PS A Review of Slipface Processes and Structures in Terrestrial Eolian Dunes, *and a Comparison with Dunes on Mars*

Steven G. Fryberger[1], Andrew Valdez[2], and Nick Jones[3]

Search and Discovery Article #51690 (2021)**
Posted March 29, 2021

[1]Steven Fryberger Petroleum, Fort Collins, CO
[2]National Park Service, Great Sand Dunes National Park, CO
[3]Consultant, Casper, Wyoming

Abstract

Avalanches can initiate anywhere on a dune slipface, although they most commonly start near the dune brink, where most grainfall accumulates and slopes are steeper. Whether or not an avalanche reaches the bottom of the slipface depends upon two primary factors: (A) The thickness and downslope extent of the grainfall layer; that is, how deeply the slipface is covered by fresh, unstable sand and (B) the shape of the dune, particularly the steepness of slope from the brink to the base of the dune.

Moisture from rainfall, dew, snow or frost; and early cementation, will cause varying degrees of sand cohesion on a dune slipface. The strength of this cohesion, and it's distribution, controls the amount of sand available for re-sedimentation as avalanches, as well as the geomorphology of the sandflow or slump. Cohesion of sand at the brink of the dune, whether in a fresh grainfall layer or underlying eolian strata, promotes the formation of a distinct alcove and scarp at the top of the flow. Alcoves form and grow due to collapse of newly-deposited grainfall layers, as well as headward wasting into the strata of the crest and brink (commonly ripple strata). Cohesion that drives the process can result from various processes. For example, airborne dust and clays, diagenesis of sand grains, moisture that is damp or frozen, or close packing of sand grains in ripple strata. It is clear that the depth of alcove and ridge formation is a function of the degree of cohesion of the sand at the top of the dune.

The degree of cohesion, and the thickness and arrangement of cohesive layers on a slipface also controls the geomorphology of avalanches. Weather conditions preceding an avalanche will affect the geomorphology of that avalanche. For example, rain in the recent past, followed by a sandstorm, may stack a thin layer of dry sand atop a damp cohesive layer. This, in turn, may cause the avalanche to be thinner than otherwise. Thin meniscus cements may exist at grain contacts if there are nearby sources of clays or abundant airborne dust. Light cohesion on sand also creates the shallow scarps that are commonly found on the margins of avalanches. These lateral scarps are thickest at the top of the avalanche,

thinning downslope. Given sufficient cohesion of the sand on the slipface, the height of the scarp is dependent upon the amount of sediment removed downslope. These features are commonly preserved in ancient rocks.

Washboard structures are common on most avalanches. They appear related to differential flow rates (shear stress) within the avalanche. Dynamically they behave like waveforms, moving downslope during the flow. They can be triggered by blocks of sand that break off at the retreating scarp of the alcove at the top of the flow. This caving of brink deposits into avalanches is common, usually in the form of soft blocks of sand that quickly lose individuality down-slope.

Avalanches commonly stop flowing from the base upward in a “propagating wave” or “deck of dominoes” style, depending upon flow smoothness, or blockiness.

As a simplification, avalanches can be roughly divided into an upper tensional domain (where most sand is removed and flow starts), a middle transitional domain and a lower compressional domain (where most sand is deposited and flow stops). Each of these domains is typified by distinctive sedimentary structures as originally observed by McKee (1971) and further described in this report (Please see Figure 5-1). A review of the dynamics of avalanches, including our videos of flows, indicates that these domains shift throughout the flow as it evolves from the first slope failure through cessation.

Introduction

In this report we review the basic process frameworks, geomorphology, and sedimentary structures of the slipfaces of modern eolian dunes from various localities. This introductory first page provides an overview of typical sedimentary structures and terminology used to describe dry sand avalanches (Figures 1-1 through 1-8). We provide a summary of our new work on the complex dune and slipface morphology of reversing dunes at Great Sand Dunes National Park - the “type locality” of that bedform as originally named by McKee (1966). We describe ancient eolian slipface sedimentary structures as seen in bedding-plane view, including rare examples of seldom-preserved upper slipface avalanche alcoves. Our examples include slipface alcoves and avalanches from rocks of the Cambrian Amin Formation, Sultanate of Oman, and the Permian Tensleep and Lyons Formations, Wyoming and Colorado, U.S.A.

There are links in this report to videos we acquired during our studies at Great Sand Dunes, in order to help readers visualize the complex, dynamic nature of what, at first glance, might seem like the simple process of sand sliding down a dune slipface. Our work has benefitted from the work of many previous researchers, most recently from scientists studying the dunes of Mars; and we include a page illustrating dunes on that planet. Scientists studying the eolian deposits of Mars have done much to advance our understanding of the geomorphology of eolian avalanches. A selection of the previous works that we relied on most are listed in the bibliography. While not exhaustive this bibliography may help the reader navigate the literature of eolian slipfaces on both Earth and Mars. We include a selection of images and links to videos of avalanche processes on Mars. These illustrate both similarities and differences between eolian processes on Earth and Mars. Mars has an eolian system that has been active for a long time geologically, and has much to teach us about eolian processes on Earth.

Acknowledgments

We thank the Fred Bunch and the National Park Service staff at Great Sand Dunes National Park, Colorado, USA, for encouragement to conduct our scientific investigations of slipfaces on the dunes in the park. We are grateful to the Lyons Quarry at Lyons, Colorado, USA for access to outcrops of the Lyons Sandstone in their quarry. We also thank Petroleum Development Oman for facilitating access to outcrops of the Amin Sandstone in the Huqf of Oman. The senior author thanks the Research Institute at the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, for the opportunity study the dunes of the Jafurah sand sea. Thanks also to the Enhanced Oil Recovery Institute of the University of Wyoming, USA, and the Bureau of Land Management for making possible our study of outcrops at Flat Top anticline near Medicine Bow, Wyoming. We thank Franci Fryberger for assistance to our field work and very helpful editorial work on this document! Note, unless specifically credited, photos and illustrations are by the senior author.

References Cited and Bibliography

Ahlbrandt, T.S. and Andrews, S., 1978, Distinctive sedimentary features of cold-climate eolian deposits, North Park, Colorado; Palaeogeography, Palaeoclimatology, Palaeoecology, 25, 327-351.

Ahlbrandt, T.S. and Fryberger, S.G., 1980, Eolian deposits in the Nebraska Sand Hills; USGS Prof. Paper 1120A, 1-24.

Ahlbrandt, T.S. and Fryberger, S.G., 1981, Sedimentary features and significance of interdune deposits; in F.G. Etheridge and R.M. Flores, eds., SEPM Special Pub. 31, Recent and ancient non-marine depositional environments, 293-314.

Ahlbrandt, T.S. and Fryberger, S.G., 1982, An introduction to eolian deposits; in P.A. Scholle and D. Spearing, eds., Sandstone Depositional Environments, A.A.P.G., Memoir 31, 11-47.

Allen, J.R.L., 1970, The Avalanching of Granular Solids on Dune and Similar Slopes; The Journal of Geology, 78, 236-351.

Allen, J.R.L., 1971, Intensity of Deposition from Avalanches and the loose packing of avalanche deposits; Sedimentology 18, 105-111.

Anderson, R.S., 1988, The pattern of grainfall deposition in the lee of aeolian dunes; Sedimentology, 35, 175-188.

Bagnold, R. A.,1941, The Physics of Blown Sand and Desert Dunes, 265 pp., Methuen, London.

Bauer, B. O., and R. G. Davidson-Arnott, 2003, A general framework for modeling sediment supply to coastal dunes including wind angle, beach geometry, and fetch effects, Geomorphology, 49(1), 89–108.

Börzsönyi, T., T. C. Halsey, and Ecke, R. E., 2008, Avalanche dynamics on a rough inclined plane, Phys. Rev. E, 78, 011306, PhysRevE.78.011306

Bourke, M. C., 2010, Barchan dune asymmetry: Observations from Mars and Earth; Icarus, 205, 183–197.

Bourke, M. C., Edgett, K. S. and Cantor, B.A., 2008, Recent aeolian dune change on Mars, Geomorphology, 94, 247–255.

Bourke, M.C., Ewing, R.C., Finnegan, D. and McGowan, H.A., 2009. Sand dune movement in the Victoria Valley, Antarctica. Geomorphology 109, 148–160.

Breed, C.S., Fryberger, S.G., Andrews, S., McCauley, C., Lennartz, F., Gebel, D. and Horstman, K., 1979, Regional studies of sand seas, using LANDSAT (ERTS) imagery; Chap. K in McKee, E.D. ed. A study of Global Sand Seas, USGS Prof. Paper 1052, 305- 397

Breton, C., Lancaster, N., and Nickling, W.G., 2008, Magnitude and frequency of grain flows on a desert sand dune, Geomorphology 95, 518-523.

Bridges, N.T. and Ehlmann, B.L., 2017, The Mars Science Laboratory (MSL) Bagnold Dunes Campaign, Phase 1: Overview and introduction to the special issue; Journal of Geophysical Research: Planets 123, 3-19.

Bristow, C.S., Bailey, S.D. and Lancaster, N., 2000. The sedimentary structure of linear sand dunes. Nature 406, 56–59.

Bristow, C.S., Duller, G.A.T. and Lancaster, N., 2007. Age and dynamics of linear dunes in the Namib Desert. Geology 35, 555–558.

Bristow, C.S., Jol, H.M., Augustinus, P., and Wallis, I.C., 2009. Slipfaceless ‘whaleback’ dunes in a polar desert, Victoria Valley, Antarctica: insights from ground penetrating radar. Geomorphology.

Bristow, C.S., Augustinus, P.C., Wallis, I.C., Jol, H.M. and Rhodes, E.J., 2010, Investigation of the age and migration of reversing dunes in Antarctica using GPR and OSL, with implications for GPR on Mars; Earth and Planetary Science Letters 289, 30-42.

Bristow, C.S., Jol, H.M., Augustinus, P. and Wallis, I., 2010, Slipfaceless whaleback dunes in a polar desert, Victoria Valley, Antarctica: Insights from ground penetrating radar; Geomorphology 114, 361-372.

Cardinale, M., et al., 2016, Present-day aeolian activity in Herschel Crater, Mars. Icarus 265 (2016) 139–148

Cornwall, C., Jackson, D.W.T., Bourke, M.C. and Cooper, J.A.G., 2015, Investigation of Martian Aeolian Dynamics using terrestrial dune analogues and airflow modelling, Fourth International Planetary Dunes Workshop (abs.)

Cornwall, C., Jackson, D., Bourke, M. and Cooper, A., 2016, Aeolian Slipface processes on Earth and Mars; Geophysical Research Abstracts 18, EGU2016-281

Cornwall, C., Bourke, M.C., Jackson, D.W.T. and Cooper, J.A.G., 2017, Grainflow morphologies and high resolution airflow modeling of Bagnold Dunes, Gale Crater, Mars; Fifth International Planetary Dunes Workshop (contribution 1961) (abs.) 2pp.

Cornwall, C., Bourke, M.C., Jackson, D.W.T. and Cooper, J.A.G., 2018a, Aeolian slipface dynamics and grainflow morphologies on Earth and Mars; Icarus 314, 311-326.

Cornwall, C., Jackson, D.W.T., Bourke, M.C. and Cooper, J.A.G., 2018b, Morphometric analysis of slipface processes of an aeolian dune: Implications for grain-flow dynamics; Sedimentology 65, 2034-2054.

Craddock, R.A., 2011, Aeolian processes on the terrestrial planets: Recent observations and future focus; Progress in Physical Geography, 36, 110-124.

Eastwood, E.N., Kocurek, G., Mohrig, D. and Swanson, T., 2012, Methodology for reconstructing wind direction, wind speed and duration of wind events from aeolian cross-strata; J. Geophys. Res., 117, F03035

Fenton, L.K. and Bandfield, J.G., 2003, Aeolian processes in Proctor Crater on Mars: Sedimentary history as analyzed from multiple data sets; Jour. Geophys. Res. 108, E12, 5129

Fenton, L.K., 2005, Potential sand sources for the dune fields in Noachis Terra, Mars; Jour. Geophys. Res., 110, E11004

Fenton, L.K., 2006, Dune migration and slip face advancement in the Rabe Crater dune field, Mars. Geophysical Research Letters, 33, L20201, doi:10.1029/2006GL027133

Foroutan, M. and Zimbelman, J.R., 2016, Mega-ripples in Iran: a new analog for transvers aeolian ridges on Mars; Icarus 274, 99-105.

Forman, S.L., Spaeth, M., Marin, L., Pierson, J., Gomez, J., Bunch, F. and Valdez, A. 2006, Episodic Late Holocene dune movements on the sand-sheet area, Great Sand Dunes National Park and Preserve, San Luis Valley, Colorado, USA; Quaternary Research 66, 97-108.

Fryberger, S.G., 1991, Unusual sedimentary structures in the Oregon coastal dunes, Journal of Arid Environments 21, 131-150.

Fryberger, S.G., 1993, A review of eolian bounding surfaces, with examples from the Permian Minnelusa Formation, USA; *in*, North, C.P and Prosser, D.J. (eds.) Characterization of Fluvial and Aeolian Reservoirs, Geological Society Special Publication no. 73, p 167-197.

Fryberger, S.G., 2009, Stratigraphy and depositional environments of the Cambrian Amin Formation, Oman; Petroleum Development Oman Exploration Report 589.

Fryberger, S.G. and Dean, G., 1979a, Dune forms and wind regime; Chap. F in McKee, E.D., ed., A Study of Global Sand Seas; USGS Professional Paper 1052, 137- 169.

Fryberger, S.G., Ahlbrandt, T.S. and Andrews, S., 1979b, Origin, Sedimentary features and significance of low-angle eolian "Sand Sheet" deposits, Great Sand Dunes National Monument and Vicinity, Colorado; Jour. Sed. Petrology, 49, 733- 746.

Fryberger, S.G., and Schenk, C.J., 1981, Wind sedimentation tunnel studies on the origins of aeolian strata; Sedimentology, 28, 805-821.

Fryberger, S.G., Al-Sari, A.M. and Clisham, T.J., 1983, Eolian dune, interdune, sand sheet, and siliciclastic sabkha sediments of an offshore-prograding sand sea, Dhahran area, Saudi Arabia; AAPG Bulletin, 67, 280-312.

Fryberger, S.G., Al-Sari, A.M., Clisham, T.J., Rizvi, S.A.R., and Al-Hinai, K., l984, Wind sedimentation in the Jafurah Sand Sea, Saudi Arabia; Sedimentology, 31, 413-431.

Fryberger, S.G., Schenk, C.J. and Krystinik, L.F., 1988, Stokes surfaces and the effects of near-surface groundwater-table on aeolian deposition; Sedimentology, 35, 21-41.

Fryberger, S.G., and Schenk, C.J., 1988, Pin-stripe lamination: A Distinctive Feature of Modern and Ancient Eolian Sediments; Sedimentary Geology, 55, 1-55.

Fryberger, S.G., Krystinik, L.F., and Schenk, C.J., 1990a, Tidally flooded back-barrier dunefield, Guerrero Negro area, Baja California, Mexico; Sedimentology, 37, 23-43.

Fryberger, S.G., Krystinik, L.F., and Schenk, C.J., 1990b, Modern and Ancient Eolian Deposits: Petroleum Exploration and Production; Published by Rocky Mountain Section, S.E.P.M. 240 pp.

Fryberger, S.G., Hesp, P. and Hastings, K., 1992, Eolian granule ripple deposits, Namibia; Sedimentology, 39, 319-331.

Fryberger, S.G., Al Kindy, S. and Najwani, H., 2006, High frequency inter-bedding of dune and extra-dune sediments in the Cambrian Amin Formation in North Oman: Control on Reservoir Properties (with analogues from modern sediments of Oman), *GEO 2006* Middle East Conference and Exhibition; 27-29 March, *2006*; Manama, Bahrain.

Fryberger, S.G., Walker, B., and Rutherford, R., 2001, Eolian Deposits of the Younghusband Carbonate Barrier, South Australia: Analog for Ancient Eolian Petroleum Reservoirs, SEPM Special Publication 71, p. 117-138.

Fryberger, S.G. and Hern, C. Y., 2014, A Geometric Approach to the Analysis of Global Eolian Hydrocarbon Reservoirs, AAPG Search and Discovery Article #41478

Fryberger, S.G., Jones, N., Johnson, M. and Chopping, C., 2016a, Stratigraphy, Exploration and EOR Potential of the Tensleep/Casper Formations, SE Wyoming, AAPG Search and Discovery Article #10851

Fryberger, S.G., Hern, C.Y. and Glennie, K., 2016b, Sedimentology of Reservoir-scale Aeolian-Fluvial Interactions, Wadi Batha, Northern Wahiba Sand Sea, Oman, AAPG Search and Discovery Article #51260.

Fryberger, S.G., Hern, C.Y. and Jones, N., 2017, Modern and Ancient Analogues for Complex Eolian Reservoirs, AAPG Search and Discovery article #51401

Grauch, V.J.S., and Ruleman, C.A., 2013, Identifying buried segments of active faults in the Northern Rio Grande Rift using aeromagnetic, LiDAR, and gravity data, South-Central Colorado, USA, International Journal of Geophysics 2013 article ID 804216 26 pp.

Greeley, R., Kraft, M.D., Kuzmin, R., and Bridges, N.T., 2000, Mars Pathfinder landing site: evidence for a change in wind regime from lander and orbiter data; Jour. Geophys. Res. 105, 1829-1840.

Greeley, R., Bridges, N.T. Kuzmin, R.O., and Laity, J.E., 2002, Terrestrial analogs to wind-related features at the Viking and Pathfinder landing sites on Mars; Jour. Geophys. Res. 107, 1-21.

Greeley, R., Squyres, S.W., et al, 2004, Wind-related processes detected by the Spirit Rover at Gusev Crater, Mars; Science 305, 810-821.

Greeley, R., Arvidson, R. E., et al, 2006, Gusev Crater: Wind-related features and processes observed by the Mars Exploration Rover Spirit; Jour. Geophys. Res. 111, 1-29

Grotzinger, J.P, et.al., 2005, Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns Formation, Meridiani Planum, Mars; Earth and Planetary Science Letters 240, 11-72.

Hayward, R.K., Mullins, K.F., Fenton, L.K., Hare, T.M., Titus, T.N., Bourke, M.C., Colaprete, A. and Christensen, P.R., 2007. Mars global digital dune database and initial science results. U.S. Geological Survey Open-File Report 2007-1158, p. 57.

Hayward, R.K., Titus, T.N., Michaels, T.I., Fenton, L.K., Colaprete, A., and Christensen, P.R., 2009, Aeolian dunes as ground truth for atmospheric modeling on Mars; Jour. Geophys. Res., 114, E11012

Horgan, B.H.N. and Bell, J.F., 2012, Seasonally active slipface avalanches in the north polar sand sea of Mars: Evidence for a wind-related origin; Geophysical Research Letters, 39, L9201, 6 pp..

Howell, J., and Mountney, N., 2001, Aeolian grain flow architecture: hard data for reservoir models and implications for red bed sequence stratigraphy; Petroleum Geoscience 7, 51-56.

Hutchinson, D. M., 1968. Provenance of sand in the Great Sand Dunes National Monument, Colorado, PhD dissertation, West Virginia University, 132 pp.

Janke, J. R., 2002, An analysis of the current stability of the Dune Field at Great Sand Dunes National Monument using temporal TM imagery (1984-1998); Remote Sensing of Environment 83, 488-497.

Jerolmack, D.J., Mohrig, D., Grotzinger, J.P., Fike, D. and Watters, W.A., 2006, Spatial grain size sorting in eolian ripples and estimation of wind conditions on planetary surfaces: application to Meridiani Planum, Mars. J. Geophys. Res. 111, E12S02.

Kocurek, G., and Dott, R.H. Jr., 1981, Distinctions and uses of stratification types in the interpretation of eolian sand; Jour. Sed. Petrology 51, 579-595.

Loosveld, R. J. H., Bell, A., and Terken J. J. M., 1996, The Tectonic Evolution of Interior Oman, GeoArabia 1, 28-51.

Lorenz, R.D. and Valdez, A., 2011, Variable wind ripple migration at Great Sand Dunes National Park and Preserve, observed by timelapse imaging; Geomorphology 133, 1-10

Madole, R.F., Romig, J.H., Aleinikoff, J.N., VanSistine, D. and Yacob, E.Y., 2008, On the origin and age of Great Sand Dunes, Colorado. Geomorphology 99, 99–119.

Madole, R.F., Mahan, S.A., Romig, J.H. and Havens, J.C., 2013, Constraints on the age of the Great Sand Dunes, Colorado, from subsurface stratigraphy and OSL dates; Quaternary Research 80, 435-446.

Malin, M.C., Carr, M.H., et al, 1998, Early views of the Martian surface from the Mars Orbiter camera of Mars Global Surveyor; Science 279, 1681-1685.

Marin, L., Forman, S.L., Valdez, A. and Bunch, F., 2005. Twentieth Century Dune Migration at the Great Sand Dunes National Park and Preserve, Colorado, relation to drought variability. Geomorphology 70, 163–183.

McCalpin, J. P., 1996, General geology of the northern San Luis Valley, Colorado, *in* Thompson, R. A., Hudson, M. R., and Pillmore, C. L., eds., Geologic Excursions to the Rocky Mountains and Beyond: Field Trip Guide for the 1996 Annual Meeting, Geological Society of America, Denver, CO, 11p.

McDonald, R.R., and Anderson, R.S., 1995, Experimental verification of aeolian saltation and lee side deposition models; Sedimentology 2, 39-56.

McDonald, R. R., and Anderson, R.S., 1996, Constraints on eolian grain flow dynamics through laboratory experiments on sand slopes, J. Sediment. Res., 66, 642–653.

McKee, E.D., 1945, Small-scale structures in the Coconino Sandstone of Northern Arizona; Journal of Geology 53, 313-325.

McKee, E.D., 1966, Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas). Sedimentology 7, 1– 69.

McKee, E.D., 1979, Ancient sandstones considered to be eolian. In: McKee, E.D. (Ed.), A Study of Global Sand Seas. U.S. Geological Survey Professional Paper 1052, 187– 233.

McKee, E.D., 1982, Sedimentary structures in dunes of the Namib Desert, South West Africa. Geological Society of America Special Paper 188, 1 –64.

McKee, E.D., 1983, Eolian sand bodies of the world. In: Brookfield, M.E., Ahlbrandt, T.S. (Eds.), Eolian Sediments and Processes. Developments in Sedimentology, vol. 38. Elsevier, Amsterdam, pp. 1 – 25.

McKee, E.D. and Tibbitts Jr., G.C., 1964, Primary structures of a seif dune and associated deposits in Libya. Journal of Sedimentary Petrology 34, 5 – 17.

McKee, E.D., Douglass, J.R., and Rittenhouse, S., 1971, Deformation of Lee-Side Laminae in Eolian Dunes; G.S.A. Bulletin, 82, 359-378.

McKee, E.D. and Bigarella, J.J., 1972, Deformational structures in Brazilian Coastal Dunes; Jour. Sed. Petrology 42, 670-681.

Milson, J. A., Mercadier, C.G.L., Livera, S.E., and Peters, J. M., 1996, The Lower Paleozoic of Oman and its context in the evolution of a Gondwanan continental margin; Jour. Geol. Soc. London 153, 213-230.

Nickling, W.G., McKenna Neuman, C., and Lancaster, N., 2002, Grainfall processes in the lee of transverse dunes, Silver Peak, Nevada; Sedimentology 49, 191-209.

Nield, J.M., Wiggs, G.F.S., Baddock, M.C. and Hipondoka, H.T., 2017, Coupling leeside grainfall to avalanche characteristics in aeolian dune dynamics; Geology, 45, 271-274.

Pelletier, J.D., Sherman D.J. et. al, 2015, Dynamics of sediment storage and release on aeolian dune slip face: a field study in Jericoacoara, Brazil; Jour. Geophysical Research: Earth Surface, 120, 1911-1934.

Schenk, C.J. and Fryberger, S.G., 1988, Early Diagenesis of Eolian Dune and Interdune Sands at White Sands, New Mexico; Sedimentary Geology, v. 55, p. 109-120.

Silvestro, S., Fenton, L..K., Michaels, T.I., Valdez, A. and Ori, G.G., 2012, Interpretation of the complex dune morphology on Mars: dune activity, modelling and a terrestrial analogue; Earth Surface Processes and Landforms, 37, 1424-1436.

Silvestro, S., and Elsayed, H., 2014, Reversing Dune; Encyclopedia of Planetary Landforms, DOI 10.1007/978-1-4614-9213-9_305-1., Springer Science and Business media, New York

Sharp, R.P., 1963, Wind Ripples; J. Geol. 71, 617–636.

Sutton, S.L.F., McKenna Neuman, C., and Nickling, W., 2013, Avalanche grainflow on a simulated aeolian dune; Journal of Geophysical Research: Earth Surface, 118, 1767-1776.

Stone, A.E.C., 2013, Age and dynamics of the Namib Sand Sea: A review of chronological evidence and possible landscape development models; Journal of African Earth Sciences, 82, 70-87.

Walker, T.R. and Harms, J.C., 1972, Eolian origin of flagstone beds, Lyons Sandstone (Permian), type area, Boulder County, Colorado; Mountain Geologist 9, 279-288.

Yizhaq, H., Isenberg, O., Wenkart, R., Tsoar, H., Karnieli, A., 2009. Morphology and dynamics of Aeolian mega-ripples in Nahal Kasuy, southern Israel. Isr. J. Earth Sci. 57, 149–165.

Zimbelman, J.R., Irwin, R.P., Williams, S.H., Bunch, F., Valdez, A., and Stevens, S., 2007, Granule ripples on earth and Mars; Lunar and Planetary Science XXXVIII (38), 2 pp.

Zimbelman, J.R., Irwin, R.P., Williams, S.H., Bunch, F., Valdez, A. and Stevens, S., 2009, The rate of granule ripple movement on Earth and Mars; Icarus 203, 71–76.

Zimbelman, J.R., 2010, Transverse Aeolian Ridges on Mars: First results from HiRISE images; Geomorphology 212, 22-29.

Zimbelman, J.R., Williams, S.H., and Johnson, A.K., 2012, Cross-sectional profiles of sand ripples, megaripples and dunes: a method for discriminating between formational mechanisms; Earth Surface Processes and Landforms 37, 1120-1125.

Zimbelman, J.R., Bourke, M.C., and Lorenz, R.D., 2013, Recent developments in planetary Aeolian studies and their terrestrial analogs; Aeolian Research 11, 109-126.

Zimbelman, J.R., 2019, The transition between sand ripples and megaripples on Mars; Icarus 333, 127-129.

A review of slipface processes and structures in terrestrial eolian dunes,

and a comparison with dunes on Mars

Steven G. Fryberger *1, Andrew Valdez *2 and Nick Jones *3

*1 Steven Fryberger Petroleum, Fort Collins, CO; *2 National Park Service, Great Sand Dunes National Park, CO, *3 Consultant, Casper, Wyoming

Abstract

Avalanches can initiate anywhere on a dune slipface, although they most commonly start near the dune brink, where most grainfall accumulates and slopes are steeper. Whether or not an avalanche reaches the bottom of the slipface depends upon two primary factors: (A) The thickness and downslope extent of the grainfall layer; that is, how deeply the slipface is covered by fresh, unstable sand and (B) the shape of the dune, particularly the steepness of slope from the brink to the base of the dune.

Moisture from rainfall, dew, snow or frost; and early cementation, will cause varying degrees of sand cohesion on a dune slipface. The strength of this cohesion, and it's distribution, controls the amount of sand available for re-sedimentation as avalanches, as well as the geomorphology of the sandflow or slump. Cohesion of sand at the brink of the dune, whether in a fresh grainfall layer or underlying eolian strata, promotes the formation of a distinct alcove and scarp at the top of the flow. Alcoves form and grow due to collapse of newly-deposited grainfall layers, as well as headward wasting into the strata of the crest and brink (commonly ripple strata). Cohesion that drives the process can result from various processes. For example, airborne dust and clays, diagenesis of sand grains, moisture that is damp or frozen, or close packing of sand grains in ripple strata. It is clear that the depth of alcove and ridge formation is a function of the degree of cohesion of the sand at the top of the dune.

The degree of cohesion, and the thickness and arrangement of cohesive layers on a slipface also controls the geomorphology of avalanches. Weather conditions preceding an avalanche will affect the geomorphology of that avalanche. For example, rain in the recent past, followed by a sandstorm, may stack a thin layer of dry sand atop a damp cohesive layer. This, in turn, may cause the avalanche to be thinner than otherwise. Thin meniscus cements may exist at grain contacts if there are nearby sources of clays or abundant airborne dust. Light cohesion on sand also creates the shallow scarps that are commonly found on the margins of avalanches. These lateral scarps are thickest at the top of the avalanche, thinning downslope. Given sufficient cohesion of the sand on the slipface, the height of the scarp is dependent upon the amount of sediment removed downslope. These features are commonly preserved in ancient rocks.

Washboard structures are common on most avalanches. They appear related to differential flow rates (shear stress) within the avalanche. Dynamically they behave like waveforms, moving downslope during the flow. They can be triggered by blocks of sand that break off at the retreating scarp of the alcove at the top of the flow. This caving of brink deposits into avalanches is common, usually in the form of soft blocks of sand that quickly lose individuality down-slope.

Avalanches commonly stop flowing from the base upward in a "propagating wave" or "deck of dominoes" style, depending upon flow smoothness, or blockiness.

As a simplification, avalanches can be roughly divided into an upper tensional domain (where most sand is removed and flow starts), a middle transitional domain and a lower compressional domain (where most sand is deposited and flow stops). Each of these domains is typified by distinctive sedimentary structures as originally observed by McKee (1971) and further described in this report (Please see Figure 5-1). A review of the dynamics of avalanches, including our videos of flows, indicates that these domains shift throughout the flow as it evolves from the first slope failure through cessation.

Introduction

In this report we review the basic process frameworks, geomorphology, and sedimentary structures of the slipfaces of modern eolian dunes from various localities. This introductory first page provides an overview of typical sedimentary structures and terminology used to describe dry sand avalanches (Figures 1-1 through 1-8). We provide a summary of our new work on the complex dune and slipface morphology of reversing dunes at Great Sand Dunes National Park - the "type locality" of that bedform as originally named by McKee (1966). We describe ancient eolian slipface sedimentary structures as seen in bedding-plane view, including rare examples of seldom-preserved upper slipface avalanche alcoves. Our examples include slipface alcoves and avalanches from rocks of the Cambrian Amin Formation, Sultanate of Oman, and the Permian Tensleep and Lyons Formations, Wyoming and Colorado, U.S.A.

There are links in this report to videos we acquired during our studies at Great Sand Dunes, in order to help readers visualize the complex, dynamic nature of what, at first glance, might seem like the simple process of sand sliding down a dune slipface. Our work has benefitted from the work of many previous researchers, most recently from scientists studying the dunes of Mars; and we include a page illustrating dunes on that planet. Scientists studying the eolian deposits of Mars have done much to advance our understanding of the geomorphology of eolian avalanches. A selection of the previous works that we relied on most are listed in the bibliography. While not exhaustive this bibliography may help the reader navigate the literature of eolian slipfaces on both Earth and Mars. We include a selection of images and links to videos of avalanche processes on Mars. These illustrate both similarities and differences between eolian processes on Earth and Mars. Mars has an eolian system that has been active for a long time geologically, and has much to teach us about eolian processes on Earth.

Acknowledgments

We thank the Fred Bunch and the National Park Service staff at Great Sand Dunes National Park, Colorado, USA, for encouragement to conduct our scientific investigations of slipfaces on the dunes in the park. We are grateful to the Lyons Quarry at Lyons, Colorado, USA for access to outcrops of the Lyons Sandstone in their quarry. We also thank Petroleum Development Oman for facilitating access to outcrops of the Amin Sandstone in the Huqf of Oman. The senior author thanks the Research Institute at the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, for the opportunity study the dunes of the Jafurah sand sea. Thanks also to the Enhanced Oil Recovery Institute of the University of Wyoming, USA, and the Bureau of Land Management for making possible our study of outcrops at Flat Top anticline near Medicine Bow, Wyoming. We thank Franci Fryberger for assistance to our field work and very helpful editorial work on this document! Note, unless specifically credited, photos and illustrations are by the senior author.

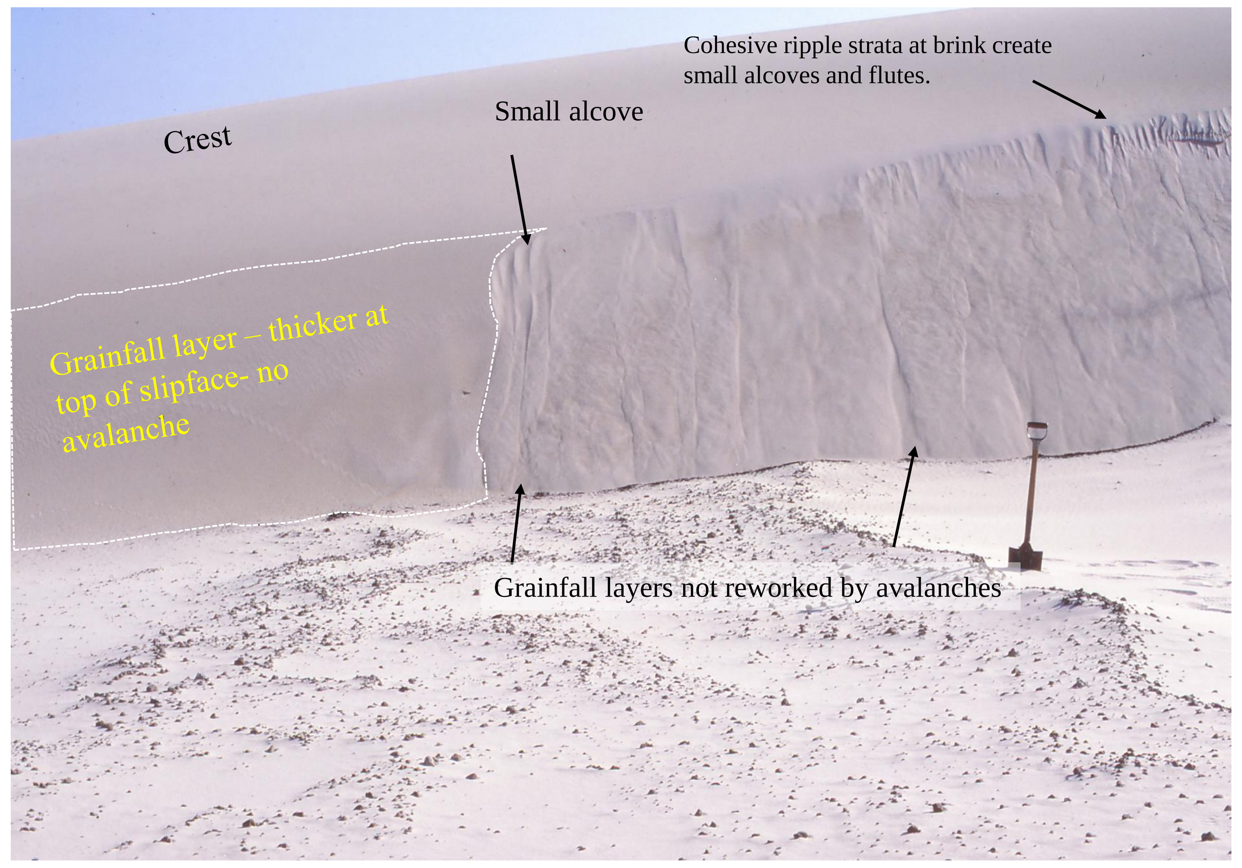


Figure 1-1 A partially-avalanched slipface (shovel for scale) on a transverse ridge, Hawks Nest dune field, New South Wales, in eastern Australia. Although thickest at the brink, and thinning downward, the grainfall layer reaches to the bottom of the slipface. This, along with a steep face, enables the avalanche to reach the base of the dune. There is no apron at the base of this slipface to cause a reduction in slope. In a few places a thin, narrow layer of grainfall has been bypassed by sand flows (arrows) suggesting that lower slope is just below the effective angle of repose, a common situation even in small dunes. View toward the northeast.

