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Article abstract

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In the last 15 years, electromagnetic current meters and optical back-scatter sensors continue to be the popular choices for velocity and suspension measurements. But various acoustic sensors provide non-intrusive, high-resolution measurements and are thus more promising. The instrumented platform RALPH developed at the Geological Survey of Canada has been continually upgraded and improved to stay at the cutting edge of shelf sediment transport technology. Sediment transport models have been significantly upgraded and calibrated based on advances incombined-flow bottom boundary layer theory and new in situ sediment transport measurements.

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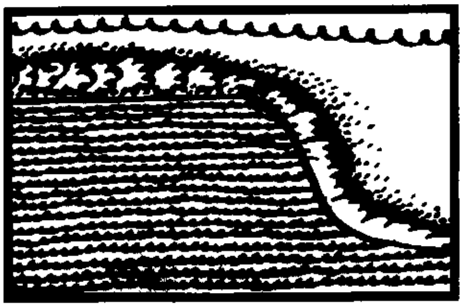

Environmental Marine Geoscience 3. Continental Shelf Sediment Transport Studies in Canada: Theories and Recent Technology Advances

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SUMMARY

This article, the first of two companion papers, provides a review of recent progresses in shelf sediment transport theories and technological advances. Surficial geology and bedform mappings in the 1970s first demonstrated the existence of various bedforms over much of the Canadian shelves, and were used to deduce sediment transport processes and pathways on these shelves. Development of *in situ* instruments and sparse field measurements started in the early 1980s; meanwhile, primitive sediment transport models were also developed.

In the last 15 years, electromagnetic current meters and optical backscatter sensors continue to be the popular choices for velocity and suspension measurements. But various acoustic sensors provide non-intrusive, high-resolution measurements and are thus more promising. The instrumented platform RALPH developed at the Geological Survey of Canada has been continually upgraded and improved to stay at the cutting edge of shelf sediment transport technology. Sediment transport models have been significantly upgraded and calibrated based on advances in combined-flow bottom boundary layer theory and new *in situ* sediment transport measurements.

RÉSUMÉ

Ce premier article de trois présente une description des progrès récents sur les théories du transport des sédiments côtiers et sur les avancées technologiques en la matière. Au cours des années 1970, les travaux de géologie des dépôts meubles et de cartographie des fonds marins ont permis la définir une variété de formes des fonds marins sur une grande partie des plates-formes canadiennes, ce qui a permis de déduire les mécanismes de transport sédimentaires à l'œuvre ainsi que les voies empruntées sur ces plates-formes. Au début des années 1980, des instruments in situ ont été mis au point et quelques mesures de terrain ont été prises alors que les premiers modèles de transport des sédiments étaient élaborés.

Durant les 15 dernières années, les courantomètres électromagnétiques et les capteurs à rétrodiffusion optique ont continué d'être les instruments privilégiés pour la mesure des paramètres de vitesse et de suspension. Cependant, divers détecteurs acoustiques qui permettent des mesures non-intrusives et de haute résolution ont un avenir plus prometteur. La plate-forme d'instruments RALPH, qui a été mise au point à la Commission géologique du Canada, a continuellement été modernisée et maintenue à la fine pointe de la technologie du transport des sédiments côtiers. Les modèles de transport des sédiments côtiers ont été considérablement raffinés grâce aux avancées de la théorie des écoulements mixtes des couches limites ainsi que des mesures in situ du transport des sédiments.

INTRODUCTION

Sediment transport on continental shelves involves complex processes of sediment erosion, transport, and deposition that occur primarily in the bottom boundary layer, *i.e.*, the interface between the seabed and the water column. These processes can greatly affect seabed stability, the dispersal and deposition of particulate material, the evolution of bedforms, the development of stratification, and the distribution and activities of benthic organisms. Thus the study of shelf sediment dynamics and transport processes has become increasingly important to oceanographers and coastal engineers as well as environmental managers (Grant and Madsen, 1986; Wright, 1989; Cacchione and Drake, 1990; Nittrouer and Wright, 1994).

Sediment transport prediction requires us to understand both the hydrodynamics of the boundary layer and the sediment dynamics in response to the driving flows (Fig. 1). Once sediment starts to move, the mobile grains and various bedforms generated by sediment movement will, in turn, affect the capability of the flow to move sediment. Consequently, sediment transport is a nonlinear problem in two-phase flow (water and grains) that contains significant feedback between the moving sediment and the flow (Dyer and Soulsby, 1988). On continental shelves, the tidal variation in the currents, and the non-linear interaction between currents and waves further complicate the sediment transport process. Activities of benthic organisms can also alter seabed topography and sediment characteristics. Because of this extremely complex nature of shelf sediment transport, we are still not capable of predicting sediment transport rates on shelves with any reasonable confidence.

