10 FINE MATERIAL IN ROCK FRACTURES: AEOLIAN DUST OR WEATHERING?

Niccole Villa,[1] Ronald I. Dorn,[1] and James Clark[2]
[1]*Department of Geography,* [2]*Department of Chemistry,*
Arizona State University

ABSTRACT

Fine material in rock crevices from the deserts of southwestern North America and Hawaii, studied by light and electron microscopy, derive from both *in situ* weathering of the adjacent rock and the accumulation of aeolian dust. In some cases, such as quartz found in Hawaiian rock crevices, we see evidence for an aeolian origin. In other cases, the texture and chemistry of the fine material indicates a weathering origin. Fines in rock fractures are analogous to soils, and a general model for development of "fissuresols" is presented. Where rocks are friable and weathering is rapid, a residual fissuresol develops. Where dust storms are common and rocks are resistant to weathering, a cumulic fissuresol forms. A continuum likely exists between these two extremes in space today, from drier to wetter climates. Fissuresols can be tens of thousands of years old and experience drastically different climates. Therefore, the relative importance of weathering and aeolian input can shift over time.

INTRODUCTION

A topic in aeolian geomorphology that has received little attention is the ubiquitous fine material in rock fractures. Although desert dust has been examined in detail (e.g., Goudie 1978, Pye 1987), only a few geomorphologists have explored fine material in rock crevices. Coudé-Gaussen et al. (1984) present evidence for an aeolian orgin for the fines found in crevices in granitic rocks in the Sinai Peninsula. In every fissure we have ever forced open with a rock hammer in arid lands, material has been found both adsorbed to crevice sides and resting loosely in the joint. We have observed fines in rock crevices from arid lands in Africa, Asia, Australia, North America, and South America, and in dozens of lithologies ranging from basalt to granodiorite to limestone. If Coudé-Gaussen et al. (1984) are correct in assuming that most fines in rock crevices are aeolian dust, then rock fissures represent an aerially extensive terrestrial dust trap, second only to plants. The question we address in this study is whether fines are aeolian in origin, as Coudé-Gaussen et al. (1984) contend, or *in situ* from rock weathering on crevice walls.

Dust in rock crevices has both theoretical and applied significance. Fines absorb water and support plant life. Fines expand and contract with wetting and drying, aiding in the weathering of rocks. Fines also contain salts that are remobilized and reprecipitated to shatter cobbles (Amit et al. 1993). The material in rock crevices can influence the nature of rock coatings on crevice walls. Such coatings may include rock varnish, calcrete, or amorphous silica.

Desert Aeolian Processes. Edited by Vatche P. Tchakerian. Published in 1995 by Chapman & Hall, London. ISBN 0 412 04241 X

Rock varnish in fractures is believed to cause the orange color of Ayers Rock in Australia (Dorn and Dragovich 1990).

The issue of whether fines in rock fissures are from *in situ* weathering or aeolian fallout has applied relevance. One of the difficulties in interpreting the geochemistry of dust in experiments is the role of humans. Even in "remote areas" dirt roads that cut across calcic soil horizons can be prominent sources of calcium carbonate. If fines in rock crevices are cumulic, they could serve as natural "background" for studies in aeolian geochemistry. This could prove useful in a comparison with contemporary pollution studies. Because heavy metals such as copper and zinc preferentially adsorb onto fines, dust in rock fractures can be used for identifying areas with higher concentrations of heavy metals.

The purpose of this paper is to (a) assess the genesis of fines in rock fissures by examining samples from the Sonoran Desert, Death Valley, California, and Hawaii at millimeter and micrometer scales; and (b) present a general model for the development of fines in rock crevices.

METHODS

Mesic and xeric samples were selected from the Sonoran Desert of Arizona, Death Valley National Monument in California, and Hawaii. The Sonoran Desert was emphasized because of the abundance of cumulic loess deposits as a result of frequent dust storms (Brazel 1989). In contradistinction, we anticipated that fines from weathering would most likely be in more moist regions where dust storms are less common.

All samples were collected from the tops of rock outcrops to avoid input by slope wash. There is the possibility for transport of fines to rock fractures by ants and other organic agents. While we cannot completely rule out this possibility, we did not observe any evidence of "organic transport." Also, the fissures were all "tight"—with openings less than 2 mm at the top—not allowing the movement of likely transport organisms. Still, we cannot truly test this hypothesis until monitoring studies are conducted.

