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Suspended sediment characteristics and drainage basin scale on the Canadian prairies

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Abstract This study was conducted to establish a conceptual model of the change in suspended sediment characteristics with increasing drainage basin scale. Suspended sediment samples were collected along the Assiniboine-Whitesand River system in the prairie/parkland region of eastern Saskatchewan, Canada. SEM/EDS analysis shows that suspended sediment particles in the upstream portions of this basin primarily consist of planktonic diatoms with small numbers of composite particles comprised of mineral grains and diatoms cemented together with clay and organic matter. In the downstream portion, suspended sediment particles have a composite structure comprised of mineral grains cemented together with clay. The downstream decrease in the contribution of organic matter and diatoms to the sediment load is explained by the change in environmental factors controlling diatom growth and by the change in dominant sediment source with changing basin scale, from farmland and alluvial and colluvial sediments in the upstream portions, to reworked glacial, glaciofluvial and glaciolacustrine deposits on the main valley floor.

INTRODUCTION

The suspended sediment of a stream may come from a number of sources. Some particles are derived from the terrestrial portion of the basin through processes such as rill, interrill and bank erosion. Other particles, for example diatoms and some calcium carbonate concretions, form through complex (bio)geochemical processes occurring within the stream itself. Finally, particles may reach the stream through the atmosphere from outside the drainage basin. Once the particles are in the stream they are modified by physical, chemical and biological processes. As a result, suspended sediment consists of a variety of complex and frequently composite particles, derived from different sources and modified to varying degrees.

Because suspended sediment characteristics reflect the contributions of the sediment sources and the subsequent modification during transport and storage within the channel system, analysis of these characteristics may provide information on sediment transfer integrated at the drainage basin scale. In recent years, a number of investigators have used this approach to evaluate the contribution of the various sediment sources to the suspended load of a stream through a comparison of the characteristics of the suspended sediment with those of the potential sources. This so-called "fingerprinting" technique has been successfully applied using a variety of properties including saturation isothermal remanent magnetism or SIRM (e.g. Oldfield *et al.*, 1979), sediment colour (e.g. Grimshaw & Lewin, 1980), mineralogy (e.g. Klages & Hsieh, 1975), radio isotopes (e.g. Lewin & Wolfenden, 1978), and geochemistry (e.g. Peart & Walling, 1986).

The majority of studies of suspended sediment characteristics are based on the analysis of bulk sediment samples of several hundreds of milligrams or more. Additional information may be derived from examining individual sediment particles in enough detail so as to be able to determine their structure which reflects, and may provide insight into, its origin and the processes involved in its formation and modification. This latter approach can, for instance, indicate whether silica is present as mineral grains, as coatings, or as diatoms. Scanning electron microscopy (SEM) has proved to be very useful in examining small objects such as water-stable aggregates and suspended sediment particles. In addition, the advent of the X-ray energy dispersive spectrometer (EDS) has permitted the researcher to investigate the chemical composition of sediment particles as small as 1 μm. The combined SEM/EDS approach has been used successfully to characterize suspended sediment from lakes (e.g. Yin & Johnson, 1984), streams (e.g. Hart *et al.*, 1993), and estuarine and marine environments (e.g. Bernard *et al.*, 1986).

The specific objective of this study is to evaluate the use of SEM/EDS analysis to determine the nature of individual suspended sediment particles in the Assiniboine-Whitesand River system at different drainage basin scales. This information will aid in deriving a conceptual model that explains and predicts the spatial and temporal variation in suspended sediment characteristics.

FIELD AREA AND METHODOLOGY

The Whitesand-Assiniboine River system is located in the prairie/parkland region of southeast Saskatchewan. The two rivers converge at Kamsack and flow eastward as the Assiniboine River into Lake of the Prairies which straddles the Saskatchewan-Manitoba border (Fig. 1). At Kamsack the gross drainage area of the Assiniboine -Whitesand river system is 12 950 km^2. Because of the irregular and hummocky topography with large numbers of small, closed depressions the effective drainage area is only 4324 km^2 (Ashmore, 1990). The climate of the region is classified as humid continental, or Dfb, in the Köppen climate system. The average annual temperature and precipitation at Kamsack are 0.9°C and 386 mm, respectively (Atmospheric Environment Service, 1982). Agriculture is the main type of land use in the basin. The soils of the area are black, degraded black and grey soils which have developed in the very thick layers of glacial, glaciofluvial and glaciolacustrine deposits (Mitchell *et al.*, 1944). In the downstream portion of the basin both the Whitesand River and the Assiniboine River occupy a former glacial spillway and are deeply incised, locally up to 80 m, below the otherwise low relief landscape. The steep valley slopes show abundant evidence of large scale mass movements and gully erosion, resulting in the transfer of surface deposits from the valley walls to the main valley floor.