Since the pioneering works in the 1960s and early 1970s (*e.g.,* Sternberg and Creager, 1965; Jonsson, 1966; Bijker, 1967; Sternberg, 1972; Smith and Hopkins, 1972), however, extensive field programs and model developments have occurred. Internationally, especially in the United States, several major field programs, *e.g.* Coastal Ocean Dynamics Experiment (CODE, Beardsley and Lentz, 1987) and Sediment Transport Events on Shelves and Slopes (STRESS, Trowbridge and Nowell, 1994), have been carried out. These large programs as well as smaller independent field studies have substantially increased the quantity of field data, and improved our knowledge of hydrodynamics and sediment transport processes in storm-dominated shelf settings. Rigorous models have been developed that are capable of predicting boundary layer structure, enhanced bed shear stress, and resulting sediment suspension and transport on shelves (Smith, 1977; Grant and Madsen, 1979, 1986; Fredsoe, 1984; Davies *et al.,* 1988). The basic concepts and new advances of shelf sediment transport have been reviewed in several publications (*e.g.,* Dyer and Soulsby, 1988; Wright, 1989; Cacchione and Drake, 1990; Nittrouer and Wright, 1994).

This article, and a companion paper in the next issue of this journal (Li and Heffler, in press), offer an overview of the status and advances of shelf sediment transport research in Canada. This first article focusses on recent progress in shelf sediment transport theories and related technological advances. A simplified introduction to the theory is first presented so that the reader can grasp the basic concepts of shelf sediment transport. This is followed by a quick review of the state of knowledge until the late 1980s. The last section discusses the recent technology advances. In the second paper, the emphasis will be on key scientific advances and future research directions. Erosion and transport of fine-grained sediment (silt and clay) are quite different from sand due to factors such as flocculation and consolidation. Advances in cohesive sediment dynamics are not covered in this review.

BASIC THEORIES OF SHELF SEDIMENT TRANSPORT

Flow on continental shelves is driven by a number of mechanisms, including winds, tides, density gradients, atmospheric pressure gradients, and the sea-surface slope (Grant and Madsen, 1986). Figure 1 schematically depicts the complex system of the flow and *bottom boundary layer* (bbl) structure over a rough sediment bed on the continental shelf. In response to wind forcing, a well-mixed surface boundary layer develops in the upper ocean. As the water flows over the seabed, a bottom boundary layer also develops close to the seabed. The surface and bottom boundary layers are normally separated by an unmixed core. The vertical extent of the upper and lower boundary layers is limited by density stratification due to temperature and/or salinity gradients. During storms, however, the entire water column can be well mixed, and the two boundary layers coalesce.

The bottom boundary layer is further divided into several sub-layers. Immediately above the seabed, a thin *wave boundary layer* exists on the order of 1-10 cm. This thin oscillatory boundary layer is embedded within a thicker *current boundary layer* controlled by wind-driven or tidal currents (Fig. 1). This *current boundary layer* consists also of two parts: a logarithmic layer immediately above the wave boundary layer, and the outer layer which accounts for 80-90% of the total bottom boundary layer thickness. Within the logarithmic layer, the mean velocity normally increases logarithmically away from the seabed and the shear stress is approximately constant with respect to elevation. Thus it is also referred to as the "constant stress layer." The outer layer is characterized by an upward decrease of shear stress.

The prediction of sediment

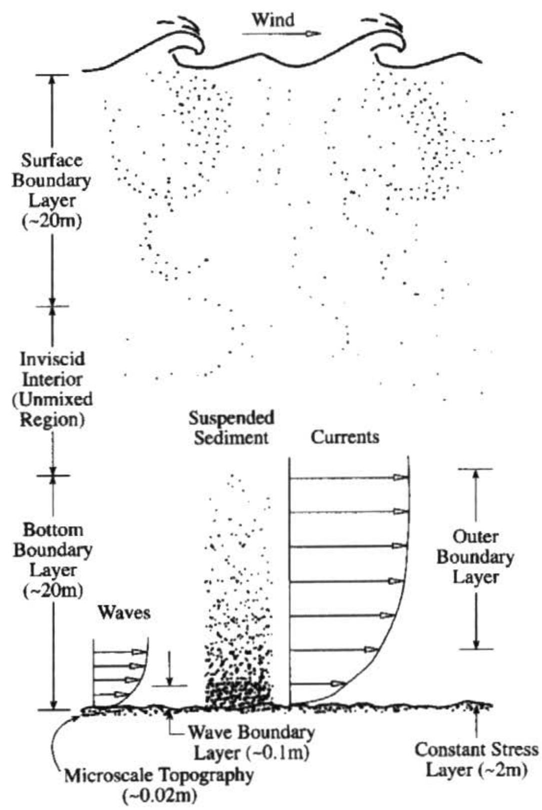

Figure 1 Schematic diagram of the complex system of the flow and boundary layer structure over a rough sediment bed on the continental shelf (modified after Trowbridge and Nowell, 1994).