After removal with a rock hammer, samples were placed in tissue paper for gentle transport to the lab, mounted in epoxy, and polished for cross-sectional analysis of the fine material/rock interface. Samples were examined with light and backscatter electron microscope (BSE). In BSE, both the chemistry and texture are imaged simultaneously; brightness is a function of average atomic number (Krinsley and Manley 1989). The contact between the fine material and the adjacent rock was analyzed chemically with a JEOL wavelength dispersive electron microprobe with ZAF corrections and a 30-second counting time. We used both a 2- and a 10-micrometer spot size in order to study this fine/rock interface. The larger spot size was used to average the geochemistry of the smallest particles, whereas the smaller spot size was used to obtain quantitative data on specific grains.

In Death Valley, we compared the chemistry of quartzite and the adjacent fines in rock fissures. About 10 grams of loose fine material was collected from each fissure, and 10 grams was powdered from the adjacent quartzite (from a position in the center of the rock). These powders were then homogenized in a flux of lithium metaborate. The resultant homogenized beads were mounted in epoxy, polished, and carbon coated. Their composition was analyzed by an electron microprobe with a 30-micrometer spot size. Five separate measurements were made on each bead. Probe totals were normalized to 100% (Table 1) to account for the lithium metaborate flux.

RESULTS

Kitt Peak, Arizona

The Kitt Peak granodiorite samples were collected along an environmental gradient from about 900 m, where creosote bush (*Larrea divaricata*) dominates, to about 2000 m, where chaparral vegetation is the dominant species. Contrary to our expectations that the desert site would have the clearest loess signal and the high elevation sites mostly weathering, both sites showed evidence of weathering and dust.

Figure 1 shows the presence of fine particles next to the unweathered rock at the 2000 m elevation site. The microprobe transect shows a similarity in chemistry across the fines/rock boundary, suggesting in-situ weathering. Figure 2 presents another sample from this high elevation site, but the texture consists of finer particles. The microprobe transect reveals a very noisy chemical signature. Certain elements (Na, Al, K, Ca, Ti) are present in the fine particles, but not in the rock which is composed of quartz. Trace elements in the quartz (Mn, Fe) are also found in much greater concentrations in the adjacent fines.

Figures 1 and 2 represent the range of observed chemistries and textures found in the Kitt Peak study. Textures and chemistries characteristic of aeolian dust appear to occur more frequently at lower elevations. The aeolian materials are most likely from dust storms associated with summer convective thunderstorms (Brazel 1989). However, these and similar observations indicate that both weathering and aeolian deposition occurs at all elevations at Kitt Peak.

Sedona, Arizona

Samples were collected from joint fractures in a fluvial sandstone member of the Supai formation in the Schnebly Hill area of Sedona. Despite the high friability of the sandstone, there was evidence of both internal and external origin of the fracture constituents. While we scanned the cross section, there were quartz grains scattered throughout the fines that were similar in size and shape to the grains in the rock. It seems plausible that weathering dislodged these grains from the crevice wall.

Table 1
Electron microprobe measurements of bulk chemistry of fine material in rock fissures in quartzite, Death Valley, California.

Collection site	Quartzite		Rock fissure			
Sea level, Hanaupah Canyon Fan, desert scrub vegetation near playa margin;	Al_2O_3	0.57	Na_2O	3.52%	MgO	3.41%
	SiO_2	98.70	Al_2O_3	10.44%	SiO_2	66.28%
	Fe_2O_3	0.73	P_2O_5	2.47%	SO_3	0.27%
pH of fissure fine material 9.8 ± 0.7			CaO	4.20%	K_2O	2.93%
			TiO_2	0.72%	MnO	0.10%
			Fe_2O_3	5.37%	BaO	0.29%
~1000 m, Panamint Range, desert scrub, on crest of hill, several kilometers from playa	SiO_2	98.56	Na_2O	2.08%	MgO	4.27%
	CaO	0.24	Al_2O_3	25.49%	SiO_2	46.30%
	Fe_2O_3	1.20	P_2O_5	3.80%	SO_3	0.38%
pH of fissure fine material 8.5 ± 0.3			CaO	5.18%	K_2O	3.55%
			TiO_2	0.90%	MnO	0.11%
			Fe_2O_3	7.77%	BaO	0.17%
~2000 m, Panamint Range, juniper dwarf woodland, east-facing slope	SiO_2	99.03	Na_2O	1.80%	MgO	3.87%
	Fe_2O_3	0.97	Al_2O_3	33.10%	SiO_2	39.3%
			P_2O_5	5.27%	SO_3	0.29%
pH of fissure fine material 8.2 ± 0.7			CaO	4.18%	K_2O	2.67%
			TiO_2	0.97%	MnO	0.21%
			Fe_2O_3	8.17%	BaO	0.17%
~3000 m, Panamint Range, limber bristle-cone pine woodland, east-facing slope	Al_2O_3	0.37	Na_2O	1.22%	MgO	3.52%
	SiO_2	99.13	Al_2O_3	29.11%	SiO_2	44.89%
	Fe_2O_3	0.50	P_2O_5	4.72%	SO_3	0.31%
pH of fissure fine material 8.0 ± 0.5			CaO	3.94%	K_2O	3.17%
			TiO_2	0.85%	MnO	0.25%
			Fe_2O_3	7.90%	BaO	0.12%