Fourteen sample sites were selected in such a way that the basin would be sampled at all scales and so that many sites would be close to existing streamgaging stations that could provide stream discharge data (Fig. 1). Samples for this study were taken during the first week of September 1994, in 1000-ml LDPE bottles. Separate samples for

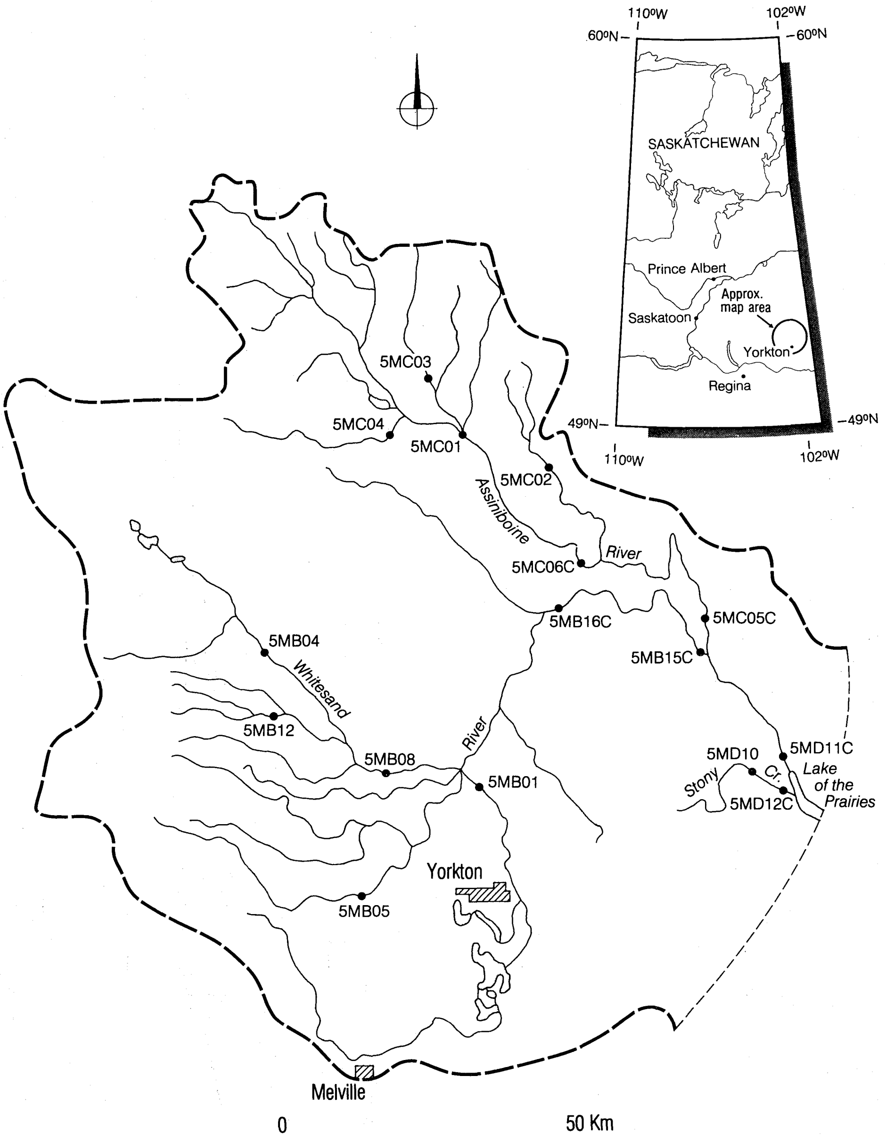

Fig. 1 Map showing the location of sampling sites in the Assiniboine-Whitesand River system, Saskatchewan, Canada.

suspended sediment concentration were collected with a DH-59 sampler.

Specimen for SEM/EDS analysis were prepared on 0.4-μm Nuclepore polycarbonate filters following the methods outlined by De Boer & Crosby (in review) within four days of collection during which period the samples were kept in the dark at 4 °C to minimize modification. Specimen were carbon and gold coated using standard methods. Instrument particulars and settings are given in De Boer & Crosby (in review).