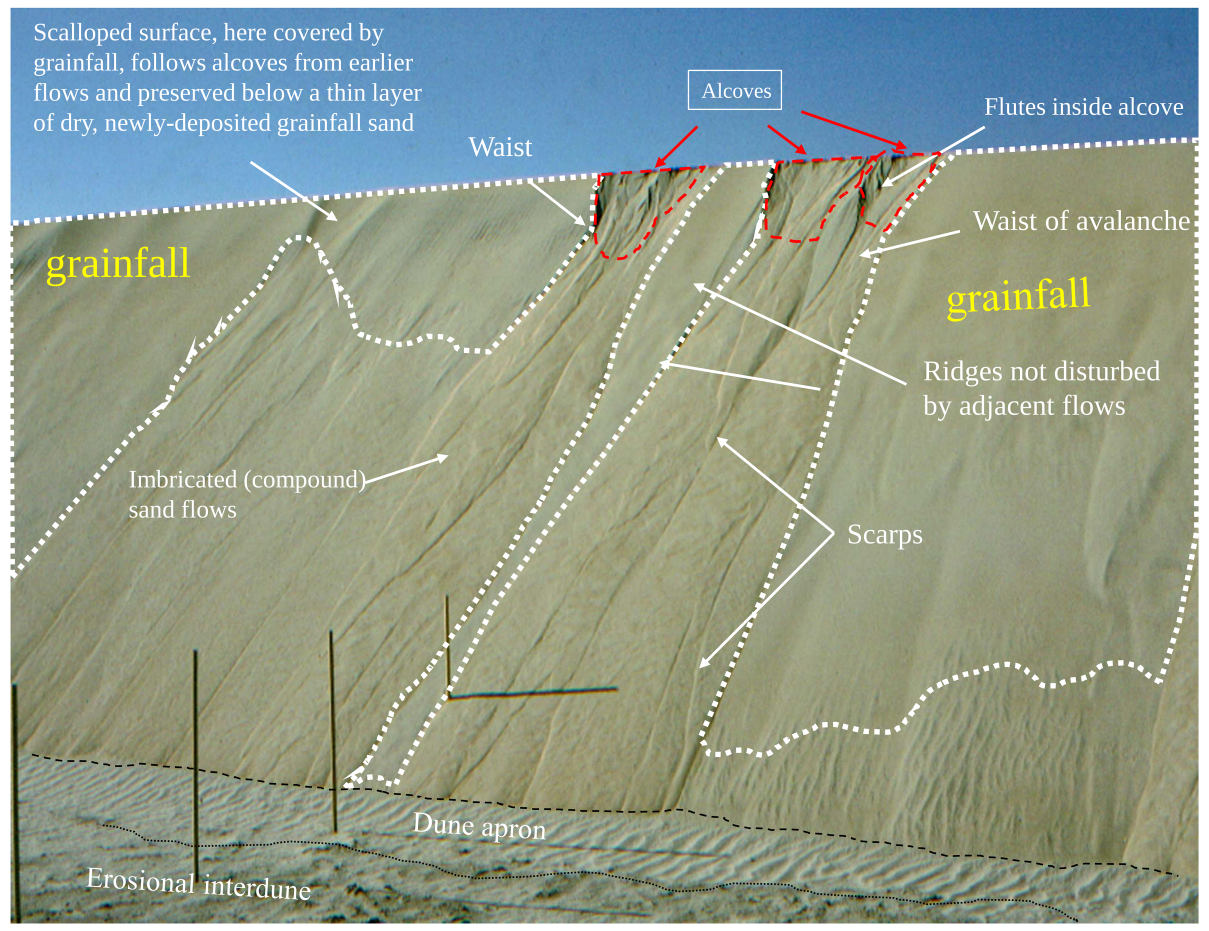


Figure 1-2 This transverse ridge dune in the Jafurah Sand Sea, Eastern Province, Saudi Arabia (4m high) extensive coverage of the slipface by a dry grainfall layer. This layer has fed dry sand flows that, for the most part, reach the bottom of the slipface. This dune is one of a number of dunes with advance rates described by Fryberger et al. (1984). Stakes visible in the image provided control to measure the advance. This slipface has typical features of dry sand avalanches (flows). Avalanching has created alcoves at the top of the slipface, with scarps supported by cohesive layers of ripple strata along the brinkline of the dune. Light early cementation, perhaps evaporites from a nearby sabkha, clay from airfall, or dampness has caused resistant flutes in the alcoves. Waists (narrowest parts) of each flow roughly mark a change from erosion to accumulation.

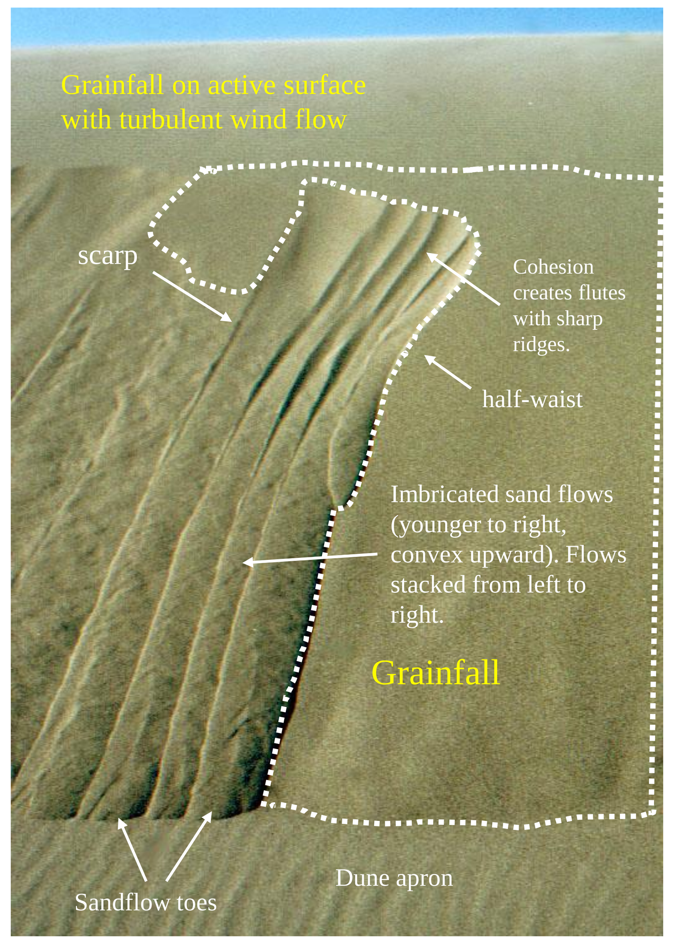


Figure 1-3 Evenly imbricated dry avalanche tongues on a small (1.5m) dune at the Oregon Dunes, USA. As with some other images on this page, fresh (non-rippled) grainfall deposits reach the base of the slipface, thus making it easier for avalanches to extend to the dune apron. There are slanted, or "dragged" washboard structures on the surface of each flow, most extending from lower left to upper right. These may reflect differential flow rates within a single avalanche. A half-waist has formed at the base of the alcove. The base of the alcove is also where net erosion changes quickly to net accumulation of recycled grainfall and ripple strata from the crest and upper slipface. This process forms the base of the sandflow and the sandflow toes. Image was acquired during a sandstorm.

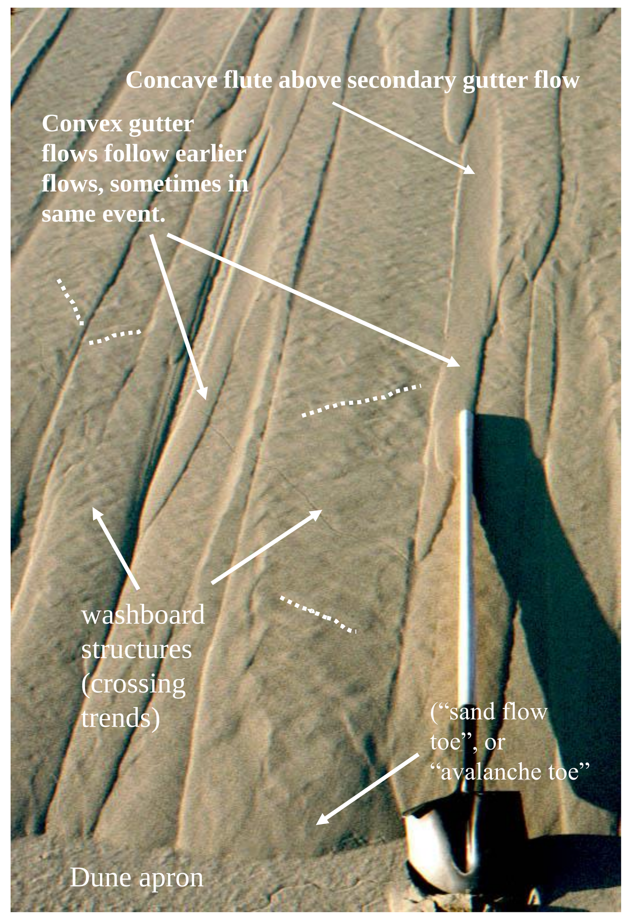


Figure 1-8 The base of the slipface of a small dune in the Oregon Coastal Dunes, USA. The dune is about twice the height of the image, shovel for scale). This slipface has several dry, straight and very narrow avalanches with secondary (gutter) flows between the primary flows. Washboard structures show faint crossing trends formed during flow. Washboard structures may propagate from flow perturbations caused by breakoff of pieces of the slightly cohesive sand at the top of the dune scarp or alcove. Videos of the avalanching process show that the washboard structures move downslope with the flow, becoming most visible when the flow stops progressively upward from the base.

Figure 1-4 Dry sand avalanches in the Algodones dune field, California, USA. The first flows reached the bottom of the slipface, however a number of secondary flows did not. This indicates that the supply of fresh sand may be limited since the first flows; or that the basal slope was shallowed below the angle of repose for dry sand (about 32 degrees) by earlier flows. The grainfall deposits that fed these avalanches evidently resided on the slipface long enough to acquire a thin layer of wind ripples built by crosswinds from right to left on the surface (white arrow). Note the cohesive scarp where sand broke away to form avalanches, just below the ripples. Shovel handle at lower left, tilted, for scale.

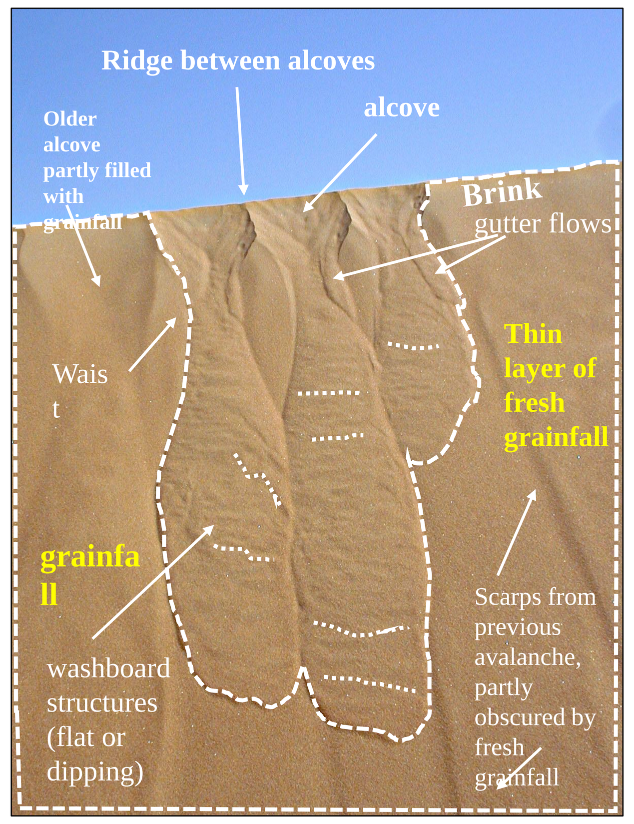


Figure 1-5 Dry avalanches (sand flows) on a 2m high barchan dune in the Wahiba Sand Sea, Oman. Insufficient grainfall accumulation along the brink of this dune prior to breakaway of the avalanches may have caused them to stop short of the base of the slipface.

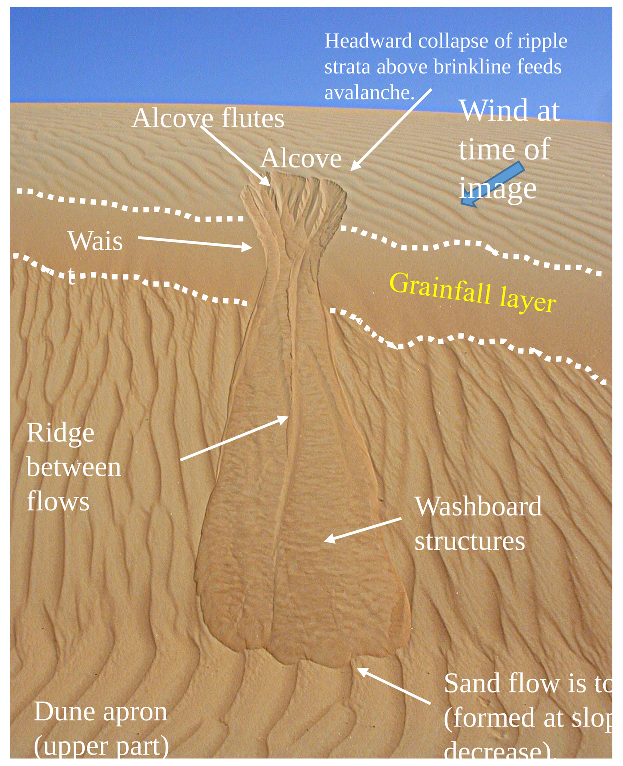


Figure 1-6 Dry sand avalanches on a small dune in the Wahiba Sand Sea, Oman. There is a narrow, thin grainfall layer along the dune brink formed by weak cross winds. Ripple orientation on the dune crest shows the crosswind direction that was bringing sand to the slipface at the time of our visit. Cohesion of ripple strata near the slipface brink has contributed to constraining the avalanches to a couple small flows that stop at a shallowing break in slope (note change in ripple orientation from slipface to apron). Avalanche is about 1 m high.

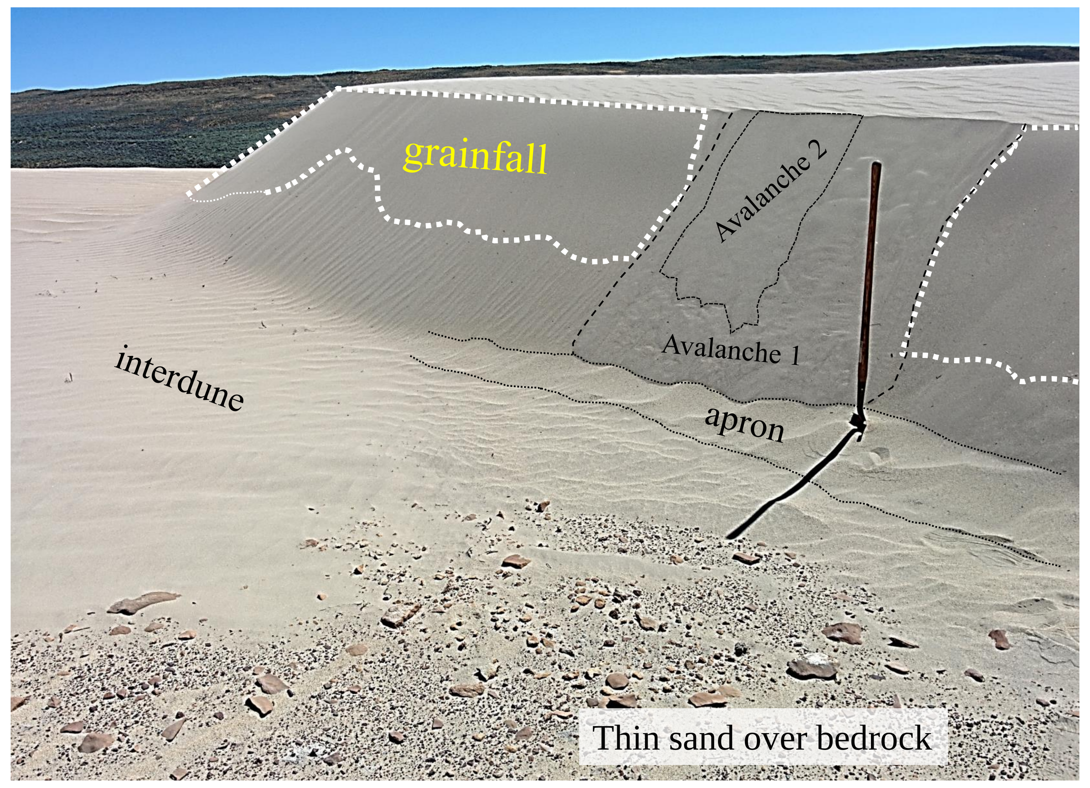


Figure 1-7 A small (1.5m) dune in the Killpecker dune field, Wyoming, USA. An early avalanche (1) reached the granule ripples on the dune apron. This has occurred despite only partial coverage of the slipface by fresh (unrippled) grainfall deposits. The later secondary avalanche (2) may have stopped due to a reduction in slope near the base of the slipface caused by sand buildup from the earlier flow. The sand in this dune has very little cohesion, thus no alcoves have formed above these avalanches. Shovel provides scale.

A review of slipface processes and structures in eolian dunes

Eolian avalanches with cohesive sand layers

Cohesion of eolian sand grains can occur due to dampness from rain, fog, dew, or melting frost and snow. Cohesion also occurs when airborne dust within the sand is remobilized by water to form meniscus cements, or minerals from the sand itself are dissolved and re-precipitated as meniscus cements (Krystinik, 1990). For example, at White Sands National Monument, New Mexico, USA the gypsum dunes are lightly cemented by re-precipitated gypsum from the sand grains. This is caused by dissolution of the gypsum sand by moisture, that later dries out to precipitate gypsum dissolved from the grains. Some tight packing arrangements – for example those typical of poorly sorted sand (commonly associated with some wind and most granule ripples) can temporarily cause resistance to slipface collapse and sandflow. Laminations within eolian primary strata commonly retain damp layers of fine, well sorted sand. These layers have enough cohesion from dampness or early cement mobilization to prop up alcoves, or in some places, comprise blocks of cohesive sand that retain some of the rectangular form as they slide down the slipface.

Where dry sand flows over damp, cohesive sand, particularly when the grainfall layer is thin, it is common to observe narrow fluted or grooved erosional surfaces beneath the flows. These surfaces commonly reflect the width of equally narrow alcoves at the top of the slipface. These narrow alcoves (Figures 2-4, 2-5, 2-6, 2-8 and 2-10) feed loose sand into flows directly below them, eventually deepening the groove along which sand flows downslope. At present, however, the controls on flute and ridge spacing are not well understood. This is because there are complex process frameworks at work in every avalanche. These involve, for example, the structure of layers of cohesive damp sand within or atop otherwise dry, loose sand (Figure 2-3). Additionally, wind direction and velocity, drying of surface sand as a function of sun angle with respect to both the slipface and the dune as a whole can control avalanche behavior. In summary, questions remain that are related to where and when avalanches and slumps initiate on a slipface. It is clear, however, that a damp surface (below dry sand flows) does tend to limit scour by the sliding grains (Figure 2-7). This limited scour may, in turn, inhibit headward erosion and collapse of eolian strata that may be lightly cemented by rock flour, water or other agents including ice.

An example of timing issues can be found on the Coorong Barrier in South Australia (Figure 2-9), and the Oregon Coastal Dunes, USA (Figures 2-1, 2-2, 2-4 and 2-5), where there is frequent rainfall. After a rain, areas of the dune exposed to the sun and wind dry faster than those still in shade. As a result, dry sand from a sunny newly-dry area, may be blown onto the still-damp slipface. On the Coorong Barrier this is common, where dune windward slopes face the rising sun and dry quickly, but northward facing slipfaces remain in the shade. This commonly results in thin, dry sand avalanches over damp sand such as those illustrated on this page.

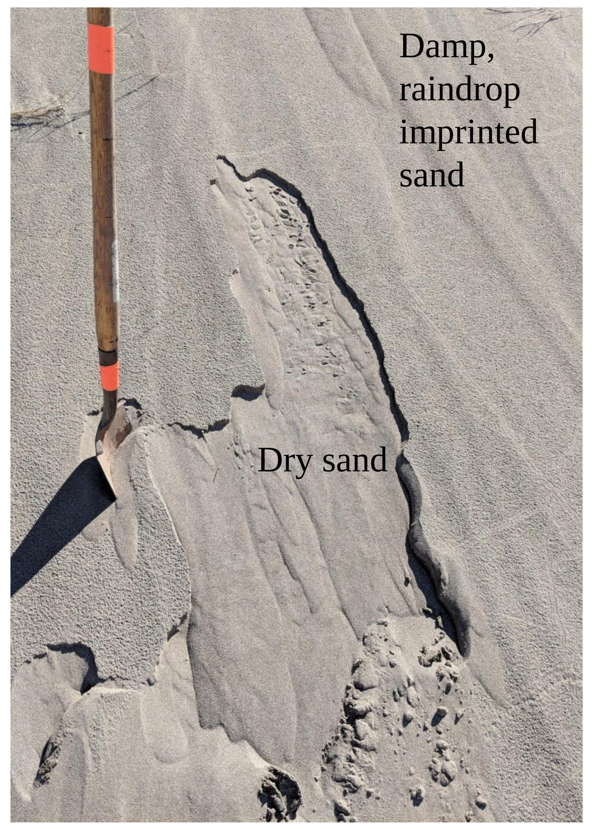


Figure 2-3 A layer of damp sand caused by rainfall overlies dry sand on a small dune at Great Sand Dunes National Park, Colorado, USA. An avalanche has occurred in the dry sand beneath, causing the damp surface sand layer to break into blocks as both dry and damp sand slid down the slipface. Shovel for scale. Orange tape markers are .5 m apart.

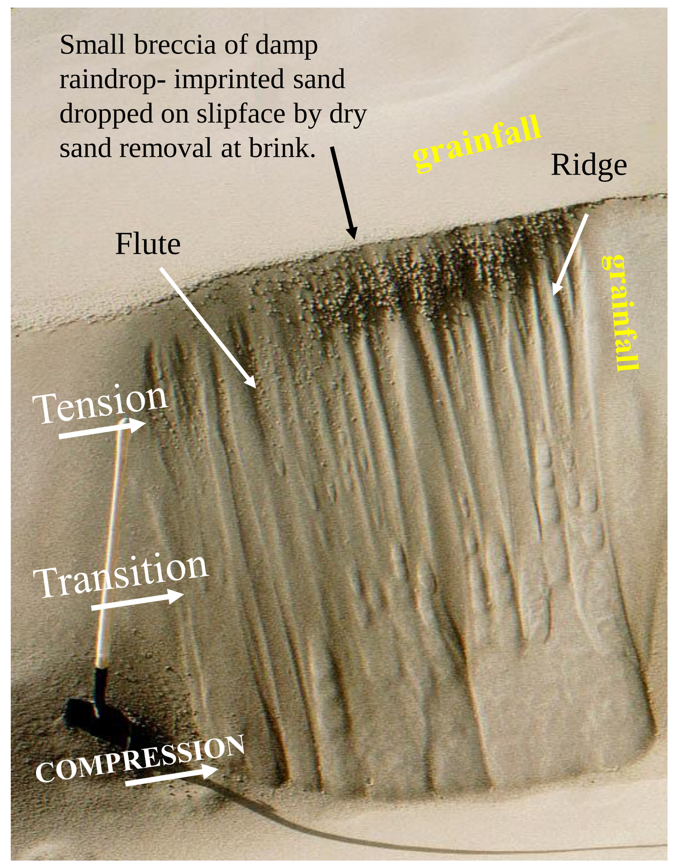


Figure 2-4 Flute and ridge "dry over damp", raindrop-impacted avalanche face on a small dune in the Oregon Dunes National Recreation Area, USA. Upper slipface is defined by presence of flutes, with some un-collapsed grainfall remaining as the intervening ridges. Middle slipface has narrow sand lobes that reflect sand supply from narrow flutes above. Despite the complications due to moisture that has caused the pronounced flute and ridge topography, the basic slipface domains of tension, transition and compression are visible. The upper slipface is characterized by small breccia fragments (cohesive sand) derived from the bumpy surface created by rainfall the previous day. Shovel for scale.

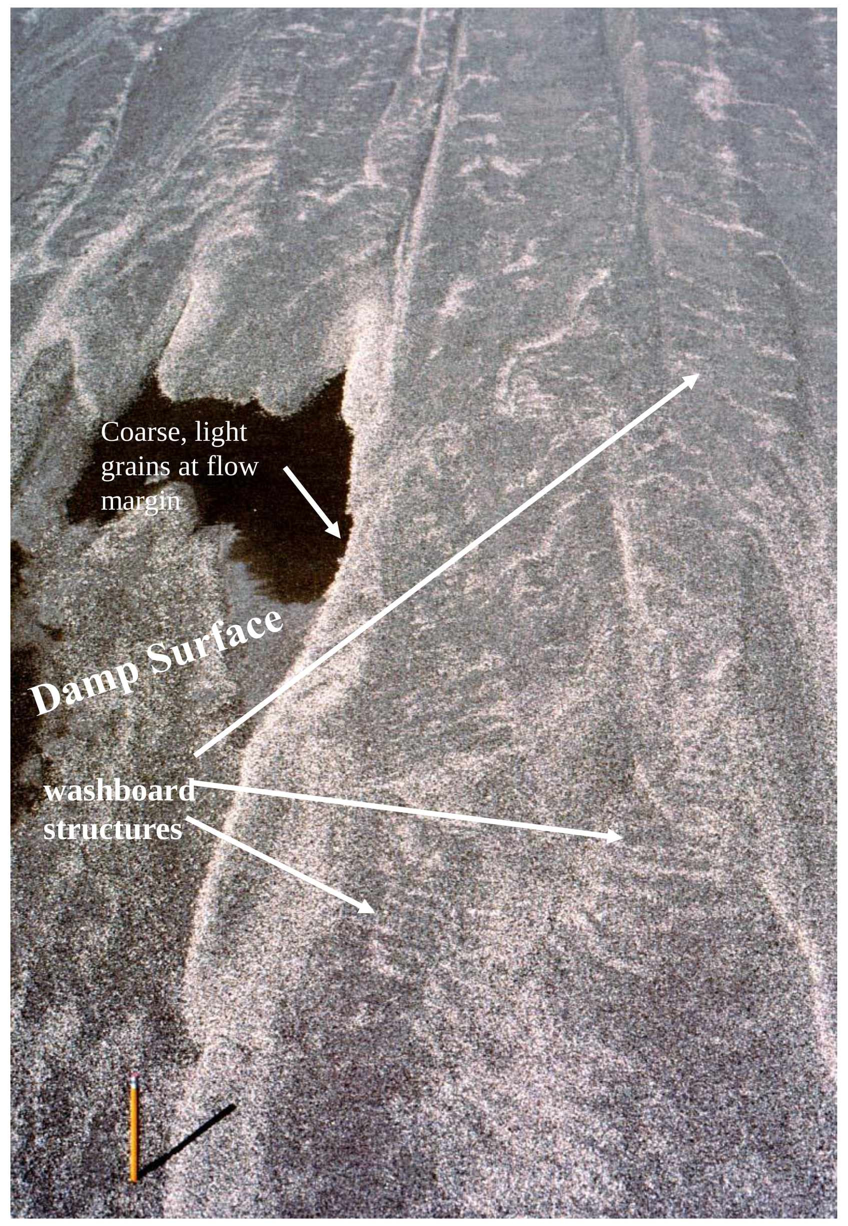


Figure 2-7 The middle and base of an eolian sand avalanche formed during winter at Great Sand Dunes, Colorado, USA. Image shows several distinct sets of washboard structures formed on imbricated dry sandflows. The avalanches flowed across a damp surface. Moist layer beneath the sandflow may have been caused by melting snow.

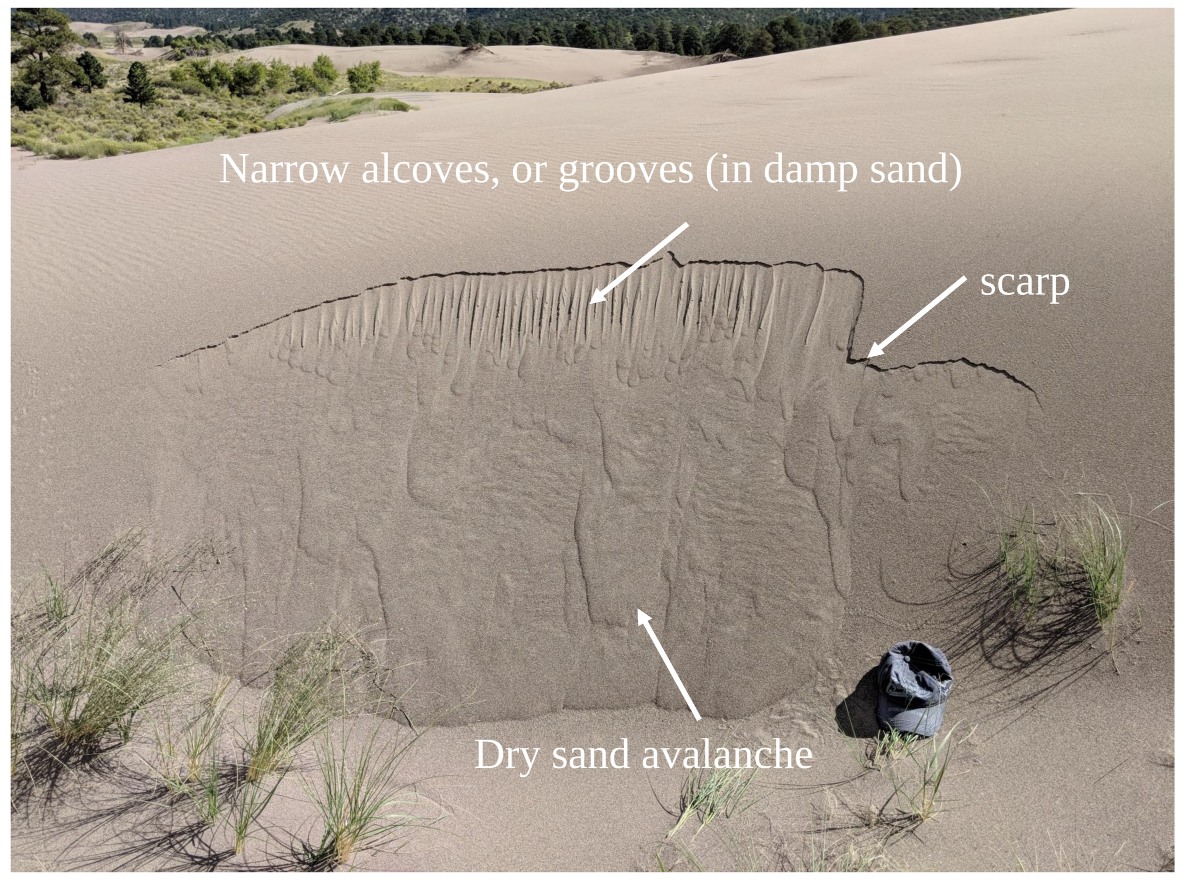


Figure 2-8 A composite avalanche on a small dune at Great Sand Dunes National Park, Colorado, USA. This avalanche consists of multiple flows. A few of the later flows have stopped partway to the base of the slipface due to slope reduction built by earlier flows. Morning dew had dampened the sand surface, creating the cohesive layer that formed the scarp (arrow) at the top of the sandflows. Beneath this dew-moistened surface layer is a second, a thin, dry layer of fresh grainfall that is now part of the avalanche. Below this dry layer, the sand is again damp and cohesive, causing multiple thin flutes to be eroded into the upper slipface instead of the larger alcoves that are more typical of avalanches in dry sand. Hat provides scale. See video link elsewhere in this report to observe this process.

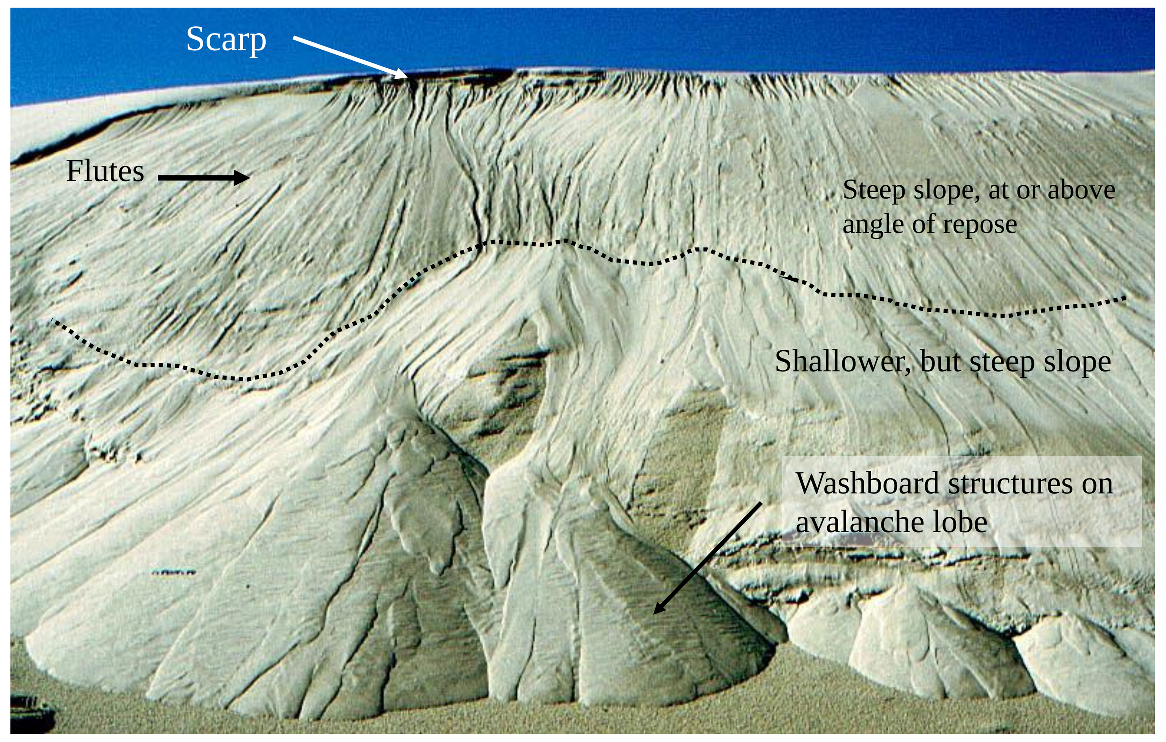


Figure 2-1 Dry sand avalanches over wet sand in the Oregon Dunes National Recreation Area, USA. During the previous 24 hours there had been rain that wet the dune sand (note raindrop imprints on apron at base of dune, and lower slipface). Drying on the south side of the dune (upwind, out of sight beyond brink) exposed newly-dry sand to wind transport. This sand briefly collected at the brink, then avalanched down the flutes on the slipface to feed lobes of thicker dry sand flows at the base of the dune. Small dry sand avalanches (flows) on the lobes have developed washboard structures. Rain-wetted ripple strata along crest have resisted collapse, forming a ragged scarp (arrow). Slipface is about 6 m high. See also Fryberger, (1991).

