Location-dependent sediment sorting in gravelly megaripples from the Rio Grande, central New Mexico


Introduction

An ongoing study of modern fluvial sediments in New Mexico has revealed that grain-size sorting in streams is dependent on sample location within portions of bedforms and on bedform position within downstream progressions of similar forms. These results have many potential geologic applications.

One of the sets of bedforms studied is straight-crested, gravelly megaripples of the Rio Grande conveyance channel near Socorro, New Mexico. Megaripples are ripple-shaped bedforms having wavelengths larger than 60 cm and a range in amplitudes larger than ripples. In streams, megaripples form under lower-flow-regime conditions and migrate downstream by progressive deposition along their slip faces (Fig. 1). The purposes of this paper are to relate grain-size distributions to the form and location of megaripples and troughs left by waning flow along the conveyance channel, to determine whether a megaripple's position within a progression may be located by analyzing its grain-size distribution, and to determine sorting mechanisms taking place along megaripples.

Description of channel conditions

The conveyance channel east of Socorro is about 23 m wide at the top and 4 m deep, with an average gradient of 0.016 (Fig. 2). During the week of April 8, 1984, flow averaged an estimated 86 m³/sec (based on flow estimation techniques of Williams, 1978). On April 14, flow in the conveyance channel was diverted back into the Rio Grande channel upstream. During the next four days, the flow dropped to an estimated 3 m³/sec, so that the channel was approximately 10 m wide and 0.2 m deep. Flow was maintained in part by seepage from the banks. On April 19, the water was clear and the tops of some of the megaripples were near the surface of the water when surveying and sampling were conducted (Fig. 3). Little sediment was in suspension. Sand was transported only where megaripples were eroded by flow in the thalweg. Most parts of the megaripples were no longer migrating downstream.

Straight-crested megaripples with wavelengths averaging 2.8 m were measured and sampled along a 30 m long reach where reworking by a low-flow thalweg had not altered the bedform configuration. After sampling was completed, the reach was surveyed using a Leitz TM 20 theodolite and a rod measuring to the nearest hundredth of a foot (about 3 mm). The megaripples had long, low-angle stoss sides, steep lee sides (at the angle of repose), and crests about 12 cm above the adjacent troughs downstream (Fig. 4). No ripples occurred on the stoss...
sides of the megaripples, except in the thalweg, where the megaripples were beginning to be reworked and fine sand was being transported. The exact timing of deposition of the megaripples is not known, but probably the formation and preservation of the bedforms lagged behind flow conditions (cf. Allen, 1982). The slip faces probably were deposited just before flow waned to the point of no sediment transport, whereas the interior portions of the megaripples were deposited during active transport conditions. Although the timing and conditions for deposition of the megaripples remain partially undetermined, the fact that they were preserved during waning flow suggests that similar sedimentary structures in geologic contexts may be examined and interpreted in a similar manner.

Sample treatment

Samples were taken from the megaripples by sampling portions of bedforms progressively upstream so that the samples remained undisturbed and uncontaminated by sediments agitated during the sampling process. Thus, troughs downstream from each megaripple were sampled first, then the lower slip faces, upper slip faces, the armor at the crest of the megaripples, and, finally, the interior portion of each megaripple. Not all megaripples within the sequence were sampled, primarily because they were all very similar in overall characteristics. We were not convinced that differences would be found between adjacent megaripples, and, therefore, we expected only slight differences between the upstream and downstream ends of the sequence. Where the megaripples were dominated by gravel, about 1 kg samples were taken in an area of 200–400 cm². The uppermost few cm were scooped by hand into a large plastic bag. The interiors of megaripples were sampled by clearing away all surface clasts from a broader area and then scooping the sample from the megaripple by hand. The dominantly sandy slip faces were sampled using film canisters that hold about 40 g of sand when full; one to two canisters were added or subtracted from the total in other parts of the distribution. In the plots that follow, some sieves caught consistently less mass than the sieves adjacent to them because of deviations in aperture size. For example, the 0.5-mm sieve nearly always had less sand in it than the 0.43-mm sieve, indicating that some apertures of the 0.5-mm sieve are too large and let too many grains through to the 0.43-mm sieve. These inconsistencies have not been corrected in the plots, but are clearly apparent as a V-shaped depression in the grain-size curves at 0.5 mm. Some curves are discontinuous at the coarse end because no clasts were caught on some sieves.

