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SEM Analysis of Quartz Sand Grain Surface Textures Indicates Alluvial/Colluvial Origin of the Quaternary “Glacial” Boulder Clays at Huangshan (Yellow Mountain), East-Central China

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Received August 13, 1996

Geomorphic features and Pleistocene deposits on Huangshan have been attributed to glaciation. Recent reassessment questions this interpretation. As part of the reassessment, quartz sand grains from deposits identified as glacial boulder clays (till composed of boulders in a clay or silt matrix) were analyzed by scanning electron microscope for evidence of their sedimentary history. Surface textures found on the boulder-clay grains were compared with those on grains with known sedimentary histories including glacial, grus, colluvial, and alluvial grains. The analysis shows that the grains lack typical glacial textures. The surface textures present indicate a complex history. Nonuniformly weathered grain surfaces point to chemical weathering of the source rock. This is supported by the deep weathering of the nonquartz clasts in the sand-sized fraction as well as in boulders at the outcrops. The close correspondence in surface-texture frequencies with those of the alluvial grains indicates an alluvial component to the grains' history. The similarity with the colluvial grains and the outcrops' structures suggest an alluvial/colluvial origin for the deposits. The history indicated by the surface textures agrees with the recent reassessment of the geomorphic features and points to warm climatic conditions in east-central China for at least part of the Pleistocene. © 1997 University of Washington.

INTRODUCTION

Huangshan (Yellow Mountain) is a granite massif located at 30°10' north latitude and 118°11' east longitude in southern Anhui Province in the People's Republic of China (Fig. 1). The mountain is about 340 km southwest of Shanghai and just south of the Chang Jiang (Yangtze River). The

maximum altitude of Huangshan is about 1841 m above mean sea level. The Early Cretaceous granite was uplifted along faults several times during the Cenozoic (Huang *et al.*, 1995). Huangshan lies in a humid subtropical area with warm summers (Espenshade and Morrison, 1978, pp. 8–9). During the winter months snow may accumulate on the mountain (Fig. 2).

Beginning in the 1920s, J. S. Lee wrote a series of papers proposing that some of the higher mountains in east-central China had been glaciated in the Pleistocene (Derbyshire, 1983, 1987). Lee (1936, 1939) described glacial cirques, U-

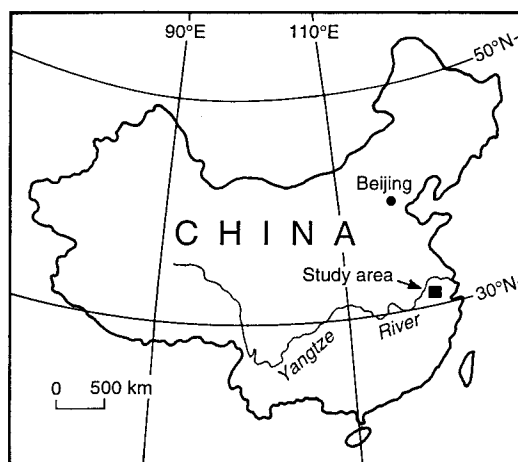


FIG. 1. Huangshan study area in China.