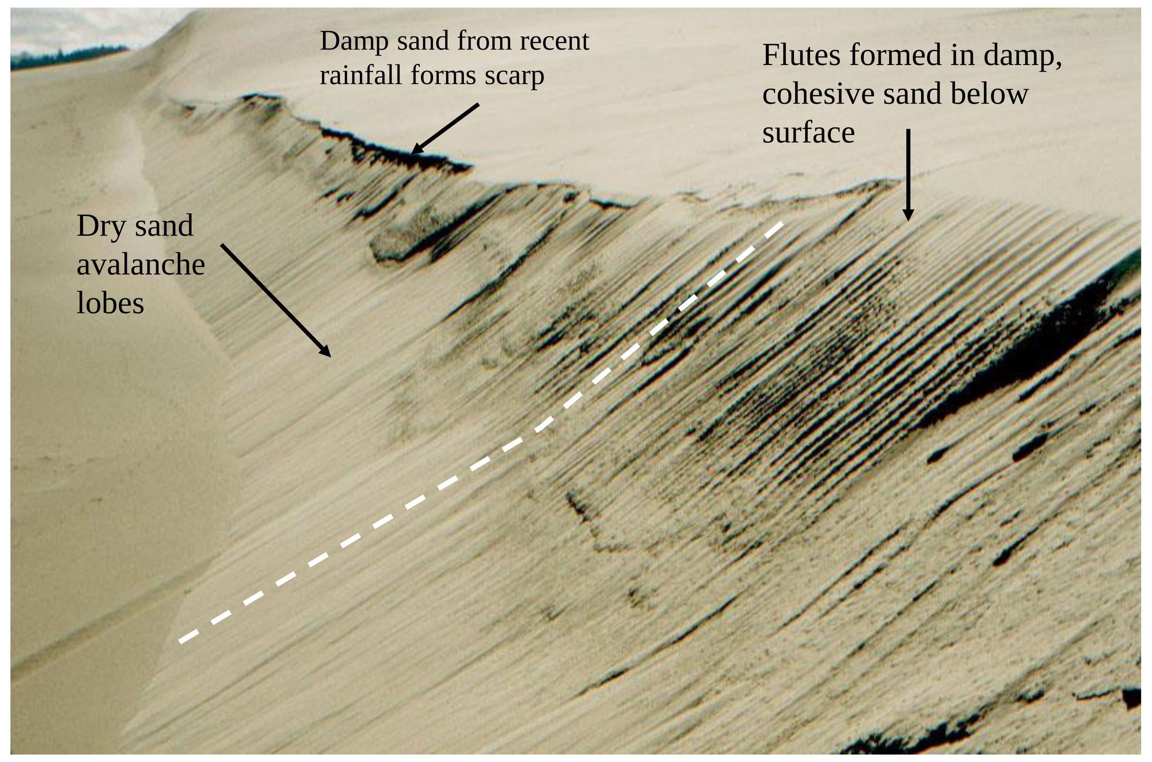


Figure 2-5 Oregon Dunes National Recreation Area, USA. A subtle break in slope (shown by the bend in the dashed line) marks the change from upper slipface flute-and-ridge topography to dry sand avalanche lobes that extend to the base of the slipface. When this image was taken, the flutes were immediately recycling the sand blown over the brink, due to the steep slope above the 32 degree angle of repose for dry sand. Lumpy shapes beneath flutes probably represent slumps of damp sand that slid partway down the slipface.

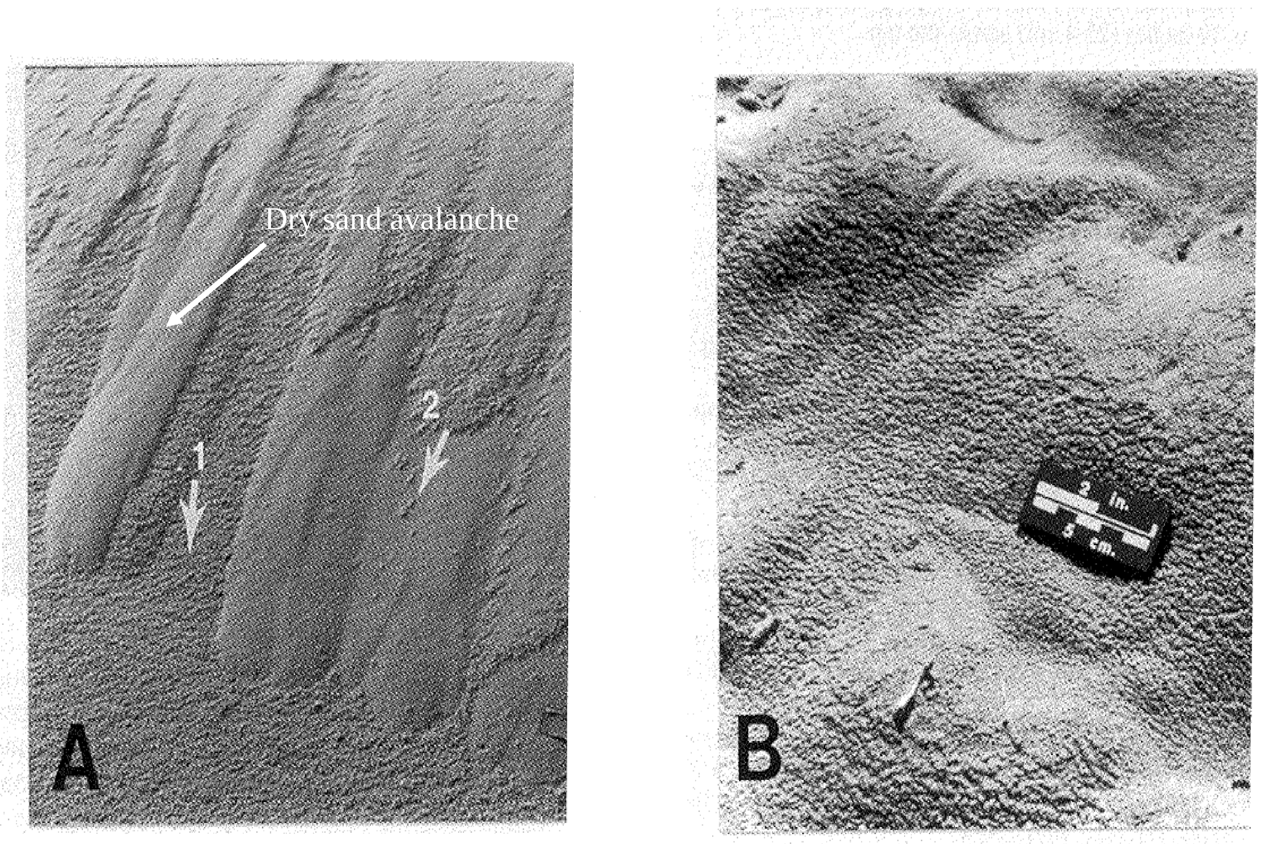


Figure 2-9 Eolian slipface processes on the coastal Younghusband Barrier, South Australia.
A) A Dry sand avalanche has partly overrun a surface with raindrop imprints (formed by a shower shortly before the image was acquired, arrow 1). Arrow 2 shows an isolated bit of rainfall-disrupted (damp) sand that has broken off the mass above and slid down the face. B) A similar raindrop-impacted surface with some adhesion features that has formed on granule ripples. These rain-formed features are widely present in the sediment, and are thus a helpful tool for recognizing eolian sediments along rainy coastlines, such as this dunefield. (after Fryberger, et al., 2001).

Figure 2-2 Flutes (white arrow) have formed on the upper two-thirds of this slipface (above dashed white line) due to flow of dry sand over wet sand (from rainfall) in the Oregon Dunes National Recreation Area, USA. These flutes feed sand flows to the lower one-third of the dune (below dashed line).

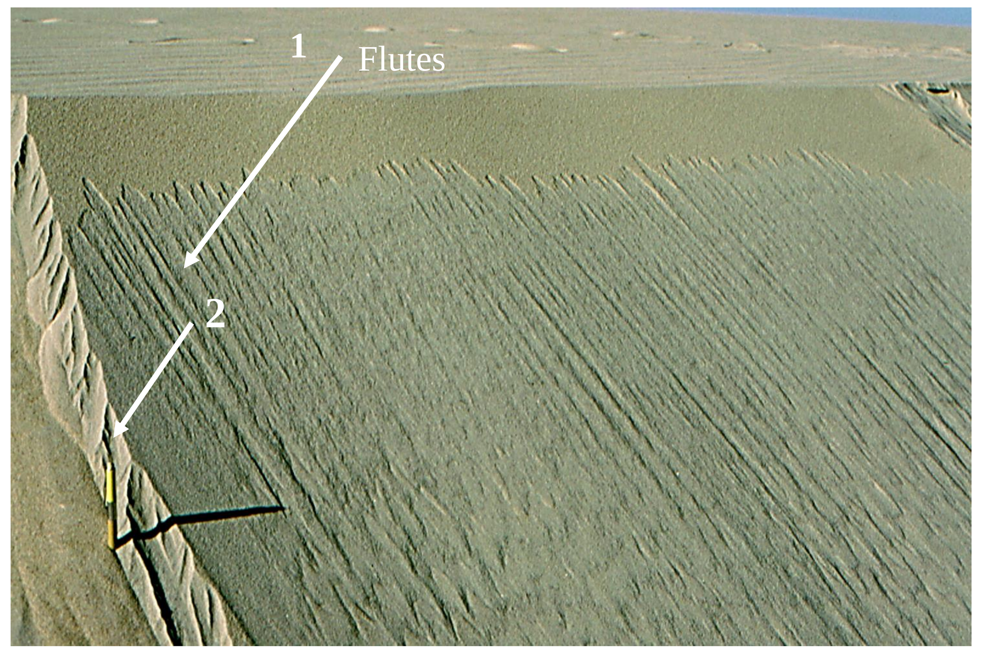


Figure 2-6 Dry sand avalanche flutes have been cut into a thin layer of damp sand by dry sand sliding down the flute from above, Jafurah Sand Sea, Eastern Province, Saudi Arabia (arrow 1). Cohesion of the underlying damp/wet sand layer is evident from a larger avalanche alcove on the left that also displays flutes and ridges indicating cohesion (arrow 2) along a prominent resistive scarp. The Jafurah Sand Sea, where this image was acquired, has many interdunal and coastal sabkhas. Some of the cohesion evident on this dune may have been caused by small amounts of evaporites incorporated into the sand by dust fall, or by saltation from sabkhas upwind. However, winter rains may also have dampened the sand. Yellow pen next to scarp for scale.

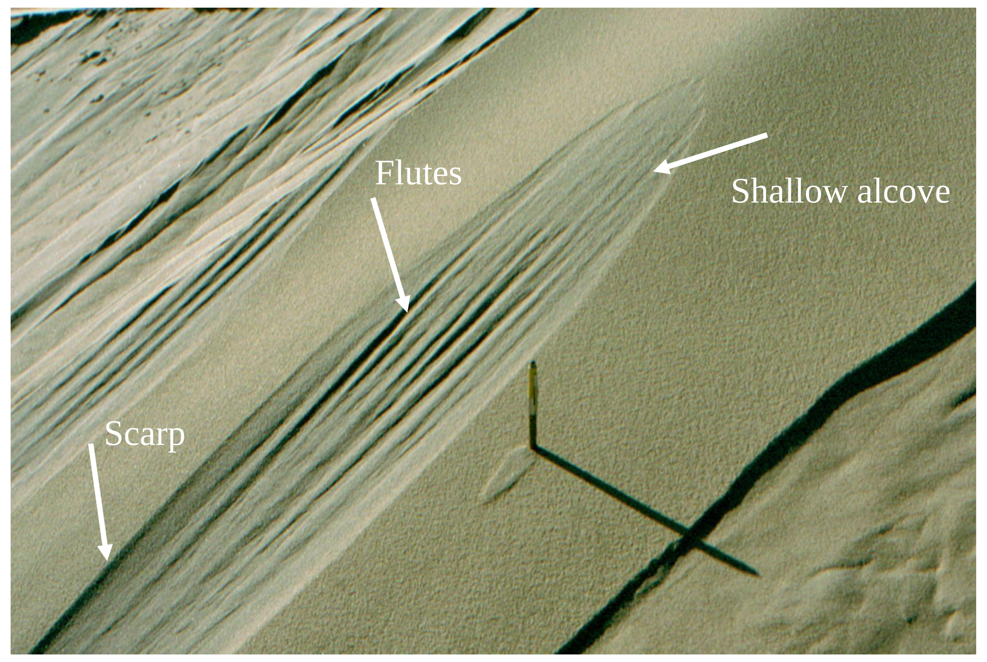


Figure 2-10 Dry sand avalanche alcove formed from a thin (less than 1 cm) dry grainfall layer over wet sand, Jafurah Sand Sea, Eastern Province Saudi Arabia. Flowing dry sand has carved flutes (arrow) in underlying (damp) cohesive sand. This alcove formed near the brink of the slipface. Pen shows scale.

Avalanche slumps of cohesive sand

Damp or wet sand on an eolian slipface initially collapses in the form of slumps that are sometimes several meters wide (Figure 3-2, 3-5 and 3-9). These commonly break into many smaller blocks as they slide downslope, especially if there is an underlying, moving avalanche of dry sand. Underlying flows of dry sand tend to pull slump blocks downslope further than they might slip otherwise, causing them to break into smaller blocks or "rubble". Small slump blocks tend to remain at positions higher up the slipface, and in the center of the avalanche. Larger slump blocks migrate to the sides of the avalanche while it is active.

The thickness of the alcove scarp, or the scarp bounding an avalanche chute, depends upon the thickness of any cohesive layer near the surface of the dune. In places where there has been heavy rainfall, this layer will be several or more centimeters thick and very cohesive compared to slightly damp sand or dry sand lightly bound by meniscus cements (Figures 3-5 and 3-6). It is common for alcoves to erode by scarp retreat into the slightly cohesive, low-angle, crestal eolian strata (commonly ripples) at the top of the dune. This process forms the distinctive scarp at the margins as described on pages above, even in dry sand. This process is amplified when strata at the brink of the dune are wet or damp, which increases cohesion, producing a thicker, sharper alcove scarp.

Avalanches with cohesive slump blocks can occur on the slipface of any size dune. Slump blocks are small, and thin, where the cohesive (damp or wet) layer involved in avalanching is also thin (Figures 3-3, 3-6, 3-7 and 3-8).

Large, thick, cohesive slumps such as those at the Oregon Dunes, USA, where there is about 73 inches (1854 mm) of rain per year, commonly have lateral thrust and shear structures onto non-slumped portions of slipface (Figure 3-2). Slump avalanches will commonly have conspicuous overthrusts and anticlines at base of the flow, if the cohesive layer is thick enough, and competent enough (Figures 3-4 and 3-1).

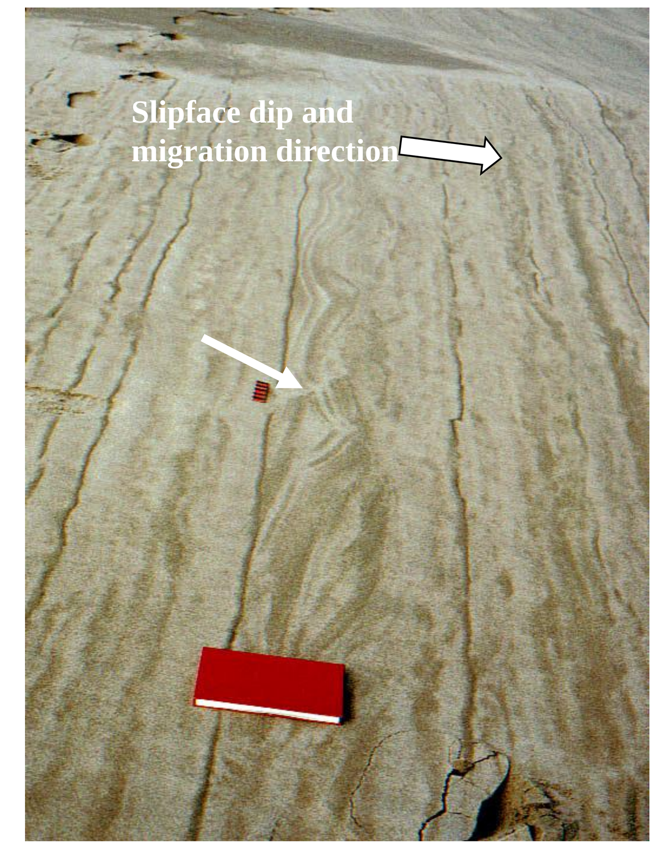


Figure 3-1 Avalanche slumps (arrow) viewed on the wind-scoured crest of a transverse ridge dune in the Oregon Dunes, USA. As the slumps progressed down the slipface, blocks rotated or deformed and were thrusted laterally to attitudes not parallel to the slipface, which dips 32 degrees to the right. Note also the fault plane created when the slump block was thrusted laterally across the slipface (arrow). For more discussion of these peculiar slumps, that are common in the Oregon Dunes, see Fryberger (1991). View to west.

Figure 3-2 Downslope failure of damp sand has formed slump blocks on the slipface of a transverse ridge dune, Oregon Dunes, USA. Several of the blocks are indicated by dashed lines. Some lateral thrusting has occurred on the right side of two of the slumps (arrows). Drying conditions have caused shallow avalanches (flows) of dry sand down the slipface, which is still underlain by damp sand. These dry sand flows are channeled into narrow flutes and grooves that feed sand fans at the base of the slipface (compare with images from Mars, page 10 of this report). Note that the dune brink-crest shown above is still cohesive from damp sand, forming a scarp. Sand cones at the base tend to aggregate contributions from several flutes. View to south.

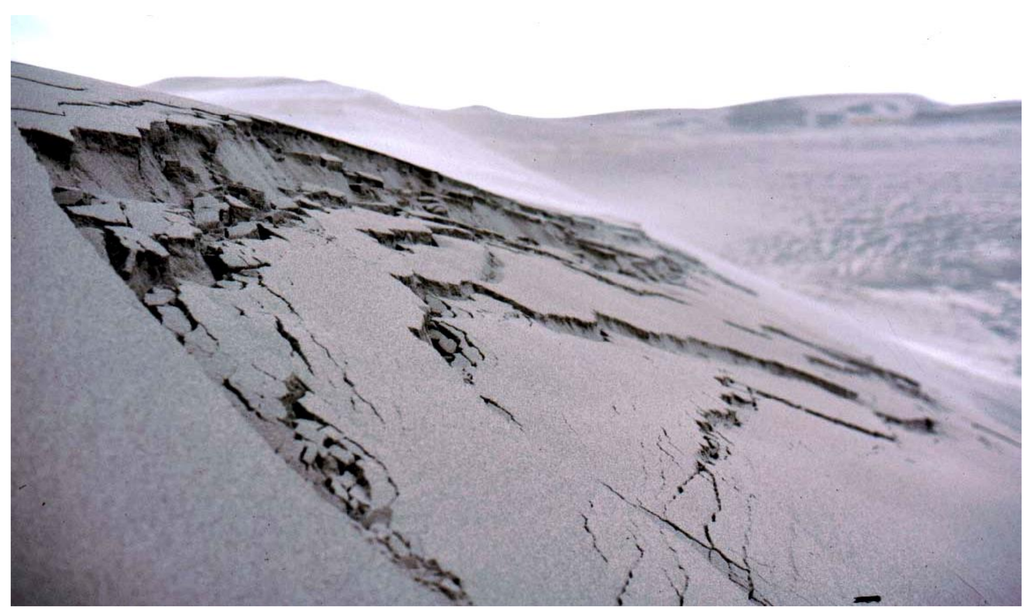


Figure 3-5 Left: An avalanche-slump on a barchan dune slipface at Great Sand Dunes, Colorado, USA in winter. The blocks shown above were formed by slumping of a 1 cm thick layer of cohesive, damp sand that overlay dry sand. The dampness was caused by melting snow. Failure of underlying, dry sand, that was already dipping at close to the angle of repose, may have ultimately been caused by the additional weight of the damp sand. It is common at Great Sand Dunes (and other dune fields) to have thin wet, damp, or dry layers interbedded on the dune slipface due to episodic rain and snowfall. For example summer rain showers at Great Sand Dunes commonly dampen the sand surface to a depth of a few centimeters. Scarp is approximately 12 inches (30 cm) high at top of the dune

Figure 3-6 Left: At Great Sand Dunes, Colorado a thin layer of wet/damp sand has broken into many small, jumbled slump blocks while riding an underlying dry sand avalanche down a slipface. The source of moisture was snow melt. Size of cohesive blocks in eolian slumps is commonly proportional to the thickness of the damp layer. Scarp is approximately 8 inches (20 cm) high on left side of image.

Figure 3-7 Left: Thin slabs of cohesive sand (arrows 1) have slid partway down the slipface of a small barchan dune. The dune is at the northern end of the Wahiba Sand Sea (also known as the *Sharqiya Sands*), in the Sultanate of Oman. This dune is in the bed of the ephemeral stream or "*wadi*" Batha. These slabs were possibly damp at the time of slumping, but our field observations suggest that cohesion here may also have been caused by clays and rock flour that formed meniscus cements between individual sand grains. These solutes are incorporated into the dunes from nearby low spots that collect ponded, suspended-load fines and evaporites deposited by Wadi Batha when floods subside (white muddy areas and polygons, arrows 2). On the left side of the slipface, dry sand avalanches become shorter in length and follow ripple troughs. This avalanche may have been caused by the geologist walking over the dune on the right side. See also Fryberger et al, (2016b) for more descriptions of the eolian dunes along Wadi Batha. Shovel provides scale.

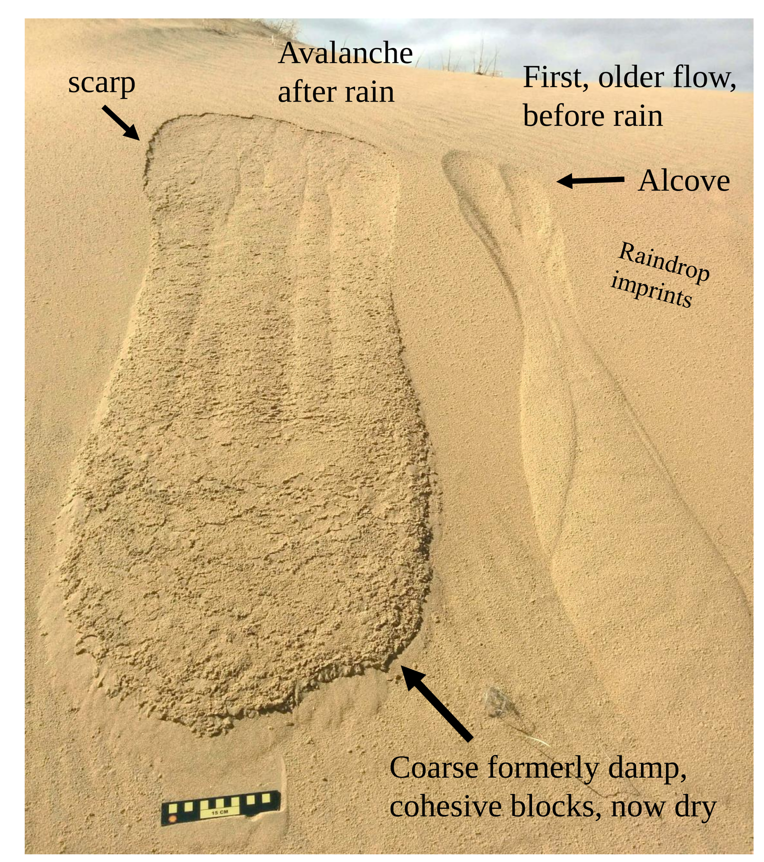


Figure 3-3 Left: Two avalanches on a small dune slipface at Kelso Dunes, California, USA, demonstrate the impact of surface moisture on sedimentary structures. Avalanche on the right is a dry (compound) sand flow with no indication of strong cohesion of the surface layer that would be caused by rainfall, although the existence of an alcove suggests light cohesion of sand at the brink. This avalanche clearly pre-dates the rain, which has left light raindrop imprints on the entire slipface. On the other hand, the avalanche on the left was formed later, after rainfall dampened the sand surface. This damp layer broke into fragments as it was carried downslope by the underlying dry sand flow. The jagged scarp at top of the flow on the left is typical of thin, cohesive (damp in this case) sand layers. Larger cohesive blocks of damp sand migrated to the margins of the avalanche (arrow) as the flow progresses. The whole slipface had dried at the time of our visit, although the effects of the previous night's rain were obvious.

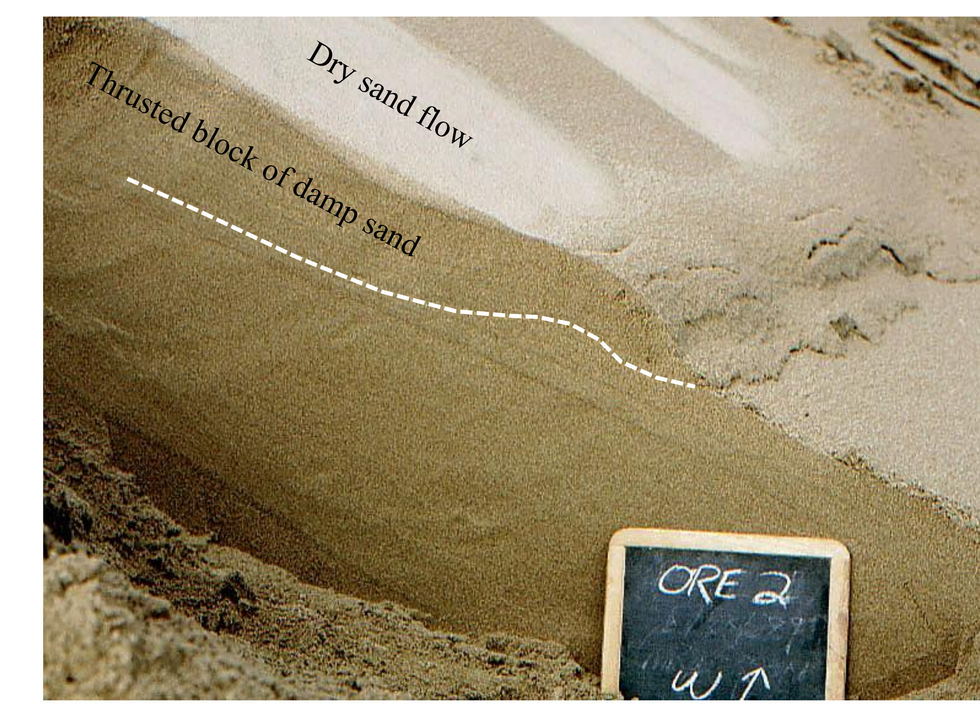


Figure 3-4 Toe of a cohesive, damp thrust block in the Oregon Dunes, USA, near the base of the dune slipface. There is an anticline visible (traced by dashed line), with folding and block faulting along top. Several dry sand avalanches have stopped at the upslope margin of the anticline. A white dashed line tracks the erosional base of the slump in the trench. View to west. Small chalk board is about 8 inches (20 cm) wide

Figure 3-8 An avalanche on the slipface of a small barchan dune on the sabkha of Laguna Manuela, Guerrero Negro, Pacific Coast of Baja, Mexico. Large and small cohesive blocks have slid down the slipface above avalanching dry sand beneath (arrow 1). The sharp breakaway along the crest is caused by cohesion of the surface layer of sand. This cohesion is probably caused by light halite or gypsum cementation, given that the dune is in a highly evaporitic depositional environment. Salt ridges are everywhere on the interdunes due to the shallow, saline water table. Cohesion might also be due to dampness associated with winter rains or the hygroscopic nature of halite crystals mixed in with the sand. Some early cementation has caused layers within the dune to resist wind scour (arrow 2). Geologist Chris Schenk provides scale.

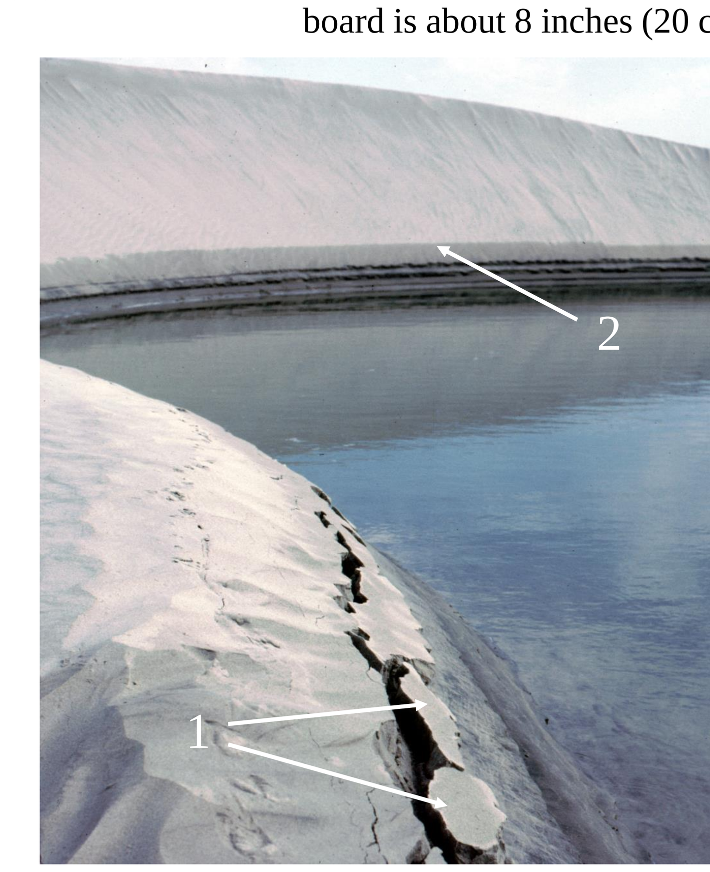


Figure 3-9 Slump blocks of wet, cohesive sand collapse into the rising tide as it undercuts an eolian dune at Guerrero Negro, Baja, Mexico. The blocks have slumped downward, rotating in both clockwise and counter-clockwise (arrows 1). Soak line of the tide is visible across the lagoon on the slipface of the same dune (arrow 2). Dune slipface on skyline is about 8 feet (2.4 m) high. (After Fryberger, Krystinik and Schenk, 1990).

A review of slipface processes and structures in eolian dunes

Slipfaces of reversing dunes at Great Sand Dunes, Colorado

A reversing dune, as the name indicates, reverses its movement, as well as its slipface orientation over time. This is usually in response to an effective wind regime with opposing, commonly bimodal, sand drift directions. Reversing dunes have ephemeral slipfaces that partially or wholly reverse, often seasonally, or in the case of Great Sand Dunes, as the result of a single sandstorm For example, strong east and northeast winds commonly reverse slipfaces built by the gentler, but more persistent, southwest winds. This creates the famous "Chinese walls" of reversed slipfaces often seen from the visitor center (Figures 4-1, 4-2).

If one of the slipfaces of a reversing dune is dominant over time, there may be slow migration of the bedform. Indeed, at Great Sand Dunes, reversing dunes exist on a spectrum from "barchan dunes that reverse now and then" to equant reversing bedforms that migrate very little and thus tend to grow vertically. Because wind regimes around Great Sand Dunes National Park are highly variable, the distribution and morphology of reversing dunes at the Park is also highly variable.

Reversing dunes, at various times of the year, have rounded plinths and well-developed aprons (similar to linear dunes to which they are related) on either upwind and downwind sides. When aprons build up, as they typically do on reversing dunes, avalanches tend to stop well above the interdune (Figures 4-3 through 4-7). In general, the more a dune is "reversing" as opposed to migrating, the more such dunes tend to grow vertically. Reversing dunes commonly develop a symmetrical cross section, because the slipfaces migrate back and forth during the year, and because reversing winds erode the upwind side of the dune to a rounded profile (Figure 4-2).

For further examples of reversing dunes, and the impact this morphology may have on dune petroleum reservoirs please see Fryberger, et al., (2017).

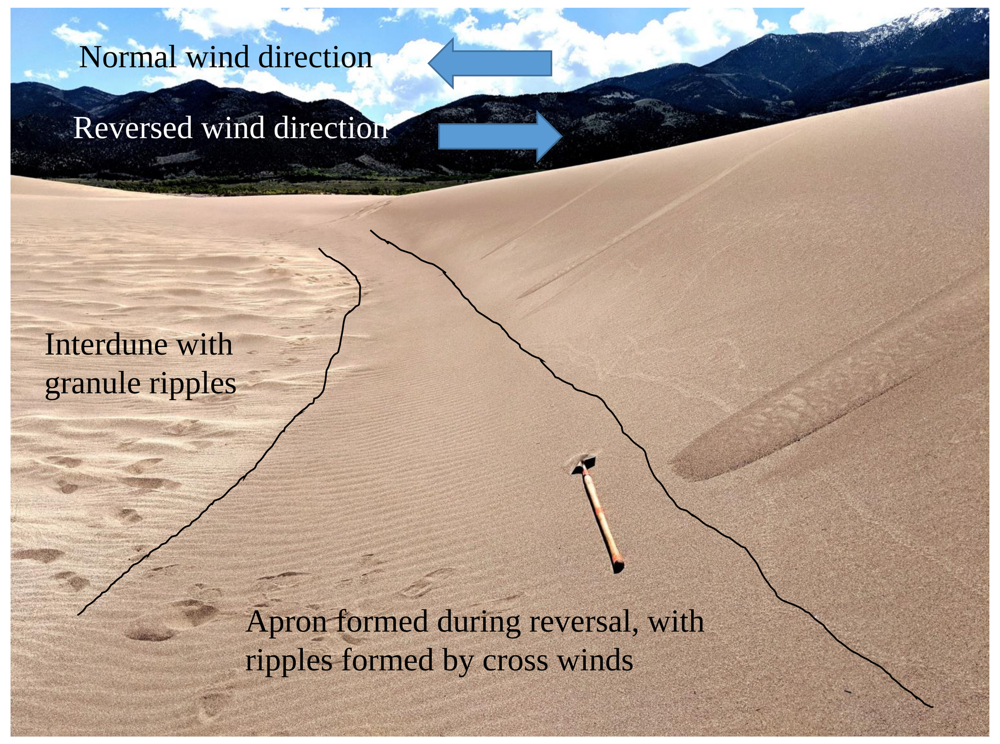


Figure 4-1 One of the effects of wind reversals (from E and NE) is to build a larger-than-usual apron at the base of the dune. Here, an avalanche formed after wind direction has returned to normal (from W and SW), has stopped at the decrease in slope where the slipface meets the apron.

Figure 4-2 An overview of the east side of the main dune mass at Great Sand Dunes National Park after a major sandstorm from the northeast (right side of image). Gentle slopes on the east side of the dunes lead to sharp, small reversed slipfaces (arrows 1). The profile of even the large dunes has been altered to form a gentle windward slope for the reversed dune (arrows 2). When winds return to the regional SW direction, the dunes will return to the profile of typical barchan dunes moving SE (toward the right). It is during seasons of east winds that the true, reversing nature of many of the dunes at Great Sand Dunes is apparent. Rainfall the night before has soaked into the sand and highlighted the crossbedding in the dunes.

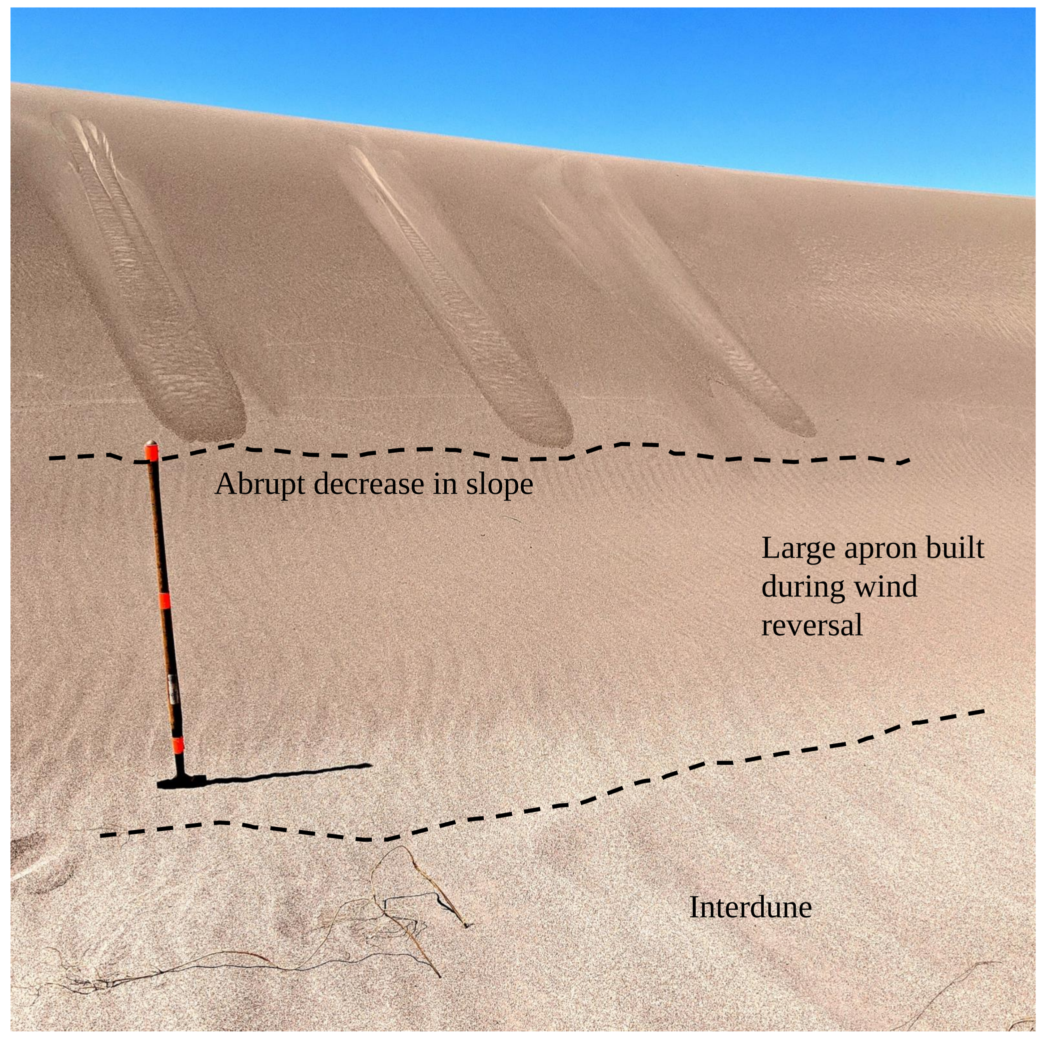


Figure 4-3 A barchanoid ridge dune at Great Sand Dunes National Park is seen here in the process of recovering from a morphological reversal created by east winds that flipped the slipface away from the viewer. The slipface is in the process of building back, toward the viewer. It has several recent avalanches formed from the fresh grainfall visible at the top of the slipface. However, these avalanches have failed to reach the base of the dune due the large apron that formed during the reversal. The slipface will eventually advance a few more meters toward the east, as it is re-built by the southwest winds. Then, avalanches will reach the white grains of the interdune in the foreground. View is toward the southwest.

