INFLUENCE OF SUSPENDED KAOLINITE ON THE CHANNEL FORM OF A POLLUTED STREAM IN CORNWALL

Key Words—China clay, Kaolinite, Pollution, Sorting, Stream channel.

Alluvial river channels construct their own cross sections by transport and deposition of the unconsolidated sediment in which they are formed. Channel sizes and shapes reflect the quantities of water and sediment and the types of sediment imposed by their catchment hydrology. The influence of the sediment load introduced to a channel reach is illustrated by an inverse correlation between the channel width:depth ratio (F) and a weighted index (M) of the percentage of silt and clay in the perimeter sediment (Schumm, 1960). The nature of the perimeter sediment depends on the dominant mode of sediment transport; a stream whose load is carried in suspension has a high percentage of silt and clay in its channel perimeter and a narrow, deep channel, whereas a bedload stream has a sandy perimeter and a wide, shallow cross section (Schumm, 1971). This relationship provides a first approximation to the complex link between sediment properties and channel form, but requires further investigation before it is possible to explain the chain of causation from sediment load to bank-material properties and thence to equilibrium channel form. In particular, it is unclear how suspended sediment becomes incorporated in the perimeter sediment, and how that sediment controls bank stability and cross section shape. The silt and clay content provides an easily measured surrogate for bank-material shear strength, but content, mineralogy, and fabric of the clay are probably more influential.

The present investigation is concerned with these problems and exploits the evidence of abnormal sediment transport in some streams in Cornwall, England, which are polluted by kaolin waste from the china clay extraction industry. Observations of stream channels on the Cornish granite moors indicate a general reduction of width:depth ratio (F) with increasing supply of kaolinized sediment. The River Fowey on Bodmin Moor, with little china clay extraction in its upper catchment, averages F = 7.9. Streams on the highly kaolinized St. Austell granite, but without clay pits in their catchment, average F = 7.0. However, those which have carried heavy loads of kaolin and mica since the early nineteenth century because of china clay extraction within their basins have average width:depth ratios of 4.1. These comparisons are between streams of similar catchment area. The low width:depth ratios of the polluted streams reflect similar channel depths, but narrower cross sections because of a plaster of fine sediment on the banks. Variations in channel shape reflect differences in (1) the proportion of fine sediment in bank material, (2) the proportion of clay minerals in the fine fraction, and (3) the fabrics of the kaolinite minerals (and hence, the plasticity of the bank material; cf. Bain, 1971). Such differences in bank-material characteristics represent responses to conditions of sediment transport, and accordingly an examination was made of the suspended sediment load of a small stream whose head is in the center of the china clay area, and which carries a
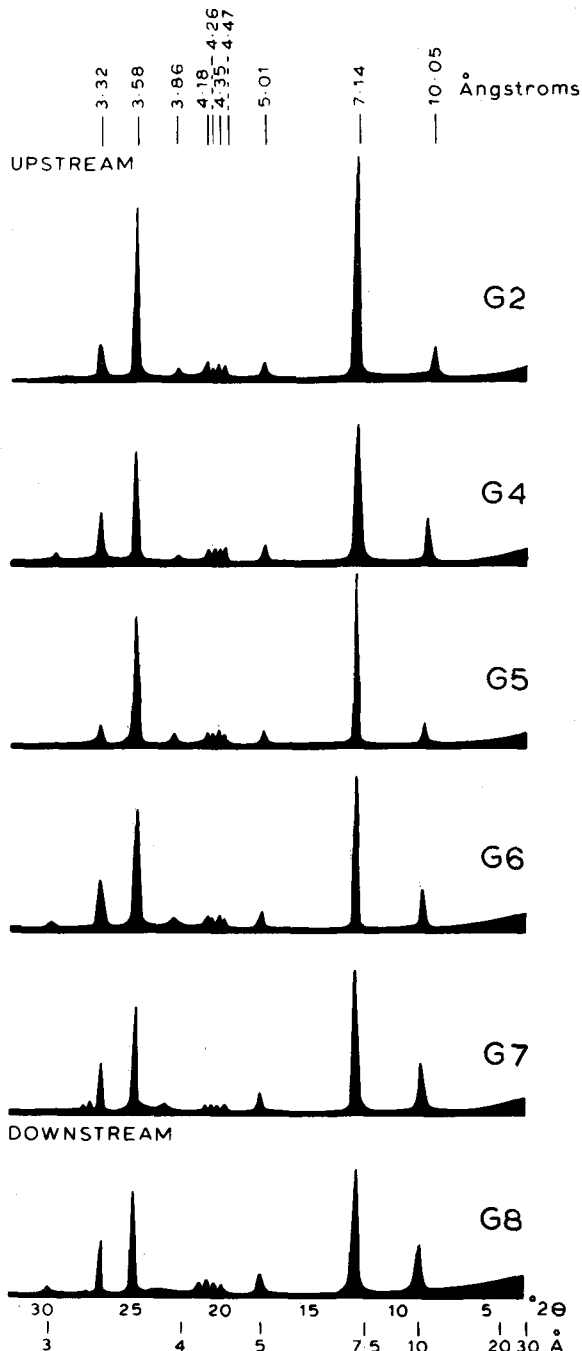
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Figure 1. Diffractograms of suspended sediment from sections of the River Gwindra, Cornwall, England. All were obtained using a Phillips PW 1050 diffractometer with divergent and receiving slits of 1° and 0.1 mm; Ni-filtered CuKα radiation at 20 mA and 40 kV, range of 2 × 10³ counts/sec, scanning rate of 1° 2θ/min, 1 sec time constant, and 10 mm/min chart speed.
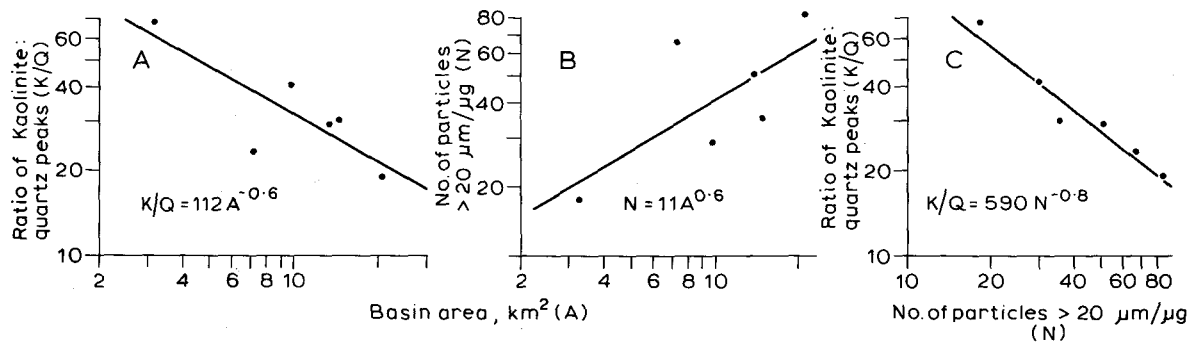
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Figure 2. Mineralogy and particle size relationships. A: downstream trend in kaolin:quartz peak-height ratio. B: downstream trend in amount of coarse particles. C: relation between peak-height ratio and particle count.