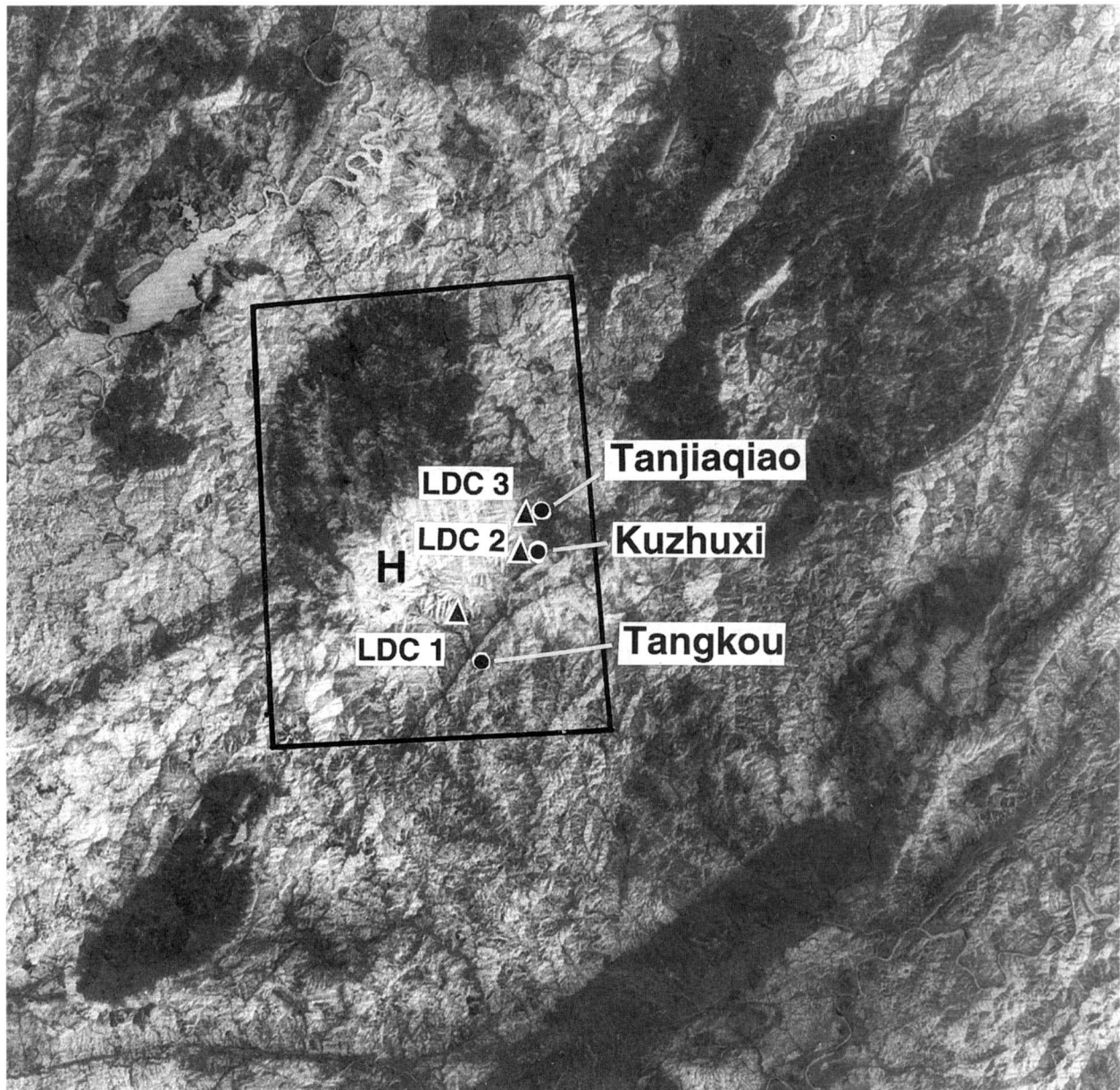


FIG. 2. Landsat image. (LANDSAT E-42429-02103-2 10 March 1989) Huangshan (H) is the bright area in the center of the image. Blocked area corresponds to Figure 3. The strong lineaments bordering Huangshan to the south and southeast are the geomorphic expressions of major faults and joints (Huang *et al.*, 1996). Sample sites (▲) of the boulder clays, LDC 1 and LDC 2, and the modern alluvium, LDC 3 are indicated. Tangkou, Kuzhuxi, and Tanjiaqiao (●) are the villages and town nearest the sample sites.

shaped valleys, erratics, striations, and other features of glacial origin on Huangshan. He also noted deposits of “moraine-like materials in the foothills and valleys” on the piedmont areas surrounding the mountain at altitudes as low as 300 m (Lee, 1936, p. 283). Lee postulated that the mountain had been glaciated in several stages. Initially this idea was viewed skeptically by some geologists. However, by the early 1960s it was the prevailing hypothesis to explain the

geomorphology and deposits on Huangshan and the adjacent mountain areas. Huang’s (1963a,b) work on the Quaternary climate and the geomorphology of the region led him to doubt Lee’s interpretation. He and other workers marshaled evidence to refute Lee’s hypothesis (e.g., Zhang and Mou, 1982; Shi, 1982; Derbyshire, 1983; Shi *et al.*, 1986; Huang, 1993, 1994; Huang *et al.*, 1995, 1996). The abundance of secondary minerals, the absence of silt, and the deep chemi-

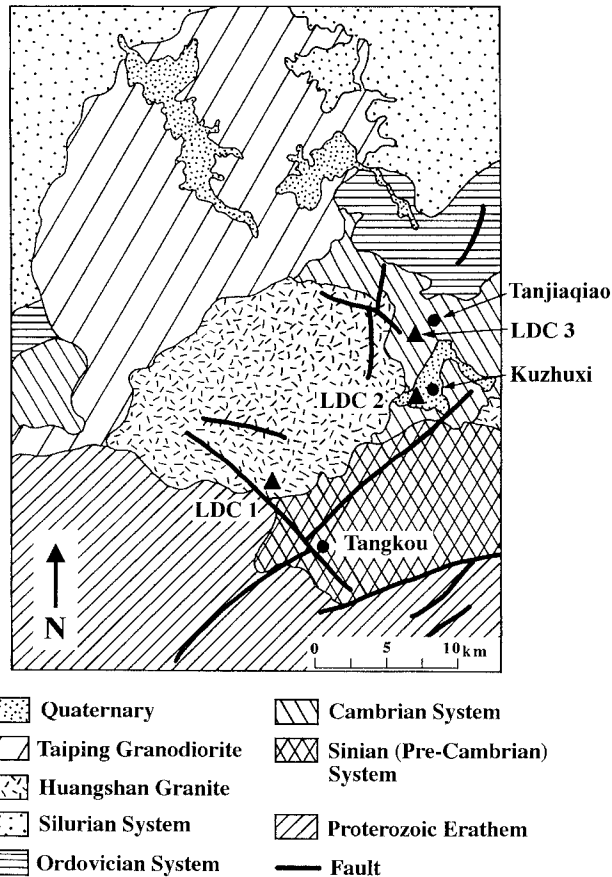


FIG. 3. The principal geologic units and major faults in the Huangshan area. Adapted from Wang (1989).

cal weathering in the “moraine” profiles at high elevations (up to 1300 m) led Derbyshire (1987) to question whether glaciation had occurred in eastern China south of the Chang Jiang. Huang *et al.* (1987) showed that the sporo-pollen assemblages from the supposed glacial boulder clays (till composed of boulders in a clay or silt matrix) on Huangshan and nearby Lushan are derived from a warm, wet environment. Diffendal and Huang (1996) reported evidence that the valleys Lee saw as glaciated are fluvially eroded valleys, developed in zones of weakness along faults and joints in the granite (compare Fig. 2 with Fig. 3). Despite the mounting evidence that nonglacial processes are responsible for the regional geomorphology and Pleistocene deposits, a glacial interpretation persists (e.g., Jing and Fu, 1989; Yang, 1990; Zhao, 1991; Jiang, 1996; Yu *et al.*, 1996).

If valley glaciers formed on Huangshan and other mountains in east-central China during the Pleistocene depositing moraines as low as 300 m, then this would have a major effect on global climate models for that time. We judge it important, therefore, to test the glacial hypothesis further. To this end, surface textures on quartz sand grains from two

Huangshan boulder clays were analyzed by scanning electron microscopy for evidence of the grains' sedimentary history.