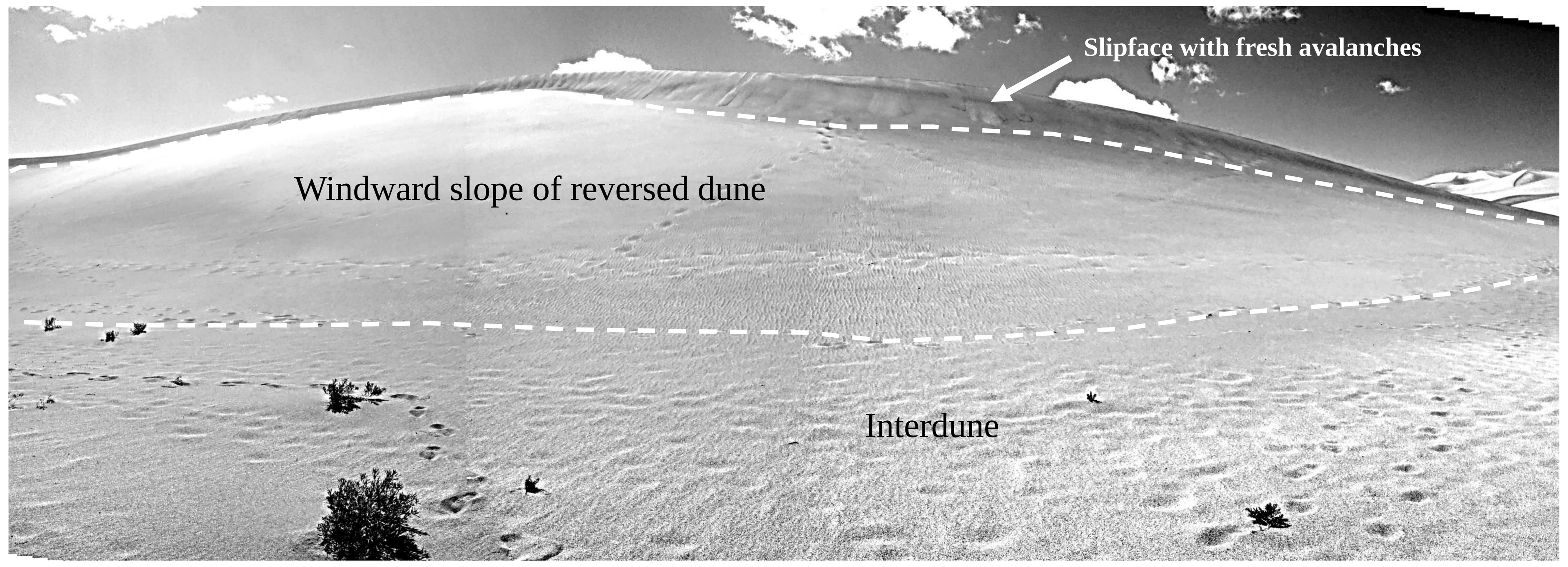


Figure 4-4 Composite image of a reversing dune at Great Sand Dunes National Park, showing the extensive windward slope of the reversed dune in the foreground. Slipface on the crest is building back toward the viewer and will eventually reach the interdune. The reversal will be recorded within the dune as an erosional surface, with a set of avalanche cross strata above it. Wind at time of the photo was toward the viewer, from the west.

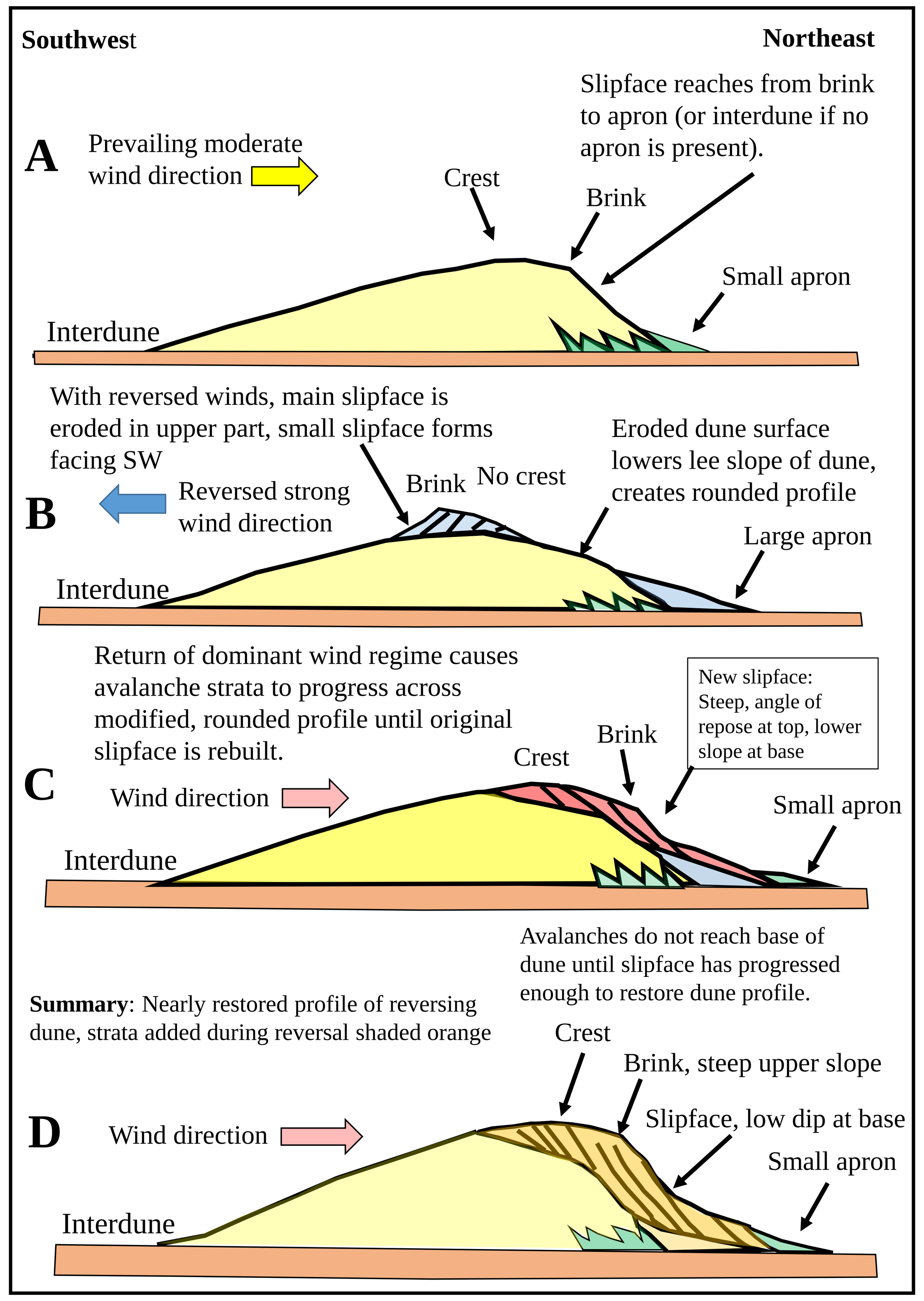


Figure 4-5 Left: Slipface dynamics on a reversing dune that migrates slowly, Great Sand Dunes National Park, Colorado USA. An example of how complexities in wind regime directly affect dune and slipface morphology.

A, shape of dune before wind reversal, viewed in cross section, advancing from left to right. Avalanches reach completely down slipface to a small apron.

B, **Wind reversal causes erosion of top part of dune**, and formation of small new slipface.

C, When wind returns to prevailing direction, slipface must rebuild across eroded upper part of dune. Avalanches do not reach bottom of dune until shape formed by prevailing winds is re-established.

D, "Barchanoid" shape is re-established, however crossbedding with the dune preserves evidence of the reversal.

Figure 4-6 View along the crest of a reversing dune at Great Sand Dunes National Park. Before this picture was taken, it had been reversed by wind from the east (left), to form the smaller, peaked secondary bedform visible here atop the underlying, primary dune. On the left, the slope of the dune has been lowered by erosion during the reversal. This image was taken during a light sandstorm from the west (right), just after the small slipface had flipped, and begun to build back toward the east (to the left). The dune will eventually return to a normal profile created by the west winds after the slope on the left is filled-in by small avalanches. View toward the south.

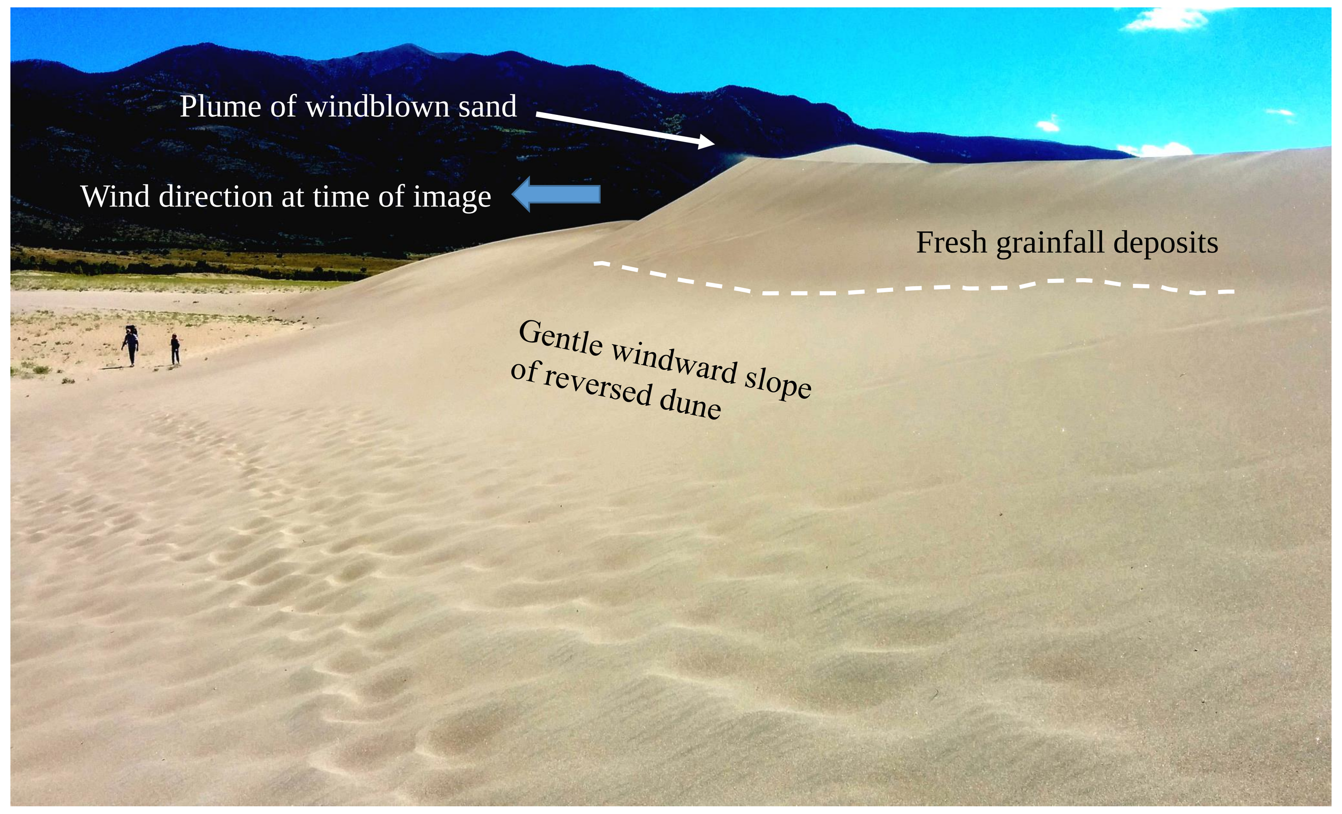


Figure 4-7 A reversing dune at Great Sand Dunes National Park. In this image the gentle slope (windward slope of the reversed dune, not a dune apron) is obvious. The sandstorm at the time (note plume of sand at top of slipface) was re-building the profile it had during the dominant (in terms of duration, if not total sand moving power) wind direction from the southwest. Hikers provide scale for this dune along Medano Creek. This is a broader view of the dune, a portion of which is also shown on the image to the left. View is to the southeast.

A review of slipface processes and structures in eolian dunes

Stress domains and the evolution of eolian avalanches

Eolian avalanches evolve through several stages. First, there is a slope failure that occurs commonly, but not always, near the top of the slipface where grainfall deposits have become oversteepened past the angle of repose for dry sand – roughly 32 degrees. This may begin in a small area that grows larger, or comprise a slump that is quite wide to begin with. Second, the initial failure area commonly evolves into an erosional alcove at the top of the flow. This alcove, and the flute below it supply loose sand to a depositional tongue of sand below (Figures 5-2 and 5-3). This tongue of newly deposited sand is thickest near the base, where there is commonly a sandflow toe; and in the center of the flow within the avalanche flute, if there is no slump. Third, almost all flows stop first at the base. This basal cessation then propagates upwards to the alcove (Figure 5-5). This causes a final compressional event within most of the flow all the way up to the alcove. Cohesive slumps follow a similar pattern, but tend to stop as a unit, rather than an upward-propagating compressional front.

Stress domains during a sandflow, as a whole (excluding the effects of basal drag), range from mostly tensional at the top of the flow to mostly compressional at the base, with an intermediate "transition zone" that changes position as the flow evolves (Figure 5-4). This evolution of stress regime produces strains reflected in a sequence of sedimentary structures typical of the stress domains, as described by McKee et al. (1971), and summarized on this page as Figure 5-1.

All avalanches experience drag along the base of the flow, where moving sand is contact with immobile sand. This creates shear stress because the upper part of the avalanche flows faster than the base. This may be the origin of wave-like "washboard" structures that usually form high in the avalanche and progress downslope along the top of the flow. One assumes they are wave forms, but this matter requires further study. Within the deposits of the slipface there are commonly compressional folds, fadeout laminae and thrusts that may all derive from the process that creates the washboard structures seen at the surface of many dry sand flows. The compressional, transitional and tensional domains, such as those described by McKee et al. (1971) shift laterally and vertically because the flow changes state as it evolves Figures 5-5, 5-6 and 5-7).

The presence of slumps (commonly caused by damp sand) will affect the dynamics of the overall avalanche event, but do not appear to fundamentally alter the evolution of stress along the avalanche. Sandflows commonly stop due to slope reduction near the base of the slipface, that is first encountered by the advancing toe of the avalanche. The slope reduction may also occur higher up the slipface depending on the morphology of the dune. Sandflows tend to stop gradationally, beginning at the base of the flow and propagating upward (Please follow the video links on Figure 5-5 to observe avalanches that we filmed during our work at Great Sand Dunes). When the toe of the sand flow (avalanche) stops, a compressional wave propagates upward through the avalanche, mainly in the center. Side flows may continue, or be initiated at this time, contributing to the aggregate volume of the flows, and deforming the previously formed washboard structures downward along the margins (Figure 5-6). The morphology of the slipface after the avalanche, to a varying degree, controls location and evolution of subsequent avalanches.

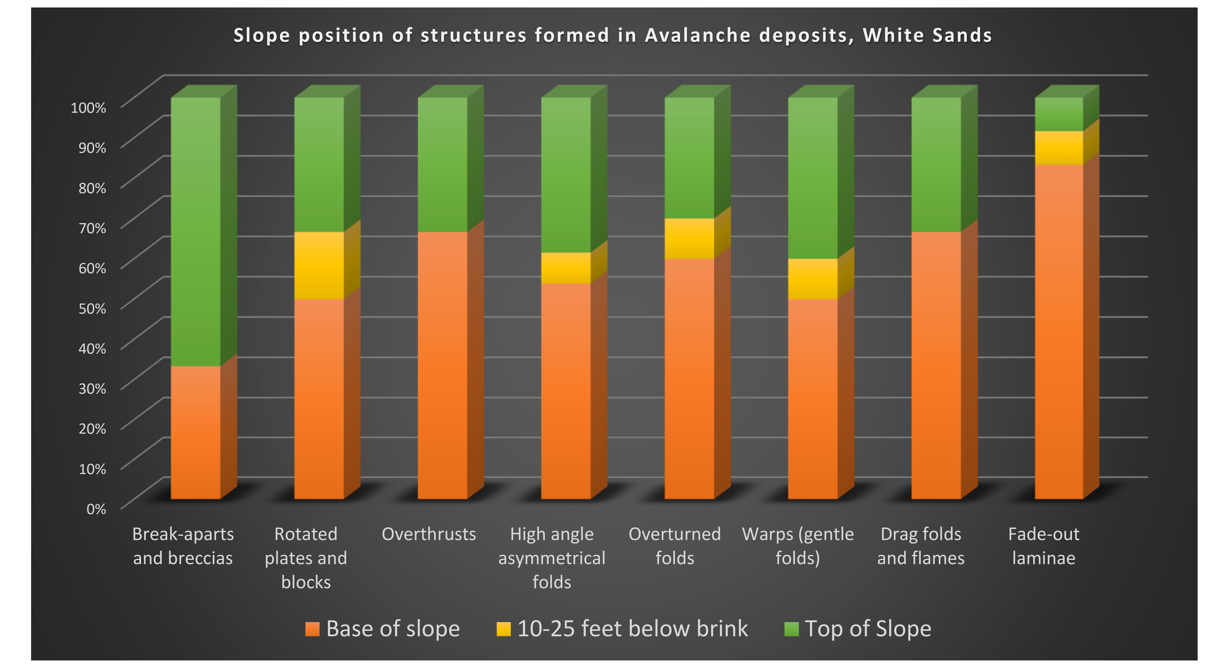


Figure 5-1 Distribution of sedimentary structures on dune slipfaces, White Sands, New Mexico, USA. After McKee et al., 1971, Table 4.

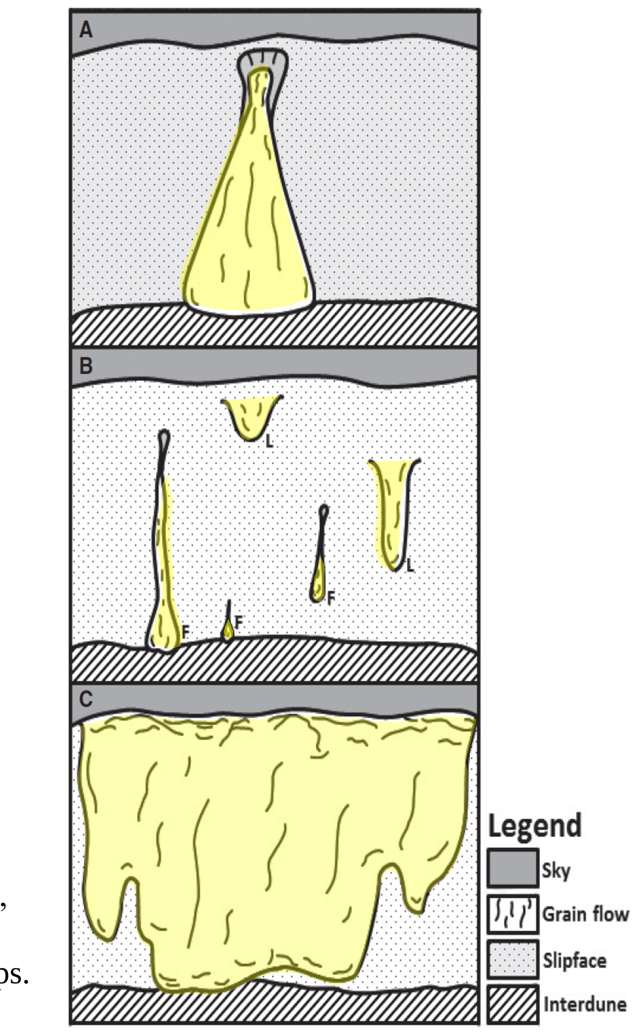


Figure 5-2 Right: Typical morphologies of grainflows, including the (A) "hourglass" shape, (B) Funnels and lobes, and (C) Slab flows that are gradational into slumps. After Cornwall et al., 2018.

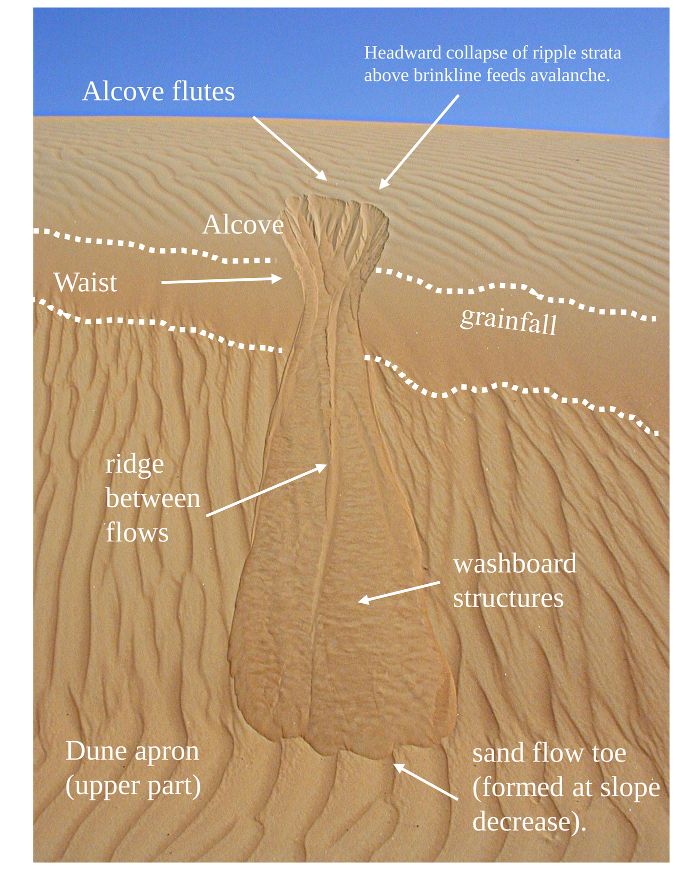


Figure 5-3 A dry sand avalanche on a small dune in the Wahiba Sand Sea, Oman. There is a narrow, thin grainfall layer at brink deposited by weak cross winds. Ripple orientation shows crosswind direction from the right. Cohesion of ripple strata on crest has also constrained this avalanche to a couple small flows that stop at a shallowing break in slope (note change in ripple orientation). This avalanche is a very good example of dry sand avalanche features, with light cohesion at top of the slipface - perhaps due to grain-meniscus cements. Dune is approximately 2 m in height.

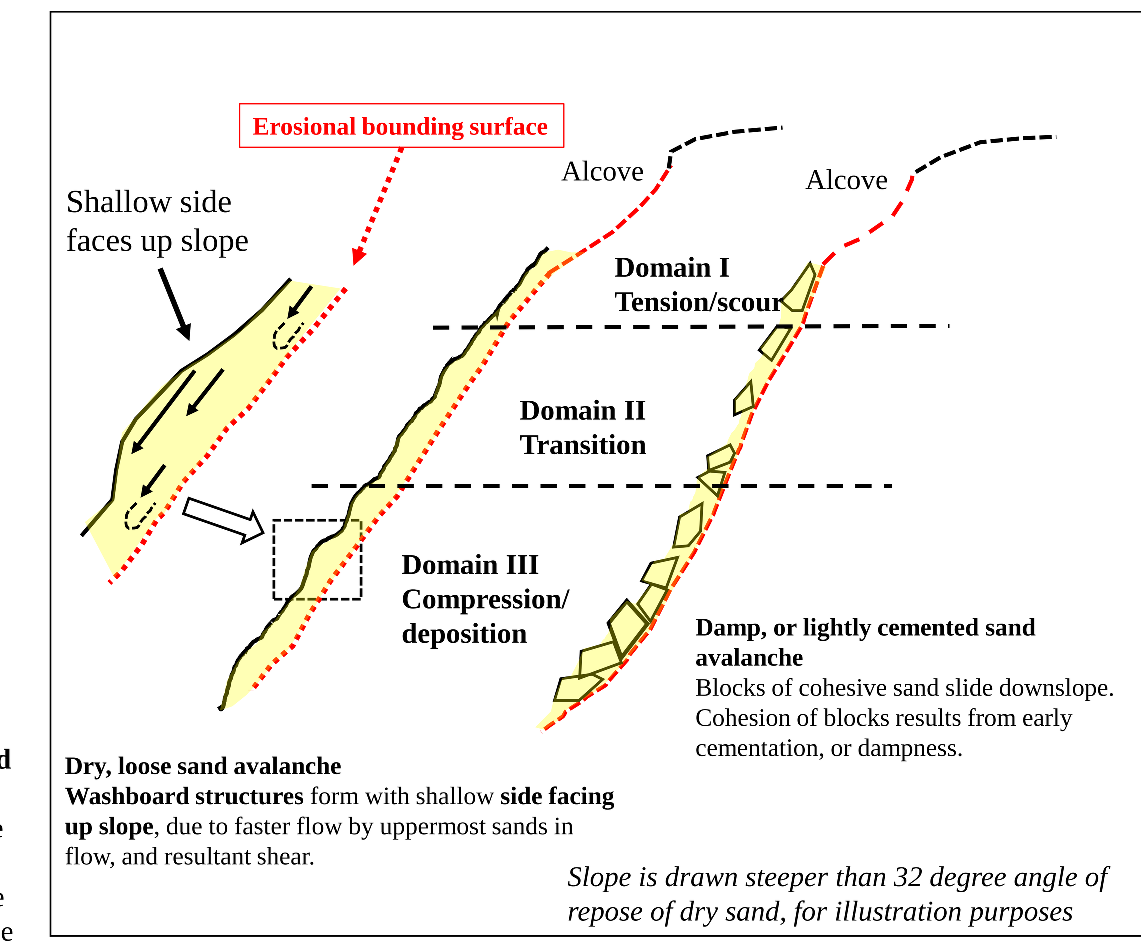
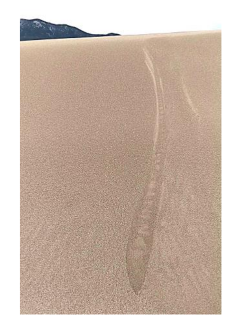


Figure 5-4 Stress domains on avalanche faces. Washboard structures and cohesive blocks in avalanches are also shown.

https://www.youtube.com/watch?v=mx23iJ-_V1Y&feature=youtu.be

https://www.youtube.com/watch?v=B65TTiySLCo&feature=youtu.be

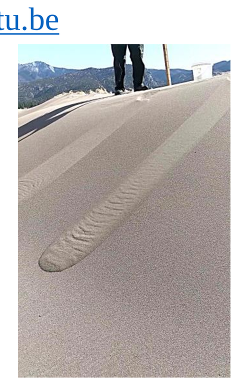
https://www.youtube.com/watch?v=tP5k3K9wEtQ&feature=youtu.be



https://www.youtube.com/watch?v=PtyXVaULdp4&feature=youtu.be

https://www.youtube.com/watch?v=Ic0g6ZQ4DmU&feature=youtu.be

https://www.youtube.com/watch?v=pgUrYxz1Ygc&feature=youtu.be

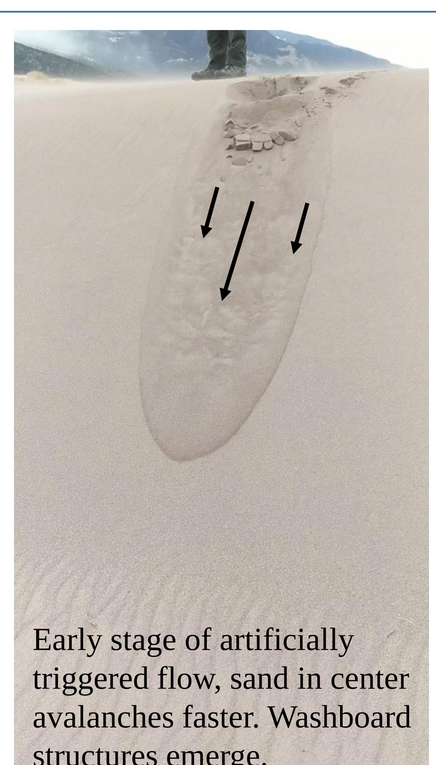


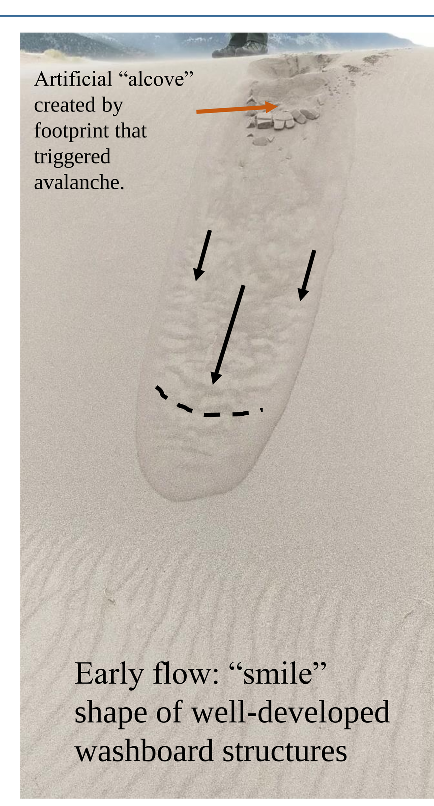
https://www.youtube.com/watch?v=1z8dgjqMZ4s&feature=youtu.be

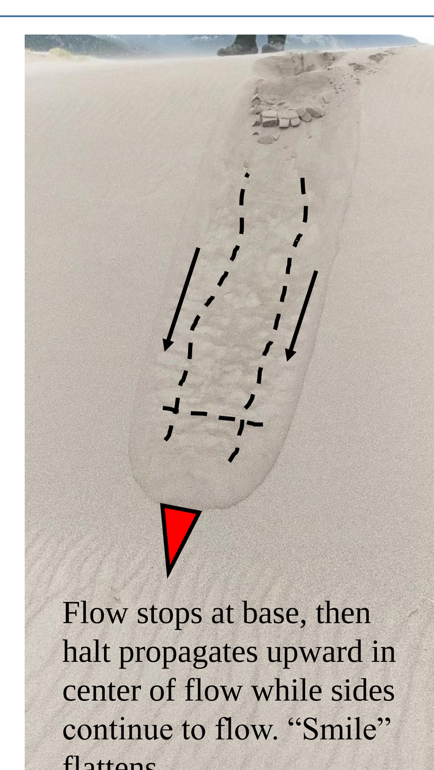
https://www.youtube.com/watch?v=0VYHz38uaDg&feature=youtu.be

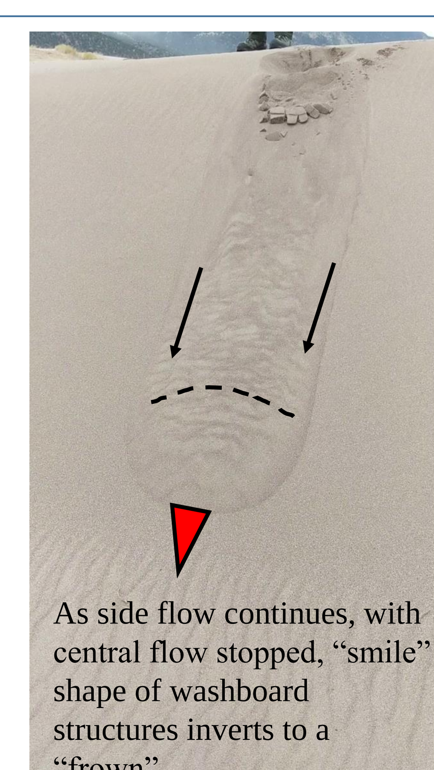
https://www.youtube.com/watch?v=va2auSeHv3M&feature=youtu.be

Figure 5-5 Videos of Avalanches, Great Sand Dunes N.P., Colorado.
We supply links here that connect to videos of eolian avalanches filmed for this study. They are worth viewing because they illustrate the evolution of slumps and sand flows: processes that are hard to describe with still images. The hyperlinks can be opened using "control-left click" or our preferred way: **right click then "open hyperlink"** seems to work well.