Results

The grain-size distributions from the megaripples depend on where samples were taken within each megaripple and associated trough downstream, and on the location of the megaripple and trough set within the sequence. The differences in grain size are reflected in the overall distributions at a given location within each megaripple, in trends downstream along each megaripple/trough sequence, and in proportions of gravel fractions and various sand fractions within individual megaripples and along the entire sequence. The grain-size data are organized in Figs. 5–9 for each location along megaripples/troughs, and the data are "stacked" from upstream to downstream to illustrate any longitudinal shifts. More subtle trends are revealed by comparing adjacent parts of megaripples/troughs for different populations/fine slopes and by examining relative percentages of different parts of the populations. These differences and trends are summarized below.

Distributions from analogous portions of megaripples

As shown in Fig. 5, troughs show a broad, skewed peak between 0.25 and 8–10 mm, a decrease in grains larger than about 10 mm, a paucity of grains between 0.075 and 0.180 mm, and a second peak at 0.063 mm. Grains between 0.85 and 8 mm increase in mass percent downstream, whereas grains between 0.355 and 0.85 mm decrease in mass percent downstream.

Grains armoring the crest of megaripples have distributions somewhat similar to troughs, because they have a general broad peak from 0.25 to 8 mm and a small peak at about 0.063 mm (Fig. 6). The broad peak greater than 0.25 mm tends to be flatter (more of a plateau) than the broad peak of the troughs, and it tends to show slightly lesser amounts of the coarser clasts (curve has a negative slope at coarser sizes). Grains between 1.4 and 4.76 mm decrease in mass percent downstream, whereas grains between 0.25 and 1.4 mm increase in mass percent downstream, with the last megaripple having a definite peak between 0.5 and 1.18 mm (this peak may be due in part to sampling the underlying megaripple interior). No trend is apparent in the amount of fine sand forming the peak at about 0.063 mm.

Samples from the interiors of megaripples show a similar broad peak from 0.25 to 6.3 mm and a precipitous decline in the amount

TABLE 1—Sieve aperture sizes in mm used in sediment analyses.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Aperture Size</th>
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<tr>
<td>0.045</td>
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<tr>
<td>0.075</td>
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<td>8.000</td>
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</table>

FIGURE 4—Longitudinal profiles of megaripples and water surface.
Progressive downstream changes in distributions from adjacent portions of megaripples

Downstream progressions along individual megaripples also reveal trends in the following sequence: 1) trough to 2) megaripple crest to 3) interior to 4) upper slip face to 5) lower slip face to 6) trough. As Figs. 5–9 show, distributions become better sorted and unimodal in progressions from troughs to lower slip faces. The coarse modes (>8 mm) of troughs decrease in crests and interiors and of sand less than 0.25 mm (Fig. 7). In comparison with samples of crest armor, interiors have fewer clasts larger than 6.3 mm. There appears to be a decrease in fine sand fraction downstream, but secondary peaks at 0.107 or 0.063 mm or both occur in all interior samples.

Upper slip faces have a narrower range of grain sizes, commonly exhibiting a peak between 0.25 and 1 mm (Fig. 8). From the upstream megaripple (J) to the next to the last megaripple (B) in the sequence, the distribution shifts to a finer peak (from 0.605–0.85 to 0.303–0.43 mm), but the last megaripple (A) is similar to the first. Moreover, samples from different parts of the upstream megaripple (active and inactive) are quite different in proportions of coarse and fine grains (Fig. 8: Ja, active, and Jb, inactive).