Evidence for an aeolian origin for the fines is seen in Figure 3, owing to the fibrous texture for the dust material. Quantitative electron microprobe measurements (10 mm spot size), on the inorganic fraction of the interface between fines and rock, show a relative enrichment in Ca, Mg, Na, and P as compared to the underlying sandstone, indicating a contribution from an outside source. The wavelength dispersive mode on the electron microprobe was used qualitatively to determine the carbon signal of the fibrous material. Carbon typically appears as black in BSE images, because of the low atomic number ($Z = 6$). The BSE image in Figure 3 was taken with very low contrast, in order to bring out the filamentous structure of the organic material in the fines.

Tempe Butte, Arizona

Figure 4 illustrates a typical fracture in the andesite at Tempe Butte, Arizona,

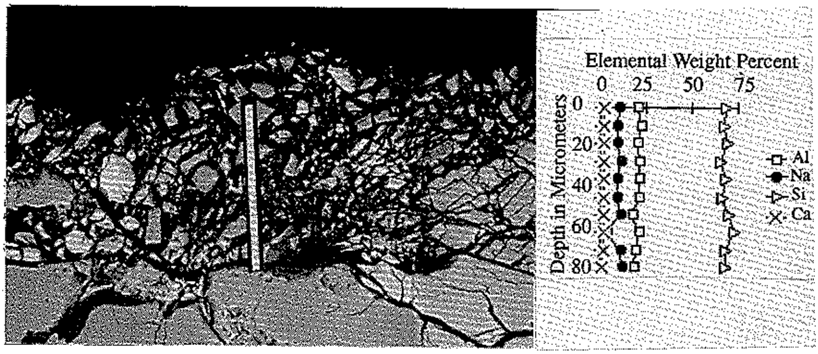

Figure 1. Backscatter (BSE) electron microscope image of a joint face in granodiorite sampled from ~2000 m at Kitt Peak. The line indicates the transect where electron microprobe measurements were made. The adjacent chart presents electron microprobe measurements (2 mm spot size) that are consistent with a plagioclase mineralogy for both the debris and the adjacent unweathered rock face.

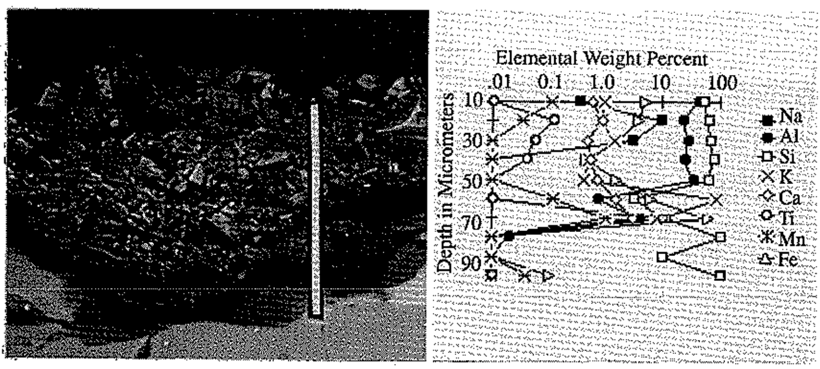

Figure 2. BSE image of a joint face in granodiorite sampled from 2000 m at Kitt Peak, within a meter of Figure 1. The corresponding electron microprobe measurements (2 mm spot size) along the transect show elements in the fine material that are not present along this fracture in quartz.

where the texture and geochemistry of the fine material is distinct from the underlying rock. In this sample, Mg, P, Fe, and Ca are more abundant in the dust than the underlying rock. This sample was collected at the very top of a fissure to avoid contamination of materials from above.