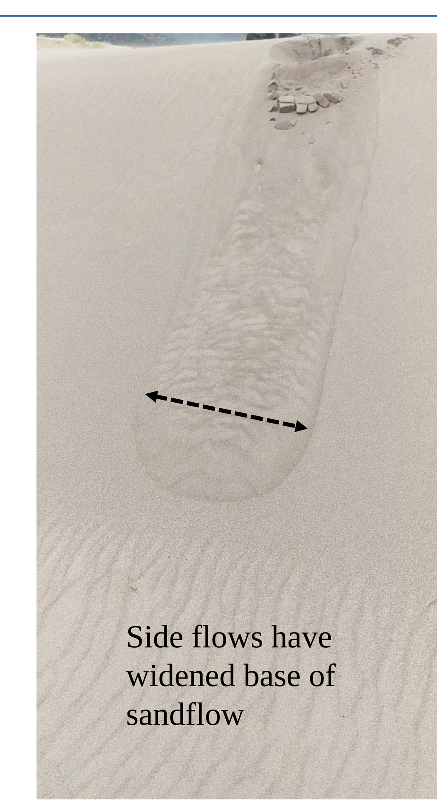
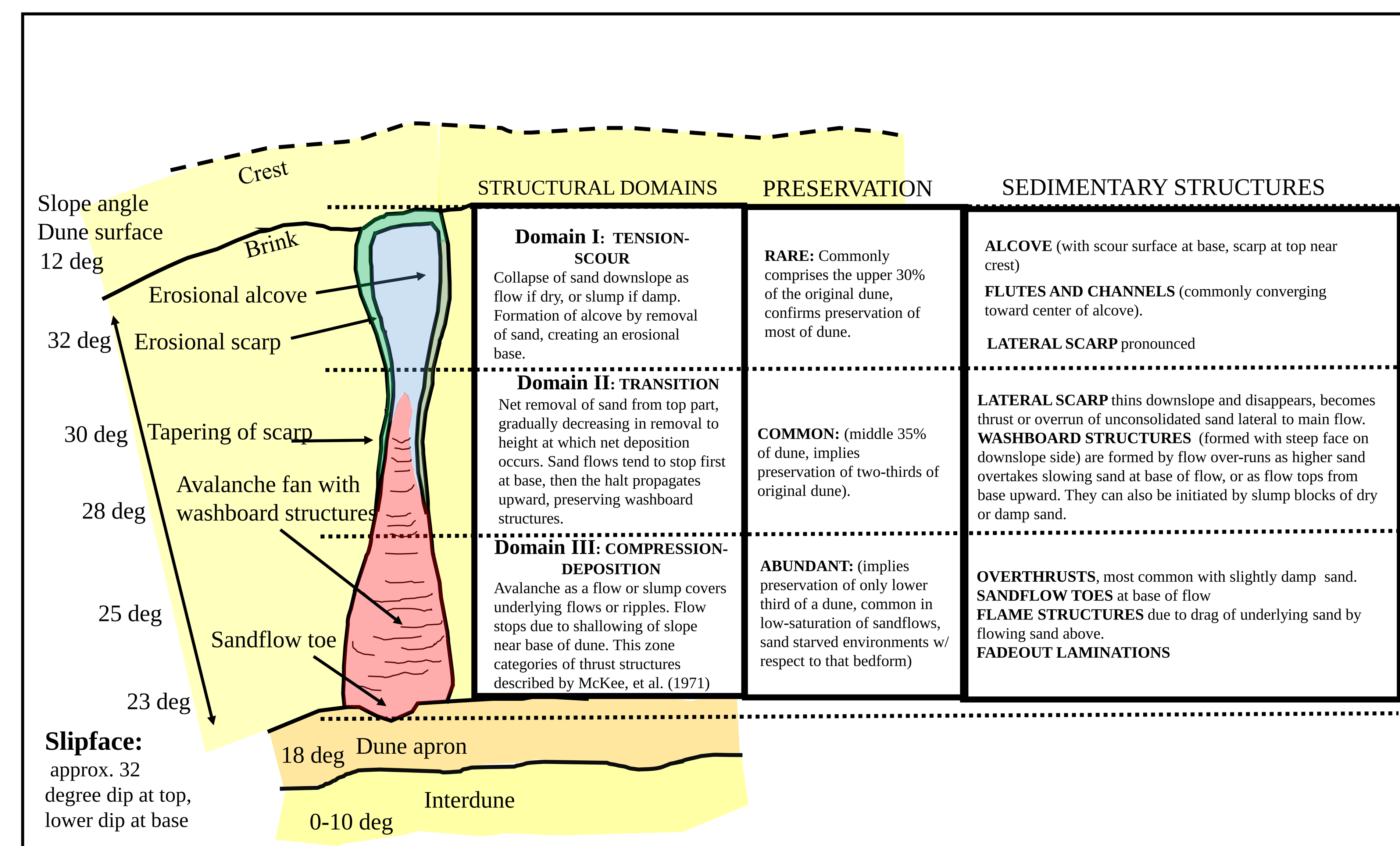


Figure 5-6 Evolution of a typical dry sand avalanche at Great Sand Dunes National Park, Colorado; here triggered by slowly stepping on sand at the top of the slipface. Note the reversal of "smile" aspect in early shape of washboard structures to "frown aspect" in later stage of flow. This effect is caused by the fact that sandflow in the center of the moving tongue of sand is faster during early stages of the flow. This effect occurs in natural as well as this artificially triggered avalanche. Once the faster central flow reaches the lower slope apron, and stops, the halt in flow rapidly propagates upward. At this point, side flows continue, reversing the "smile" effect to a "frown", by inverting the drag structures. Length of arrows suggests velocity (relative) of sandflow down the slipface. Although triggered artificially, this sequence is nevertheless typical of many natural avalanches. Although washboard structures seem to emerge from dynamics of the sand flow process, they are more distinct in sand with slight early cementation. Sequence of images is compiled from a video acquired for this study at Great Sand Dunes National Park. **The link to our video of this avalanche is on this page**.



STRUCTURAL DOMAINS	PRESERVATION	SEDIMENTARY STRUCTURES
Domain I: TENSION-SCOUR Collapse of sand downslope as flow if dry, or slump if damp. Formation of alcove by removal of sand, creating an erosional base.	**RARE:** Commonly comprises the upper 30% of the original dune, confirms preservation of most of dune.	**ALCOVE** (with scour surface at base, scarp at top near crest) **FLUTES AND CHANNELS** (commonly converging toward center of alcove). **LATERAL SCARP** pronounced
Domain II: TRANSITION Net removal of sand from top part, gradually decreasing in removal to height at which net deposition occurs. Sand flows tend to stop first at base, then the halt propagates upward, preserving washboard structures.	**COMMON:** (middle 35% of dune, implies preservation of two-thirds of original dune).	**LATERAL SCARP** thins downslope and disappears, becomes thrust or overrun of unconsolidated sand lateral to main flow. **WASHBOARD STRUCTURES** (formed with steep face on downslope side) are formed by flow over-runs as higher sand overtakes slowing sand at base of flow, or as flow tops from base upward. They can also be initiated by slump blocks of dry or damp sand.
Domain III: COMPRESSION-DEPOSITION Avalanche as a flow or slump covers underlying flows or ripples. Flow stops due to shallowing of slope near base of dune. This zone categories of thrust structures described by McKee, et al. (1971)	**ABUNDANT:** (implies preservation of only lower third of a dune, common in low-saturation of sandflows, sand starved environments w/ respect to that bedform)	**OVERTHRUSTS**, most common with slightly damp sand. **SANDFLOW TOES** at base of flow **FLAME STRUCTURES** due to drag of underlying sand by flowing sand above. **FADEOUT LAMINATIONS**

Figure 5-7 Organization of eolian sand avalanches during mid-flow (bedding plane view)

A review of slipface processes and structures in eolian dunes

Wind tunnel studies of avalanche structures

This page provides a summary overview of the sedimentary structures within avalanche strata as observed in the laboratory and field. In the late 1970's, Chris Schenk and I constructed a wind tunnel at the U.S. Geological Survey in Denver to study eolian ripple and avalanche strata. Questions had arisen about how to interpret sedimentary structures of ancient eolian dunes we were studying. The experimental setup included a sand feed device, and a large fan to draw "wind" with entrained sand along the rectangular tunnel, which in turn led to the artificial slipface. We obtained our sand from dunes near Great Sand Dunes National Park, Colorado. After we created a "sandstorm", that consisted of blowing sand down the tunnel onto the slipface, we could clearly observe the sedimentary structures typical of dry sand avalanches (Fryberger and Schenk, 1981).

The vertical distribution (top or bottom) of avalanche structures is complex, because stress domains shift geographically from the beginning to the end of a sandflow within each individual avalanche (This process can be seen in the videos linked in Figure 5-5). Thus, the domains described here for upper, middle and lower slipface all overlap depending upon the evolution of each individual slipface. However, the tensional (Figures 6-1 and 6-2),, shear/transitional (Figures 6-4 and 6-5) and compressional (Figures 6-7 and 6-8) domains are consistent in their sedimentary features, as illustrated on this page.

To help connect the wind tunnel images with real dunes, we include here several views of modern dune strata at Great Sand Dunes National Park, USA and the Jafurah Sand Sea, Eastern Province, Saudi Arabia (Figures 6-3, 6-6, 6-8 and 6-9) . These images illustrate that it is possible to interpret eolian avalanche strata with respect to position on a modern dune slipface. With good exposures in ancient rocks, as illustrated on pages 7, 8, and 9 below, one can also recognize the tensional transitional/shear and compressional domains of ancient slipfaces, if they are preserved. This is possible despite truncation of cross-bedding by various erosional bounding surfaces between and within eolian bedforms. Cross bedding, naturally, is the view most common to geologist working in ancient rocks. However, the easiest interpretation approach would naturally be to make use of exposures of slipface deposits not as cross beds, but as surfaces dipping toward the viewer. With a good knowledge of the sedimentary structures that typify the top, middle and base of sand flows, it should be possible to take the next step and interpret the degree of preservation of ancient slipfaces. This may enable better understanding of how any given ancient eolian sand sea evolved - by providing information on the changes in the saturation state of net and gross sand flow, and other variables affecting bedform preservation in these systems.

Extensive eolian sedimentation, as well as wind erosion (ventifaction) of bedrock has been documented on Mars. Interpretation has improved and expanded as data from landers and satellites increased in quality. As we acquire more knowledge of eolian sedimentary structures on earth, we can use this information to refine our understanding of ancient and modern wind directions and eolian facies on Mars (For example, see Grotzinger, et al., 2005).

Structures most common in the upper part of an eolian avalanche (tensional, erosional domain)

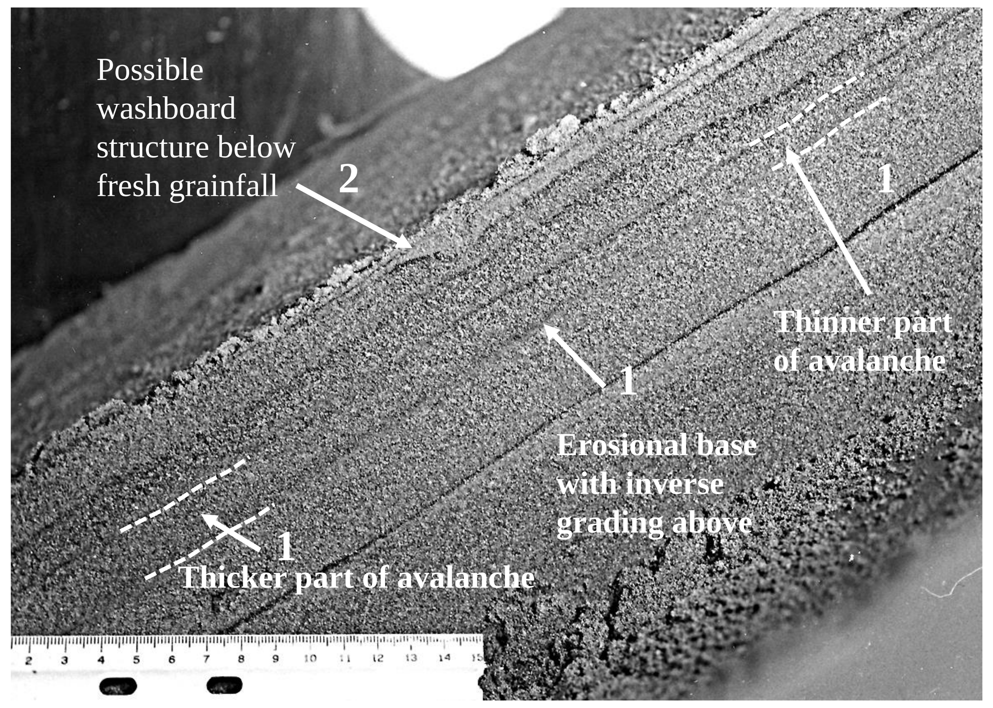


Figure 6-1 Cross-sectional view of upper slipface avalanche strata. It was formed on an artificial slipface in a wind tunnel, here seen through the Plexiglas wall of that tunnel. Wind from right to left. This view shows downslope thickening and inverse grading of two avalanches (white arrows 1), both of which thicken downslope. Also visible is what appears to be a single rotated block of sand (marked by a thin layer of dark magnetite, arrow 2). This block may represent the washboard structures typically found on dune avalanches, even on thinned strata near the base of the alcove at the top of the avalanche. After Fryberger and Schenk, (1981).

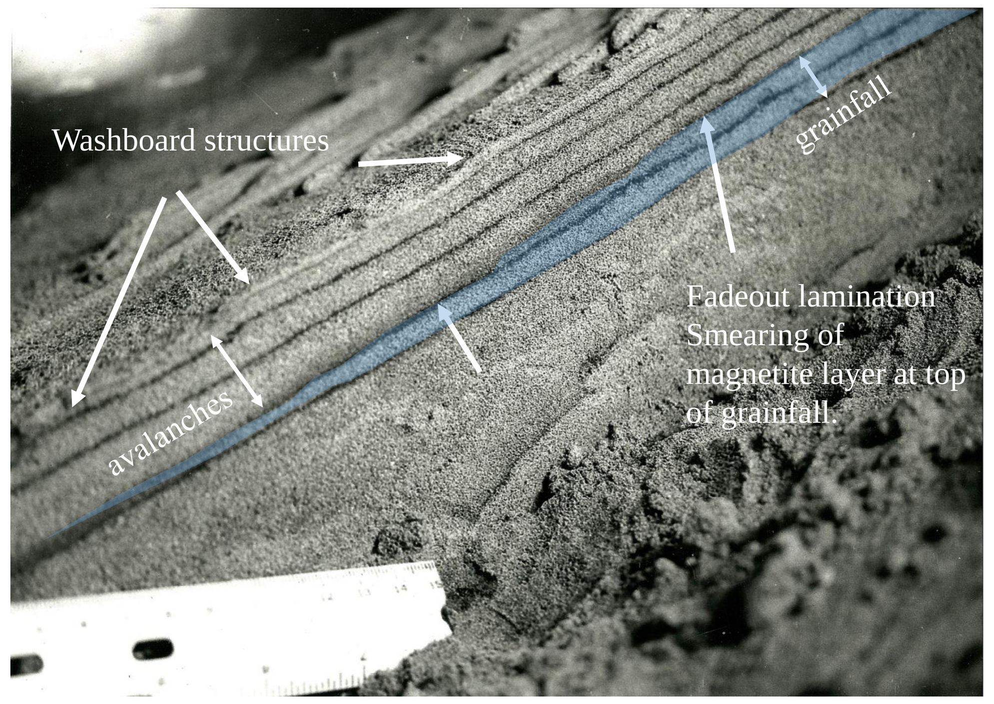


Figure 6-2 The upper slipface of a 2 m. high "dune" in a wind tunnel. Young avalanches truncate older ones and grainfall layers along erosional bounding surfaces. Individual avalanches thicken downslope, a process that ultimately results in a reduction of slope below the angle of repose (about 32 degrees) and termination of later avalanches farther up the slipface. Washboard structures are visible at the top of the last flow. Grainfall layers shaded blue for clarity.

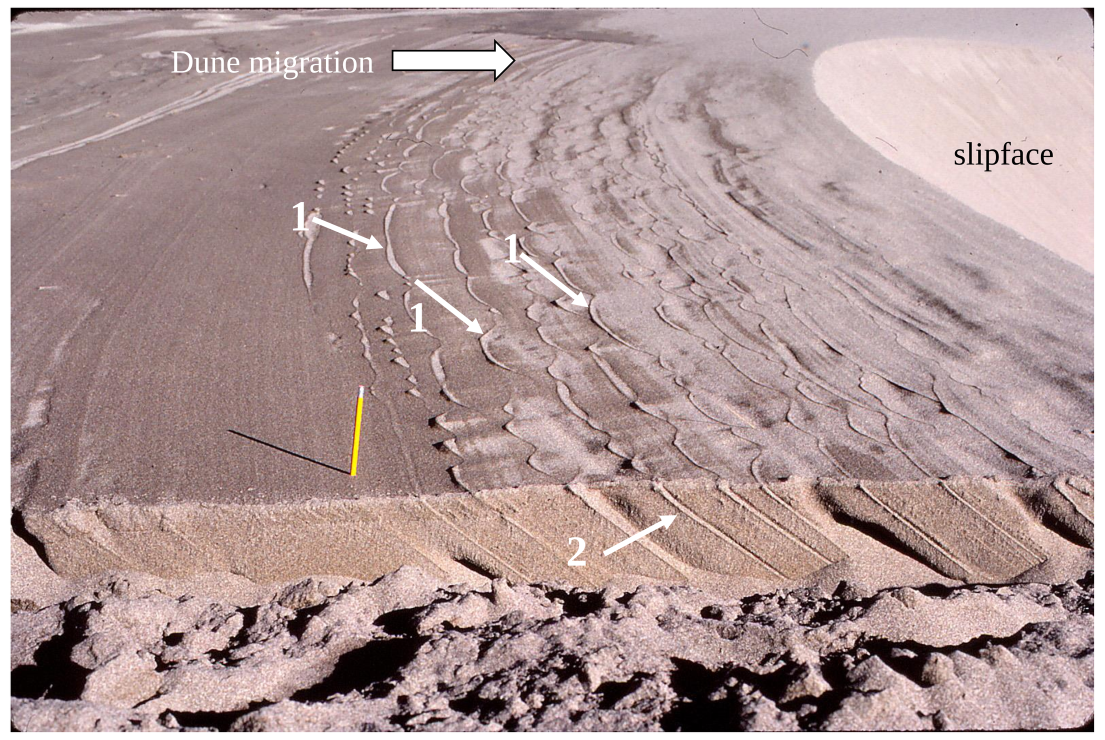


Figure 6-3 Upper slipface sedimentary structures in a reversing dune at Great Sand Dunes National Park, Colorado. The flat surface on the top of the dune was created by wind scour of damp sand. It exposes the curved bases of alcoves and flutes at the top of the slipface (now filled with windblown grainfall, arrows 1). The trench in the foreground shows the erosional lower bounding surfaces of sand flows (arrow 2). Most of the finely-laminated sand in this view appears to be grainfall strata, because it lacks the sharp, inverse grading and pin-stripe lamination of eolian ripple strata. (Fryberger and Schenk, 1988). Pencil for scale.

Structures most common in the middle of an avalanche (transitional/shear domain)

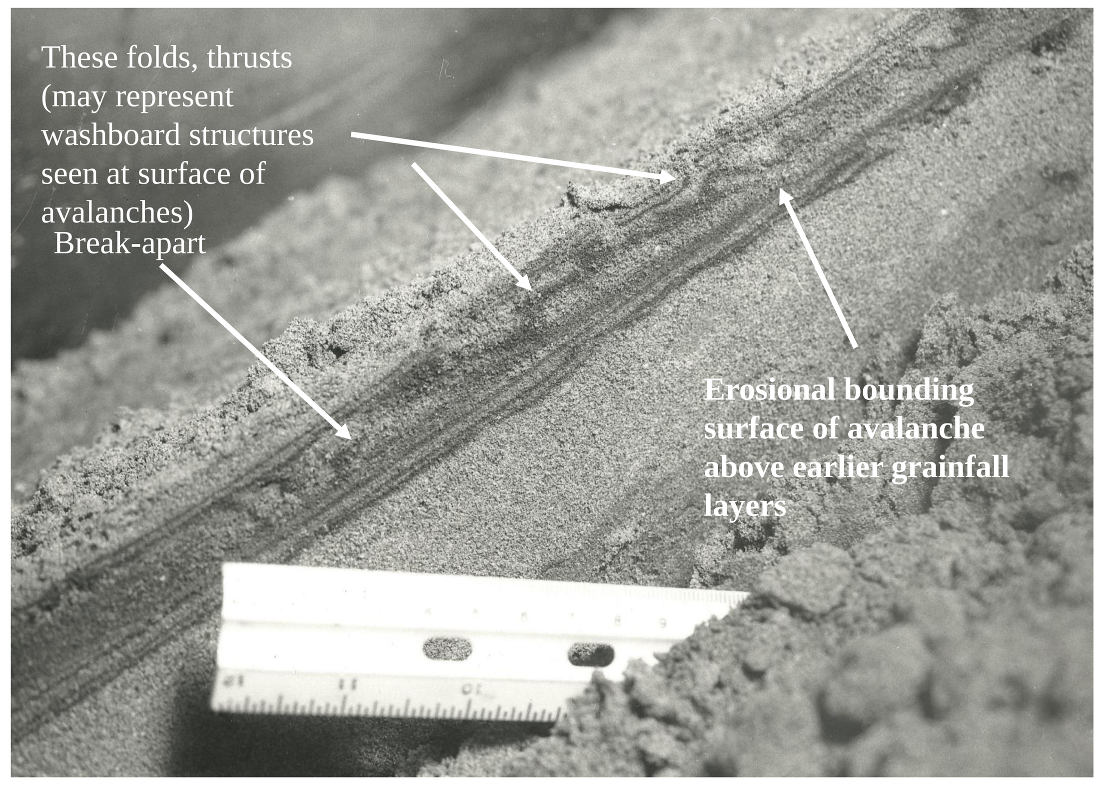


Figure 6-4 Left: Middle slipface avalanche structures on a 2.5 m long wind tunnel slipface at the U.S.G.S. wind tunnel, Lakewood Colorado, USA. This portion of the slipface has compressional folds and thrusts, as well as break-apart structures that reflect tensional forces within the sand flow. It is possible that the folds and thrusts, if viewed from the surface of the avalanche, would be the washboard structures commonly seen on slipfaces in the field. Thin layers below this avalanche are grainfall layers truncated near the top of the slipface by the erosional lower bounding surface of the flow.

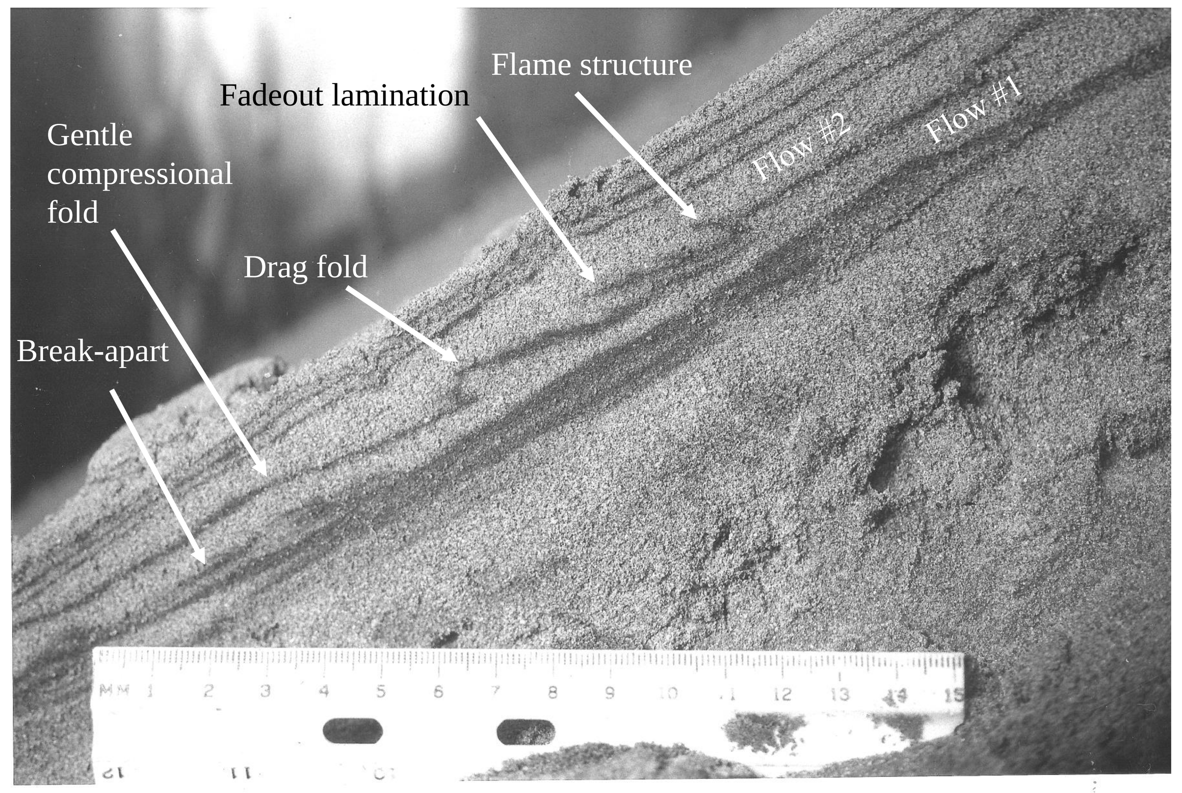


Figure 6-5 Left: Middle slipface avalanche structures on a 2.5 m long wind tunnel slipface at the U.S.G.S. wind tunnel, Lakewood Colorado, USA. This part of the slipface is a mixed compressional and tensional domain, thus sedimentary structures common to both are visible in this image. Compressional/tensional structures include the drag fold, that evolved from a compression (the original fold) and shear (the drag). There are also gentle folds at the top of the sandflow. Fully tensional structures include the flames and break-apart laminations. Dark layers are magnetite used to mark events in the wind tunnel.

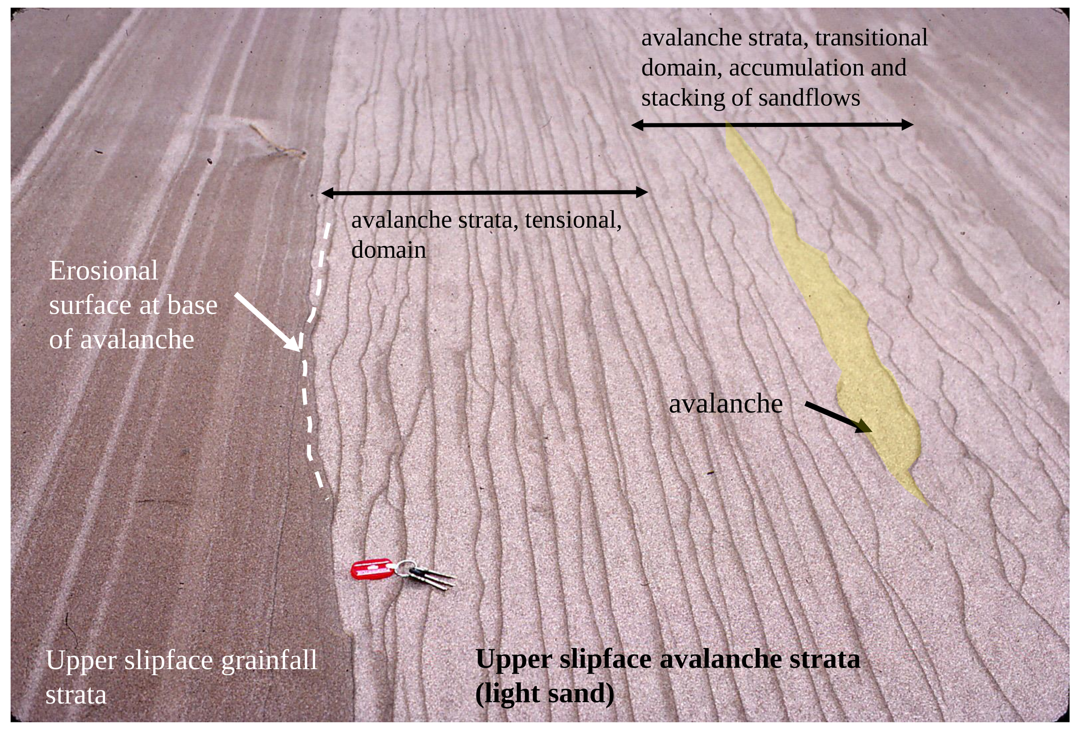


Figure 6-6 Upper-slipface sedimentary structures in a barchan dune at Great Sand Dunes National Park, Colorado. This bedding-plane exposure at the top of the dune was scoured by wind erosion during winter. On the left are mostly grainfall strata (dark layers). In the middle are avalanche strata preserved in alcoves and flutes that formed during avalanches. The dashed white line shows base of an alcove, or avalanche waist in which some of the avalanche sand has been preserved. On the right, convex (to-right) buildups of avalanched sand reveal the transition from a tensional regime to an increasingly compressional regime as the slipface evolved. A portion of a single avalanche is shown by yellow shading.

Structures common at the base of an avalanche (compressional/ depositional domain)

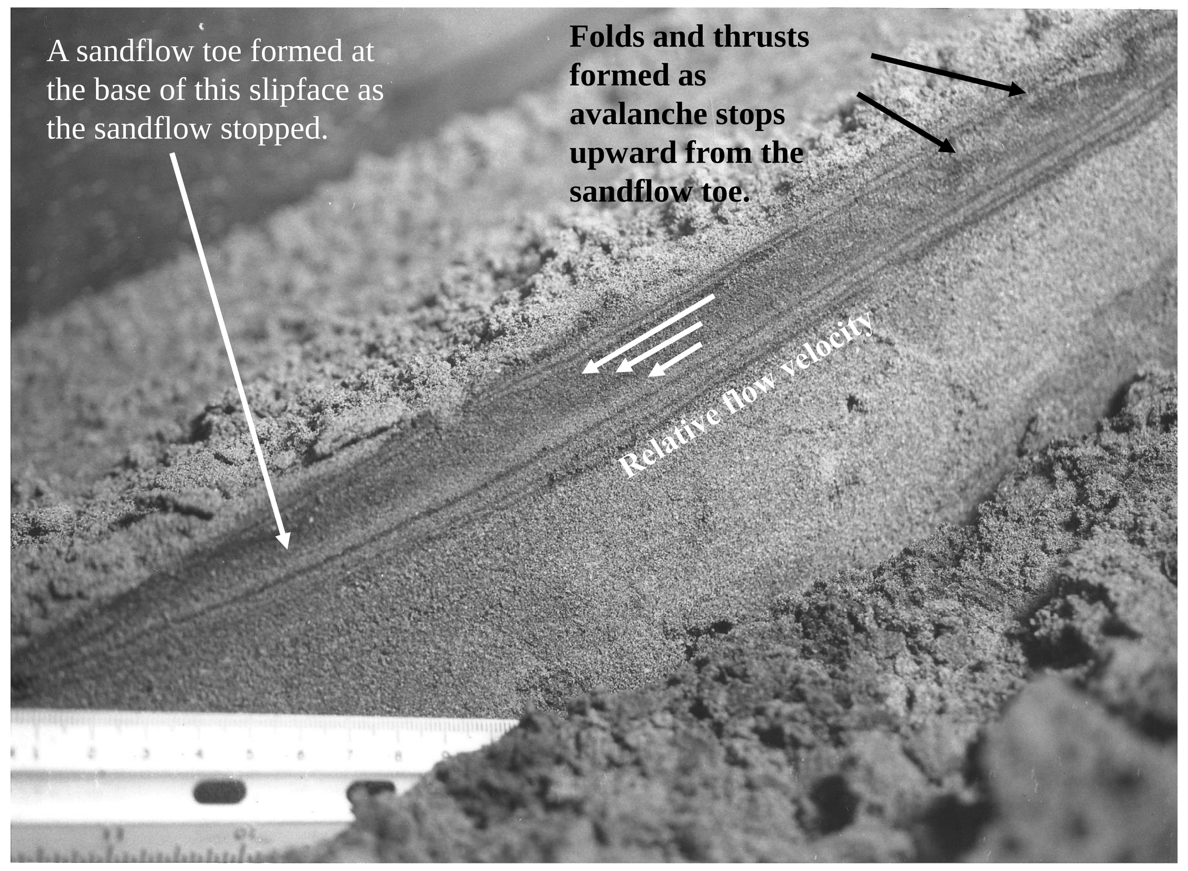


Figure 6-7 Most dry sand avalanches terminate in sandflow toes that pinch out downslope. The base of the slipface, as shown in this wind tunnel cross section, is typically dominated by lateral compression and vertical shear stress. Compression occurs partly because flows usually stop first at the sand flow toe; then progressively upward to the top of the flow. Commonly, portions of avalanches remain in the lower parts of alcoves, or in the neck separating the alcove from the main flow. Please see the video links to modern avalanches on page 5, above, that help make this process clear. Shear stresses are set up within the flow because sand flows most rapidly at the top, slowest at the base where in contact with drag created by underlying sand.

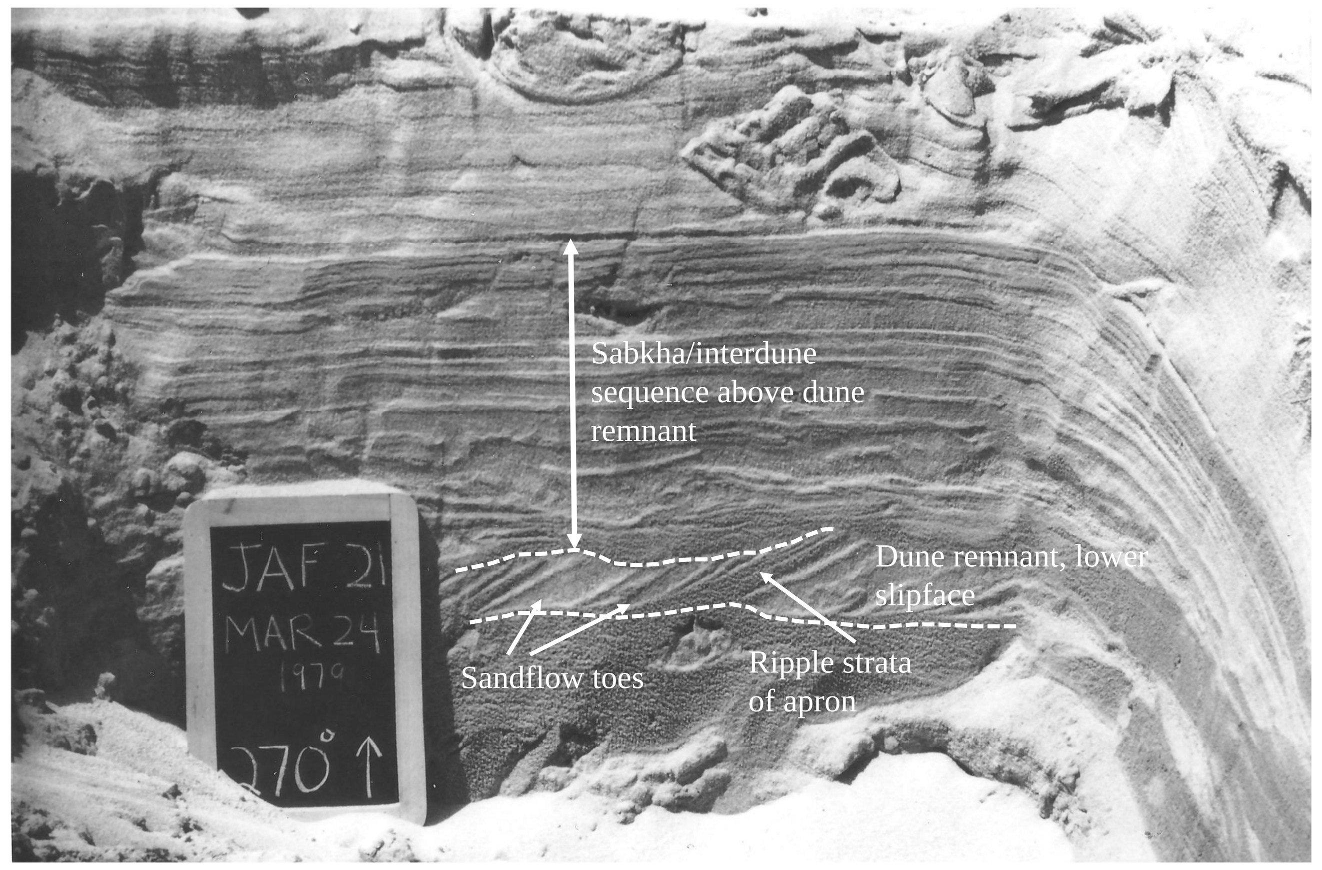


Figure 6-8 A thin base-of-slipface dune sequence has been preserved beneath sabkha deposits in the Jafurah Sand Sea, Eastern Province, Saudi Arabia. Top of the dune sequence is an erosional bounding surface formed by uneven wind scour of damp sand (Stokes surface). The dune sequence is mainly avalanche sand flow toes and eolian ripple strata of the dune apron. The ripple strata have slightly lower dip than the avalanche strata. This thin dune preservation suggests under-saturation of regional sand flow – not unexpected on coastal sabkhas in the Jafurah. Chalk board is about 20 cm wide.