Lower slip faces are much better sorted than either the troughs or the rest of the megaripple locations. They have a single, relatively narrow peak, slightly skewed toward the fine side (Fig. 9). The peak of the distribution shifts downstream from 1.18–1.4 to 0.71–0.85 mm. The amount of grains between 0.063 and 0.71 mm increases downstream, affecting the slope of the fine side of the distribution, but no separate peak of fine sand occurs. Grains between 1.4 and 2.83 mm decrease downstream, but the last lower slip face (A) has an increase in granules between 3.35 and 4 mm.


discussion

Rather than merely comparing grain-size distributions of adjacent samples, discussion of the above results focuses on the sorting mechanisms responsible for producing the distributions and on interpreting the distributions based on the proposed sorting mechanisms.

Sorting mechanisms

Numerous factors determine the grain size and sedimentary structures within each reach of a stream. In general, dominant grain size along stream beds and character of flow (such as velocity, depth, stream power, and shear stress) determine bedforms. For example, stream beds with a preponderance of grains larger than 0.6–0.7 mm do not develop rip-
TABLE 2—Examples of longitudinal ranges in weight percent of selected large clast sizes from portions
of megaripples along the conveyance channel of the Rio Grande; *armor and interior sampled together in megaripple A; b, only Jb, inactive upper slip face, represented here.

<table>
<thead>
<tr>
<th>megaripple</th>
<th>percent &gt; 2 mm in troughs</th>
<th>percent &gt; 0.6 mm in lower slip</th>
<th>percent &gt; 0.6 mm in upper slip</th>
<th>armor</th>
<th>interior</th>
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<tr>
<td>J</td>
<td>75.3</td>
<td>99.8</td>
<td>83.7</td>
<td>83.7</td>
<td>71.4</td>
</tr>
<tr>
<td>C</td>
<td>75.1</td>
<td>97.7</td>
<td>75.4</td>
<td>65.6</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>73.6</td>
<td>91.8</td>
<td>76.5</td>
<td>77.2</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>72.2</td>
<td>81.9</td>
<td>52.3</td>
<td>83.0</td>
<td></td>
</tr>
</tbody>
</table>

Interpretations of distributions based on sorting mechanisms

These mechanisms of grain movement in megaripples suggest that the interiors of the bedforms should be made up of upper and lower slip faces, and that pavement on crests and stoss sides of megaripples should be derived in part from reworking megaripple interiors along with addition of grains that passed over previous bedforms. These implied relations appear to be substantiated by the grain-size distributions illustrated in Figs. 5–9.

The interiors of megaripples appear to be made up of sediments from the slip faces, although some clasts coarser than those of the slip faces also occur. These coarse clasts in the interior of the megaripples may be due to flow conditions at an earlier time of deposition; the sampled slip faces formed later during waning flow. Megaripple interiors C and J are similar to upper slip faces, whereas A and B appear to contain components of both upper and lower slip faces. In part, this may be a problem of sampling at equal depths or at equivalent positions in adjacent megaripples.

The excellent degree of sorting of the lower slip faces is unexpected considering the proposed mechanism of intermittent avalanching of grains down the slip face. In bedforms studied in other streams, the lower slip faces are the least well sorted locations. If avalanching was the chief sorting mechanism, coarser grains should be expected at the base of the slip face. Instead, the shape of the grain-size distributions suggests sorting during unidirectional flow similar to that of sand in ripples and plane beds. Therefore, the sand of the lower slip face may be re-sorted and accumulated by reverse flow in the wake of the megaripples. Under this mechanism, avalanching coarse grains either may be trapped occasionally at the base of the slip face or may roll to the trough and continue downstream. The medium to coarse sand, on the other hand, may accumulate at the base of the slope where the reverse currents begin to rise. Riper sand would continue in suspension or perhaps would be deposited on the upper slip face.

