{8}$$

where V is the lobe volume and λ is the porosity (assume λ=0.35) (Jerolmack et al. 2004). The time for the formation of each of the ten lobes of the southern Melas fan was calculated, and these were added to get an estimated time of formation of ~106 years.

This calculation assumes that each lobe was formed by one turbidity flow event, which is conservative in that it likely would have taken several flows to develop lobes with levee-bounded channel networks (Yu et al. 2006). Experiments on turbidity currents show that multiple flow events are needed to form channel networks on the surfaces of submarine fans (Yu et al. 2006). Thus, what we recognize as a lobe in a plan-view of the Melas fans likely took several flow events to form. This could be tested by a rover mission, which could examine each lobe in cross-section to determine the number of flow events required to form each lobe.

Our calculation also assumes there was no hiatus between different turbidity flow events, and so the actual formation time is likely to be longer. Laboratory and field experiments show that although turbidite events appear to take place on the order of hours to days, the time between events is on the order of years to thousands of years (Rothman et al. 1994). If there was a hiatus of 10 years between each event, the southern fan would have taken ~200 years to form, but if the hiatus was 1000 years then it would have taken ~10,000 years to form. The above timescale estimate does not take into account the formation time of the northern Melas fan, but assuming it took a comparable amount of time to form, this would double the amount of time standing water would have been required in the basin. By comparing analogous formation times for terrestrial submarine fans of comparable size, subaerial fan deposits on Mars, and our own calculations, we estimate a formation timescale of 10^2 to 10^4 years.

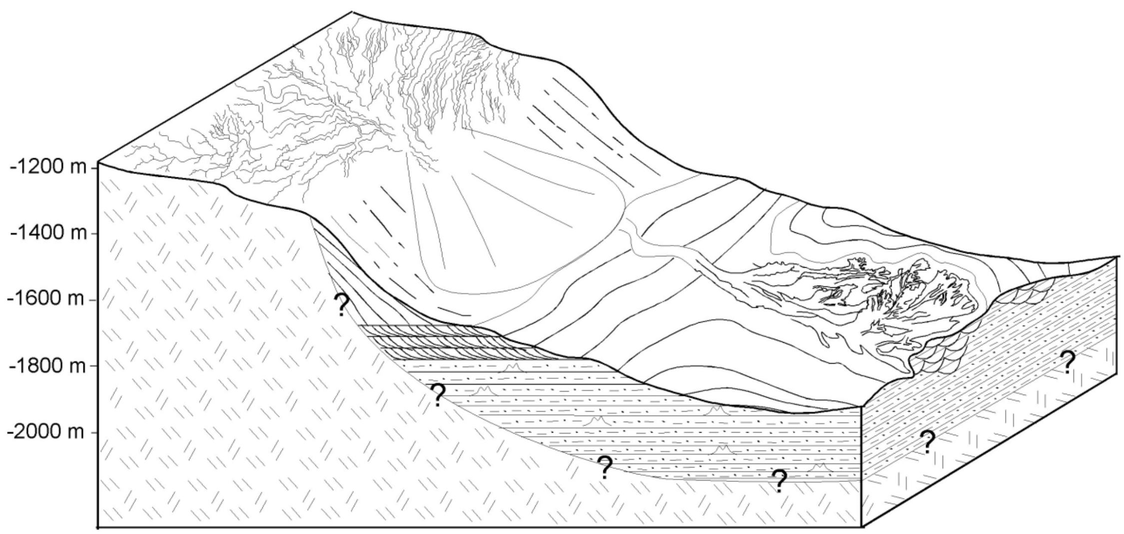

Figure 3.12 Ideal schematic arrangement of environments including sublacustrine fans, clinoforms, alluvial fan and incised channels; actual topography represented by white line in Fig. 3.2b. The inferred sublacustrine fans occur in the topographically lowest part of the basin.

6.5 Sublacustrine fans as terminal sediment sinks

We suggest that Southern Melas Basin could represent a complete erosional-to-depositional system, from the fluvially-incised source region in the surrounding highlands to the terminal sediment sink formed by the sublacustrine fans in the topographically lowest part of the basin (Fig. 3.2b, 3.12). Sediments are moved from their source in the surrounding mountainous areas to their sink in depositional areas by the sediment transport system (Allen 2008). Fluvial incision of bedrock, interpreted to be caused by runoff from precipitation, drains the ridges bordering the western and eastern parts of the basin (Mangold et al. 2004; Quantin et al. 2005). Sediments generated during erosion of the upland areas were transported by fluvial drainage systems to form a classic, cone-shaped alluvial fan at the western edge of the basin where confined channel flow emerges onto the fan surface (Quantin et al. 2005). The preservation of sediments in the alluvial fan depends on whether there is accommodation space available to store the sediment over the long term. Accommodation space can be generated when the graded profile of these streams moves upwards in response to a rise in base level or to uplift of the source area (Viseras et al. 2003). The amount of sediment permanently stored in the alluvial fans is likely small compared to the total flux of sediment (Allen 2008). Sediments which pass through the alluvial fan could then be deposited as the clinoforms, which could record a potential shoreline or the upslope channel levee part of the submarine fan system (Dromart et al. 2007). The clinoforms give way further down the topographic profile to a sublacustrine fan, very similar in morphology to the Mississippi submarine fan (Fig. 3.2b, 3.12). This ultimate topographic low in the system then provides the terminal sink for the sediments (Leeder 1999).