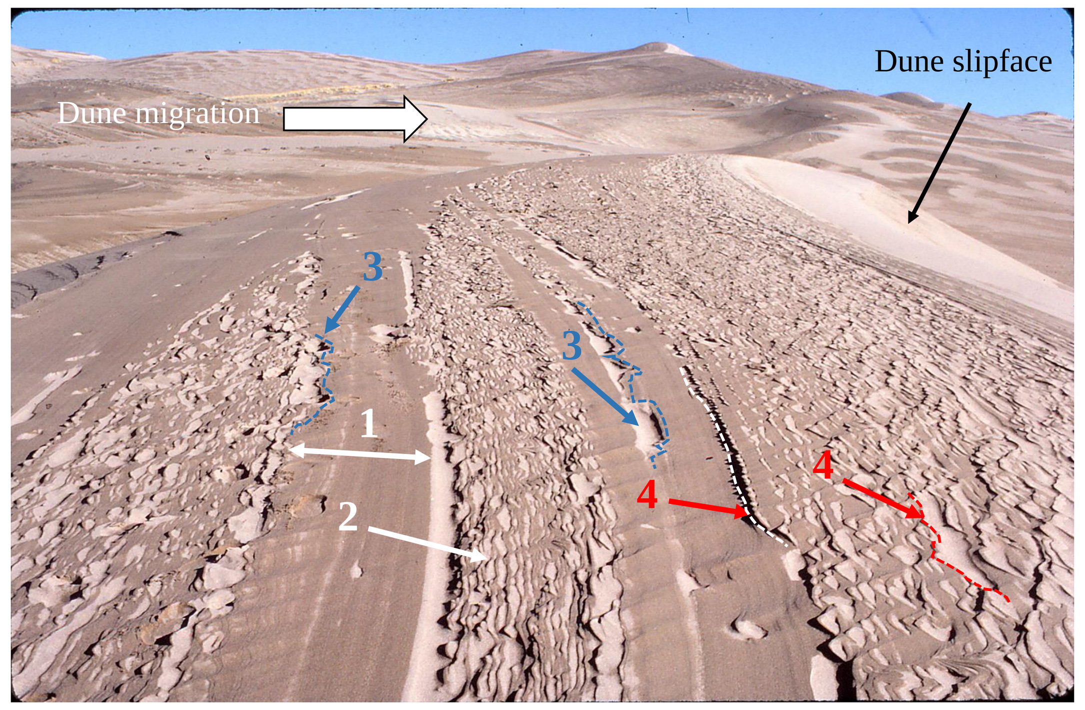


Figure 6-9 A bedding-plane view of upper-slipface sedimentary structures on a barchan dune, Great Sand Dunes National Park, Colorado, in winter. Grainfall strata comprise the fine-grained, evenly-laminated, dark brown sand (arrow 1, about .5 m wide). The fine-grained sand is well sorted. It is damp because the small capillary voids retain moisture from snowmelt. This is in contrast to the light-colored, coarse avalanche layers that have less ability to store moisture (arrow 2). The banded zones (shown by arrow 2) point to alternate dry and damp layers that appear to have resulted from avalanching at the dune brink. Some of the damp layers may be thin layers of grainfall. Avalanches eroding dark grainfall sands created the small alcoves that appear to have been filled by light colored avalanche (?) sand. Possible slumps are shown by blue arrows 3. Red arrows 4 show possible avalanche flute and alcove scour surfaces. Larger elements may represent linked, or adjacent avalanche flutes. Dune is approximately 5 meters high at the slipface.

A review of slipface processes and structures in terrestrial dunes

Ancient eolian avalanche structures, Cambrian Amin Sandstone, Huqf Uplift, Oman

The (Cambrian) Amin Formation at Wadi Sumaynah in the Huqf uplift of North Oman (Figures 7-1, 7-2, 7-3, 7-4 and 7-8) preserves an excellent ancient example of the geomorphology of eolian avalanches, including the alcoves and flutes that typically form on the upper slipface of a dune. Our earlier field work had confirmed the eolian origins of the Amin in the Wadi Sumaynah area using sedimentary structures such as sand flow toes and inverse-graded ripples. It was a pleasant surprise to come across this outcrop during a follow-up visit, because alcoves typically formed at the top of modern eolian avalanches were well preserved in these very ancient rocks (Figures 7-5, 7-6, 7-7, 7-8 and 7-9) . Preservation of the uppermost parts of slipfaces has been a rarity in our experience, because they are commonly truncated before the next set of cross beds is deposited. The reader can compare the striking similarity of this Cambrian outcrop to modern (upper) slipfaces illustrated elsewhere in this report.

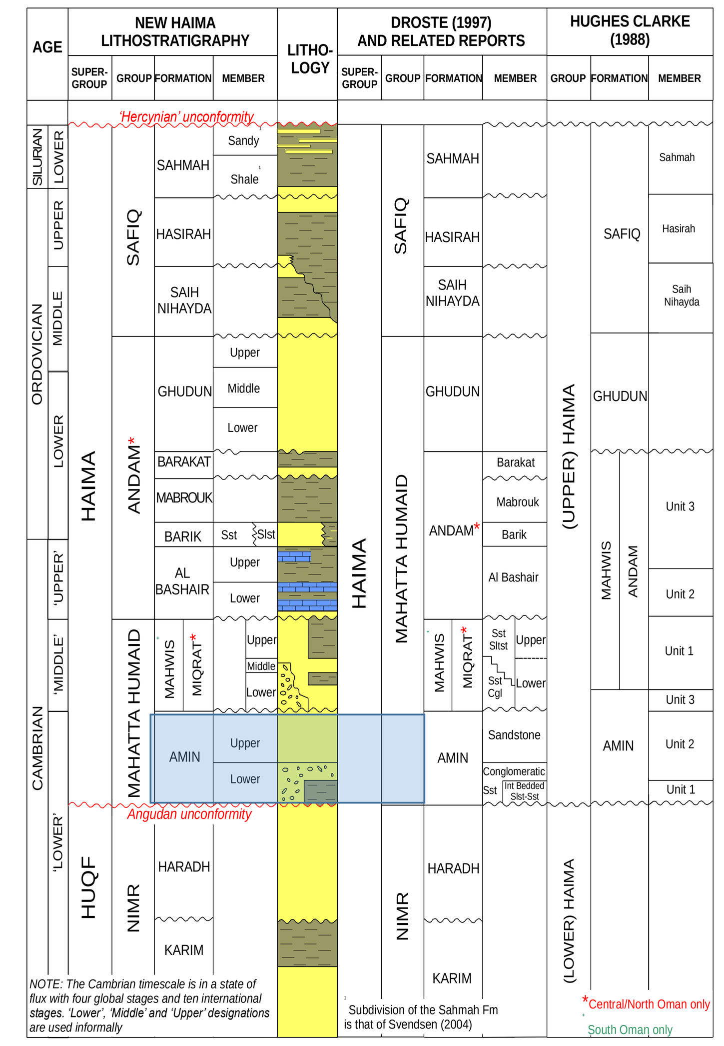


Figure 7-1 Stratigraphic column for the Haima and part of the Huqf Groups, Oman. The Amin is comprises a mainly continental sequence that lies just above the Angudan Unconformity in North Oman. After Fryberger, (2009) and Fryberger et al., (2006).

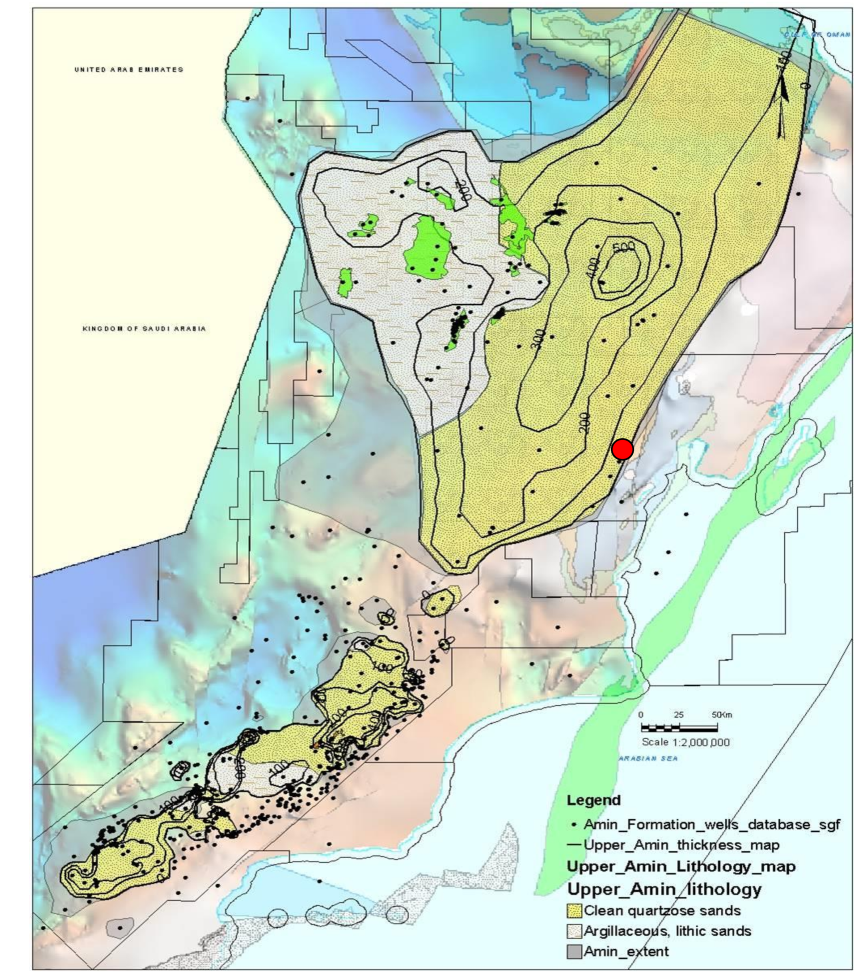


Figure 7-2 Map showing the general distribution of lithofacies in the Upper Amin Formation in North and South Oman. After Fryberger et al., (2006).

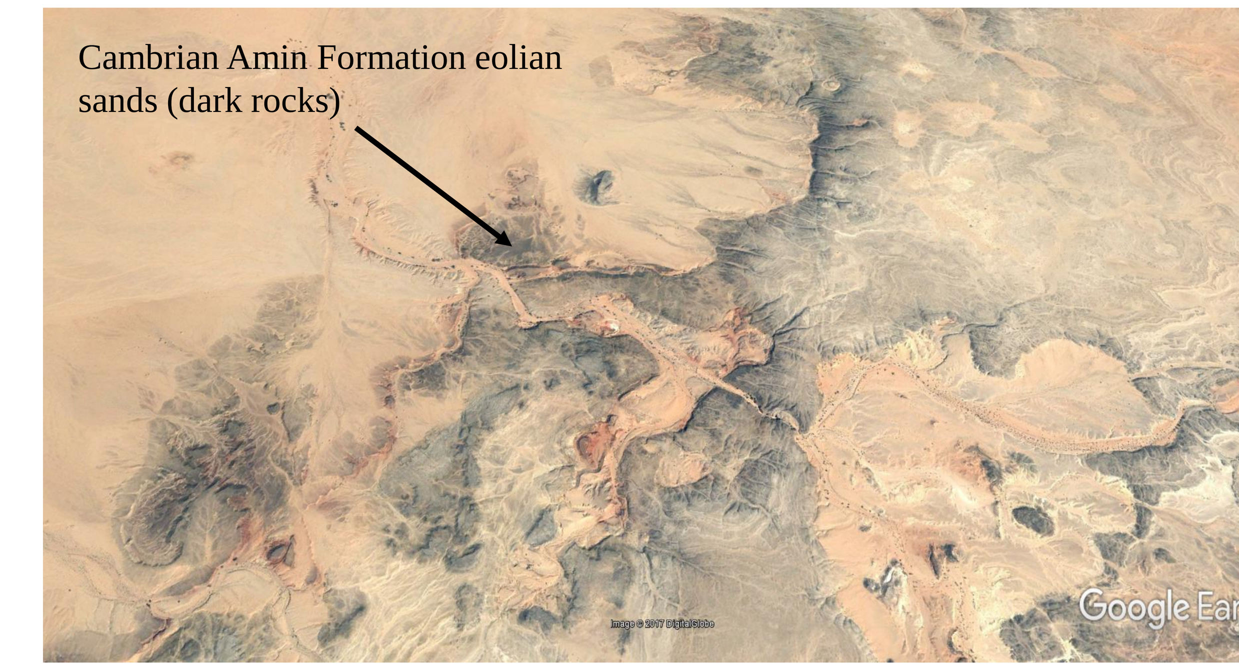


Figure 7-3 Satellite view of the Wadi Sumaynah area. Dark rocks are the Amin outcrops. The outcrops illustrated on the page are from exposures along Wadi Sumaynah, a dry wash that extends through this area. Image is approximately 4 north to south. Image courtesy of Google Earth.

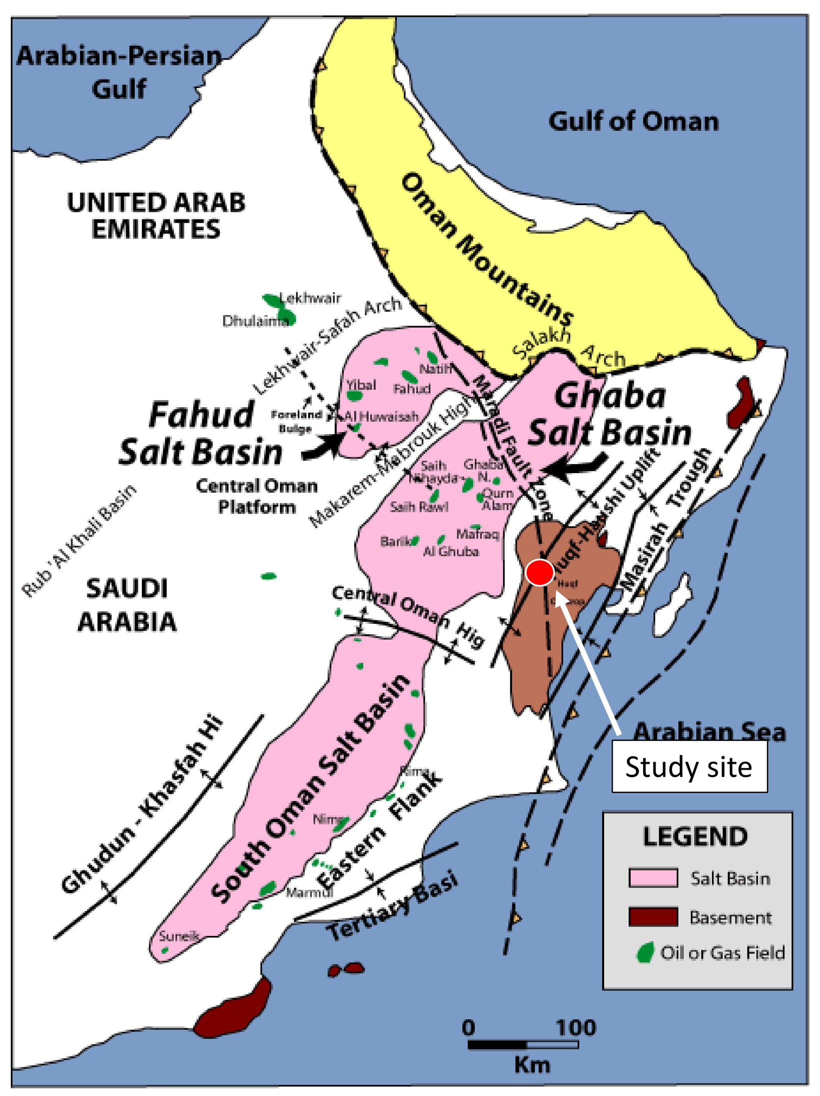


Figure 7-4 Tectonic map of Oman, showing the major salt basins and their relationship to the Huqf uplift. After Loosveld, et al., (1996).

Figure 7-5 Wadi Sumaynah, Oman: Oblique view of upper slipface with avalanche alcoves and flutes, view to south. These small dunes were migrating westward. Ancient wind was from the left. Slipface is about 1 m high.

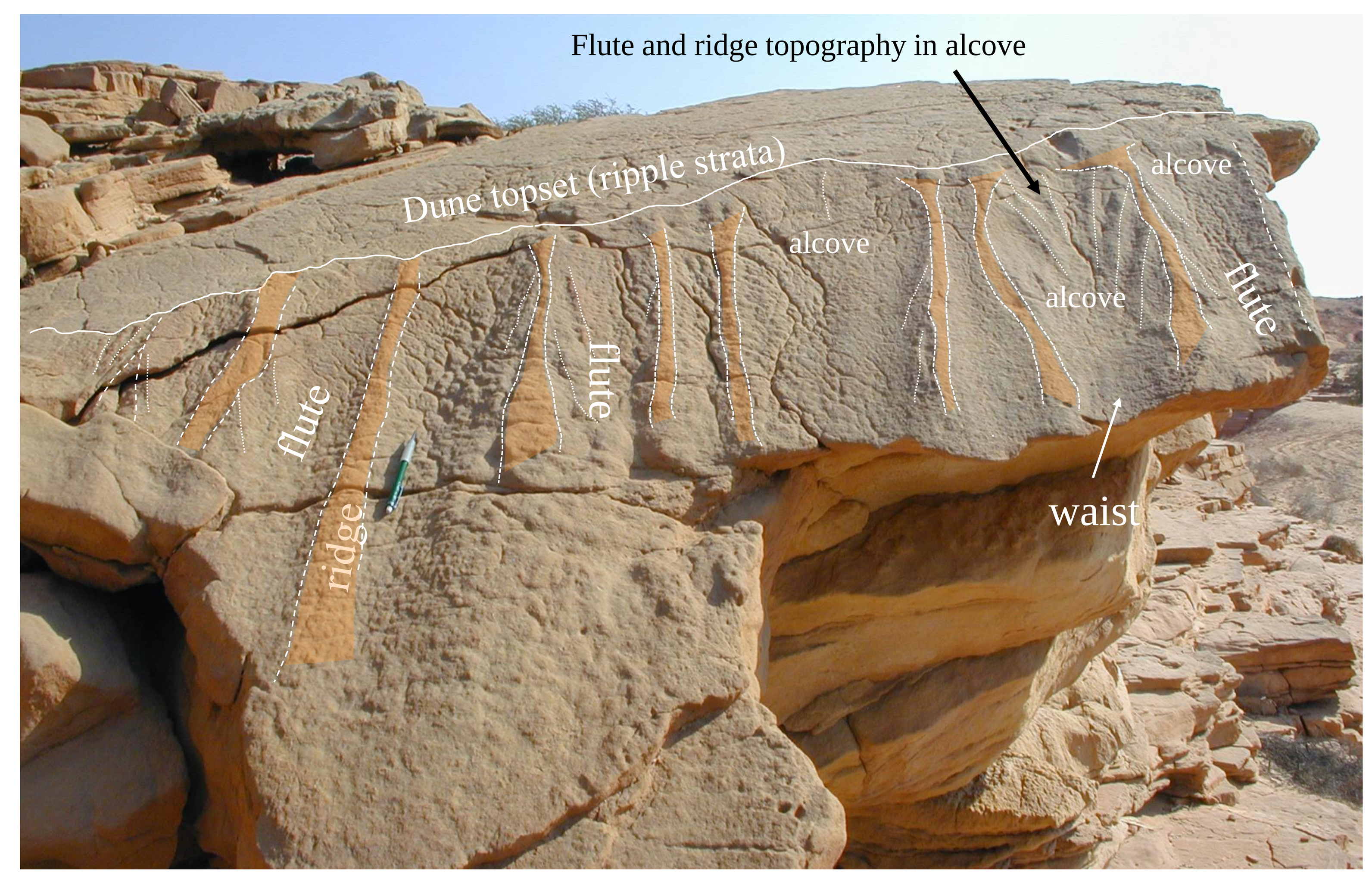


Figure 7-6 Eolian dune alcoves and flutes, along with dune crestal (topset) bedding are visible in this (Cambrian) Amin outcrop. Thus, most of the dune been preserved at this place. View is "into the wind". It is not known why these structures, that are seldom preserved, survived here. Mechanical pencil on the slipface provides scale.

Figure 7-7 Outcrop view of the Wadi Sumaynah avalanche scars (same picture as that on the left; without geological interpretation. Direction of view is toward the east. Mechanical pencil on slipface for scale.

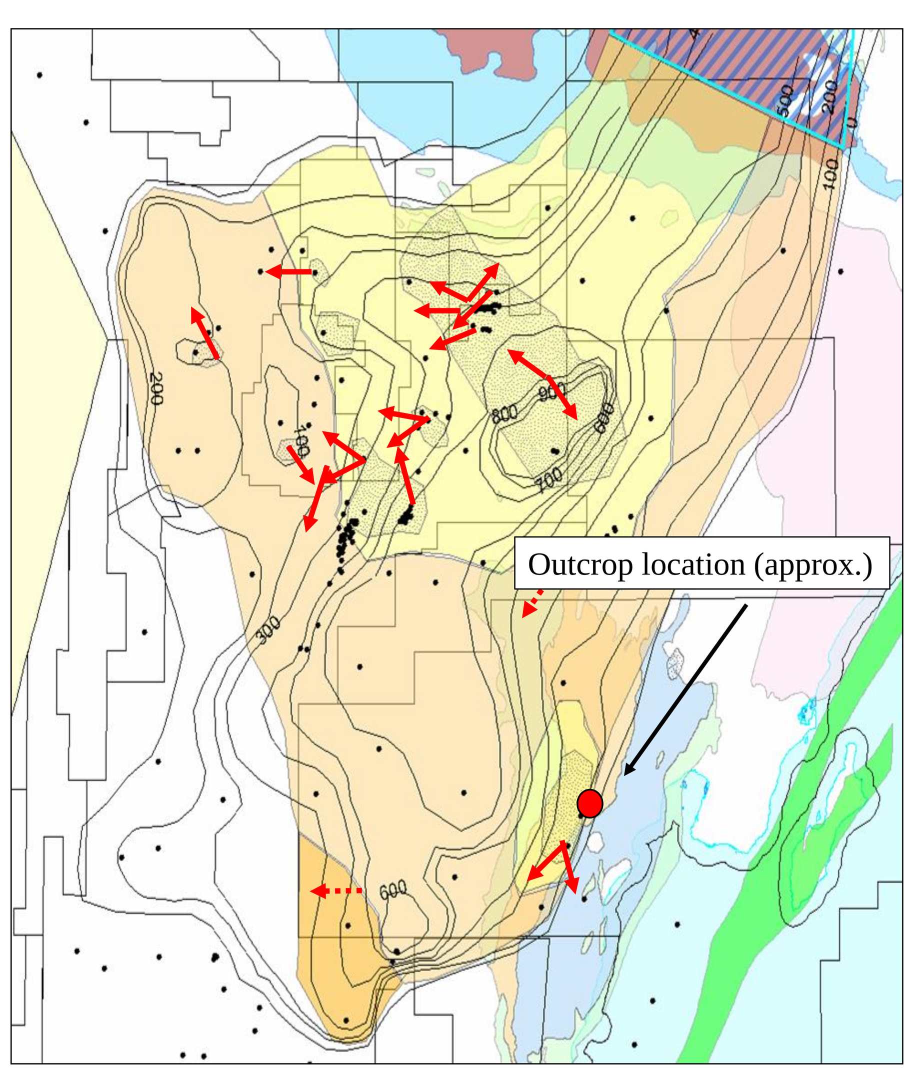


Figure 7-8 North Oman wind directions (red arrows) in the Amin Formation eolian sands. Although winds are variable, many of the arrows indicate winds from east to west, matching the outcrop wind directions. Also shown, Upper Amin depositional environments and Amin Formation isopach map. Eolian dune environments shown by dots. Red dot shows approximate location of the outcrop we studied in the Huqf Uplift. After Fryberger, (2009).

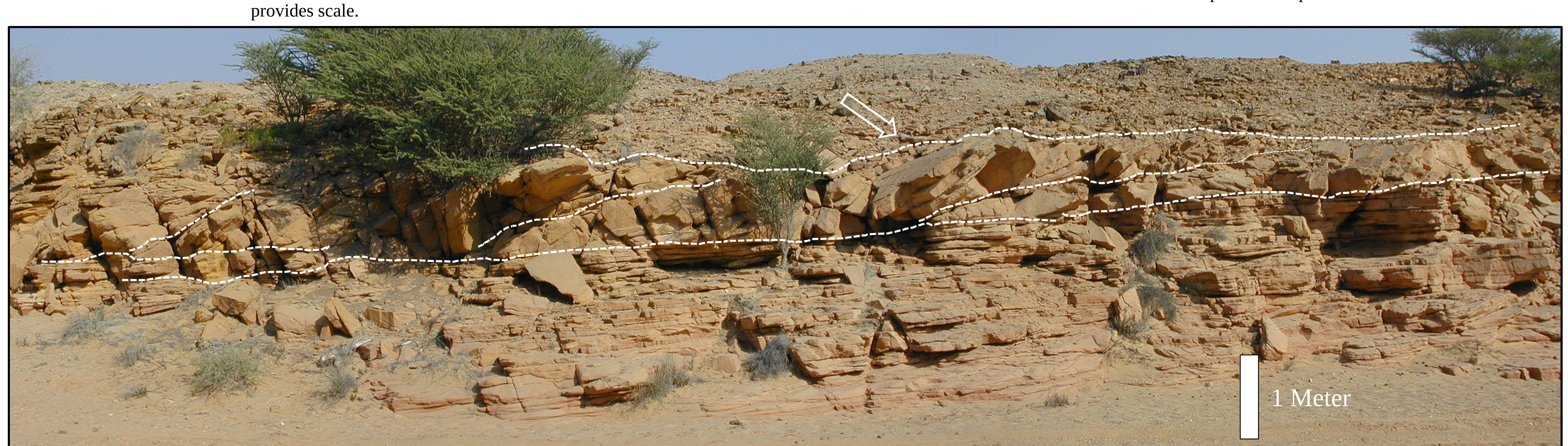


Figure 7-9 Avalanche scars and alcoves described here were found on top of the slipface indicated by the arrow. Crestal ripple strata are also preserved. These observations prove this is a small dune that is almost 100% preserved, and not a partly-preserved large dune. View is to the north from the channel of Wadi Sumaynah. This appears to be the first sizeable dune preserved above the thin dune and sand sheet remnants below, perhaps indicating a change in the eolian system dynamics at this time. Outcrop is about 2.5 m high.

A review of slipface structures in eolian dunes

Ancient eolian avalanche structures, Permian Upper Tensleep Sandstone, Flat Top Anticline, Wyoming, USA

An outcrop of eolian sandstone with well-preserved upper slipface ridges and flutes was found while measuring a section in the Upper Tensleep Sandstone (Permian) at Flat Top anticline, Wyoming. USA (Figures 8-3 and 8-4). At Flat Top, which is 6 miles north of the town of Medicine Bow, eolian sedimentary structures are well-exposed in gentle cliffs. We came across a thin dune with possible alcoves and upper slipface sand flows, well preserved ridges, and avalanche flutes (Figures 8-1, 8-2, 8-5, 8-6 and 8-9). This small dune extended for 10 meters along the outcrop (Figures 8-7 and 8-8) . Cementation in this dune is more complete than dunes above and below. Perhaps early cementation as well as other factors have helped preserve this dune almost in entirety.

One of the outcomes of our work is the conclusion is that there is much that can be learned by observing bedding plane views of eolian dunes, especially slipface deposits. The percentage of slipface preservation, from base to alcove, may provide a useful clue to the eolian "system state" when the sediments were deposited – if it is possible to acquire sufficient measurements from outcrop to be statistically significant.

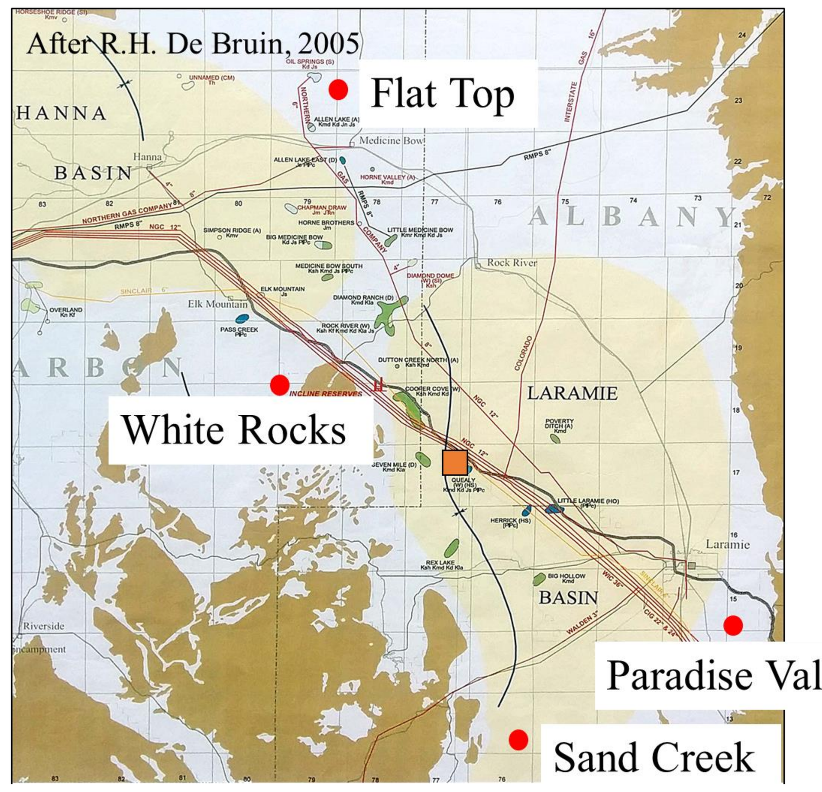


Figure 8-3 Map showing the Laramie and Eastern Hanna Basin Oil Fields, with location of sections measured for a report by Fryberger et al., (2016b). Quealy dome oil field, in the Tensleep eolian reservoir, is shown by the orange square.

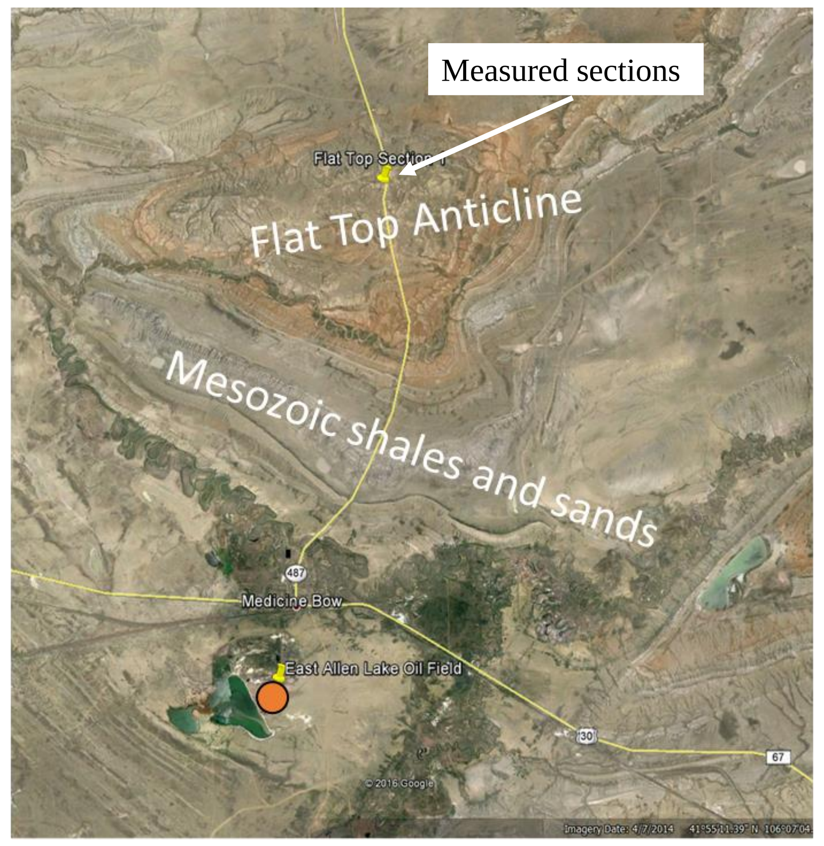


Figure 8-4 Satellite view of the Flat Top Anticline, surrounded by exposures of the red-beds of the Permo-Triassic Goose Egg Formation. East Allen Lake oil field (orange dot) produces from the Tensleep just south of the town of Medicine Bow. The Tensleep outcrop we studied is about 6 miles north of Medicine Bow. Image Courtesy of Google Earth.

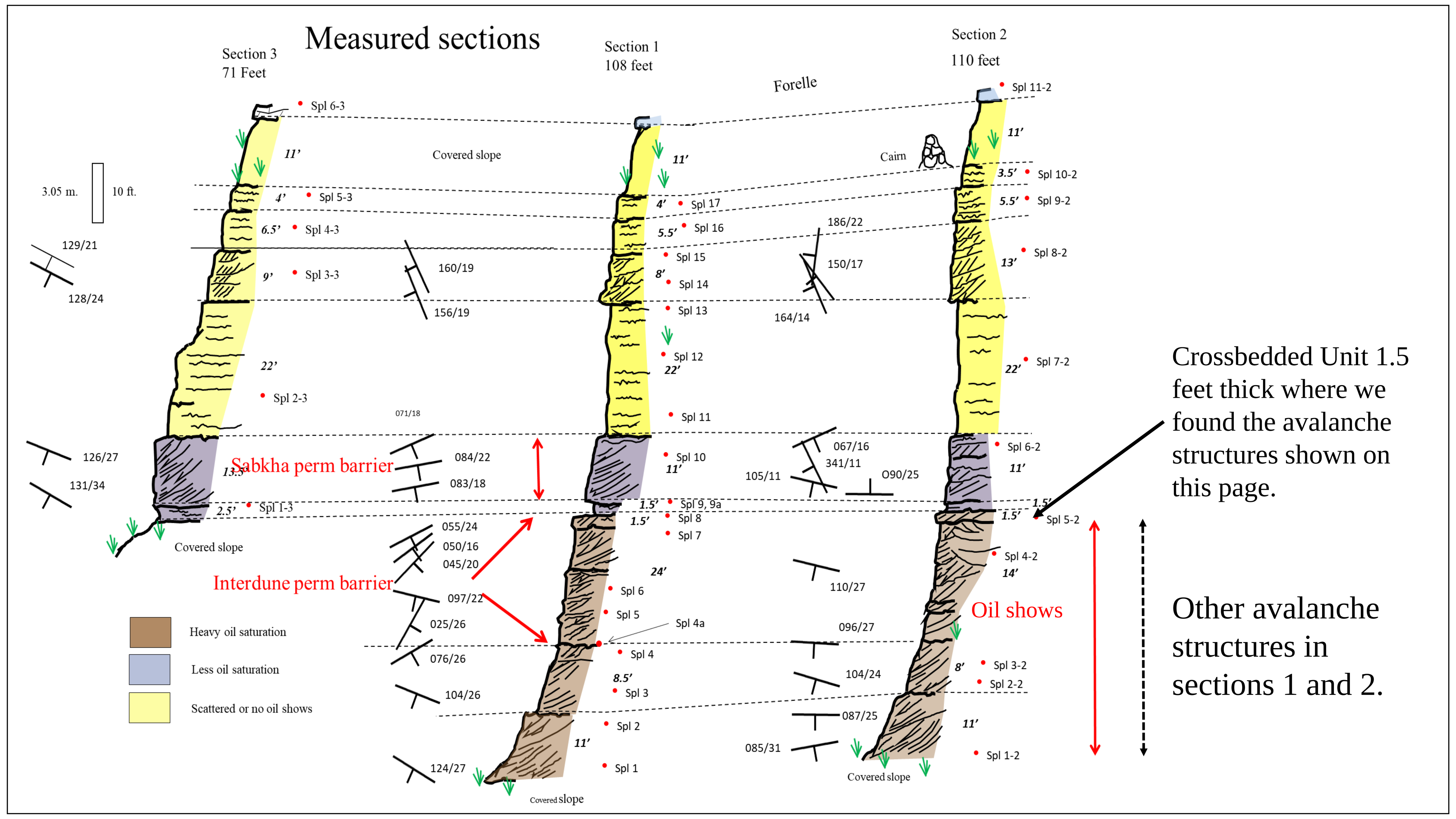


Figure 8-7 Three measured sections in the Permian Upper Tensleep Formation, Flat Top Anticline, Medicine Bow, Wyoming. Black, solid arrow shows the thin eolian sandstone unit in which the preserved alcoves were found.