Armored could have been derived either by 1) reworking megaripple interiors, removing large amounts of finer clasts, and accumulating coarser clasts as lag, or by 2) additions of coarser clasts in a mobile bed that moved over the troughs and up stoss sides of the megaripples. The nearly flat "plateaus" between 0.25 and 8 mm of the grain-size distributions of the armor (Fig. 6) could indicate either that clasts in that size range were equally mobile because of equal shear stress to move all sizes (cf. Andrews, 1983) or that the clasts were differentially exposed to shear stress depending on size and placement of surrounding grains (Parker and Klingeman, 1982). The plateau of nearly equal amounts of grains is much wider (8 mm is 32 times as big as 0.25 mm) than predicted by Andrews (roughly 14 times from 0.3x to 4x0.5). This discrepancy may indicate that the larger grains are moving under a nearly constant low value of critical dimensionless shear stress. Lower shear stress in troughs would force accumulation of otherwise mobile large grains, accounting for the slight "hump" in the mass of coarse grains (Fig. 5).

If megaripples and troughs migrate, stoss sides of megaripples must be progressively eroded away as the form shifts downstream. The differences between crest armor and trough armor may be explained either by progressive accumulation (lag) of coarse grains or by additions of coarse grains in transit from upstream. Based on the results of Andrews (1983) and Parker and Klingeman (1982), armor is not due to lag. Therefore, the coarse grains must come from upstream, probably from erosion and overpassing of stoss sides of megaripples. The relative abundance of coarse grains in troughs compared to crests may be due to the relatively weak overall currents in the zone of reattachment (Fig. 1). Large grains may not be moved out of this area as readily as smaller grains.

The abrupt decrease in mass percent of grains less than 0.25 mm in the armor of crests and troughs suggests an efficient sorting process such as suspension of finer grains, but secondary peaks commonly occur at 0.60–0.107 and 0.063 mm in the armor of the troughs and crests. This sorting of secondary modes takes place despite the fact that no ripples form along beds with average grain size larger than about 0.6 mm. Bridge (1981) explored the production of grain-size distributions with abrupt decreases in the amount of fine grains due to suspension. Most of his theoretical distributions show an abrupt decrease in amounts of grains finer than a given size determined by the strength of bed shear stress. For example, Bridge's calculated grain-size distribution for a mean shear stress of 0.4 dynes/cm² yields a curve that abruptly declines in mass of grains less than 0.21 mm in diameter.

Bridge (1981) proposed two alternatives to explain the presence of fine grains in gravelly deposits. He suggested that some fines may be present due to entrainment and infiltration between larger grains, particularly as flow wanes, and that fines may be present due to mechanical crushing of some clasts between larger clasts. Mechanical crushing to produce fines in the range of the grains seen in the megaripples appears to be extremely unlikely. Some trapping of fines may occur because the bedforms are loosely packed. However, if one assumes that the 0.25 mm grains (the smallest grains in great abundance) control the size of interstices between
grains, the largest space between grains would be about 0.100 mm with cubic packing and 0.039 mm for close rhombohedral packing (derived from formulae in Pettijohn, 1957). Under rhombohedral packing, void fillers could be between 0.104 and 0.056 mm in size, but the void-filling grains could not filter between grains. In any case, smaller grains should be favored over larger grains in an entrapment process, and such definite peaks at about 0.083 mm should not be expected. Therefore, some sorting process of fine sand along the bed must be taking place. The mechanism appears to take place during mobile conditions rather than after movement of all coarse grains has ceased because some subpavement samples exhibit secondary peaks. Fine grains may be sorted into secondary peaks by reverse flow up the slip face, but this mechanism would not explain secondary peaks in armor. The small modes of fine sand in armor suggest that secondary currents sort fine sand moving between larger grains, but the nature of the sorting processes producing secondary peaks of sand remains to be examined further.

The downstream trends in grain-size distributions from analogous portions of megaripples along such a relatively short reach are difficult to explain, but may be considered in terms of 1) changes in flow conditions, 2) pulses of sediment, and 3) relative mobility of grains. The actual explanation may be a combination of these factors. Deposition (and erosion) at each point along each megaripple/trough must be controlled by local flow conditions and availability of grains. The sampled reach is only a small portion of the conveyance channel containing megaripples. No obvious changes in channel geometry or size of bedforms occur along the reach, so changes in average flow conditions along the reach appear to be unlikely causes of changes in sediment sorting. However, the reach is in a gently curving portion of the channel (Fig. 2) and flow could change along the curve. Possibly the waning stages of deposition changed progressively downstream so that deposition, particularly along slip faces, continued downstream after it had ceased upstream.