heavy load derived from runoff over old waste tips and drainage from tailings lagoons.

SUSPENDED SEDIMENT MINERALOGY

Samples of suspended sediment were collected using a depth- and width-integrated sampling procedure at six cross sections on the River Gwindra, which is a left bank tributary of the River Fal. Samples were taken with a US DH-48 suspended-sediment sampler. Concentrations decreased irregularly downstream from a maximum of 950 mg/liter at the upstream site to 46 mg/liter near the junction with the Fal, while discharges increased from 23 to 202 liter/sec at the time of sampling (a period of low summer discharges; concentrations are higher during storm runoff, but no longer reach the peaks of 28,000 mg/liter observed in the 1950s and 1960s prior to stringent pollution control). The erratic downstream variation of concentration reflects point inputs of sediment and of diluting, unpolluted tributaries; the general trend, however, is for declining relative and absolute rates of sediment transport downstream.

The mineralogy of the suspended sediment samples was determined by X-ray powder diffraction methods. No pretreatment of the samples was attempted because of the small quantities, and because the relative dominance of mineral species within the whole sample was of immediate concern. However, each sample was filtered through Millipore 0.22-μm filter paper. The diffractograms in Figure 1 are arranged from upstream to downstream sampling sections, and are simple to interpret. Sharp peaks at 7.14 and 3.58 Å indicate the dominance of kaolinite, as the milky coloration of the stream attests. Also present in the patterns are peaks of muscovite-illite (10.05, 5.01, and 3.32 Å), goethite(?) (4.18 Å), gibbsite (4.35 Å), and quartz (4.26 Å). The sequence of diffractograms suggests that, with the exception of the second site, there is a downstream trend in which the dominance of kaolinite decreases. However, although each slide (air dried) was prepared from 0.05 g of sediment, weight control was not sufficiently accurate for direct quantitative comparison between peak heights. Instead, ratios of peak height above background were used for comparison. The use of peak-height ratios in environmental discrimination was demonstrated by Sawhney and Frink (1978) in their study of estuarine clays. Quartz is a convenient internal standard; however, it proved impossible to use the 3.34-Å peak of quartz because overlap with the broad 3.32-Å peak of illite-muscovite prevented discrimination. However, the 4.26-Å peak of quartz has been used in quantitative petrology (Cosgrove and Sulaiman, 1973), as long as it was 5–10 counts/sec above background (Schultz, 1964). Since this requirement was satisfied here, the ratio of the 7.14-

Å kaolinite peak and the 4.26-Å quartz peak was used to characterize the mineralogy of the stream sediments.