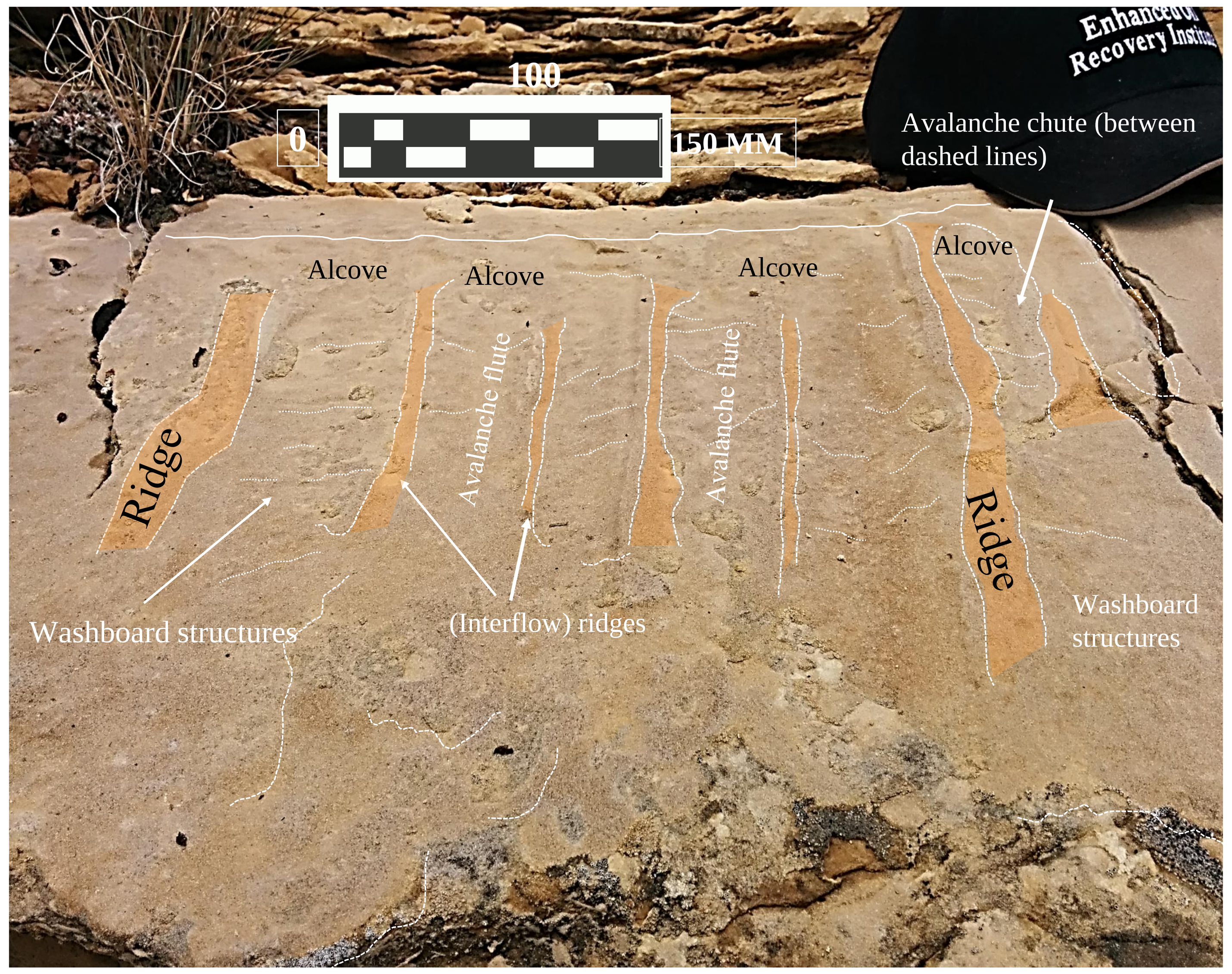


Figure 8-1 Upper Tensleep dune slipface, left side. Avalanche flutes that are mostly empty, or with little avalanched sand suggest that this outcrop is in the middle, or near the top of the ancient dune at Flat Top anticline. Alcoves, if present, are subtle. Some sand remains in the avalanche flutes, showing washboard structures, indicated by finer dashed lines. Concave shape of flutes, as well as narrow ridges indicate this topography is not eolian ripples. Uninterpreted images are presented on the right side of this page for comparison.

Figure 8-2 Upper Tensleep dune slipface left side, without geological interpretation.

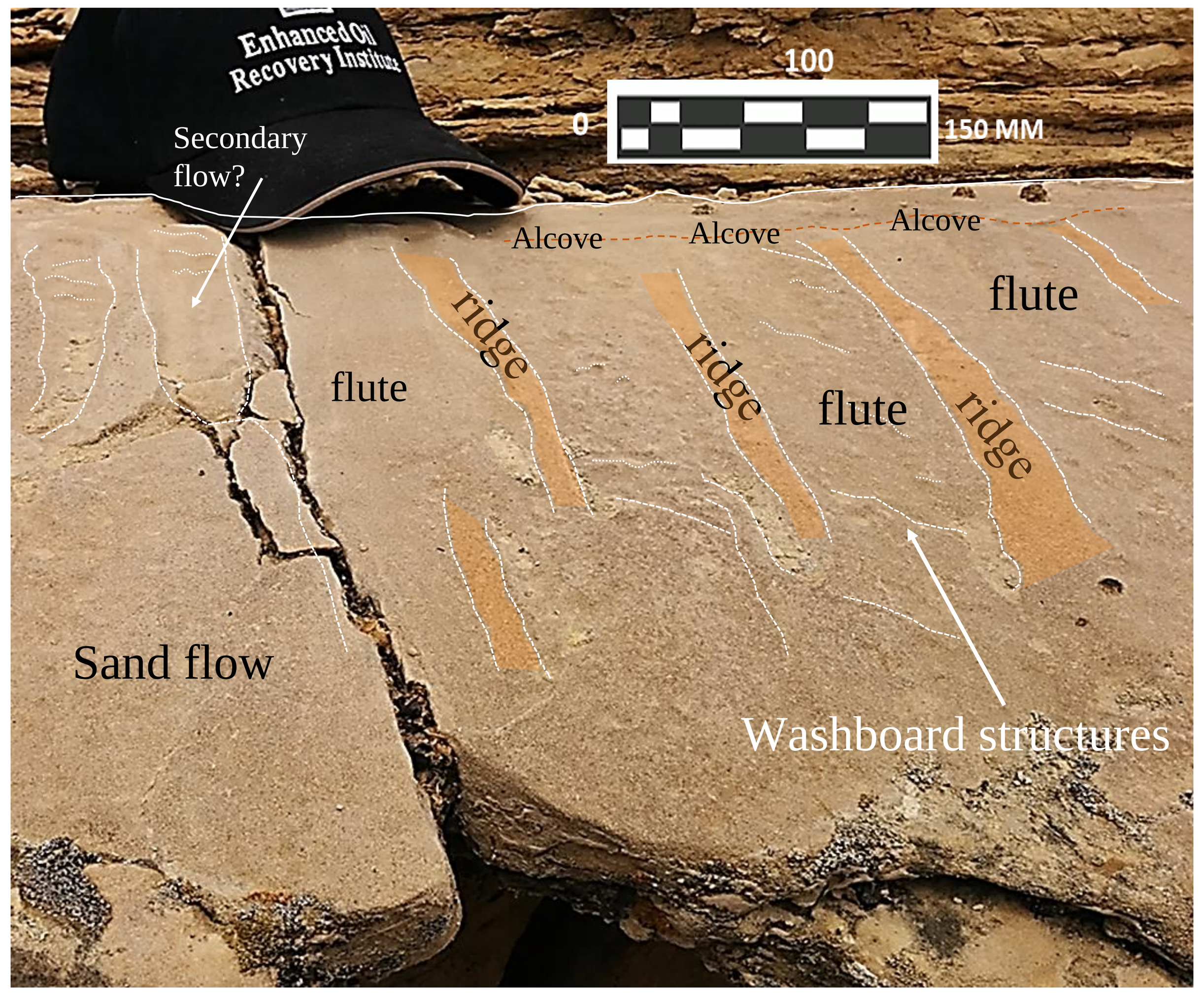


Figure 8-5 Upper Tensleep dune slipface, right side. This side of the slipface continues the pattern of ridge and flute topography, with some sand remaining in the flutes as is typical with modern eolian avalanches**.** As with left side of the slipface, washboard structures are present on avalanched sand remaining in the flute. These flutes seem slightly more full of avalanched sand than the left side of the slipface. This slipface was closely studied to make sure we were not confusing avalanche chutes with very low angle truncation of wind ripples.

Figure 8-6 Tensleep dune slipface right side, without geological interpretation

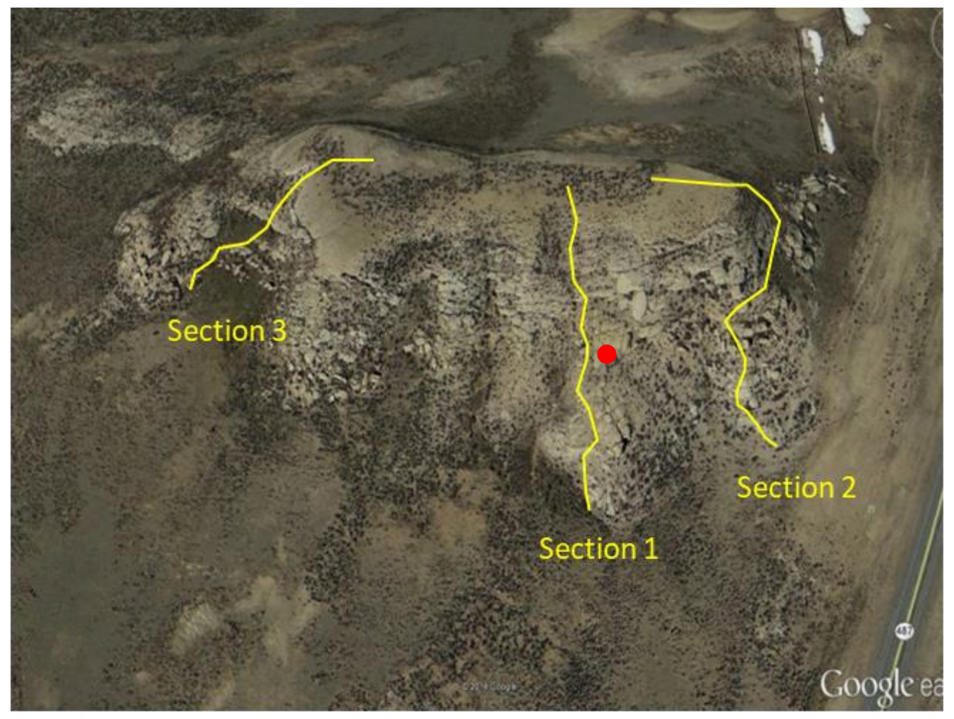


Figure 8-8 Light gray exposures of the Upper Tensleep Formation are visible on the crest of Flat Top Anticline. Routes of the measured sections are shown by yellow lines. Red dot shows approximate location of the preserved upper slipface flutes. Image courtesy of Google Earth.

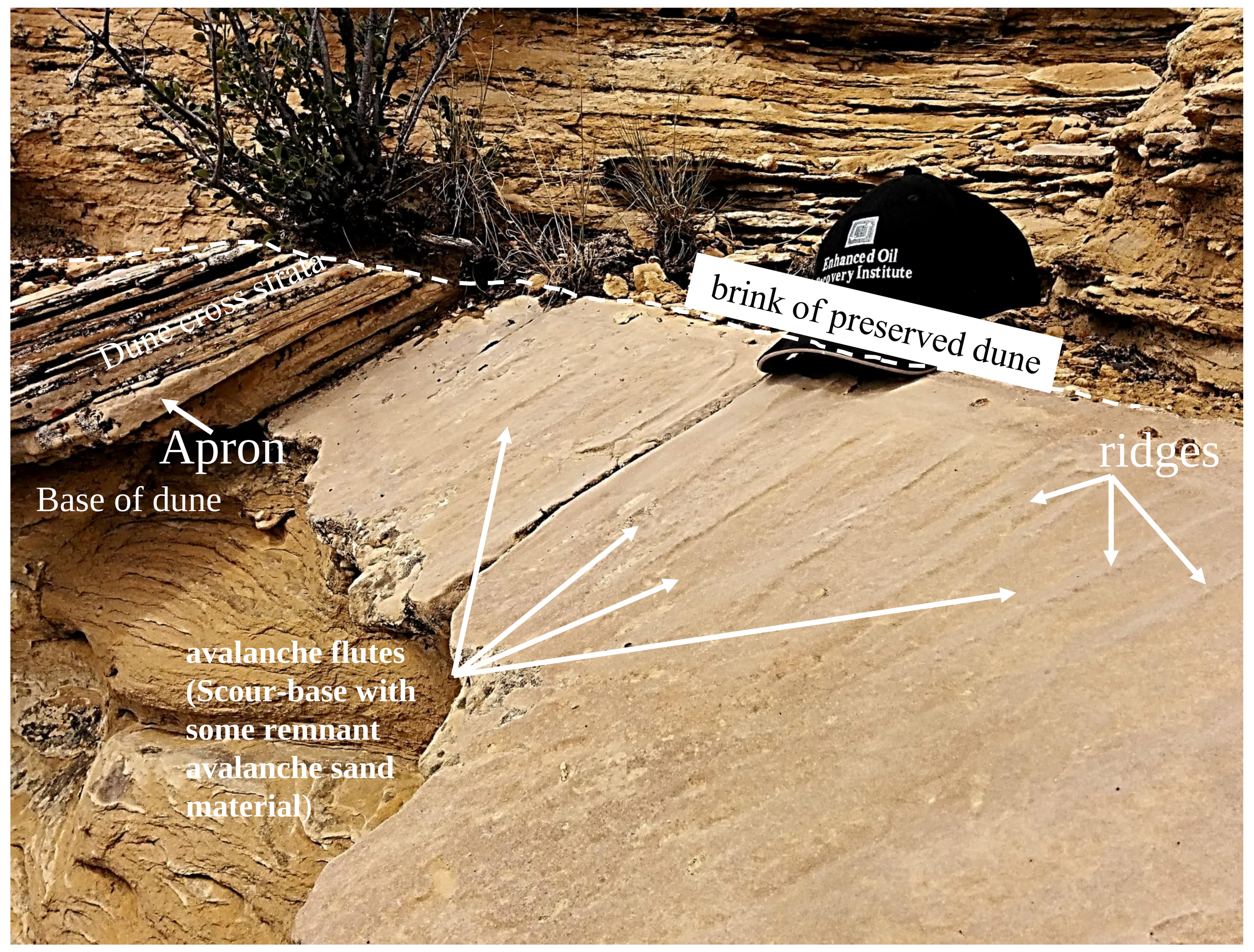


Figure 8-9 Upper Tensleep dunes slipface oblique view: This view shows the relief on avalanche that is created by the flutes and ridges. On the left, in cross-section, are avalanche and ripple strata at the base of the dune. Preserved portion of the bedform is 1.5-2 ft. (.46 - .61m.) in thickness at this locality. The dune thins along outcrop, and ultimately pinches out. The presence of flutes with little of the avalanche preserved; but without the alcoves (which form at the very top of the slipface) indicate that this slipface was about 80-90% preserved.

Ancient eolian slipface structures, Lyons Quarry, Permian Lyons Formation, Lyons, Colorado, U.S.A.

The Lower Permian Lyons Sandstone is widespread in the subsurface of Eastern Colorado, and outcrops along the hogbacks of the Colorado Front Range. There are particularly good outcrops of dunes in the Lyons Formation near the town of Lyons (Figure 9-4). The Lyons was recognized as eolian by Walker and Harms (1972) on the basis of bedding style, lag surfaces, raindrop imprints, and eolian ripples. We reproduce here the excellent example of a preserved avalanche, almost complete, that was illustrated by Walker and Harms in that publication (Figure 9-7). We also include outcrops we saw at Lyons Quarry, north of the town of Lyons, Colorado. It is clear, in our experience, that sedimentary structures on modern dune slipfaces are commonly passed along to ancient dune sandstones. Most of the examples we found at Lyons Quarry appear to be from the middle or base of the original avalanche (Figures 9-1 through 9-3; 9-5, 9-6, and 9-8 through 9-11). We have not yet found any upper avalanche alcoves or flutes preserved in the Lyons that are similar to those we found in the Amin and Tensleep. Nevertheless, the clarity of the preserved structures in the Lyons is impressive, as illustrated on this page. The most common features preserved in the Lyons outcrops we studied are washboard structures, drag folds and the scarp commonly found near the top of the avalanche, in the tensional stress domain, that is formed by withdrawal of sand at the margin of the flow.

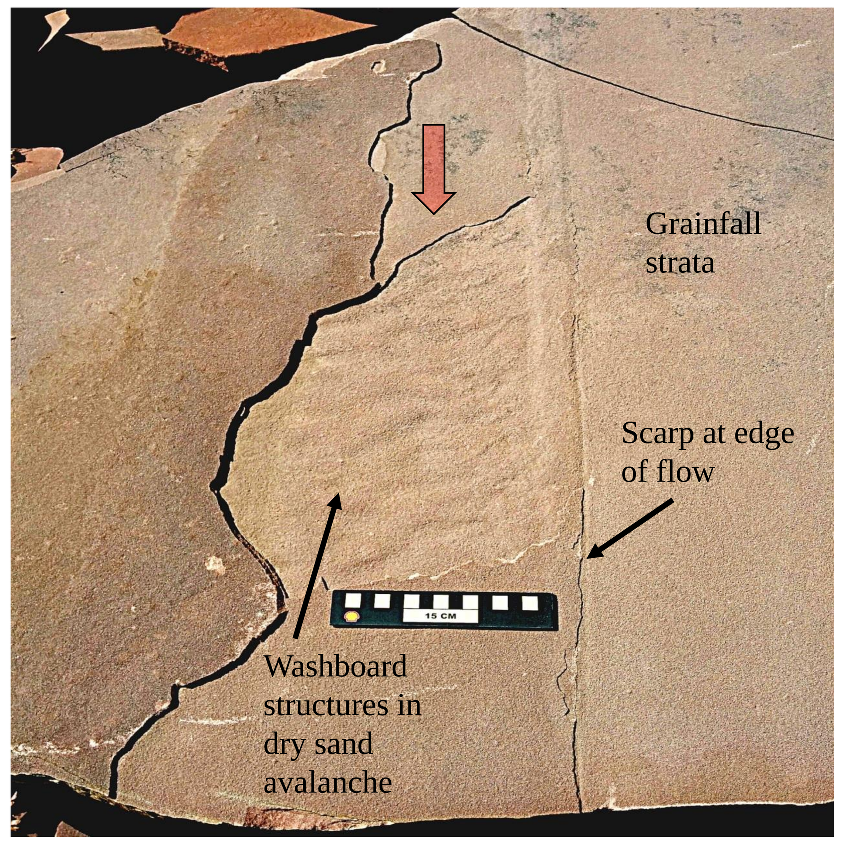


Figure 9-1 A small slab shows typical features of the upper avalanche, including washboard structures and scarp.

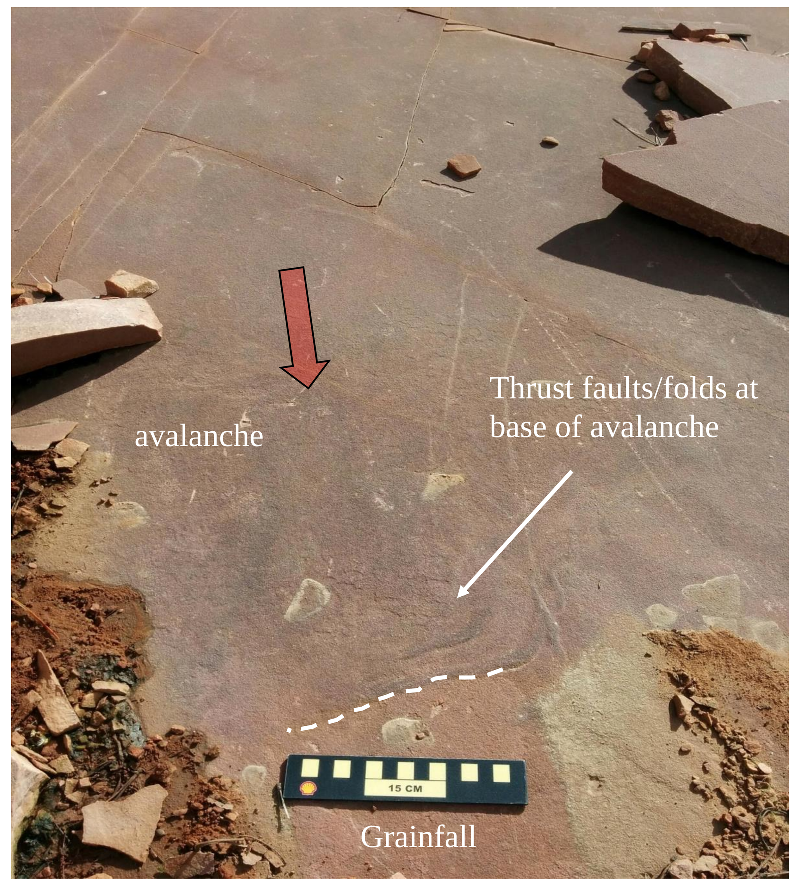


Figure 9-2 Base of an avalanche, with overthrusts and stacked tongues of sand. Avalanche probably stopped at a slight decrease in slope of the slipface. Folds suggest that part of the avalanche may have been damp.

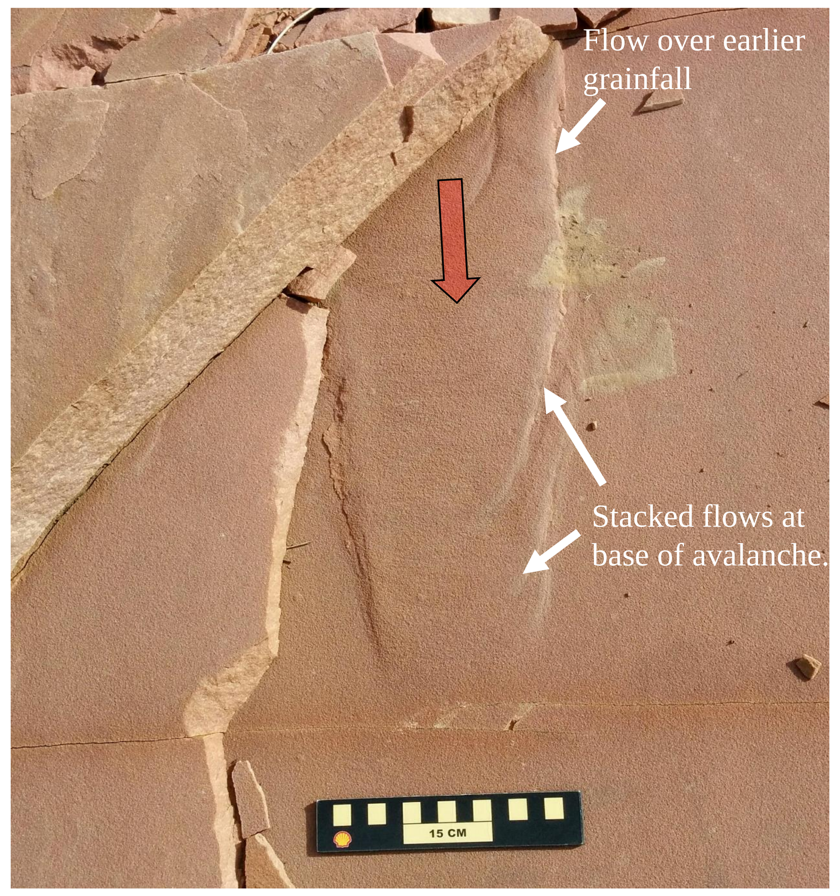


Figure 9-3 A dry sand avalanche has stopped partway down the slipface. It has over-ridden grainfall deposits. Flows shown by arrows were stacked when the base of the avalanche stopped before the flow as a whole.

Direction of avalanching, all images

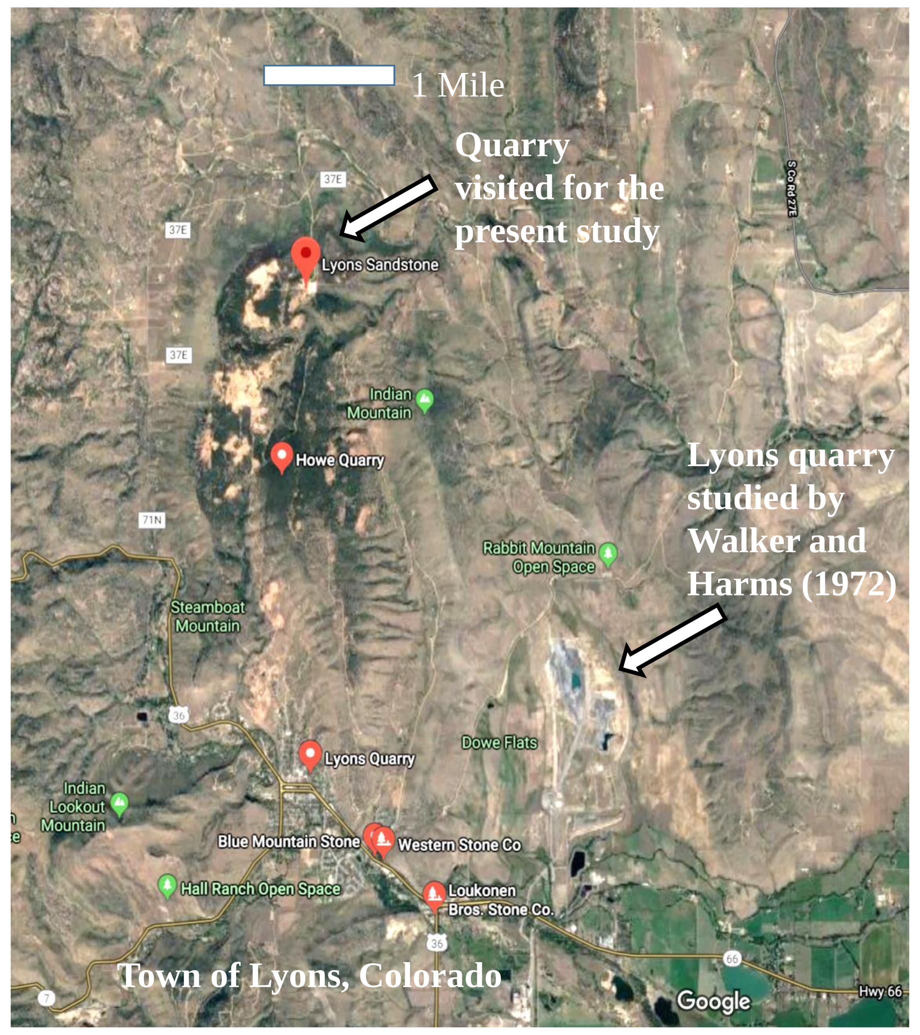


Figure 9-4 Satellite image showing the location of Lyons Sandstone Quarries near the town of Lyons, Colorado (arrow). Courtesy of Google Earth.

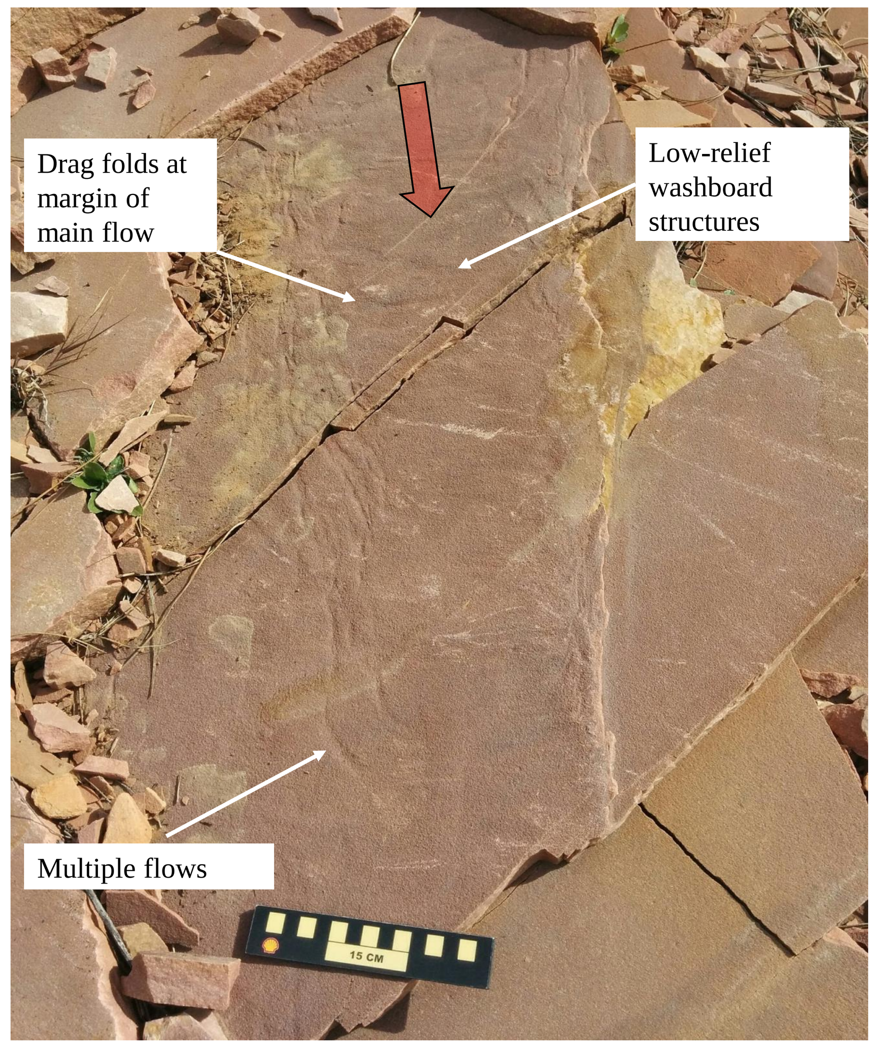


Figure 9-5 An avalanche sequence of several stacked flows, consisting of a large flow in the center of the image with smaller flows along the left side. Subtle washboard structures are visible throughout the flow.

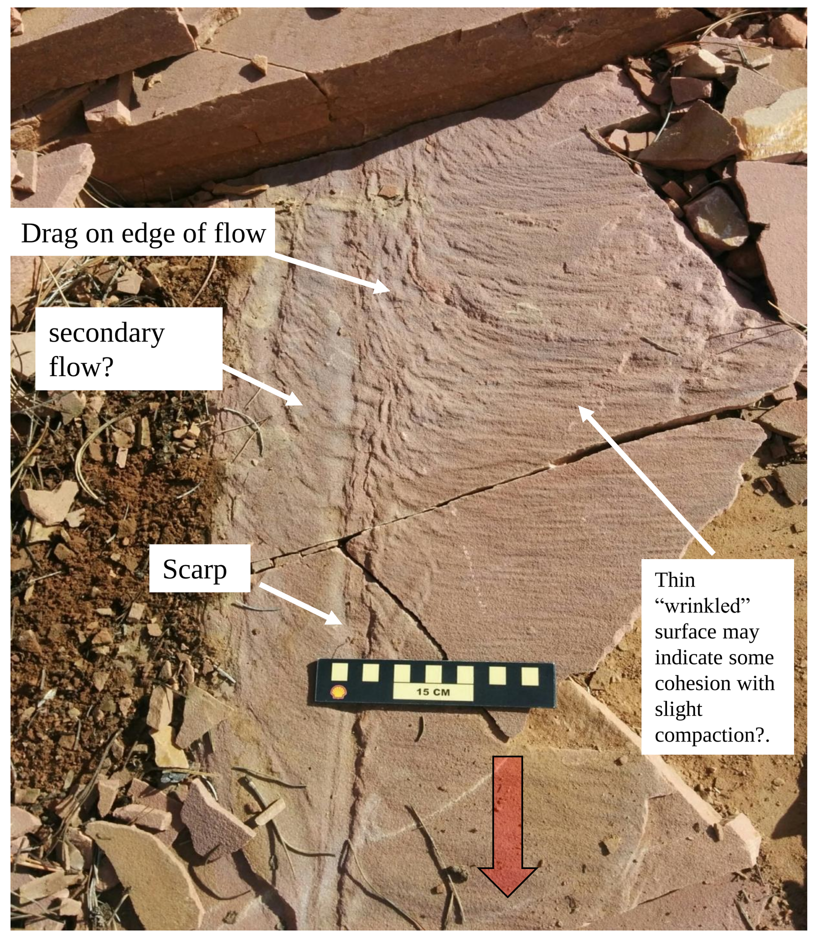


Figure 9-6 An avalanche that shows drag of washboard structures along the left side of the flow, and a possible secondary flow. A clear scarp indicates the cohesive margin of this ancient flow. The pattern of wrinkles on the avalanche may indicate that the flow had some surface cohesion. Structures at the top of the flow may be compressional effects on partially cohesive, damp sand.

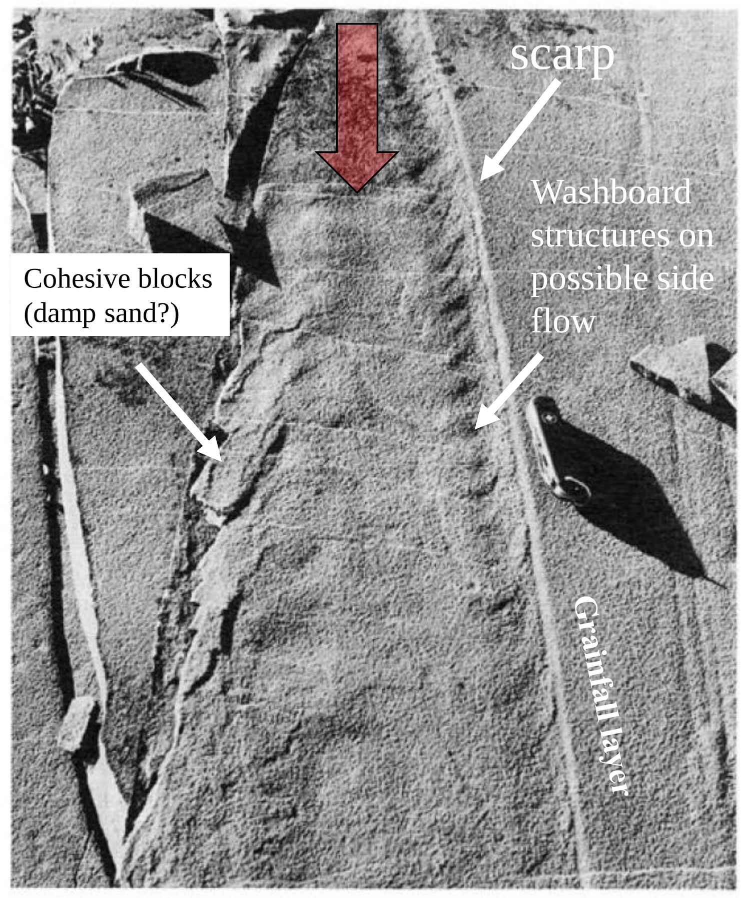


Figure 9-7 A dry sand avalanche in the Lyons Sandstone, with scarp and washboard structures. The avalanche is bordered by an undisturbed grainfall layer. This image was originally figure 14 of Walker and Harms in their definitive work on the Lyons Sandstone. It remains one of the better-preserved ancient avalanches observed in the Lyons (after Walker and Harms, 1972).

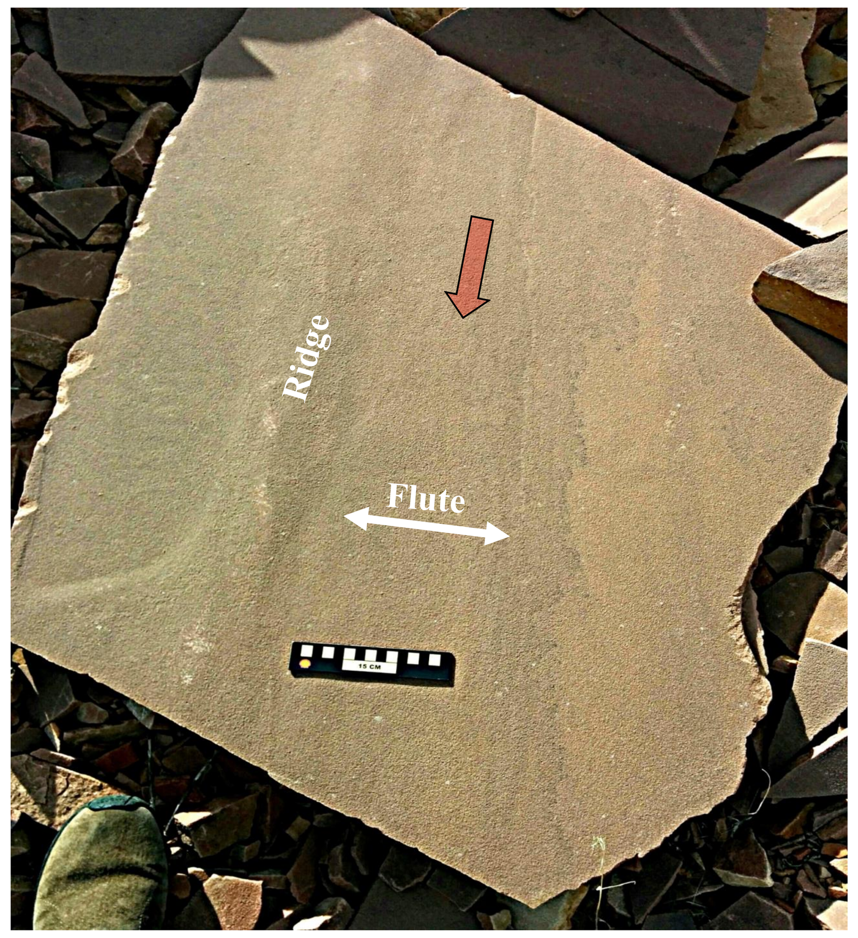


Figure 9-8 A flute, or pathway of an avalanche below an alcove, with ridges on either side. It would appear that this rock was originally high in the dune, because the flute, along with thin sand flows was not filled by other avalanches or by grainfall before preservation. Approximate width of flute is shown by white arrow.