transport is to relate the frictional force exerted by the fluid on the bed to the mass of sediment moved. The frictional force exerted by the flow over a unit area of the bed is defined as the bed shear stress, τ. Due to the co-existence of waves and currents on the shelf, τ is split into two components, the wave shear stress, τ_w and the current shear stress, τ_c. The wave shear stress, τ_w, is associated with the oscillatory motions induced by the waves near the bed. It is calculated from the fluid density, ρ, the maximum nearbed wave orbital velocity, u_b, and an empirical wave friction factor f_w:

$$\tau_w = 0.5\rho f_w u_b^2 \tag{1}$$

The wave friction factor f_w is a function of wave orbital excursion amplitude and bottom roughness height k_b and can be obtained from the empirical formula of Swart (1974).

The current shear stress, τ_c, is associated with lower frequency tidal and wind-induced steady flows, and can be determined by fitting the profile of the measured mean velocity u in the logarithmic layer to the von Karman-Prandtl equation as given below:

$$u = (u_{*c}/\kappa)\ln(z/z_0) \tag{2}$$

where u_{*c} is the current shear velocity which relates with shear stress τ_c through $\tau_c = \rho u_{*c}^2$, $\kappa = 0.4$ is the von Karmon constant, z is height above seabed, and z_0 is the bottom roughness length, which is related to the bottom roughness height k_b by $k_b/30$. For flat sandy beds with no movement of sediment, k_b is equal to 2.5 times mean sediment grain size D. When sediment is in transport, the value of k_b mostly depends on ripple geometry and the thickness of the bedload layer. If mean velocity was measured only at one height (conventionally at 100 cm above the bed, thus u_{100}), the current shear stress τ_c can also be estimated using a quadratic stress law that relates τ_c and u_{100} through the drag coefficient C_{100}:

$$\tau_c = \rho C_{100} u_{100}^2 \tag{3}$$

The value of C_{100} ranges from 0.001 to 0.006 and depends on sediment types and bedform dimensions (Dyer, 1986).

Currents and waves co-exist practically all the time in most shelf settings. The non-linear interaction between currents and waves over a rough bottom generates a combined shear stress, τ_{cw}, which is greater than the simple addition of the current and wave shear stresses. Furthermore, the currents in the logarithmic layer also experience a stronger apparent bed roughness length z_{0c} due to the presence of the wave boundary layer. Several bottom boundary layer models have been developed for combined waves and currents (*e.g.*, Smith, 1977; Grant and Madsen, 1979, 1986; Fredsoe, 1984; and Davies *et al.*, 1988). Due to its relative simplicity and successful application on the Northern California shelf, the model of Grant and Madsen (1979, 1986) has been widely accepted (Dyer and Soulsby, 1988; Cacchione and Drake, 1990). To calculate the enhanced wave shear velocity and combined wave-current shear velocity u_{*cw}, the Grant and Madsen (1986) model approximates the combined-flow friction factor f_{cw} from a series of equations that require knowledge of wave orbital velocity, wave period, bottom roughness length, the angle between waves and currents, and the current shear velocity estimated from measured velocity data. As these equations contain co-varying parameters, they must be solved iteratively to converge on the estimate of the combined-flow friction factor f_{cw}. Details of the Grant and Madsen theory and its equations can be found in Grant and Madsen (1986) and Li and Amos (1995).

With the derivation of u_{*c} and u_{*cw}, the profiles of the mean current velocity in the log layer and within the wave-current boundary layer are expressed respectively as:

$$u = (u_{*c}/\kappa)\ln(z/z_{0c}) \quad z \geq \delta_{cw} \tag{4a}$$

$$u = (u_{*c}/\kappa)(u_{*c}/u_{*cw})\ln(z/z_0) \quad z \leq \delta_{cw} \tag{4b}$$

where δ_{cw} is the thickness of the combined-flow wave boundary layer.