METHODS

Surface Textural Analysis

Scanning electron microscope (SEM) examination of quartz sand grains from different sedimentary environments has revealed that certain sedimentary processes impose characteristic sets of surface textures on the grains (Margolis and Kennett, 1971; Krinsley and Doornkamp, 1973). These textures and the frequencies with which they occur, in turn, can be used to determine the sedimentary histories of quartz grains. Culver *et al.* (1983) found that this technique, applied by five different analysts to sand grains from the same eight sedimentary settings, ranging from glaciation to *in situ* granite weathering, reliably revealed the history of sand grains. We argue that if Lee's boulder clays are the product of glaciation, then the quartz sand grains from the deposits should bear a set of surface textures typical of those on glacial sand grains. Alternatively, the boulder clays may be the product of other processes. Huang (1963a,b), and Derbyshire (1987) proposed that boulder clays in the Lushan area are alluvium and debris-flow deposits. In order to discover the processes that have influenced the Huangshan boulder-clay grains, the surface textures on the grains were assessed and the results compared to sets of surface textures typical of glacial, grus, colluvial, and alluvial grains.

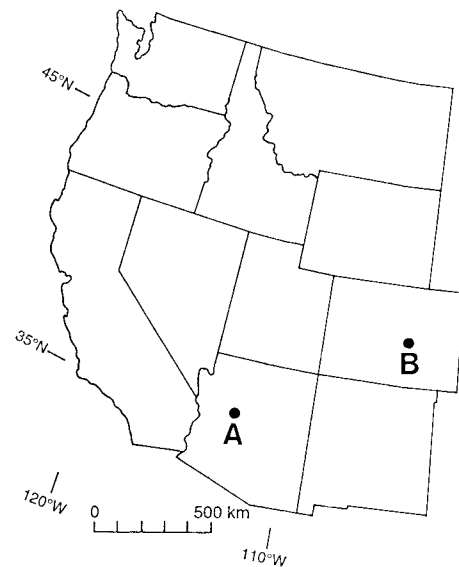


FIG. 4. Location map showing grus samples localities. (A) Arizona Sample 1 collected at Kuhne Hill, NE1/4, SE1/4, SW1/4, Sec. 9 T13N, R2W, Prescott 7.5' quadrangle. Arizona Sample 2 collected at NE1/4, SW1/4, NW1/4, Sec. 36, T14N, R2W, Prescott 7.5' quadrangle. (B) Colorado sample collected in North Cheyenne Canyon, SE1/4, NW1/4, SW1/4, NW1/4, Sec. 33, T14S, R67W, Manitou Springs 7.5' quadrangle.

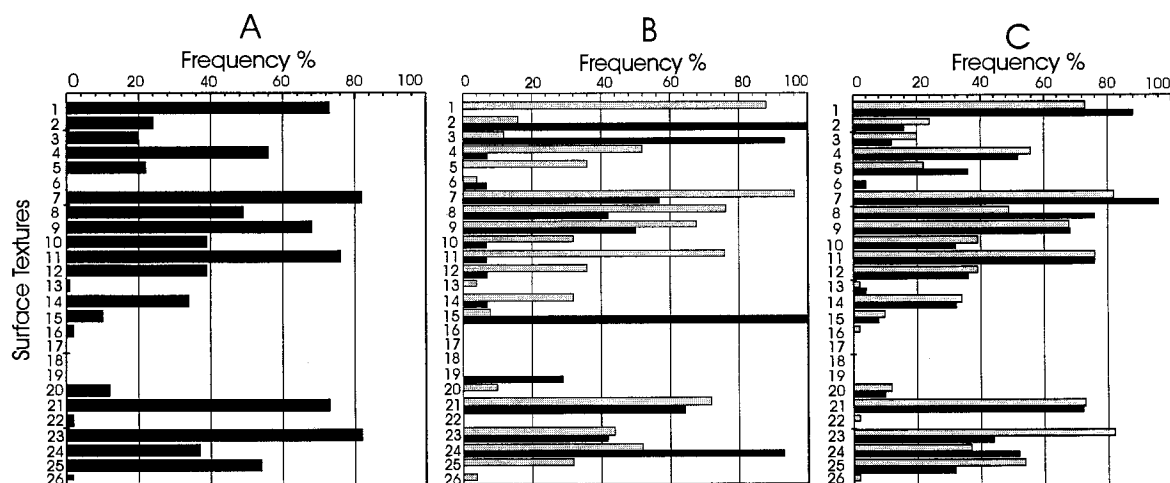


FIG. 5. Surface-textures frequency graphs. (A) LDC 1, (B) LDC 2-A (▨) vs LDC 2-R (■). (C) LDC 1 (▨) vs LDC 2-A (■). Numbers correspond to surface textures listed in Table 1. Surface-texture frequencies for alluvium and grus came from the samples analyzed in this study as well as from those reported by others (Margolis and Kennett, 1971; Bull *et al.*, 1987). Frequencies for glacial grains came from Margolis and Kennett (1971) and Margolis and Krinsley (1974) and that for colluvial grains from Bull *et al.* (1987) and Goudie and Bull (1984).

Sample Preparation and Analysis

Fine grained sediment was collected from two boulder-clay sites on the Huangshan piedmont (Fig. 3). Additional samples were taken from a Huangshan stream bed (Fig. 3) and three grus deposits in North America (Fig. 4). A 5 g aliquot was split from each sample and cleaned by boiling in a concentrated solution of HCl and SnCl₂ (Krinsley and Doornkamp, 1973; Bull, 1986). The boulder-clay grains were heavily coated with clay and required additional treatment with sodium hexametaphosphate (Calgon) and brief sonication (Dowdeswell *et al.*, 1985) to remove the clay. Thirty-five to 40 quartz grains were randomly selected from the 1000–200

μm size fraction of each sample. These were mounted on aluminum stubs and coated with gold before viewing in a JOEL JSM-T330 SEM at 15 kV. Each grain within each sample was evaluated for the presence or absence of 26 surface textures (Table 1). The results were compiled into a percentage frequency graph for each sample (Fig. 5).