At Tempe Butte, we conducted a separate test for the relative contribution of aeolian dust and weathering products. Ten 2 x 2 cm samples were collected from rock fractures on a prominant south-facing knob of andesite. The upper part of these fractures were all touching the surface of the rock, so there was no source of weathered material from higher up in the rock fracture. First, the distribution of fine material was mapped. Then, this material was washed away and scrubbed gently with tap water and a toothbrush, revealing rock coatings

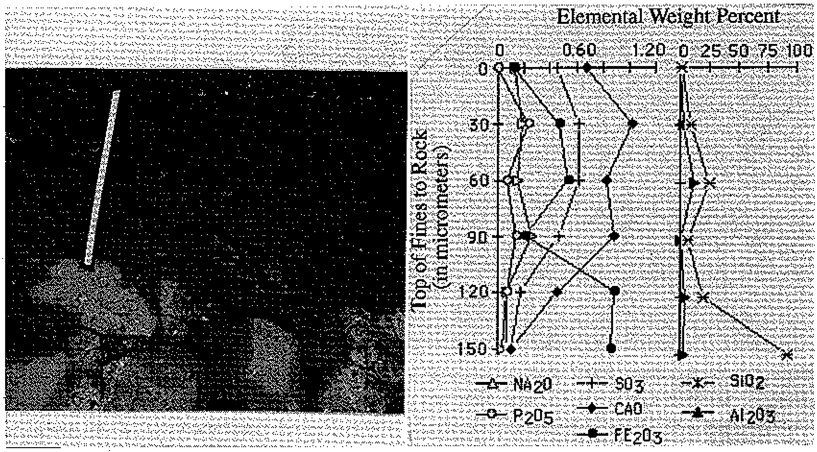

Figure 3. BSE image of a joint face in Supai sandstone sampled from the Sedona region of Arizona, showing the fibrous texture of the dust material.

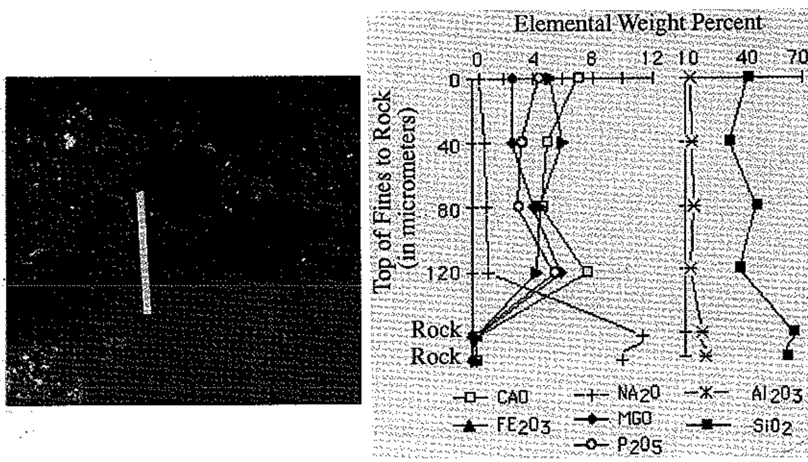

Figure 4. BSE image of fracture in andesite at Tempe Butte in Arizona. In this case, there was no coating between the fine material and the adjacent rock. The corresponding probe profiles (10 mm spot size) show a distinct change in chemistry from the fine material in the crevice to the adjacent rock.

of crack varnish and calcium carbonate. Lastly, the distribution of these coatings was mapped (Figure 5).

The only potential source of weathered fines appears to be from places where a coating was not present. Light microscope examination of these fissure sides reveals a thin weathering rind (<2 mm). Evidence for *in situ* clays or spalling of silt- or clay-sized particles in the weathering rind was not found. Similar results were also obtained by Colman and Pierce (1981).

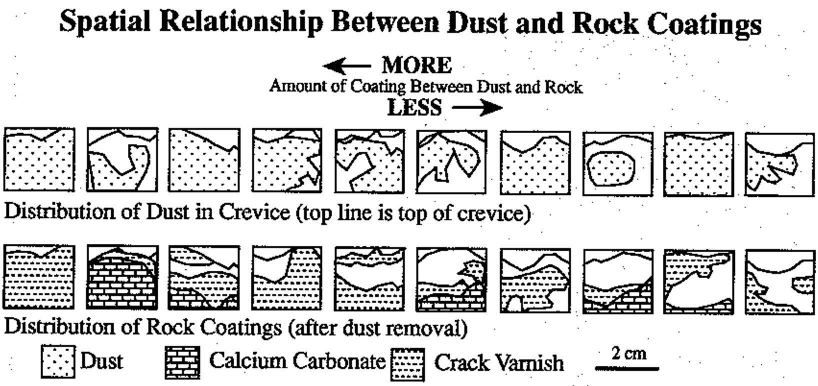

Figure 5. The distribution of dust and the underlying rock coatings in andesite fissures at Tempe Butte, Arizona. When rock coatings of orange varnish or carbonate rest directly under the dust, the source of the fine material cannot be from the underlying andesite rock, especially when the coating is at the top of the fracture. The lack of a coating could allow any weathering of the andesite to contribute to the fissuresol.