As flow velocity or bed shear stress increases beyond certain thresholds, sediment transport occurs in two modes: bedload transport at lower shear stresses, in which sediment grains intermittently slide, roll, or saltate in a thin layer close to the seabed; and suspended load at higher shear stresses, in which sediment particles are thrown up into the water column by turbulence, and advected downstream by the ambient currents above the bedload layer. One of the simpler and relatively better tested formulae for calculating bedload transport rate q_b in the shelf environment is that of Einstein-Brown (Brown, 1950):

$$q_b = 40Dw_s(\theta - \theta_{cr})^3 \tag{5}$$

where w_s is the sediment particle settling velocity, θ and θ_{cr} are, respectively, the applied skin-friction Shields parameter (caused by grain size roughness) and the critical Shields parameter for bedload transport. In generalized form, θ is given as $\tau/(\rho_s-\rho)gD$ in which g is gravitational acceleration and ρ_s is sediment density.

Estimation of suspended load transport rates involves multiplying the velocity profile of equation (4) and the profile of the suspended sediment concentration (ssc) and then integrating the results over the water depth. The most popular model of ssc prediction was that of Rouse (1937) modified for application to marine environments (*e.g.*, Sternberg, *et al.*, 1986; Glenn and Grant, 1987). The time-averaged sediment concentration C_z at height z for a single size class in a non-stratified flow is given as:

$$C_z = C_0\,(z/z_0)^{-\alpha} \quad \text{for } z \leq \delta_{cw} \tag{6a}$$

$$C_z = C_{\delta cw}\,(z/\delta_{cw})^{-\alpha} \quad \text{for } z > \delta_{cw} \tag{6b}$$

where C_0 is the reference concentration at the height of z_0 and $C_{\delta cw}$ is the concentration at the top of the wave-current boundary layer predicted by equation (6a) at $z = \delta_{cw}$. The Rouse suspension parameter α in equation (6) is a function of the ratio of particle settling velocity over flow shear velocity, w_s/u_*. The value of C_0 mainly depends on the applied bed shear stress and sediment resuspension efficiency (Smith and McLean, 1977).

HISTORICAL REVIEW TO LATE 1980S

Surficial Geology and Bedform Mapping on the Eastern Canadian Shelf

As in the United States and Europe, shelf sediment transport studies in Canada started with surficial geology and bedform mapping in the late 1960s and 1970s (*e.g.*, James and Stanley, 1968; Drapeau, 1970; Evans-Hamilton Inc., 1972, 1975, 1976; King and MacLean, 1976; Fader and King, 1981; Twitchell, 1981; Amos and Asprey, 1982; Geonautics Ltd., 1982). These earlier works not only delineated the sediment distribution on Canadian continental shelves, but also showed the existence of various bedforms over much of the eastern seaboard of Canada. The results from these earlier studies have been reviewed and used to deduce sediment transport processes and pathways on Canadian shelves (Amos and King, 1984; Barrie *et al.*, 1984; Hoogendoorn and Dalrymple, 1986; Amos and Nadeau, 1988; Amos, 1990; Amos and Judge, 1991). The surficial geology and bedform characteristics indicate the following:

1) Surficial sediments of most parts of the eastern Canadian continental shelves (Fig. 2a) are mobile. During the Holocene sea-level rise, glacio-marine sediments were reworked by a winnowing process: the finer fractions were entrained, transported from the banks and deposited in adjacent deeper basins, while the coarser materials remained as a veneer of sand and gravel on the banks and were worked into various bedforms by the modern-day oceanographic processes.
2) On the Labrador and northeast Newfoundland shelves (Fig. 2a), sediment transport is strongly limited by ice cover in the winter months. The existence of ripples, subaquatic dunes, and well-sorted gravel indicate intermittent transport of sediment in depths of less than 120 m and the net transport is believed to be to the southeast.
3) On the Grand Banks of Newfoundland, tidal and geostrophic currents are of low magnitude and storms are the main cause of sediment transport in depths as great as 150 m. On the north, west, and southwest Banks, sand is winnowed and transported to the south leaving behind well-sorted gravel lag deposits. The seabed of the eastern and southern parts of the Banks is covered mainly by medium sand on which subaquatic dunes of various sizes and sand ridges have developed. These bedforms indicate migration (transport) to the south.
4) A full range of sand sizes occur on Sable Island Bank (SIB, Fig. 2a). Patches of coarse sand occur on the western bank, and the sand fraction then decreases in size to the east becoming medium sand, fine sand, and very fine sand. Patches of coarse sand are found on the western, northern, and central parts of Banquereau Bank. The remainder of the bank is covered by medium sand. Sediment transport on the Scotian Shelf occurs principally during storms. Bedload mode is predominant and the net transport direction is to the east and northeast on Sable Island Bank, but to the east and south on Banquereau. Wave-ripples develop in water depths of 100-150 m during storm events, and wind-induced mean flows produce large-scale bedforms such as subaquatic dunes, sand ribbons, and sand ridges. Although modern, these large-scale bedforms become moribund between storms and are degraded by the fair weather wave conditions and/or bioturbation activities of benthic organisms. The large-scale sand bodies on SIB are modern shelf-edge storm