During analysis it was found that the majority of particles had a composite structure, with pronounced variability of the EDS signature from place to place. The composite nature of the particles precluded the use of automated methods such as employed by Bernard *et al.* (1986) which obtain an EDS signature at the particle centroid. Instead, analysis consisted of taking EDS readings from enough points, from 6 to 15, on a particle that the complexity of the particle could be adequately described. Particle morphology and the EDS readings taken from each point on a particle were interpreted by the operator and recorded on an electron micrograph. The raw EDS data for the elements Si, Al, Ca, Mg, Fe, Na, K, Ti, S, P and Mn were stored for future use. Most organic material is not identifiable with this technique because it does not give a discrete EDS signature and does not maintain its original shape once dried. This analysis was performed on randomly selected, representative particles on each filter.

RESULTS AND DISCUSSION

Figures 2 through 5 show representative suspended sediment particles from two upstream sites (5MB04 and 5MB01) and two downstream sites (5MC05C and 5MD11C). Figure 2 shows a particle from site 5MB04 (Whitesand River near Sheho). This largely organic particle was one of the few such particles on the filter because the suspended sediment was dominated by numerous *Stephanodiscus* diatoms. The particle in Fig. 2 has a composite structure, consisting of an aggregate of illite and mixed layer clays combined with a large amount of unidentified organic material and calcium carbonate.

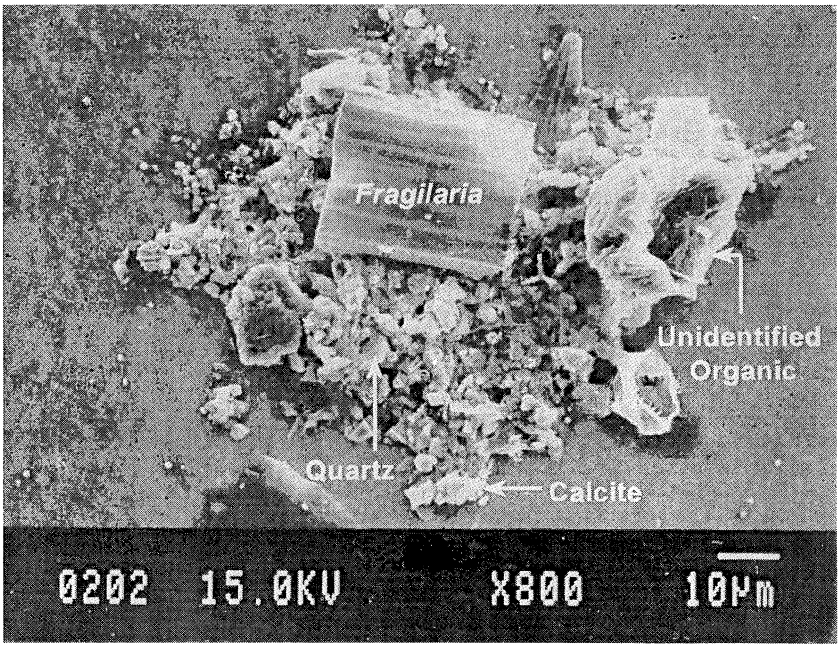

Fig. 2 A composite particle from site 5MB04 that is largely a mixture of illite and mixed layer clays with a large amount unidentified organic material and calcium carbonate.

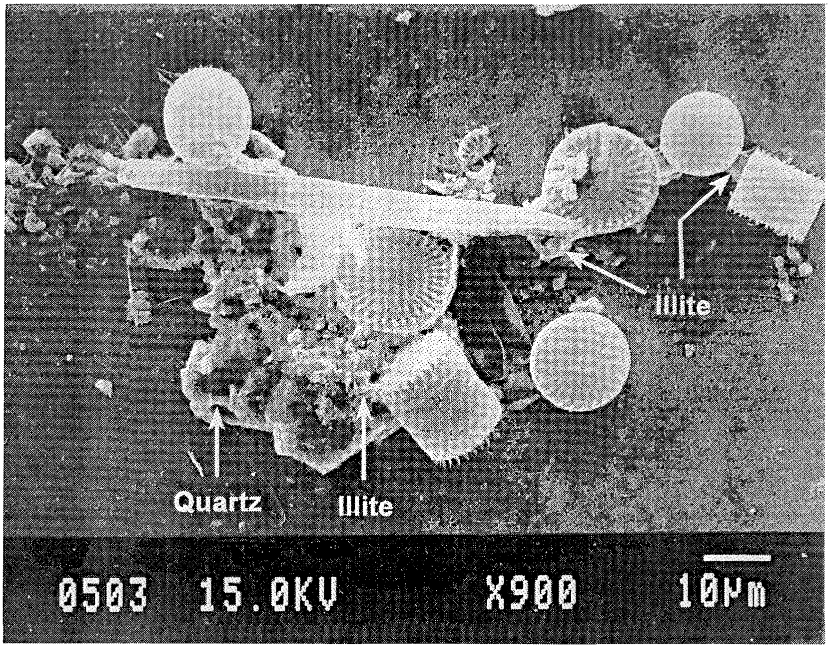

Fig. 3 A composite particle from site 5MB01 consisting of *Stephanodiscus* diatoms and a large quartz grain bound together by illite and calcium carbonate.