RESULTS

Boulder-Clay Surface Textures

The boulder-clay grains in LDC 1 (Fig. 5A) are angular, of medium relief with abundant mechanical textures associated

TABLE 1
Surface Textures Used in Analysis

No. Morphological	No. Mechanical	No. Chemical
1. Angular outline	6. Small conchoidal fracture-b ^a	21. Solution pits
2. Rounded outline	7. Large conchoidal fracture-b	22. Chemical V-shaped pits
3. Low relief	8. Straight steps-b	23. Adhering particles
4. Medium relief	9. Arcuate steps-b	24. Limited silica precipitation
5. High relief	10. Imbricated blocks-b	25. Extensive silica precipitation
	11. Large breakage blocks-b	26. Euhedral crystal overgrowths
	12. Fractured plates-b	
	13. Striations-t ^b	
	14. Edge abrasion-t	
	15. Mechanical V-shaped pits-t	
	16. Straight grooves-t	
	17. Curved grooves-t	
	18. Meandering ridges-t	
	19. Irregular depressions-t	
	20. Upturned plates-t	

^a Mechanical textures followed by -b are produced when grains break, either on release from the parent rock or during transport.

^b Mechanical textures followed by -t are produced during grain transport.

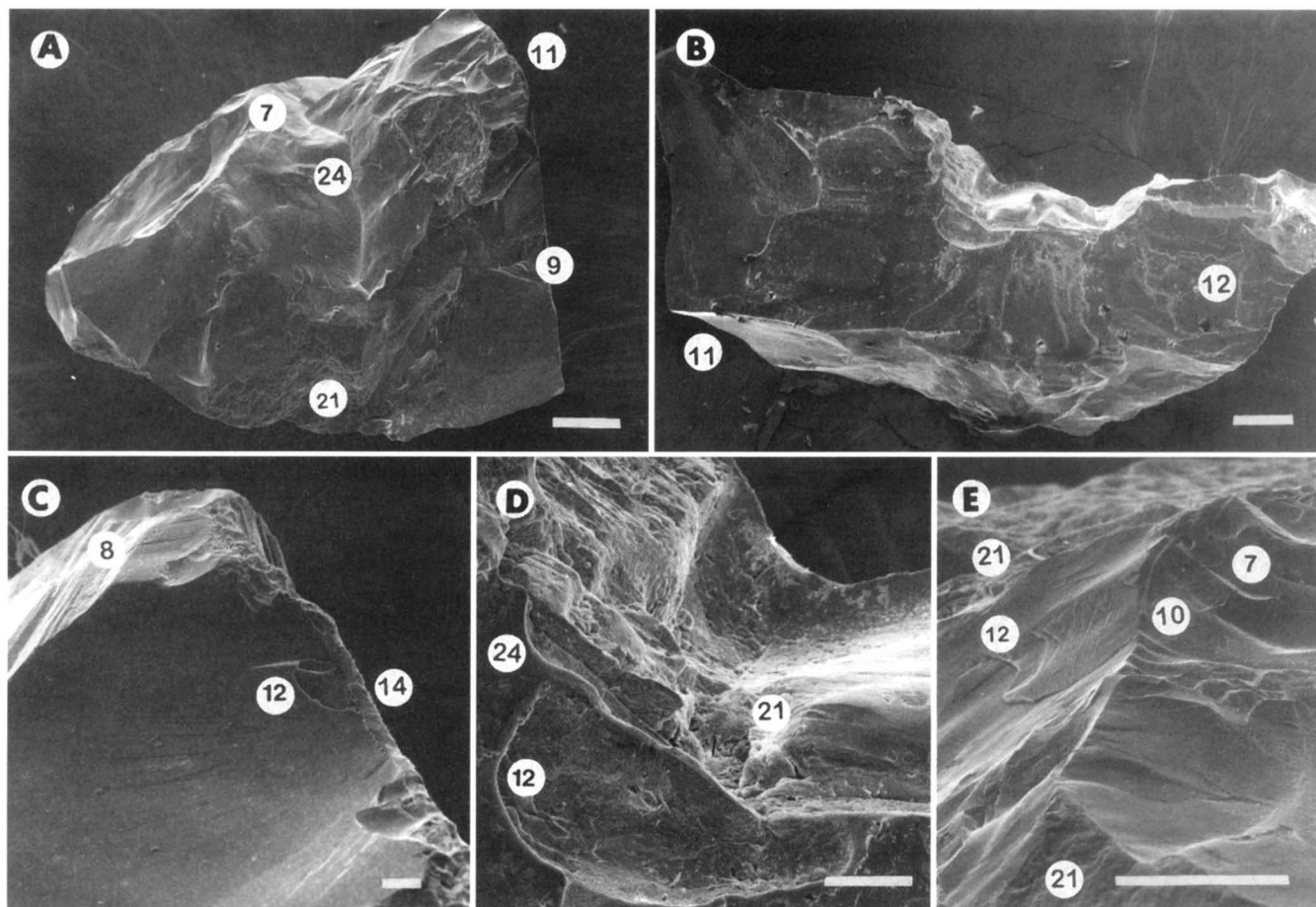


FIG. 6. Micrographs showing grain morphology and textures typical of LDC 1 and LDC 2-A. (Numbers on images correspond to surface texture numbers in Table 1.) (A and B) Grains with angular outline with medium relief of the grain surface and textures resulting from mechanical and chemical processes including conchoidal fractures (7), straight and arcuate steps (8 and 9), large breakage blocks (11), and fractured plates (12). Areas of chemical dissolution (21) and silica precipitation (24) are also present. Scale bars = 100 μm . (C) Top of grain A at higher magnification reveals straight steps (8), fractured plates (12), and edge abrasion (14). Scale bar = 10 μm . (D) Enlargement of upper central area of grain B showing silica dissolution (21). Scale bar = 75 μm . (E) Note the nonuniform weathering of the grain's surface. In the central area of the micrograph the grain's surface is fresh with fractured plates (12), imbricated blocks (10), and conchoidal fracture (7) while the upper and lower areas of the micrograph show a weathered surface with silica dissolution (21). Scale bar = 50 μm .

with breakage (Table 1) including conchoidal fractures, straight and arcuate steps, large breakage blocks, and fractured plates (Figs. 6A–6C). Of the mechanical textures associated with grain transport, only edge abrasion (Texture 14 in Table 1) is common (Fig. 6C). The grains also display silica dissolution and precipitation textures indicative of chemical weathering (Table 1; Figs. 6D and 6E). In addition, the grains show nonuniform weathering of the grain surfaces (Fig. 6E): freshly broken or only slightly weathered areas lie adjacent to areas that have undergone intense chemical weathering.