The uniformity or periodicity of sediment transport cannot be assessed without measurements of flow and sediment discharge during formation of the megaripples. Different pulses of grains may have reached different portions of the reach at different times during deposition, providing more coarse grains to upstream megaripples than to downstream megaripples, or providing more grains in the range of 0.85–8 mm to downstream troughs after passing upstream bedforms.

The trough farthest downstream contains all but the coarsest clasts, so most sizes of grains have been transported through the reach. The largest grains must be less mobile than smaller grains so that movement of large grains from trough to trough is slowed. Therefore, upstream troughs should have more large clasts than downstream troughs, until large clasts have migrated throughout the reach to achieve equal rates of movement from bedform to bedform. The possibility of larger-scale periodicity in deposition along the conveyance channel cannot be evaluated.

Conclusions

In gravely megaripples along the conveyance channel of the Rio Grande, grain-size distributions and some of their derivative parameters can be used to locate samples within a longitudinal sequence of bedforms. Each part of a megaripple (crest, interior, upper slip face, lower slip face, or trough) has a diagnostic grain-size distribution. Distributions from each portion of megaripples change slightly downstream so that locating a sample within a train of megaripples is possible. Along a reach of only 10 megaripples, the crests, lower slip faces, and troughs of upstream megaripples are coarser than their downstream counterparts. Similarly, the crossover points between grain-size curves of crests and troughs shift to finer sizes downstream. Although the mass percent of all clasts larger than 0.6 mm in troughs shows no significant trends downstream, the mass percent of clasts larger than 2 mm decreases downstream. In lower slip faces, the mass of clasts larger than 0.6 mm decreases downstream.

Sorting mechanisms that produce different grain-size distributions along megaripples apparently are related to mobile-bed formation of armor along troughs, stoss sides, and crests and to flow separation, avalanching, and reverse flow along slip faces. Suspension of fines less than 0.25 mm appears to take place from troughs to crests of megaripples. Fine sand is also sorted into secondary modes that may indicate the presence of secondary currents between larger gravel clasts. The changes in distributions downstream over a distance of only 30 m may include changes in flow conditions, pulses of sediment, and/or relative mobility of the largest grains.

The grain-size distributions illustrated above show the importance of knowing the location of samples with respect to bedforms. Only the grain-size distributions of the lower slip faces appear to have relatively simple probability distributions. The variation in grain-size distributions along bedforms demonstrates that many fundamentally different distributions occur in fluvial deposits.

The technique of relating grain-size distributions to location within bedforms suggests several potential directions for further study. Where grain-size data are gathered from different bedforms formed under known flow conditions, it may be possible to relate the distributions to flow conditions more quantitatively. Alternatively, more data may demonstrate that several sets of flow conditions can produce similar distributions or that one set of flow conditions can produce dissimilar distributions. If quantification of flow conditions is possible using grain-size distributions from similar bedforms, it also may be possible to determine what entire bedforms were like from the portions that are preserved in geologic sections as well as their relative longitudinal position within a progression of bedforms.

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References


Richard H. Jahns fellowship in field geology at Stanford

Richard H. Jahns was Professor of Geology and Dean (1965–79) and Professor of Geology and Applied Earth Sciences (from 1979 until his death in December 1983) at Stanford University. Gifts received in his name will be placed in the Richard H. Jahns Fellowship in Field Geology fund and will always be so designated. The fund income, but no part of the principal, may be used in perpetuity to support graduate fellowshipships to support graduate science research that involves substantial observation and mapping of geologic relationships in the field. Fellowships from the fund will only be awarded to students who have completed their basic graduate coursework and who have proposed projects that support earth-science research. Fellowships will be restricted further to students who bear substantial, independent responsibility for the conception and conduct of their research and priority will be given to doctoral candidates. Fellowships from the fund will be awarded by the Dean of the Earth Sciences School in amounts reasonably necessary for completion of the supported research.