Figure 6 illustrates a lightly weathered rock, where rock varnish separates the rock from the dust. The fine material could not have weathered from the immediately adjacent andesite because of the presence of the rock coating. The combination of rock coatings separating dust from rock, and the lack of silt and clay weathering products, indicates that the fines have an aeolian origin.

We caution the possibility for an "optical illusion" effect in studies of dust in rock fissures. Our initial qualitative field observations revealed that basalt and andesite joint fractures in the Tempe Butte, Arizona, area contain a plethora of fine material, more so than granodiorite at Kitt Peak or sandstones at Sedona. This may simply reflect the texture of rock weathering products. Granodiorite weathers to grus, sandstone to sand. On the other hand, the weathering of basalt and andesite produces weathering rinds and cobble-sized angular fragments (Colman and Pierce 1981). We suspect, therefore, that the fines in basalt/andesite fractures look like "pure" loess, and the lack of visual contamination by sand-sized material creates the illusion that extrusive rocks are more efficient dust traps. A test of this hypothesis requires controlled monitoring studies.

Death Valley, California

Death Valley is a graben located in one of the most arid regions of North America. Yet, adjacent to this desiccated lowland are the semi-arid slopes of the Panamint Range. The latter rise to over 3000 m. The higher elevations are mantled with coniferous vegetation. We collected quartzite samples from the floor of Death Valley to the 3000-m-elevation environmental gradient. Quartzites contain only minor amounts of trace elements, and thus are ideal for assessing the amount of external components to rock crevice fines.

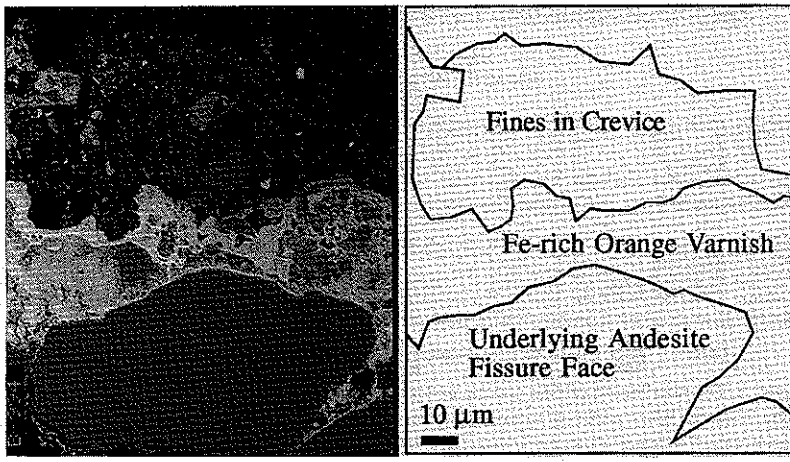

Figure 6. BSE image of fracture in andesite at Tempe Butte in Arizona. Taken from same outcrop less than a meter from the sample in Figure 4, this fracture displays a coating of orange (Mn-poor, Fe-rich) rock varnish that separates the fines from the rock. It is quite likely that the fines are incorporated into the orange crack varnish as it grows; this is indicated by the detrital grains within the orange varnish.

The bulk analysis of the fine material in quartzite crevices in Death Valley National Monument reveals distinct geochemistries (Table 1). There are abundant elements in the rock fissure fines that are not present in measurable quantitites in the quartzite. These elements are found in both arid environments, such as adjacent to the salt playa, as well as in the subalpine environment, among the coniferous vegetation.

There is also evidence that quartzite weathering is contributing silica to fissures. Observations of cross sections with BSE provided textural evidence for etching on crevice walls (Figure 7). This etching may be similar to the solution features observed on quartz grains with the secondary electron microscope (e.g., Tchakerian 1991). It is possible that the higher concentration of SiO_2 in the fissure dust at the playa margin is the result of higher pH, gypsum, and halite aiding in the dissolution of quartzite (Table 1). In contrast, frost weathering of quartzite could have contributed to the higher SiO_2 concentrations in fissures atop the Panamint Range (Table 1).