Sample LDC 2 is composed of two distinct populations (Fig. 5B). One population, designated LDC 2-R, makes up 35% of the sample. These grains (Figs. 7A and 7B) are well rounded, of low relief, and have abundant mechanical

V-shaped pits (Figs. 7C and 7D) which are associated with high-energy subaqueous transport (Krinsley and Doornkamp, 1973). The other population, LDC 2-A, is composed of angular grains of medium relief. Fewer than 10% of these grains bear mechanical V-shaped pits. The close similarity between LDC 2-A and LDC 1 (Fig. 5C) indicates a similar origin for these grains. Their data are combined for subsequent environmental comparisons. The surface textures of LDC 2-R indicate a different sedimentary history. They possess a morphology and a set of surface textures characteristic of beach sand grains (Margolis and Kennett, 1971). Although the source of these grains has not been determined, they are probably reworked from the Precambrian or Paleozoic sandstones overlying the margins of the granite massif.

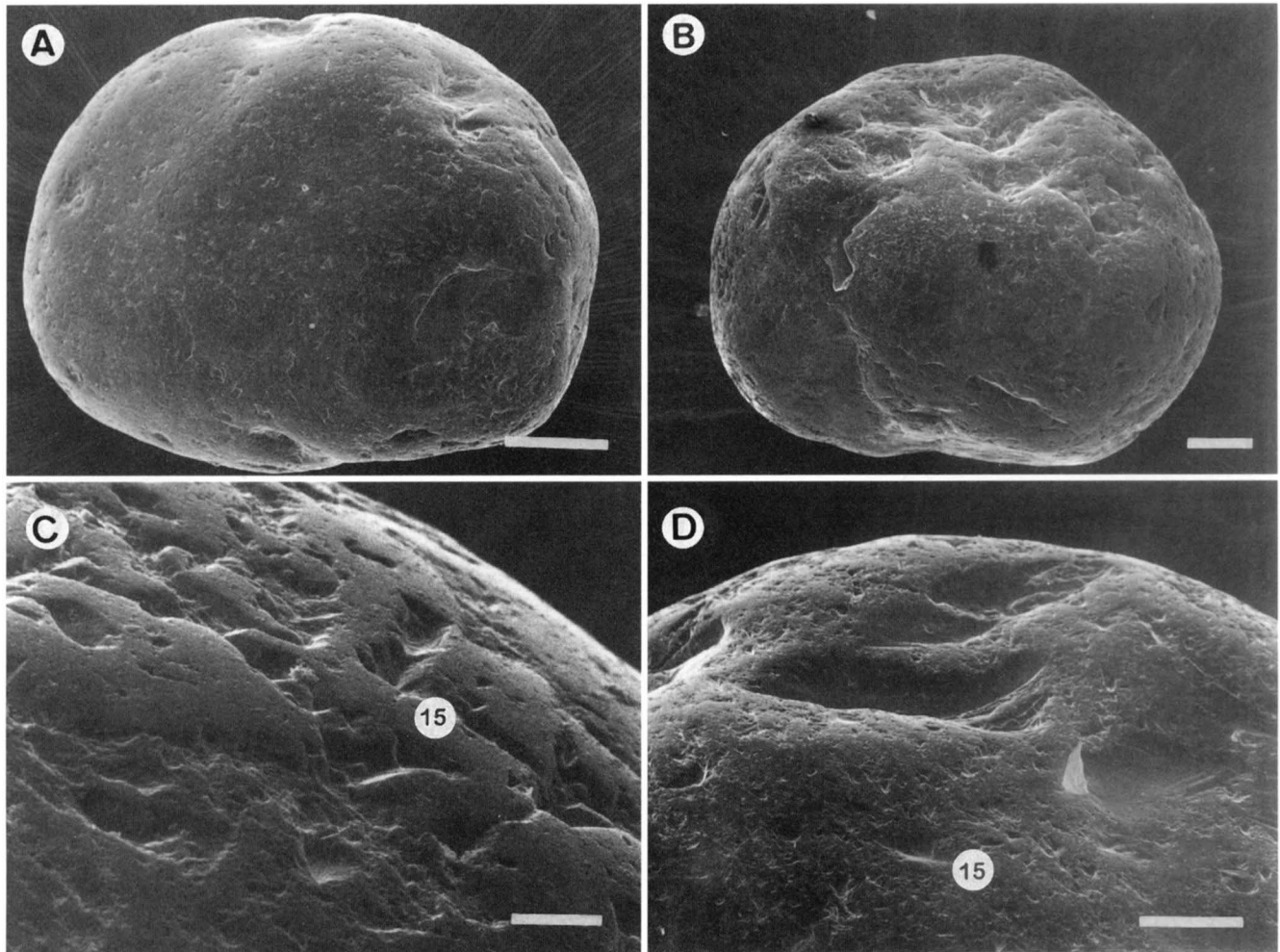


FIG. 7. Micrographs of LDC 2-R. (A and B) (Numbers correspond to surface-texture numbers in Table 1). Grains with rounded outline and low relief. Also, there are abundant mechanical V-shaped pits (15) on grain surface. Scale bars = 100 μm . (C) Grain A surface at higher magnification showing at least two populations of pits. Scale bar = 10 μm . (D) Grain B surface at higher magnification showing mechanical V-shaped pits (15) and irregular depressions (19). Scale bar = 25 μm .