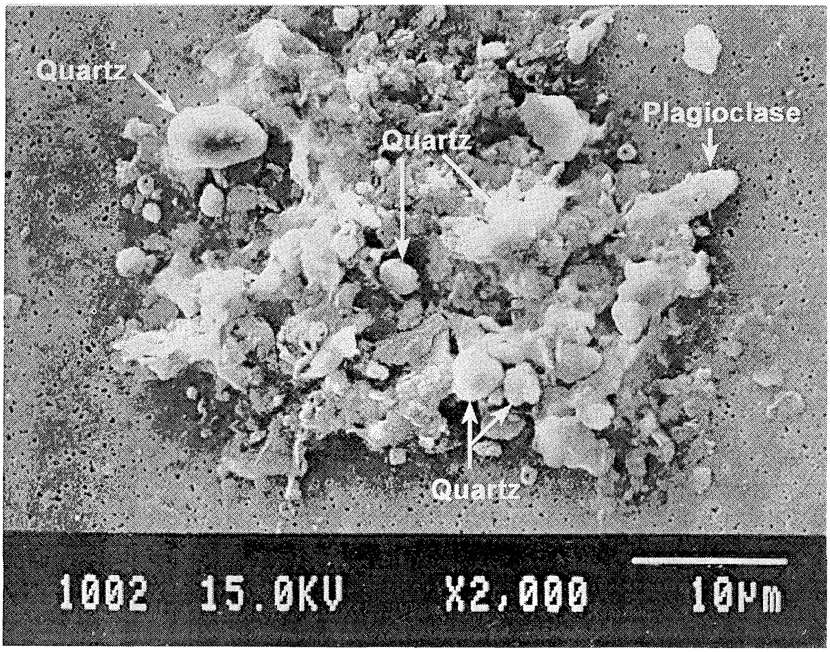

Fig. 4 A composite particle from site 5MC05C comprised of an clay aggregate (illite) with a few mineral grains.

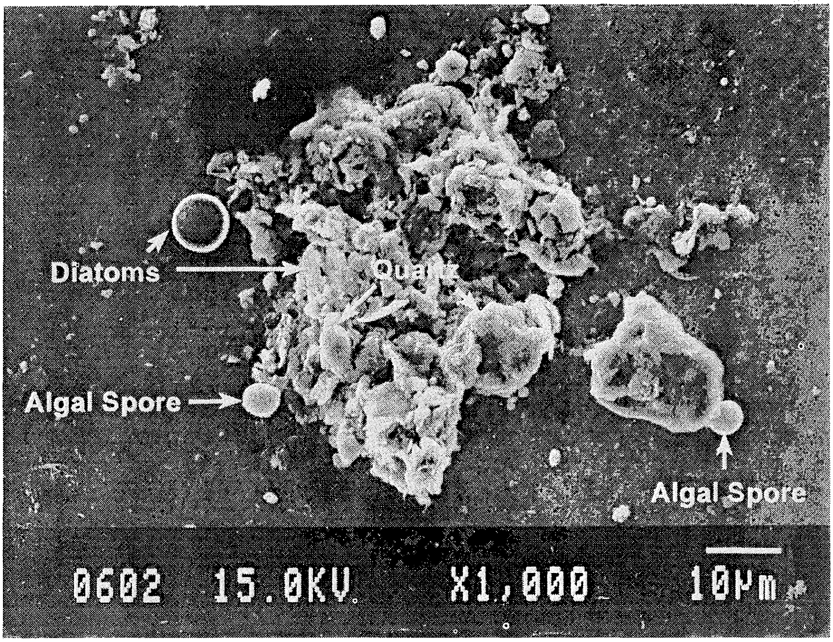

Fig. 5 A composite particle from site 5MD11C consisting of quartz grains, diatom fragments, and algal resting spores cemented with illite.

The calcium carbonate is possibly secreted by aquatic organisms as it is not found to a large degree in the soils of the drainage basin.

The particle shown in Fig. 3 is from site 5MB01 (Yorkton Creek near Ebenezer), located on an upstream tributary of the Whitesand River. This particle illustrates the abundance of diatoms in the upstream areas. The diatoms, mostly *Stephanodiscus*, and a large quartz grain are bound together with illite clay, calcium carbonate and organic material. The calcium carbonate is possibly the result of organic secretion.