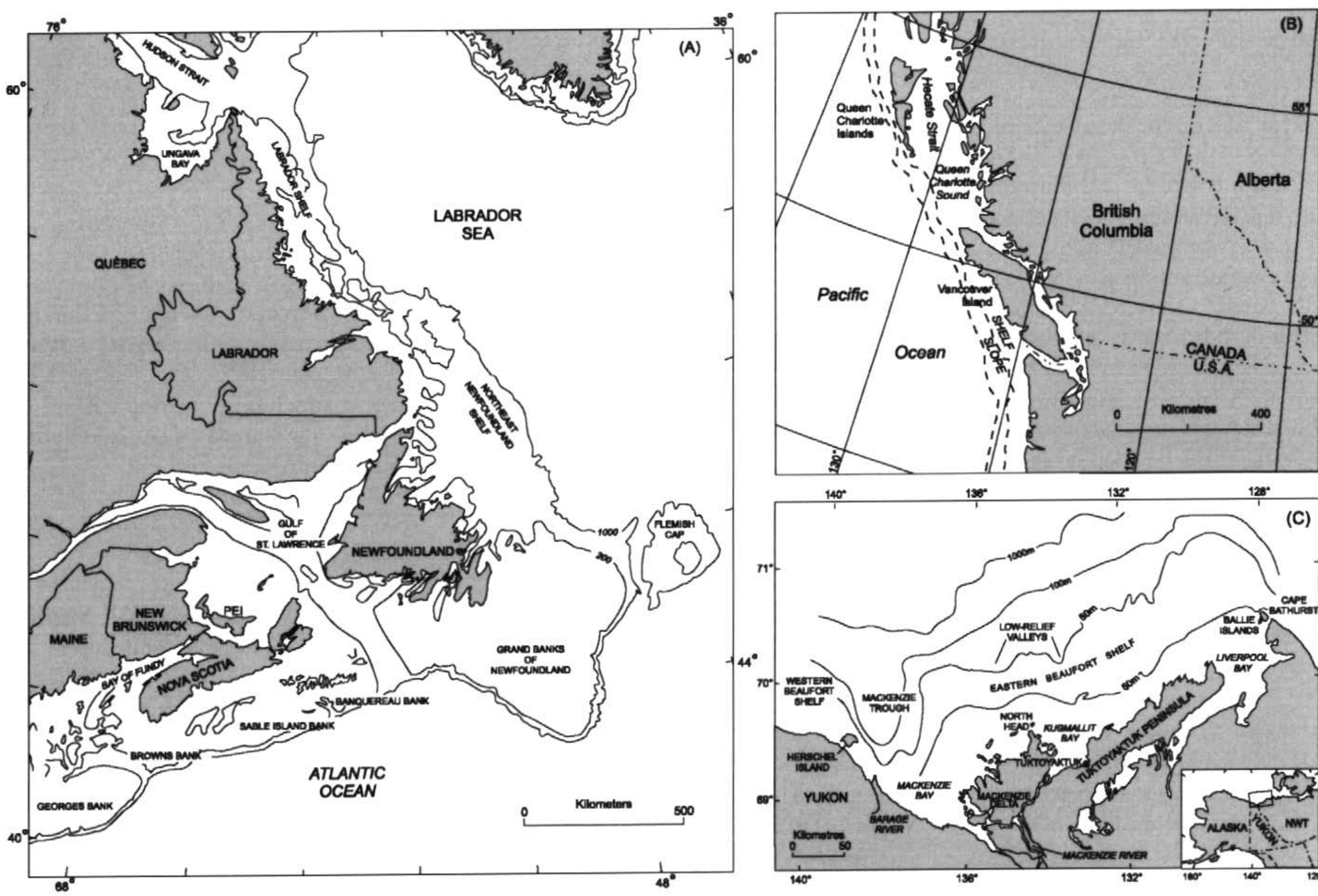

Figure 2 Location maps showing (**A**) eastern Canada shelf, (**B**) western Canada shelf and (**C**) the Beaufort shelf.

sand ridges, not sand waves or submerged barrier islands as were once thought. Morphology and internal structures suggest that these sand ridges migrate at very low rates to the east. Sand transport over the bank edge and spill-over to the deep water does not appear to take place because of veering of the current to a direction parallel to the local isobaths at the bank edges. This phenomenon is also evident on Banquereau and Georges Banks. Transport at the shelf break is largely unknown, although Hill and Bowen (1983) found that this is restricted to fine sediments that generally move along isobaths to the southwest on Sable Island Bank. Pockets of sand and gravel are also found on the rocky inner Scotian Shelf, and they can be reworked into ripples and large-scale wave ripples during storms (Judge *et al.*, 1987; Forbes and Boyd, 1987; Forbes and Drapeau, 1989).