Grus Surface Textures

All three grus samples (Figs. 8 and 9) show angular grains of medium relief with high frequencies of conchoidal fracture, fractured plates, and solution pits (Textures 7, 12, and 21), low frequencies of straight steps (Texture 8), and few mechanical textures associated with grain transport. Also, nonuniform weathering of the grains' surfaces is typical of these grains. The two Arizona samples differ from the Colorado sample in having a higher percentage of rounded grains and more extensive silica precipitation (Texture 25). Between 10 and 20% of the grains in Arizona Sample 1 and the Colorado sample show edge abrasion (Texture 14). This texture is strongly associated with abrasive processes (Krinley and Doornkamp, 1973; Bull, 1986). Marshall *et al.* (1987) produced it experimentally on Brazilian quartz in an abrasion device. In a study of surficial sediments in Swazi-

land, Bull *et al.* (1987) found that the presence of edge abrasion distinguished colluvial grus and *in situ* grus. However, the Arizona and Colorado samples had undergone little down slope movement. Both Arizona samples were collected within 1 m of their source rocks and the Colorado sample was taken 4 m downslope from the source rock. This suggests either that edge abrasion requires only a small increment of downslope movement to develop or that other factors influence its development.

DISCUSSION

Comparison with Grains with Known Sedimentary Histories

Boulder-clay grains vs glacial grains. Whereas approximately the same percentage of boulder-clay and glacial

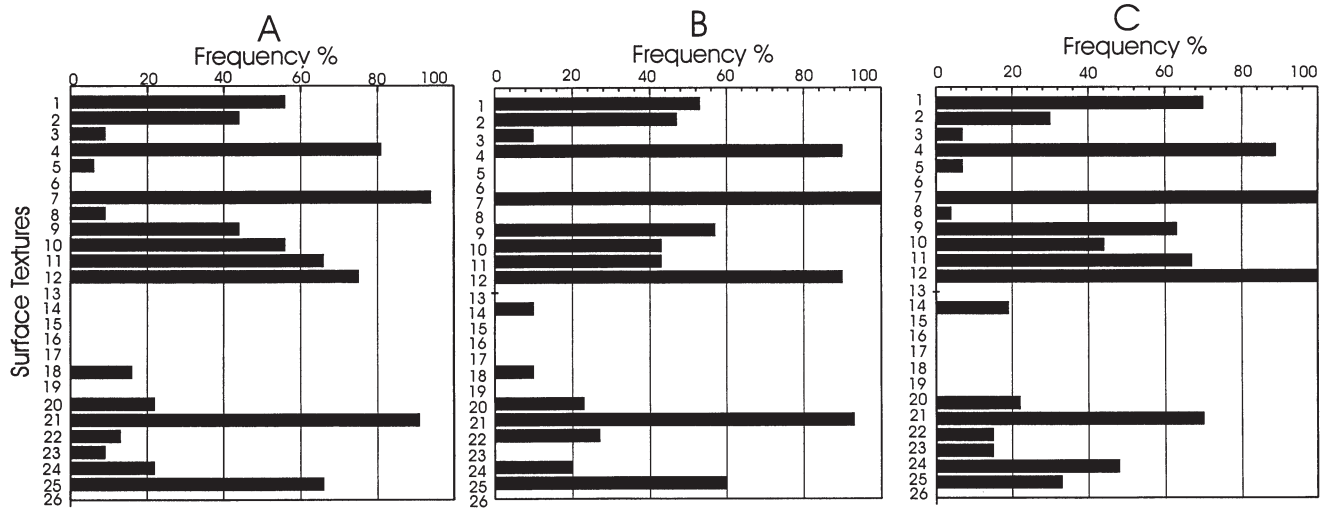


FIG. 8. Surface-texture frequency graphs. (A) Arizona sample 1. (B) Arizona sample 2. (C) Colorado grus grains. Numbers correspond to surface textures listed in Table 1.