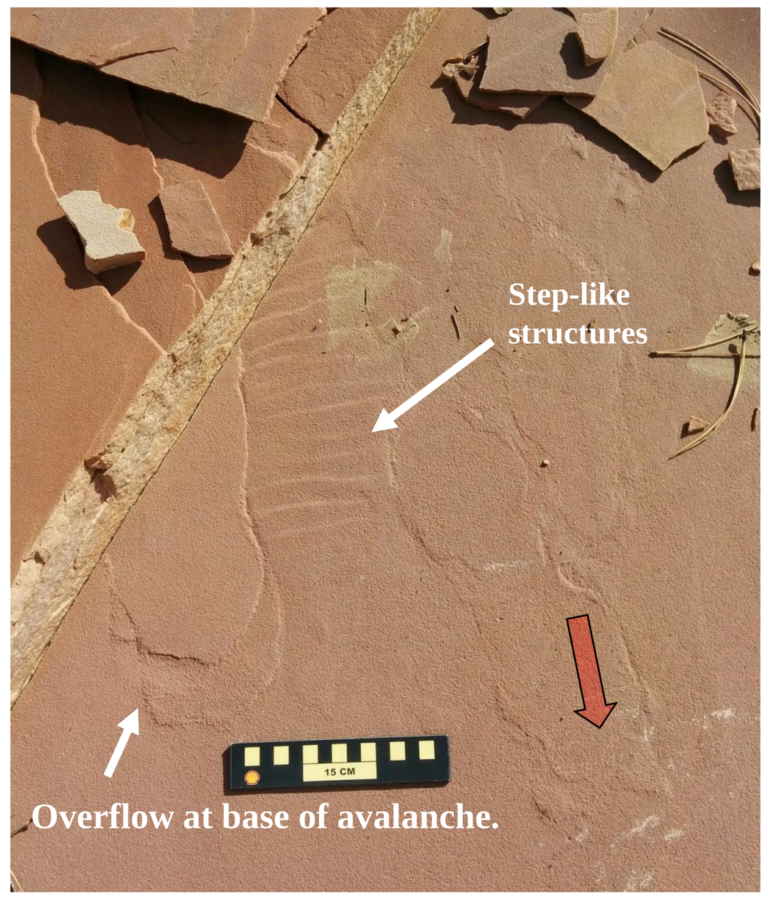


Figure 9-9 Several small sand flows over grainfall deposits, possibly near the top of a slipface. Step-like structures visible between the flows may represent contemporaneous thrusts, small cohesive blocks, or washboard structures. It is possible they are eolian ripples, however wind would have to have been blowing up the slipface .This exposure is not extensive enough to be sure.

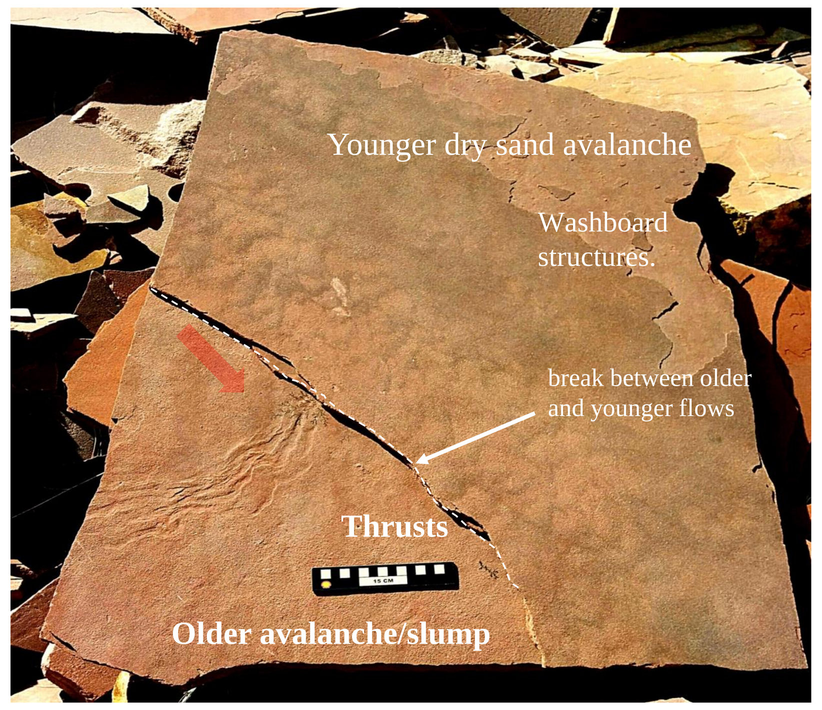


Figure 9-10 Two avalanches, exposed from stacked, thin layers of the ancient slipface. On the lower slipface, compressional ridges may mark the lower portions of a sandflow that had some cohesion – perhaps dampness. Indeed, the entire layer may represent a slump. The overlying avalanche appears to have been in dry sand, with a normal set of washboard structures on most of the surface. Slight offsets in the sets of washboard structures may indicate adjacent flows.

Figure 9-11 An ancient eolian slipface on a barchan dune, Permian Lyons Sandstone, Lyons Sandstone Quarry. Most of the quarry consists of ripple strata in linear dunes, that splits well to form decorative flagstone. However, at the top of the Lyons Formation at this quarry, there are some barchanoid dunes that have also been quarried. Slipface deposits, whether still attached, or loose as broken slabs, (such as those in this image), have well-preserved eolian sedimentary structures. Field assistant Franci Fryberger provides scale on the ridgeline.

Modern and ancient eolian dunes on Mars

At this stage of exploration, it is known that many of the dune fields on Mars are active as shown by the images on this page (Figures 10-1 through 10-5) (Zimbelman et al., 2009). Migrating barchanoid dunes are common, as well as slowly shifting dunes akin to reversing or linear dunes. Processes on dune slipfaces are similar to those on earth, and produce a similar slipface geomorphology as illustrated on this page. Granule and wind ripples are widespread on Mars, as are eolian interdunes and sand sheets. The eolian sabkha facies commonly seen on earth, is undoubtedly less common in modern sediments on Mars due to lack of water. However, this facies may be relatively common in eolian rocks on Mars dating from eras where there was free water, as described by Grotzinger, et al., (2005). Although the gravity is less, the atmosphere of Mars is much less dense than that of Earth; thus, higher threshold wind velocities are required to move loose sand than on Earth. However, some sand may move, or initiate saltation under the influence of vorticity associated with relief of the dunes, surrounding terrain, or dust devils - the latter of which generate strong cyclonic winds over small areas as they drift across the Martian surface. There are some places where it is evident that eolian dunes on Mars have lithified and thus comprise eolian sandstones, as shown on Figure 10-3 , and described as by Grotzinger, et al., (2005).

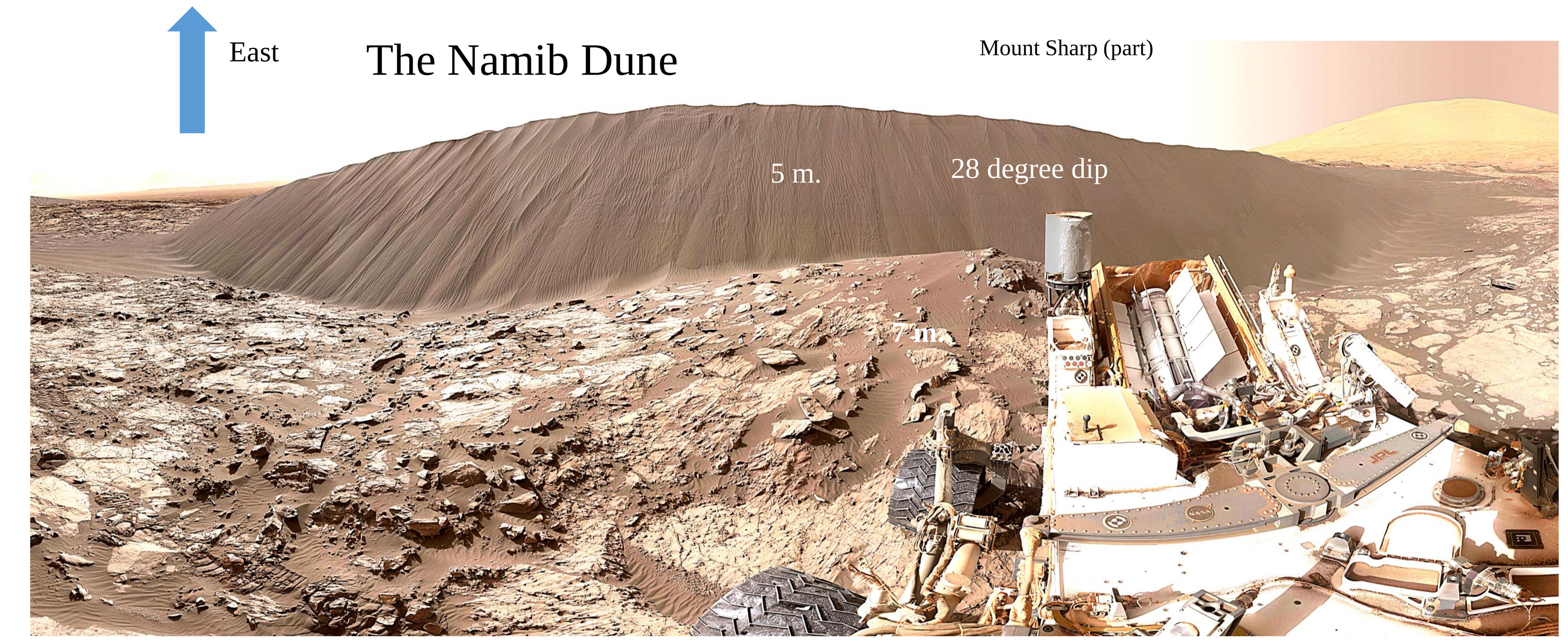
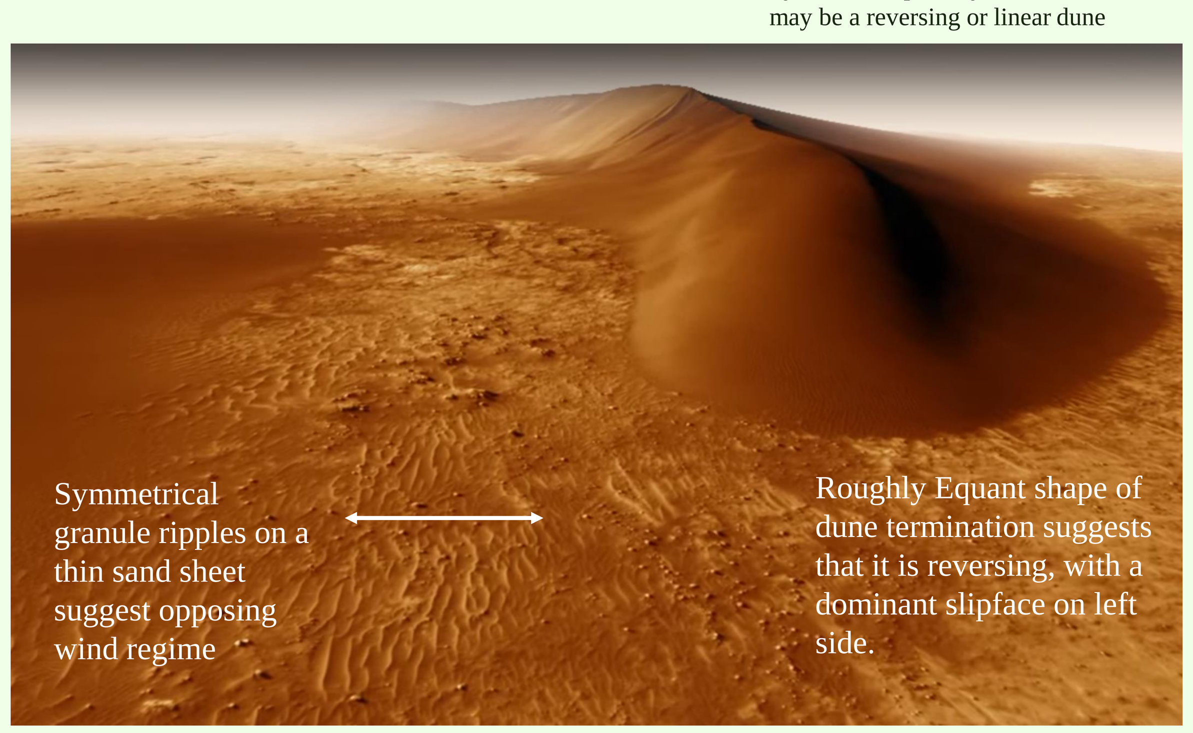
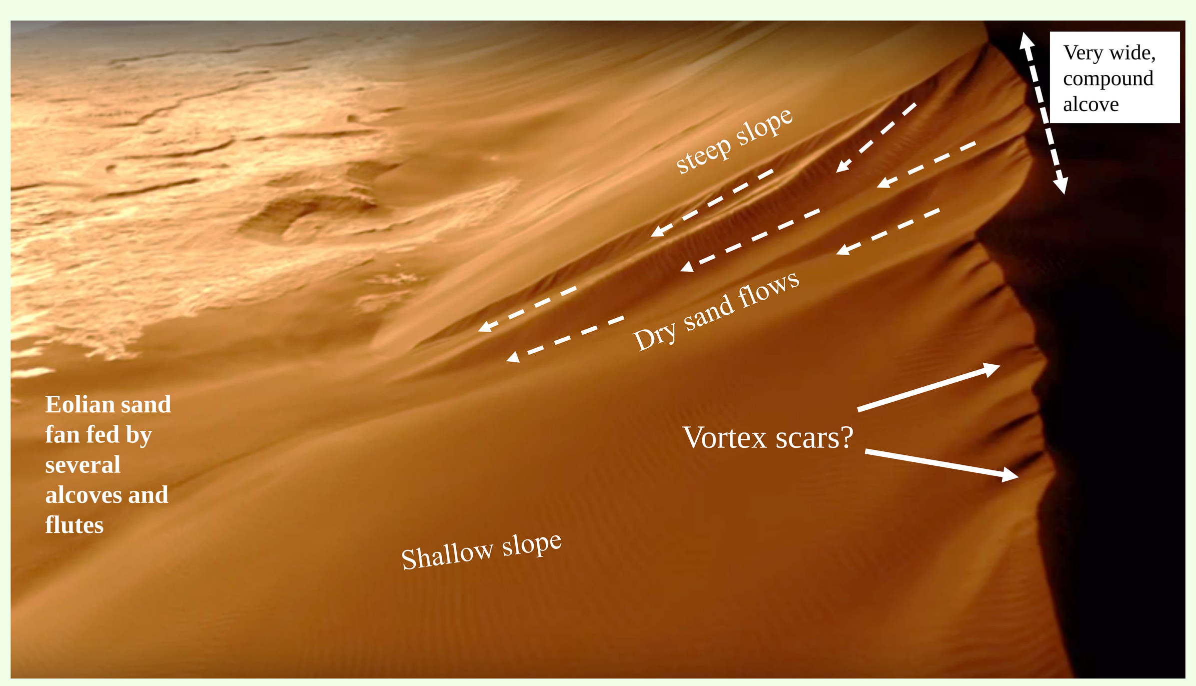


Figure 10-1 This view of the downwind face of "Namib Dune" on Mars covers 360 degrees, including a portion of Mount Sharp at right on the horizon. The site is part of the dark-sand Bagnold Dune Field along the northwestern flank of Mount Sharp. Images acquired from orbit indicate that dunes in the Bagnold field move as much as 3 feet (1 meter) per Earth year. The component images of this scene were taken on Dec. 18, 2015, by the Mast Camera (Mastcam) on NASA's Curiosity Mars rover during the 1,197th Martian day, or sol, of the rover's work on Mars. (edited from original caption provided by NASA).





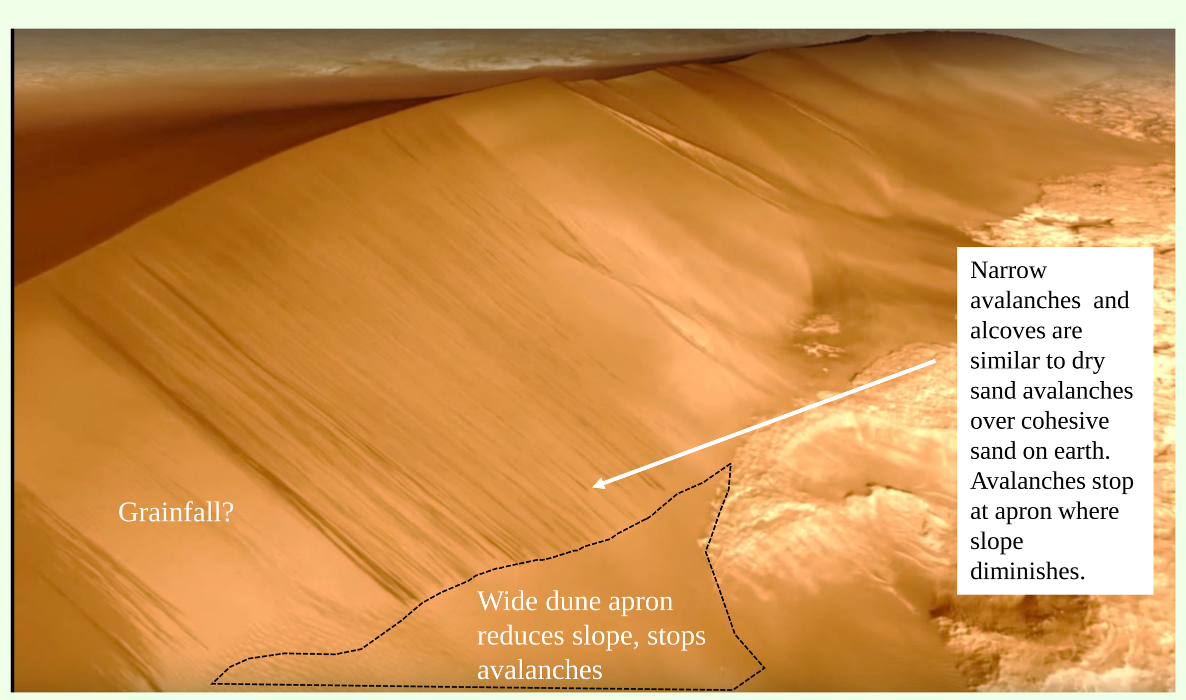
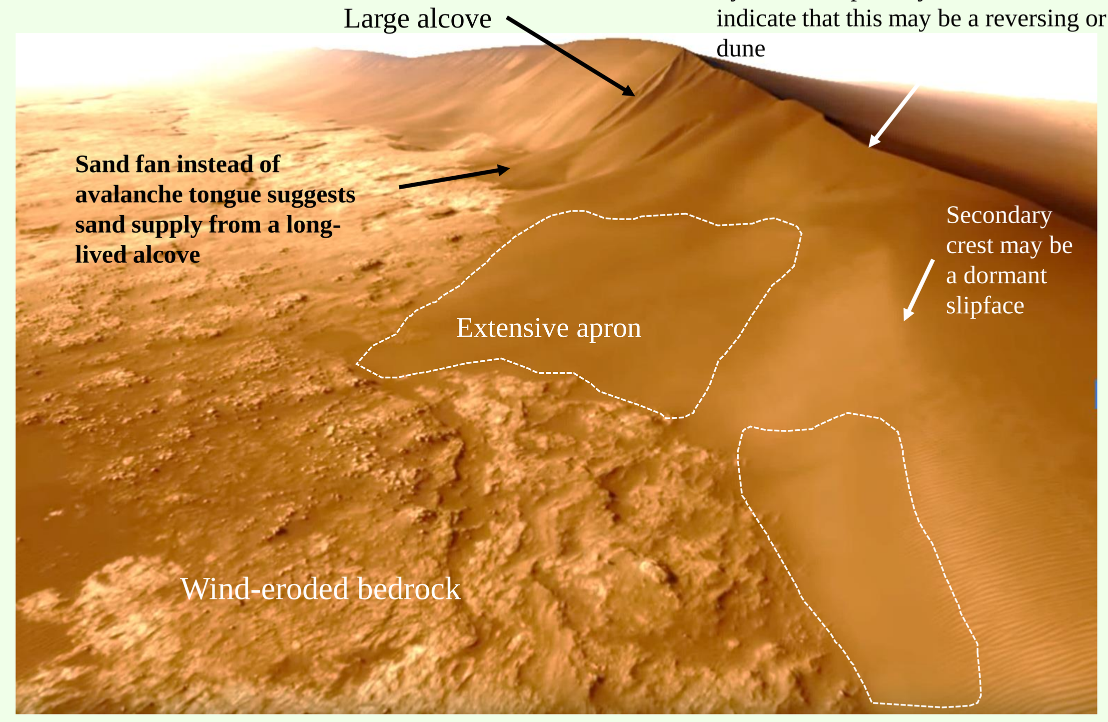


Figure 10-4 The images above are from two animations that were created using NASA's HiRISE DTM and image data. The videos linked below follow two different flight paths along the crest of this 200 m high reversing (?) dune on Mars. The two have two significantly different styles of avalanche (see notations on images, above). The image data resolution is 0.25 meters, the elevation data resolution is 1 meter. There is no vertical exaggeration and the color is false. Both the lower resolution and a higher resolution video, each with a slightly different "flight path" are linked below.
Original https://www.youtube.com/watch?v=7J8nbuKyLPs&t=34s
High Resolution http://www.youtube.com/watch?v=SyeK-q...
Data credit: NASA/JPL/University of Arizona. (Edited from original caption courtesy of NASA, JPL, and U of Arizona)



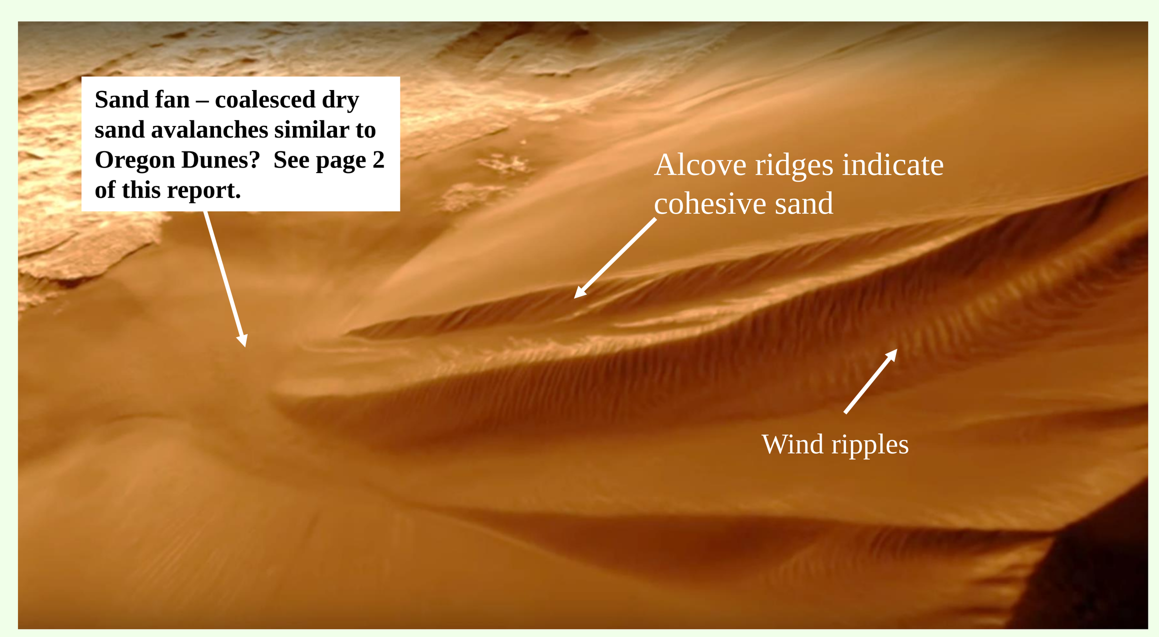


Figure 10-4 continued

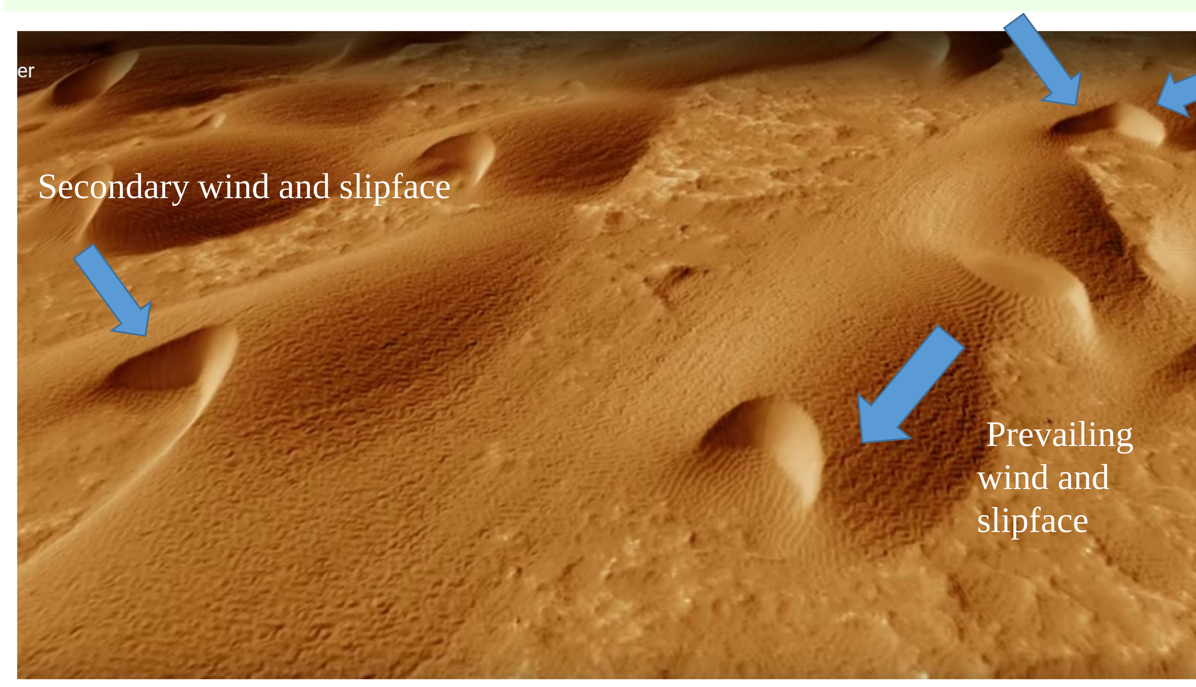


Figure 10-5 A flyover animation of dunes in Herschel Crater reveals that they exist in a bimodal effective wind regime. The video plainly shows two sets of slipfaces facing in different directions. The image above is a still taken from the video linked below. It was created using image and digital terrain model data from the High Resolution Imaging Science Experiment (HiRISE) camera aboard the Mars Reconnaissance Orbiter. Adrian Lark creates these animations using a 3D engine that he wrote that generates the fly-throughs in real-time. Courtesy of the Bruce Murray Space Image Library. See also Cardinale, et al., (2016) for discussion of the wind regimes of Herschel Crater.
https://www.planetary.org/multimedia/space-images/mars/dunes-in-herschel-crater-mars.html

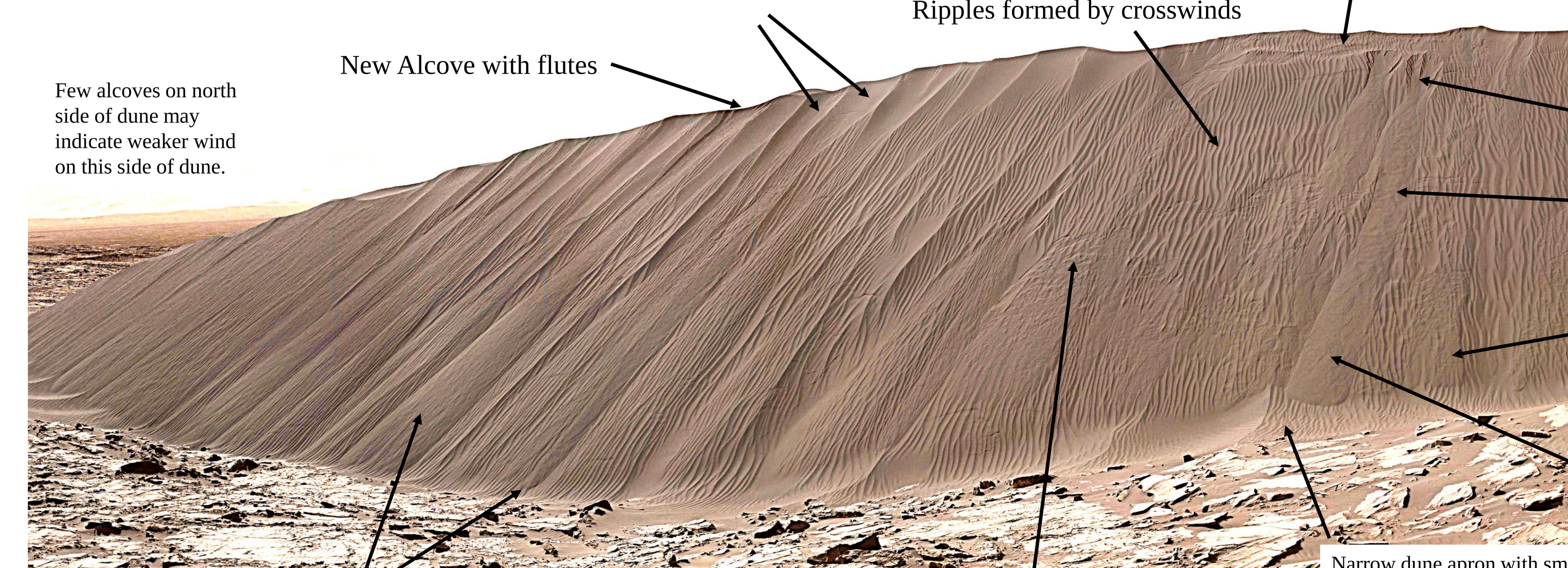


Figure 10-2 Recent history of the "Namib" dune shown above is recorded by slipface structures visible on this image.

1. Wind from the east, formation of older dry sand avalanches and alcoves.
2. Crosswind from the south (from right on image) that formed ripples on older avalanches.
3. Development of cohesion on the sand surface.
4. Formation of plates and breccia as cohesive portions of the slipface slump downslope.
5. A new sandstorm, or period of wind from the east.
6. New avalanches and alcoves form (unrippled avalanches visible on the current slipface)

https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA20281

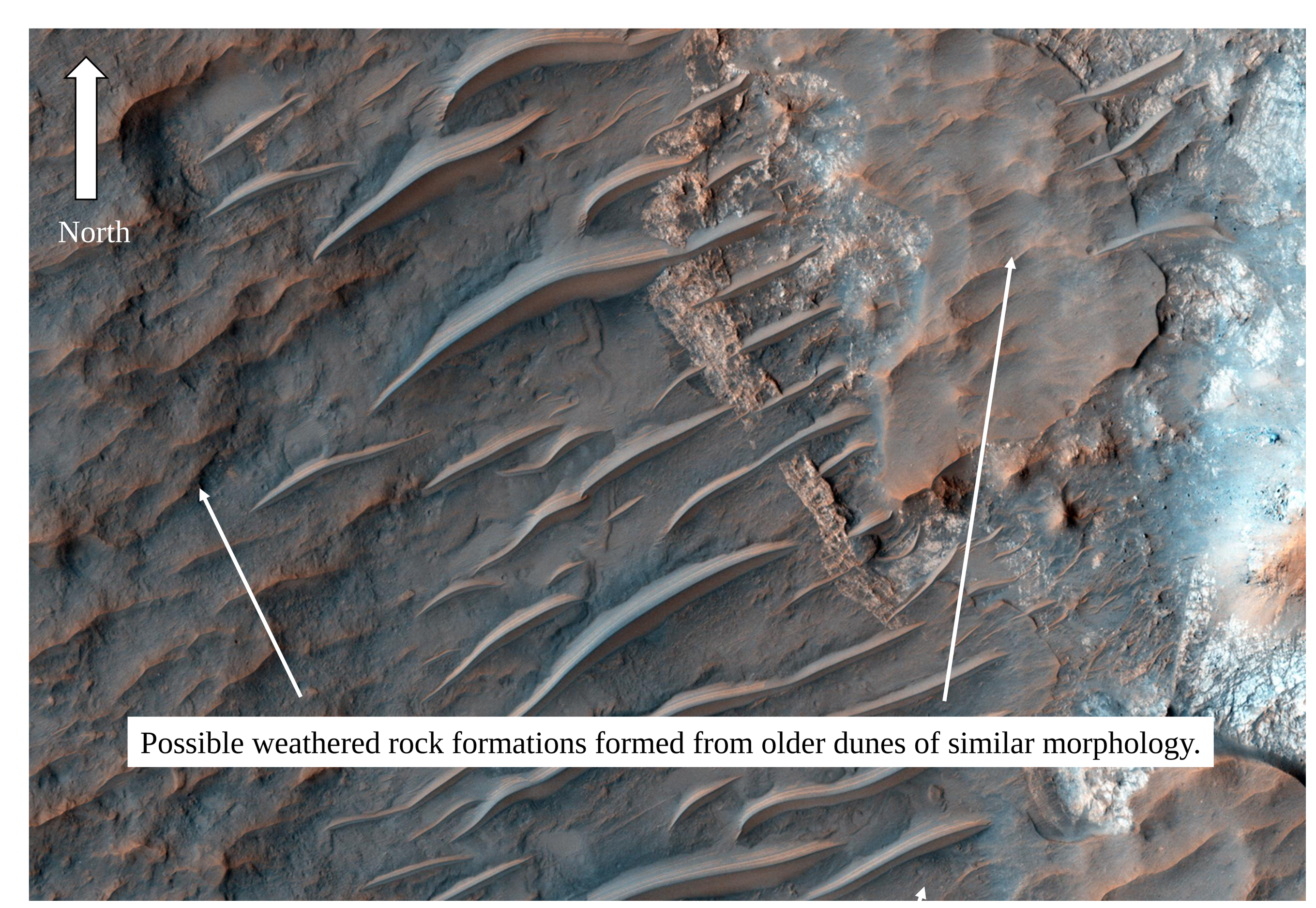


Figure 10-3 Mars images such as this one, near modern, active dunes sometimes reveal an earlier history of eolian deposition and erosion on surrounding terrains. The image at left shows modern linear or reversing dunes, as well as what appear to be two formations of ancient lithified eolian dunes of similar morphology. The tropics of Mars are commonly populated with "transverse eolian ridges," or TARs (Zimbelman et al., 2010, 2012, 2013 2019). These distinctive, modern dunes are up to 6 meters tall and are spaced a few tens of meters apart. The stratigraphy of these dunes may be similar to reversing dunes at Great Sand Dunes and other places on Earth. The Martian dunes similar to those shown here are typically oriented transverse to modern day wind directions, and are common in channels and crater interiors. Sarah Mattson of the University of Arizona discovered the banded TARs on this image (best observed using the link provided below) in Iapygia, south of Syrtis Major. These features resemble TARs elsewhere on Mars, except that they show bands or layers on their northwest faces but fewer or none on the southeast sides.
(Caption edited from original provided by NASA)
http://static.uahirise.org/images/2014/details/cut/ESP_020782_1610-1.jpg
This is a stereo pair: ESP_021639_1610.