Hawaii

The higher elevations of the volcanoes in Hawaii are above the trade-wind inversion, and are extremely arid. Plant cover is extremely sparse. Figure 8 shows fines in rock fractures from within a few hundred meters of the summits of three of the larger volcanoes in the Hawaiian chain: Mauna Kea and Hualalai on Hawaii, and Haleakala on Maui. The presence of quartz is especially significant, given the fact that free quartz is rare in basalts. The quartz probably originates from Asia and is transported by upper-level winds (Beget et al. 1993).

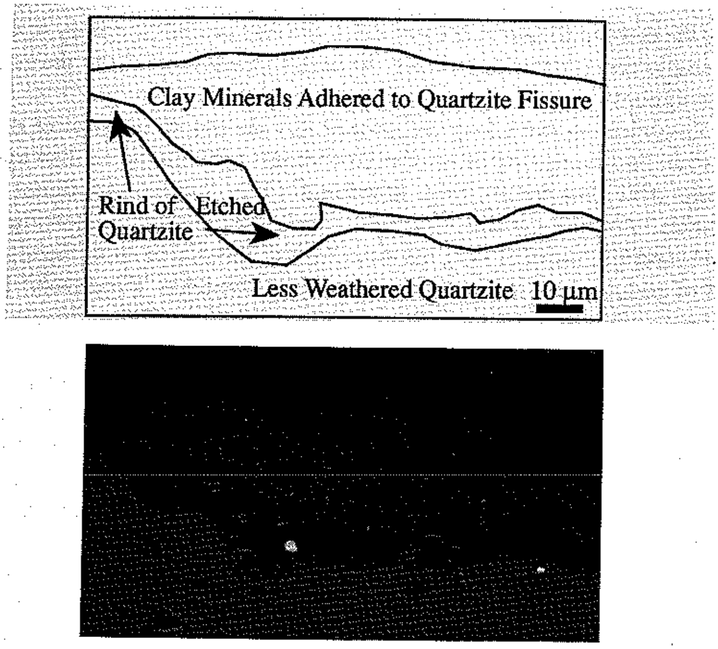

Figure 7. BSE image of clay minerals next to quartzite, from 2000-m site in Death Valley (see Table 1). The bright particle is a clast of barium sulfate. Note the enhanced etching of the quartzite along the fissure margin.

The presence of quartz in the Hawaiian rock fractures suggests an aeolian origin for some of the fracture constituents. The top BSE image in Figure 8 is of a rock fracture just beneath glacially polished basalt near the summit of Mauna Kea. It is probable that these fractures have been receiving aeolian dust input since Mauna Kea was last deglaciated about 15,000 yr B.P. (Dorn et al. 1991). Individual quartz grains identified by electron microprobe analysis are indicated in Figure 8. The middle BSE image is of a rock fracture near the summit of Haleakala Volcano, Maui. The bottom image is an SEM micrograph of a sample of tephra from near the summit of Hualalai Volcano, Hawaii, and shows the surface topography. The quartz in Figure 8 was identified by EDS as pure Si.

The upper two images in Figure 8 show evidence of silica glaze (Curtiss et al. 1985) between the quartz and the basalt. The enrichment of silica in the glaze, sometimes 40% SiO_2 more than the underlying basalt, has been an uncertainty in silica glaze research in Hawaii (Curtiss et al. 1985). We suggest that some of the silica is derived from the weathering of quartz loess.

DISCUSSION

Our analysis indicates that the fine materials in arid-land rock fractures derive from both aeolian dust and weathering. In some instances, aeolian dust appears to be the dominant source. In other cases, the texture and chemistry of the fine material is consistent with a weathering origin. In still other cases, the evidence is ambiguous.

Geoscientists have long recognized that the parent material of dryland soils can be a composite of weathered bedrock and cumulic aeolian material (Jenny 1941, Nikiforoff 1949, Marchand 1970, Yaalon and Ganor 1973, Mabbutt 1979, Gerson and Amit 1987, Bach, this volume). Following Jenny (1941) and Nikiforoff (1949), we view the fine material in rock fissures as the start of pedogenesis. Accordingly we propose the term "fissuresols" for the evolution of fines in rock crevices. We also recommend that fissuresols be further subdivided into residual soil or a cumulic soil types.

Figure 9 presents a general model of fissuresol development that is consistent with the evidence presented in this study. On one end of the spectrum, fines in rock fissures are completely external and form a cumulic fissuresol. On the other end, fines are entirely derived from weathering. Polygenetic fissuresols form when both weathering and aeolian dust contribute to the development of fines.