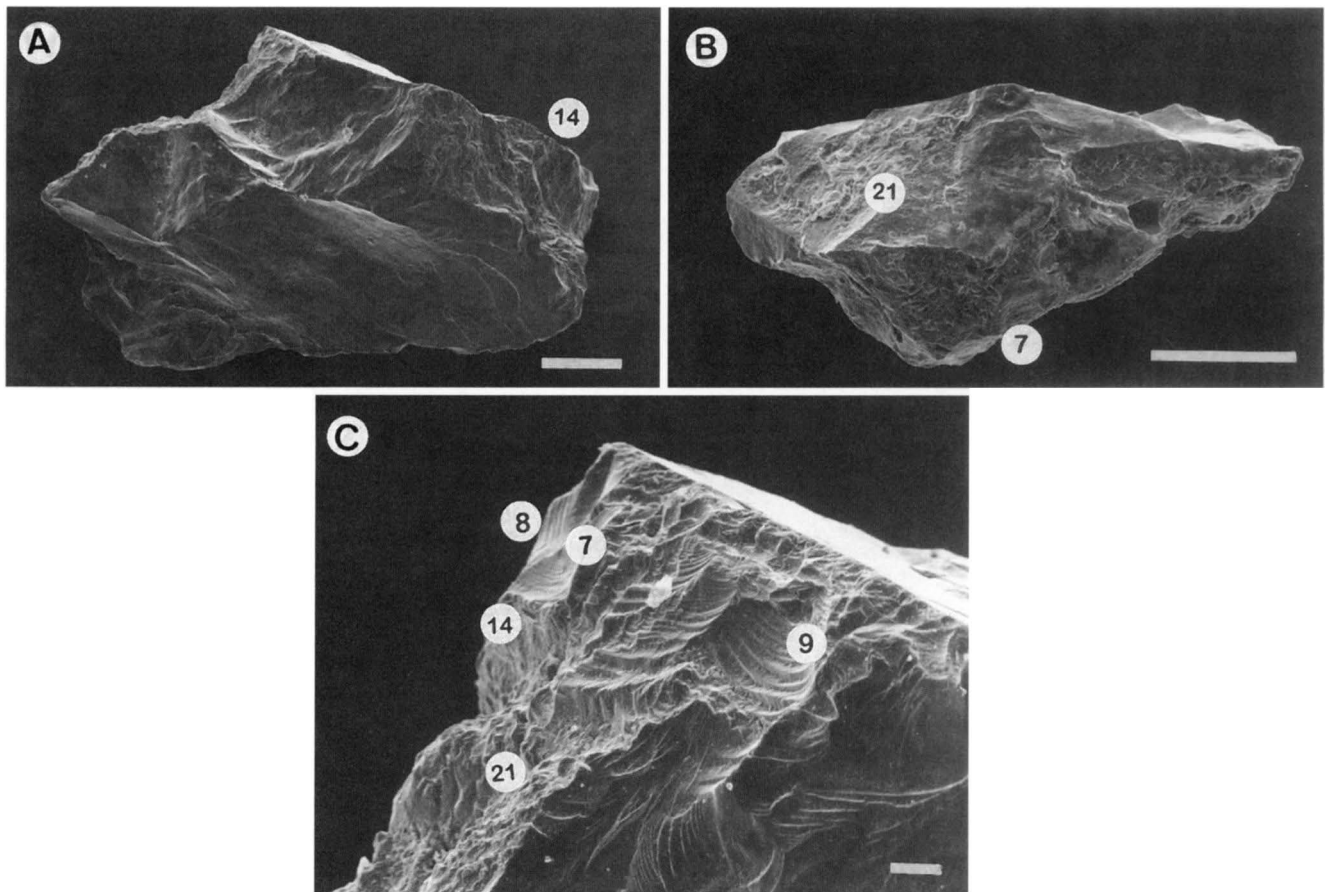


FIG. 9. Micrographs of grus. (Numbers correspond to surface texture numbers in Table 1.) (A) Colorado grus grain showing angular outline and nonuniform weathering. Edge abrasion at 14. Scale bar = 100 μm . (B) Arizona grus grain with angular outline, nonuniform weathering, and greater silica dissolution (21) and precipitation (24). Scale bar = 100 μm . (C) Top of grain A at higher magnification showing conchoidal fracture (7) with straight (8) and arcuate steps (9) and edge abrasion (14). Areas of silica dissolution (21) are also present. Scale bar = 10 μm .

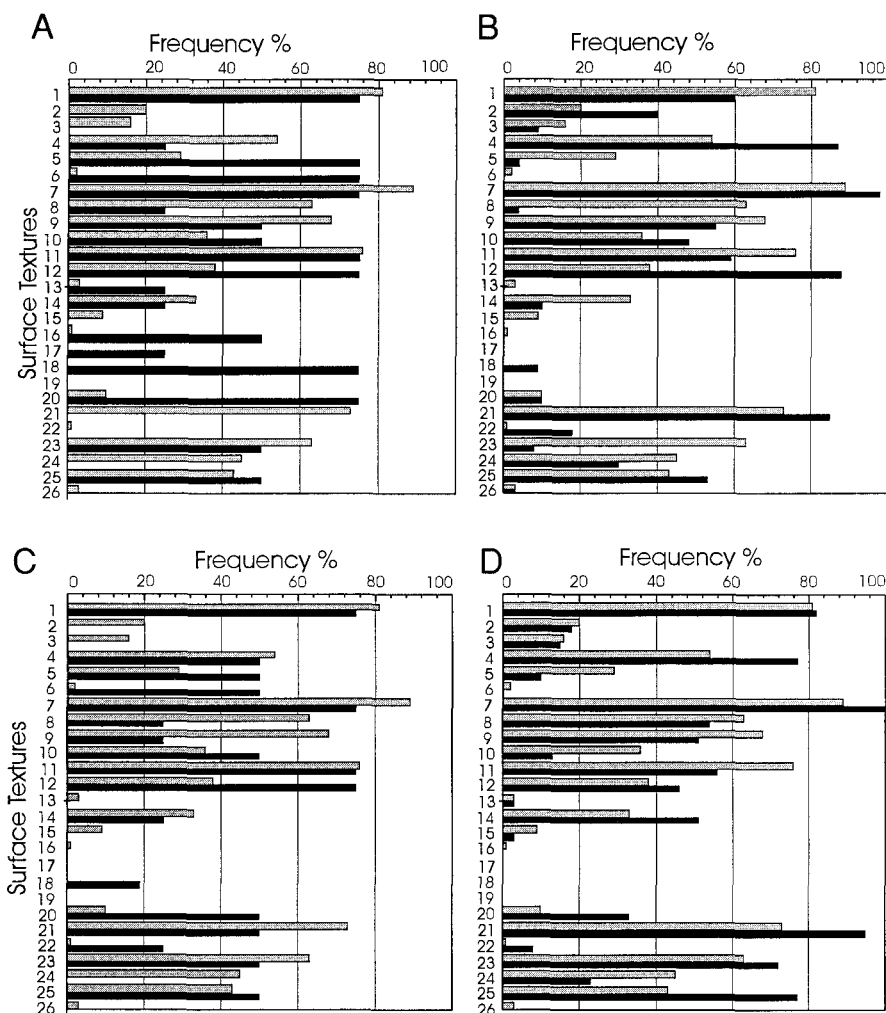


FIG. 10. Surface-texture frequency graphs. (A) Boulder-clay grains (▨) compared to glacial grains (■). (B) Boulder-clay grains (▨) compared to a composite surface texture graph of the Arizona and Colorado grus samples (■). (C) Boulder-clay grains compared to colluvial grains (■). (D) Boulder-clay grains (▨) compared to the Huangshan alluvial grains. Numbers correspond to surface textures listed in Table 1.

grains are angular in outline, the boulder-clay grains have lower relief of the grain surface than is typical for glacial grains (Fig. 10A; Textures 4 and 5). In addition, the boulder-clay grains essentially lack the mechanical textures associated with transport that are typically present on glacial grains: striations, straight and curved grooves, and meandering ridges (Fig. 10A; Textures 13, 16, 17, and 18). The surface textures present on these grains do not indicate a glacial history for the boulder clays.