The above interpretation assumes that the various elements of the geomorphic system are all the same age. If these features have different ages, then the linkages between elements in the sediment transport system would not necessarily hold. However, even if not all of these elements are the same age, they still represent pieces of the sediment transport system. For example, cross-cutting relationships suggest there are several generations of valley networks preserved in the ridges surrounding Southern Melas Basin (Quantin et al. 2005). It is not possible to determine which generation of the drainages may have fed the depositional fans currently preserved in the bottom of the basin. Similar to the valley networks, perhaps the currently exposed clinoforms overlie a set of older buried clinoforms that are the same age as the depositional fan. As sediments were transported into the basin, the depositional system could have responded with retrogradation, aggradation, or progradation of the sediment depocenter further into the basin; these dynamic responses depend on how the incoming sediment flux balances with basin subsidence and lake level (Flemings and Grotzinger 1996; Hodgson et al. 2006).

We are assuming here that the sediments described in Southern Melas Basin post-date canyon formation and can therefore be linked to the modern geomorphic surface. If these sediments are actually older than the basin itself and have been exposed through erosion of the basin floor, then the depositional fans would predate, and thus not be related to the clinoforms, the alluvial fan, or the valley networks. Conclusive stratigraphic contacts that show that layered sediments underlie the volcanic material composing the ridges in Melas Chasma have not been observed. Areas where stratigraphic contacts are conclusive, such as to the east of Southern Melas Basin, show these layered materials onlap the ridges. Thus, there is no evidence to suggest that the layered materials in Southern Melas Basin are older than the basin.

3.7 Conclusions

The novel depositional fans in Southern Melas Basin have a unique morphology which includes multiple lobes with dendritic finger-like terminations that branch off at high angles in the downstream direction. The southern fan is located at a higher stratigraphic level than the northern fan, and layers near the fans show evidence for hydrated minerals including opaline silica and jarosite. The Melas fans appear morphologically similar to deltas and submarine fans; however, the details of the morphology and their basin position suggest that they are likely to be sublacustrine fans. Quantitative comparisons of the channel patterns present on the Melas fans show they are consistent with the channel patterns observed on terrestrial submarine fans, although the channel pattern on deltas is similar. A rover mission could acquire the detailed facies information necessary to conclusively discriminate between submarine fans and deltas. Estimates of minimum fan formation timescales suggest the fans formed in 10^2 to 10^4 years, and thus a stable body of water must have been present for at least this long. The preservation of valley networks in the topographic highs surrounding the basin, an alluvial fan where these valley networks drain into the basin, clinoforms, and depositional fans in the lowest part of the basin, suggest that the entire depositional system is preserved from the source area to the sink. This suggests that Mars was capable of supporting surface liquid bodies of water for a significant period of time during the initial stages of Valles Marineris formation.

Apex latitude (N)	Apex longitude (E)	Fan gradient (°)	Reference
-1.4	58.3	4.75	Kraal et al 2008
-1.46	58.39	4.06	Kraal et al 2008
-7.27	356.22	2.64	Kraal et al 2008
-18.09	322.89	2.66	Moore & Howard 2005
-18.32	340.11	2.21	Moore & Howard 2005
-18.41	323.35	5.67	Moore & Howard 2005
-20.1	123.2	6.41	Kraal et al 2008
-20.34	324.21	1.3	Moore & Howard 2005
-21.14	320.66	1.83	Moore & Howard 2005
-21.35	72.68	1.82	Moore & Howard 2005
-21.47	67.22	1.48	Moore & Howard 2005
-21.52	320.09	2.03	Moore & Howard 2005
-21.66	72.56	1.82	Moore & Howard 2005
-21.68	66.41	2.25	Moore & Howard 2005
-22.36	66.53	3.24	Moore & Howard 2005
-22.73	74.46	2.23	Moore & Howard 2005
-22.76	74.03	1.42	Moore & Howard 2005
-23.04	74.74	3.21	Moore & Howard 2005
-23.14	73.83	3.6	Moore & Howard 2005
-23.31	73.99	3.59	Moore & Howard 2005
-23.32	27.07	2.58	Moore & Howard 2005
-23.37	74.58	2.33	Moore & Howard 2005
-23.45	74.35	1.96	Moore & Howard 2005
-23.56	27.44	2.08	Moore & Howard 2005
-23.62	27.18	2.56	Moore & Howard 2005
-23.91	28.15	2.08	Moore & Howard 2005
-24.31	28.29	1.67	Moore & Howard 2005
-24.84	27.42	2.16	Moore & Howard 2005
-24.96	325.71	1.52	Moore & Howard 2005
-25.88	324.85	2.66	Moore & Howard 2005
-26.23	331.52	2.1	Moore & Howard 2005
-26.43	324.84	2.53	Moore & Howard 2005
-27	332.99	2.33	Moore & Howard 2005
-27.58	332.85	2.36	Kraal et al 2008
-27.65	332.93	1.58	Kraal et al 2008
-28.04	332.91	1.55	Kraal et al 2008
-28.09	332.77	2.26	Kraal et al 2008
-28.49	84.07	1.77	Moore & Howard 2005
-28.54	84.51	3.21	Moore & Howard 2005
-33	84.26	1.32	Kraal et al 2008
-33.02	84.19	1.58	Kraal et al 2008
-49.6	113.6	2.33	Kraal et al 2008
-51	114.3	1.85	Kraal et al 2008
-51	113.5	2.33	Kraal et al 2008
	Average	**2.5°**	

Table 3.4 Compilation of Martian alluvial fan gradients. The average gradient is 2.5°.