Figure 2A is a plot of the kaolin:quartz peak-height ratio (K/Q) against the basin area (A, km^2) tributary to each sampling section. The decreasing dominance of kaolinite downstream is evident, with the second site downstream having a lower K/Q ratio than its location would suggest. Figure 2B illustrates downstream variation in the particle size of suspended sediment. The data were obtained by dispersing the suspended sediment ultrasonically, diluting it to a known concentration in particle-free salt solution, and counting particles greater than 20-μm nominal diameter by a Coulter Counter with a constant threshold setting. Results were expressed as the number of particles coarser than 20 μm per μg of sediment, and the figure illustrates a downstream coarsening of the suspended sediment. Again, the second site is anomalous, with more coarse particles than expected. Figure 2C combines the two trends by plotting the kaolinite:quartz peak-height ratio against the particle count (N) and confirms the expected result that where K/Q is high, the number of coarse particles is low. On this graph the anomaly of site G4 disappears, which itself indicates the consistency of the results. This site is just downstream from an extensive depot and construction site, and runoff from this introduces coarse, sandy sediment into the

Figure 3. Scanning electron micrograph of suspended sediment from section G7. This representative micrograph illustrates the relation between particle size and mineralogy, the dominant fabric of the kaolinite, and the poorly sorted nature of the suspended sediment.

stream. Thus, there is less kaolinite, relative to quartz, and more coarse particles in the suspended sediment of this section. Scanning electron micrographs, of which a representative example is shown in Figure 3, further support the association between coarse particle sizes and quartz and muscovite (e.g., the grain ~40 μm in length to the left of center), and fine particles and kaolinite. The kaolinite has a fine-grained fabric composed of platy and elongated crystals, and is probably of hydrothermal origin, in contrast to the highly porous, plastic, larger crystals in the form of 'books' or 'accordions' which result from weathering and sedimentary processes (Keller, 1976; Keller and Hanson, 1975).

The pattern emerging from this analysis is thus one in which the nature of the suspended sediment changes downstream. The relative decline in the amount of kaolinite and the downstream reduction in total sediment load point strongly to selective deposition of the finer kaolinite component of the suspended sediment by flocculation. This is supported by a white slime on the bed material (cobbles) of the stream, and by the laboratory and field investigations of Edzwald and O'Melia (1975) which indicate relative instability and early flocculation of kaolinite compared to illite and montmorillonite. Although no water quality data are available for the River Gwindra at the time of sampling, it is similar to other streams for which available data suggest increasing solute load downstream. The River Fowey, draining from the Bodmin Moor granite, also heads in moorland and flows off the granite through lower lying agricultural areas. Here concentrations of Ca^{2+} and Mg^{2+} triple downstream. A similar downstream increase in the concentration of bivalent cations in the River Gwindra might be expected, over a period of time, to encourage flocculation by cation bridging so that the kaolinite becomes progressively incorporated into the perimeter sediment of the channel. Thus, a mechanism exists whereby bank materials can differ in the importance and nature of the fine fraction which is considered to influence channel shape.

SUMMARY

The X-ray powder diffractograms of suspended sediment from the River Gwindra illustrate a simple mineralogy dominated by kaolinite and mica, and the scanning electron micrograph suggests a particle-size differentiation between these minerals. The sediment is sufficiently rich in kaolinite to belie the term 'micaceous waste' often applied to this pollution. Adjustments in the mineralogy and particle-size properties downstream strongly suggest that flocculation leads to addition of the kaolinite to channel perimeter sediment. Bank-material samples from polluted streams are seen to contain more silt and clay than unpolluted streams, and higher kaolin:quartz and kaolin:mica ratios in the 2-μm size fraction (Richards, 1979). Thus, the cohesion supplied to stream banks by the addition of clay deposited from suspension is a major contribution to the enhanced bank stability which enables the streams to maintain a relatively narrow cross section compared with unpolluted streams of comparable discharge.

The results of this analysis demonstrate the manner in which

sediment load can be incorporated in channel perimeter sediment, and subsequently influence channel form. The simple mineralogy and consistent fabric of the clay mineral involved makes it easy to identify the link, which would be less apparent if several clay minerals were mixed in the suspended load, or if the kaolinite included different fabrics which would influence plasticity and stability of bank material in different ways (Dumbleton and West, 1966). However, the potential of clay mineralogy in studies of the relationships between sediments and channel forms is clearly considerable.

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