Boulder-clay grains vs grus grains. A broad similarity is seen between the boulder clay grains and the grus grains (Fig. 10B). However, more of the boulder-clay grains are angular with a wider range of surface relief (Fig. 10B; Textures 1, 2, 3–5) as well as a higher frequency of edge abrasion (Texture 14). The boulder-clay grains also bear mechanical V-shaped pits that are absent in the grus. Both samples

show nonuniform weathering of the grains' surfaces, characteristic of grains released from their source rock by chemical processes (Krinsley and Doornkamp, 1973). Chemical textures are well developed on grain surfaces long exposed prior to their release, while these textures may be absent or poorly developed on adjacent surfaces where attachment to the source rock excluded or limited weathering. Nonuniform weathering of grains in the boulder clays indicates that predominantly chemical processes removed these grains from their source rock. Their greater angularity, higher frequency of edge abrasion, and the presence of mechanical V-shaped pits suggest that the boulder-clay grains were subjected to one or more physical weathering process following release.

Boulder-clay grains vs colluvial grains. There is a clear similarity between the boulder-clay grains and the colluvial grains (Fig. 10D) in grain angularity and in mechanical fea-

tures present, including edge abrasion (Texture 14). However, the boulder clays include more rounded grains and grains with low surface relief. The boulder-clay grains also show mechanical V-shaped pits not found on colluvial grains. Meandering ridges (Texture 18), present on some of the colluvial grains, are not found on the boulder-clay grains. If the boulder-clay grains have undergone colluviation, and the general similarity with the colluvial grains suggests that they may have, then subsequently some other process must have acted on the boulder-clay grains to produce mechanical V-shaped pits and increase rounding.

Boulder-clay grains vs alluvial grains. The closest correspondence in both the surface textures present and the frequencies with which they occur is found between the boulder clays and the Huangshan alluvium (Fig. 10C). The grains are alike in angularity and relief, as well as in the presence and frequency of chemical and mechanical textures including edge abrasion. Mechanical V-shaped pits (Texture 15), indicative of subaqueous transport (Krinsley and Doornkamp, 1973), occur with a higher frequency in the boulder-clay samples, suggesting that these grains may have been in subaqueous transport either for a longer time or under higher energy conditions than the grains in the modern alluvium. The close correspondence between the boulder-clay grains and the alluvium clearly indicates an alluvial episode for the boulder-clay grains.

Surface Textural Evidence Considered with Field Evidence

While surface textural analysis clearly indicates an alluvial component in the sedimentary history of the boulder-clay grains, a colluvial component is also possible. The morphology of the boulder-clay deposits observable in the outcrops suggest that both processes have been at work. Some clasts ranging up to boulder size in the outcrops of LDC 1 and LDC 2 (Fig. 11) show a vertical long-axis orientation. In addition, stratification with some inversely graded layers occurs in the outcrop of LDC 2 (Fig. 11). These depositional features distinguish debris-flow deposits from stream deposits (Collinson and Thompson, 1989).

The deeply weathered condition of boulders in the deposits, similar to that found in the boulder-clay deposits on the nearby Lushan massif, is typical of deposits developed in a warm, humid climate (Derbyshire, 1983). This deep weathering is also evident in the finer fraction. In sample preparation the nonquartz clasts in the boulder-clay samples shed approximately 20% of their weight as clays. X-ray diffraction of the material shed showed it to be predominantly kaolinite, a chemical weathering product of granite in warm, humid climates.

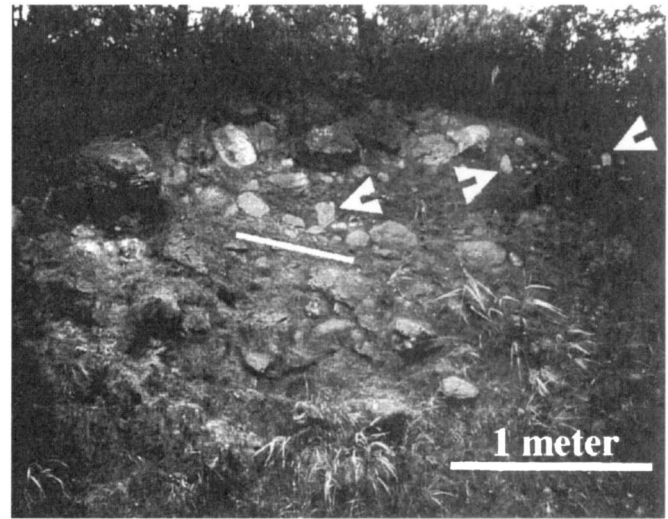


FIG. 11. Boulder-clay deposit LDC 2. Vertical clasts at arrows. Inversely graded layer detectable above white bar.

CONCLUSION

Evidence from quartz sand-grain surface textures does not support a glacial history for the boulder-clay deposits of Huangshan. Instead, analysis of the boulder-clay grains indicates that the grains have undergone chemical weathering which imparted a high frequency of chemical weathering textures on the grains' surfaces and produced nonuniformly weathered grains. This is supported by deep weathering of nonquartz clasts found in the 1000- to 200- μm fraction as well as in the boulders seen in the outcrops. Subsequent colluviation of the grains, suggested by surface texture analysis, is clearly indicated by the vertical clasts and inverse grading seen in the structure of the outcrops. The close correspondence with the alluvium in the surface textures present and their frequencies shows that the grains have undergone subaqueous transport. The deep weathering of the deposits and the evidence of intensity of chemical weathering seen on the quartz sand grains is consistent with the growing body of data that argues for warm humid climatic conditions in east-central China during the part of the Pleistocene when the boulder clays were deposited.

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