The particle shown in Fig. 4 is from site 5MC05C (Assiniboine River upstream of the confluence with the Whitesand River). This entirely mineral particle is an illite clay aggregate with a number of small grains of quartz and plagioclase.

Another downstream example in Fig. 5 is a particle from site 5MD11C (Assiniboine River upstream of Lake of the Prairies). This particle is a clay (illite) aggregate with some quartz grains. The only indication of organic material are two broken diatom frustules and two organic structures which are probably algal resting spores.

In general, suspended sediment particles at upstream sites consisted of diatoms and of composite particles comprised of diatoms and mineral grains cemented with organic matter and clay (illite). At some sites, e.g. site 5MB04, diatoms made up the majority of suspended sediment particles. At downstream sites the suspended sediment consists of composite particles comprised of mineral grains cemented with clay. The observed spatial pattern in suspended sediment character likely results from a change in environmental conditions affecting diatom growth and from a change in the dominant sediment source with changing scale. The two main environmental factors controlling planktonic diatom growth are, first, the availability of silicon in solution, primarily orthosilicic acid

$Si(OH)_4$, which is needed for making the frustules; and second, the presence of turbulence to prevent the diatoms from sinking (Round *et al.*, 1990). Furthermore, diatom growth is controlled by light, turbidity, and water chemistry and temperature. At present, little is know about the systematic change of these factors with drainage basin scale. Regarding the sediment sources, in the headwater tributaries the sediment sources are the farmland topsoil, and the alluvial and colluvial sediments exposed in stream banks. These materials are organic-rich and, additionally, may have their organic components preferentially eroded. As a result, the suspended sediment consists primarily of diatoms and of composite particles comprised of mineral grains and diatoms bound together with clay and organic matter. In downstream locations the dominant sediment sources are the reworked glacial, glaciofluvial and glaciolacustrine deposits which are stored in the deeply incised main valley, and which are transferred by large scale mass movements and gully erosion from the valley slopes to the valley floor. Bank erosion of the sediment stored on the valley floor leads to a sharp increase in suspended sediment concentrations in the downstream portions of the basin, were sediment concentrations are typically 10 to 40 times higher than those in the upstream portion. As a result, the organic-rich sediment derived from the upstream reaches of the basin is effectively diluted with mineral sediment. Future studies will include fluorescence microscopy and X-ray diffraction in order to more fully investigate the organic and inorganic components of the suspended sediment.

CONCLUSIONS

It has been demonstrated that there is a distinct spatial pattern of suspended sediment characteristics in the Whitesand and Assiniboine River systems. Specifically, in the upstream parts of the drainage basin suspended sediment consists of planktonic diatoms (mainly *Stephanodiscus*) and composite particles comprised of mineral grains, diatoms, organic matter, clay (mainly illite) and calcium carbonate. The contribution of diatoms and organic matter decreases sharply with increasing basin scale, and at downstream locations the suspended sediment consists of composite particles comprised of mineral grains, clay (mainly illite), and small numbers of diatoms fragments with little if any organic matter.

The downstream change in suspended sediment characteristics is likely the result of a change in the dominant sediment source with changing basin scale. In the upstream portions the non-diatom component of the suspended sediment is derived mostly from organic-rich farmland soils and alluvial and colluvial sediments. In downstream locations the dominant sediment sources are the unconsolidated, reworked glacial, glaciofluvial and glaciolacustrine deposits which are transferred by large scale mass movements and gully erosion from the steep valley slopes to the main valley floor. Bank erosion of these deposits stored on the valley floor leads to a sharp increase in suspended sediment concentrations in downstream direction. As a result, the organic-rich sediment component derived from the upstream reaches of the basin is effectively diluted with mineral sediment.

The change of suspended sediment characteristics and concentration with spatial scale provides an example of a morphological constraint (De Boer, 1992a). Such a constraint prevents extrapolating information from small basins to larger scales because large scale basins contain landscape features which are absent in small scale basins. In this particular example, the landscape feature imposing the morphological constraint is the main valley floor which receives and temporarily stores the unconsolidated deposits transferred from the steep valley walls by mass movements and gully erosion. Thus, even though drainage basins consist of a nested hierarchy of smaller systems and it would be expected that processes operating in the smallest units (i.e. basins) would affect the output of the larger ones, in reality the linkage between the different scales is weak because the operation at different levels within the hierarchy is controlled by different factors (De Boer, 1992b).

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