Lithology certainly plays a key role in determining whether the fissuresol is residual or cumulic. Friable rocks favor the development of residual fissuresols that are characterized in the field by a lack of rock coatings and a flaked texture on the crevice sides. Lithologies resistant to weathering would favor the development of cumulic fissuresols, which are characterized in the field by rock coatings on crevice sides. We are presently testing this model with artificial fissures that are placed in different natural settings and monitored over time. We are controlling most of the important variables involved in fissuresol development, such as vegetation, microclimate, topography, lithology, and dust storm frequency.

Climatic change may also be an important variable. Arid climates with abundant dust storms (Brazel 1989) would favor cumulic fissuresols. Moister climates tend to enhance weathering and the development of residual fissuresols. We suspect that a polygenetic fissuresol, however, might not truly represent a penecontemporaneous combination of dust and weathered crevice walls. Inputs from aeolian dust or weathering could be periodic. A rock fracture forced open during sample collection at Ayers Rock, Australia, yielded a varnish radiocarbon age of ~27 ka (Dorn and Dragovich 1990). This is best interpreted as a minimum age for the fracture. This example indicates that rock crevices could be potentially old enough to have experienced drastically different climates. It is quite possible that a fissuresol, now found in an arid climate and receiving mostly dust, could have fragments left by rock weathering during a more humid climate.

ACKNOWLEDGMENTS

This research was funded by an REU supplement to a NSF Presidential Young Investigator Award (to Dorn). Thanks to Tanzhuo Liu for assistance in sample

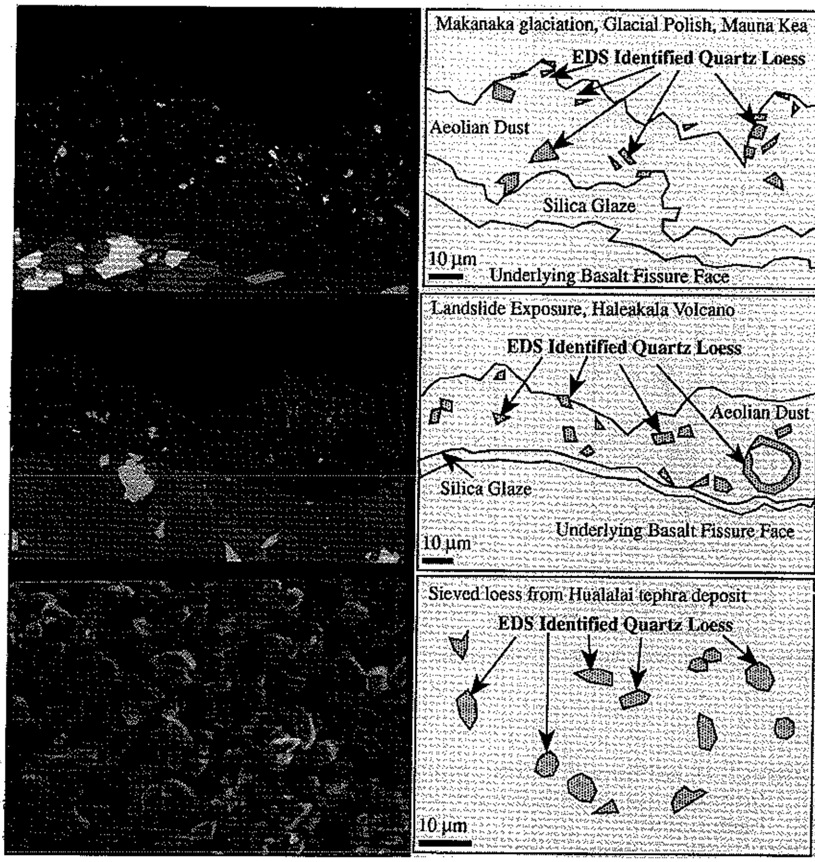

Figure 8. Electron micrographs of quartz in Hawaii. Top: BSE image of fracture near Mauna Kea summit. Middle: BSE image of fracture from Haleakala summit. Bottom: secondary electron image (showing topography) of tephra deposit near summit of Hualalai.

preparation, Tom Paradise and Greg Pope for discussions, and Kevin White (University of Reading), Andrew Goudie (University of Oxford), and Vatche Tchakerian (Texas A&M University) for valuable comments on the manuscript. However, the conclusions remain our own.

REFERENCES

Amit, R., Gerson, R., and Yaalon, D. H. (1993) Stages and rate of the gravel shattering process by salts in desert Reg soils. *Geoderma*, v. 57, p. 295-324.

Beget, J. E., Keskinen, M., and Severin, K. (1993) Mineral particles from Asia found in volcanic loess on the island of Hawaii. *Sedimentary Geology*. v. 84, pp. 189-197.