5) Georges Bank is dominated by a gravelly seabed but sand is present on the bank top. Various bedforms ranging from dunes, to sand waves, and tidal sand ridges have been found on Georges Bank, Browns Bank, and in the Northeast Channel. Bedforms on Georges Bank appear to be migrating to the southeast, but the net transport direction on the southwestern Browns Bank and in the Northeast Channel seems to be landward in a northerly direction.

Studies on the Western Canadian Shelf and the Arctic Shelf

On the Pacific coast, the focus has been mainly on surficial geology and bedform mapping with little effort in sediment dynamics studies. The continental shelf of the western Canada (Fig. 2b) is physiographically and sedimentologically complex due to the active tectonic setting, extensive glaciation, and a wide range of wave and current conditions. The shelf morphology and sediment distribution has been studied, among others, by Luternauer and Murray (1983), Bornhold and Yorath (1984), and Bornhold and Barrie (1991). Shelves off southwestern Vancouver Island and in Queen Charlotte Sound are characterized by shallow, broad banks and intervening deep troughs. The shelf along the northwestern Vancouver Island slopes more uniformly seaward except for a topographically rugged inner shelf zone. Sediment derived from erosion of the land is mostly trapped in coastal fiords and straits. This sediment-starved condition coupled with the tectonic and oceanographic setting has led to glauconitic smectite development on many outer shelf areas, accumulation of muds in the troughs, and patchy sands and gravels of variable calcareous content on bank tops. The sand and gravel patches on bank tops are often covered by ripples and megaripples, indicating processes of active sediment transport. Oceanographic setting has been described by Thomson (1981), Luternauer (1986), and Crawford and Thomson (1991). Measurements using moored current meters suggested that the strongest currents of the Vancouver Island shelf can reach 0.6-1 m/s in later fall and winter and are dominantly to the northwest. Current measurements in Queen Charlotte Sound generally indicate northeasterly or southwesterly maximum currents that range from 0.4 m/s to 1 m/s. The maximum bottom currents on the Queen Charlotte Islands shelf and in Hecate Strait (Fig. 2b) also show a pattern of northwesterly flows, with southward flows in the southwest portion of the Strait. The peak values range from 0.4 m/s to 0.9 m/s. Waves on the western Canadian shelf come from the northern, southern, and western sectors, but the largest are from the southwest. The peak storm wave periods can reach 17-20 s and maximum wave heights can reach 17 m, but are less than 5 m for 90% of the time.

The occurrences of bedforms and their implications on sediment transport were presented in Yorath *et al.* (1979), Belderson *et al.* (1982), and Luternauer (1986). The wave and current regime on the shelf of western Canada is capable of generating oscillatory bedforms with wavelengths as long as 4-5 m and heights of up to 0.5 m in fine gravel in water depths of at least 60 m, and with wavelengths of 0.3 m to 1 m and heights of up to 0.3 m in coarse sand in water depths of at least 105 m. Small ripples formed in medium to coarse sand under combined flows can occur in water depths at least up to 130 m. Sand bands and patches, mainly influenced by tidal flows, occur to depths of at least 100 m. Barchanoid sand waves and relative edge sharpness of sand patches suggest net transport to the northeast on the banks in Queen Charlotte Sound, while the asymmetry of wave ripples on the southwest Vancouver Island shelf indicates northwesterly transport in this region.

The majority of sediment transport studies on Canadian Arctic shelves were made on the Beaufort shelf (Fig. 2c). This region is characterized by the rich sediment supply from the Mackenzie River and sea-ice coverage for 9 months of a year so that wave effects are limited to storms during ice break-up. Pelletier (1975) developed the first conceptual model for sediment dispersal on the Beaufort Shelf based on surficial sediment distribution and grain size analysis. Pelletier suggested that sedimentation on the Beaufort Shelf was controlled by the sediment input through the Mackenzie plume and relatively high energy near the coast. Sediment transport was to the east on both the inner and middle shelf. As more wave and current data became available, this model was further revised, largely by Harper and Penland (1982), and Fissel and Birch (1984). By integrating these revisions and new data from Davidson *et al.* (1988) and Hill and Nadeau (1989; see later discussion), Hill *et al.* (1991) have summarized the major characteristics of sediment transport and dispersal on the Canadian Beaufort Shelf:

1) The Mackenzie plume with relatively high concentration of suspended sediment extends over much of the shelf during the open-water summer months. The position and dynamics of the plume is alternately controlled by the prevailing northwesterly or easterly winds, but net transport is to the east. The distribution of Holocene mud on the shelf closely matches the maximum extent of the plume (restricted to water depths <100 m).
2) In water depths <10 m, wave oscillations combine with strong coastal currents during storms to cause high bottom shear stress, massive resuspension, and predominantly alongshore transport of sediment on the inner shelf. As the storm wanes, deposition in the form of graded silt and clay beds occur.
3) Sediment transport to the middle and

outer shelf occurs in both surface plume and near-bottom suspensions, largely through diffusive leakage, not advection. Bottom sediment here is only affected by extreme events, with recurrence intervals of 1 year or more. The essentially low-energy regime on the mid to outer shelf favours settling of sediment from suspension and plume to deposit in topographic lows, principally in the cross-shelf valleys.

Field Measurements, Instrumentation and Modelling Development

In contrast to the extensive surficial geology studies and bedform mapping, *in situ* measurements of flow dynamics and sediment transport on Canadian shelves were very sparse and only started in the early 1980s. As evidence accumulated that oceanographic processes were strong enough to cause sediment movement and bedform development over much of the eastern Canadian continental shelf, it became clear that the study of sediment transport required instruments that could measure simultaneously waves, currents, and sediment response near the seabed for extended periods of time. The first Canadian instrumented tripod for sediment transport study, RALPH (Heffler, 1984), was designed and built at the Geological Survey of Canada Atlantic (GSCA). The frame of the early version RALPH was an aluminum pipe tripod on which only basic sensors were mounted: a pressure transducer, two Marsh McBirney current meters, a SeaTech transmissometer, and a Super-8 mm time-lapse movie camera. RALPH was first successfully deployed in June-July of 1982 on Sable Island Bank, although the results were published several years later (Amos *et al.*, 1988; further discussion in Li and Heffler, in press).

A geological and sediment dispersion study was conducted at the Venture and Olympia sites on Sable Island Bank in the winter of 1984-1985 (Hodgins *et al.*, 1986a; Hodgins and Sayao, 1986). Radio-isotope sand tracers were used at these sites to estimate net sediment transport during the experimental period. Sea Data 635 and 621 burst current meters and the GSC instrumented tripod RALPH were used to measure the characteristics of the bottom boundary layer. The measured current data showed that mean currents at Venture have a predominant SSW-NNE direction with speeds up to 32 cm/s. By contrast, instantaneous wave orbital velocities were as high as 2 m/s during typical winter storms. The medium sand tracers at Venture were found to be mobile, and the mean mass transport rates ranged from 17-20 $kg \cdot m^{-1}\ hour^{-1}$. A consistent direction of movement was not found; rather, the cloud appeared to have been transported in directions consistent with wave and current conditions between detections. The magnitude and direction of sediment transport predicted by various models differed significantly from that of the tracer experiments.

Huntley and Hazen (1988) deployed an instrumented tripod similar to RALPH at two Scotian Shelf sites: an inner shelf site at Cow Bay and an outer shelf site at southwest Sable Island Bank. The tripod contained two Marsh McBirney current meters, a pressure sensor, an optical transmissometer, a digital compass, and a stereo camera. The power and data were transmitted between the surface vessel and the tripod through electrical cables. Shear velocities were estimated from the measured vertical velocity data using a modified energy dissipation method. The observed shear velocities were considerably larger than would be predicted from the log-profile method on the basis of the observed bottom roughness and the mean flow alone. This indicated that waves were important in enhancing the friction velocities. The theory of Grant and Madsen (1979) had been used to predict the friction velocities, and the predicted values were in good agreement with the observed shear velocities.

In a field study by Hill and Nadeau (1989), borehole data were combined with CTD (conductivity, temperature, depth) casting, attenuance meter profiling, and *in situ* measurements by a burst-sampling current meter and an optical backscatter sensor to document the type of sediment accumulation on the inner Beaufort Sea shelf, and relate the facies to oceanographic processes. The massive to graded, thick silt beds in water depths of between 4 m and 6 m was interpreted to result from maximum resuspension by waves during storms. Seaward of this resuspension zone, resuspension occurred only under low-frequency, large storm waves. This was reflected in the deeper water facies where bioturbated clay became dominant, with thin silt beds representing infrequent effects by the largest storms. A maximum of near-bottom turbidity in approximately 5 m of water observed during storms supported the concept of the maximum resuspension zone, and the time series data of waves and suspended sediment concentration confirmed that the resuspension was directly related to wave energy.