Brazel, A. J. (1989) Dust and climate in the American southwest. *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*. Kluwer Academic Publishers, New York, p. 65-96.

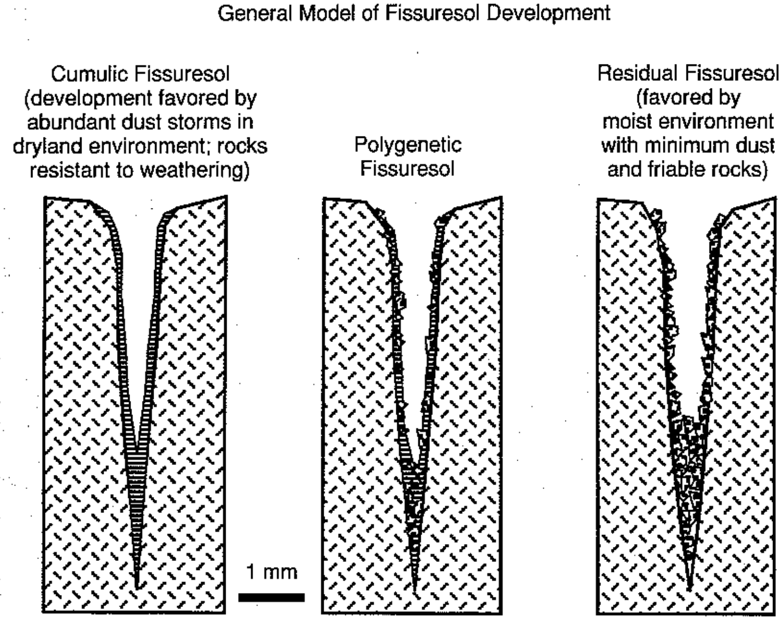

Figure 9. Generalized model of fissuresol development in rock fractures.

Colman, S. M., and Pierce, K. L. (1981) *Weathering Rinds on Andesite and Basaltic Stones as a Quaternary Age Indicator, Western United States.* U.S. Geological Survey Professional Paper, v. 1210.

Coudé-Gaussen, G., Rognon, P., and Federoff, N. (1984) Piegeage de poussières éoliennes dans des fissures de granitoides due Sinai oriental. *Compte Rendus de l'Academie des Sciences de Paris II*, v. 298, p. 369-74

Curtiss, B., Adams, J. B., and Ghiorso, M. S. (1985) Origin, development, and chemistry of silica-alumina rock coatings from the semiarid regions of the island of Hawaii. *Geochimica et Cosmochimica Acta*, v. 49, p. 49-56.

Dorn, R. I., and Dragovich, D. (1990) Interpretation of rock varnish in Australia: Case studies from the Arid Zone. *Australian Geographer*, v. 21, p. 18-32.

Dorn, R. I., Phillips, F. M., Zreda, M. G., Wolfe, E. W., Jull, A. J. T., Kubik, P. W., and Sharma, P. (1991) Glacial chronology of Mauna Kea, Hawaii, as constrained by surface-exposure dating. *National Geographic Research*, v. 7, p. 456-471.

Gerson, R., and Amit, R. (1987) Rates and modes of dust accretion and deposition in an arid region, the Negev, Israel. *Journal Geologic Society London Special Publication*, v. 35, p. 157-169.

Goudie, A. S. (1978) Dust storms and their geomorphological implications. *Journal of Arid Environments*, v. 1, p. 291-310.

Jenny, H. (1941) *Factors of Soil Formation.* McGraw-Hill, New York.

Krinsley, D. H., and Manley, C. R. (1989) Backscattered electron microscopy as an advanced technique in petrography. *Journal of Geological Eduction*, v. 37, p. 202-209.

Mabbutt, J. A. (1979) Pavements and patterned ground in the Australian stony deserts. *Stuttgarter Geographische Studien*, v. 93, p. 107-123.

Marchand, D. E. (1970) Soil contamination in the White Mountains, eastern California. *Geological Society of America Bulletin*, v. 81, p. 2497-2505.

Nikiforoff, C. C. (1949) Weathering and soil evolution. *Soil Science*, v. 68, p. 219-230.

Pye, K. (1987). *Aeolian Dust and Dust Deposits.* Academic Press, London.

Tchakerian, V. P. (1991). Late Quaternary aeolian geomorphology of the Dale Lake sand sheet, southern Mojave Desert, California. *Physical Geography*, v. 12, p. 347-369.
Yaalon, D. H., and Ganor, E. (1973) The influence of dust on the soils during the Quaternary. *Soil Science*, v. 116, p. 146-155.