As *in situ* measurement tools were developed and deployed on Canadian shelves, shelf sediment transport models were also developed. A 1-D physical model SED1D was developed at the Geological Survey of Canada (GSC) and described by Martec Ltd. (1982). The model adopts the Grant and Madsen (1979) combined-flow bottom boundary layer theory to predict bed shear stress and velocity profiles near the seabed. The magnitude and direction of sediment transport is then predicted using one of several bedload and total load transport algorithms. As a further step, GSC and Martec also developed a 2-D model SED2D (Martec Ltd., 1983) that calls and applies the 1-D model at each grid point to predict regional patterns of sediment transport. There have been some upgrades and calibrations of these models (Li and Amos, 1995, 2001), discussed further in a later section. Besides boundary layer dynamics and direct transport models, McLaren (1981), and McLaren and Bowles (1985) devised a deductive model that uses spatial changes in grain-size parameters of bottom sediments to indirectly derive sediment transport direction. There were subsequent studies that either supported or questioned the applicability of this model in some environments, and there has been no study that demonstrates the application of this model in open continental shelf environments.

The State-of-the-art Review of Hodgins *et al.*

Hodgins *et al.* (1986b) provided an earlier state-of-the-art review of topics related to seabed stability and sediment transport on continental shelves. It was found that while progress had been made in understanding the physics governing sediment transport and algorithms for transport rate prediction, much uncertainty remained due to crude parameterization of the bottom boundary layer and bed shear stress, and the paucity of field data for model calibration. Major problems to be solved included dynamics of the wave-current boundary layer, the resolution of form drag and skin stresses in the presence of ripples, and how bedforms affect wave-current dynamics and sediment transport. In reviewing various sediment transport measurement techniques, the acoustic profiling instruments for suspended sediment and Doppler velocity profilers that were under development appeared promising for direct estimates of suspended load transport. However, both optical and acoustic techniques needed to be refined to distinguish grain size effects from concentration effects. The lack of a reliable method for measuring bedload transport continued to be a major problem. It was believed that numerical modelling of sediment transport was still in its infancy. The central problem was the lack of reliable hydrodynamic field data and *in situ* sediment transport measurements. The primary requirement was for field experiments to measure boundary layer hydrodynamics, sedimentary environments, and sediment motion so that predictive models could be calibrated. Based on these reviews and the requirements of Canadian offshore oil and gas development, Hodgins *et al.* recommended several priorities in sediment transport research. These include better understanding of the physical processes and shear stress parameterization in the bottom boundary layer, development of acoustic instruments for suspended and bedload transport measurements, measurement and prediction of sand transport rates on Sable Island Bank, and understanding the migration processes of the sand ridges on SIB.

Figure 3 Photograph showing the EMCM array (black balls, on the left portion of the photo) and the OBS array (on the vertical triangular frame, right portion of the photo) that are mounted on the GSC instrumented platform RALPH.

RECENT TECHNOLOGICAL AND MODELLING DEVELOPMENTS

Since the mid- to late 1980s, many of the technological advances mentioned by Hodgins *et al.* (1986 b) have occurred. The following is a review of some of the promising new sensors, techniques, improved instrumentation platforms, and modelling development.

Sensors for Discrete Current and Suspended Sediment Measurements

Electromagnetic current meters (EMCM) and optical backscatter sensors (OBS) continue to be the popular choices for velocity and suspended sediment concentration measurements in both nearshore and shelf sediment transport studies (*e.g.*, Cacchione *et al.*, 1987; Wright *et al.*, 1991; Hay and Wilson, 1994; Green *et al.*, 1995; Li *et al.*, 1999a). EMCMs operate on the Faraday law: a voltage is induced when a conductor (seawater) moves relative to a magnetic field (generated by an electromagnet inside the probe). The most common version is the 2.5 cm diameter probe produced by Marsh McBirney. A miniature version of 1.5 cm diameter is available but its field application is not tested (Wright, 1989). EMCMs can be deployed as close as 10 cm to the bed and can sample as quickly as 5 Hz. Figure 3 shows the EMCM array that are mounted on the GSC instrumented platform RALPH. The instantaneous velocity recorded by the EMCM array on RALPH in a 1996 deployment on Sable Island Bank is plotted in Figure 4. InterOcean also produces large-diameter (30 cm) probes with all electronics, data logging, and power enclosed in the sphere (S4 wave-current meters). Acoustical current meters also continue to be used in some studies (*e.g.*,, Grant *et al.*, 1984; Li *et al.*, 1997).

Optical backscatter sensors were pioneered by Downing *et al.* (1981) and they measure suspended sediment concentration by emitting infrared light and detecting the intensity of the radiation backscattered by the sediment particles in suspension. At present, OBS are probably still the most commonly used devices for measuring suspended sediment concentrations. OBS respond

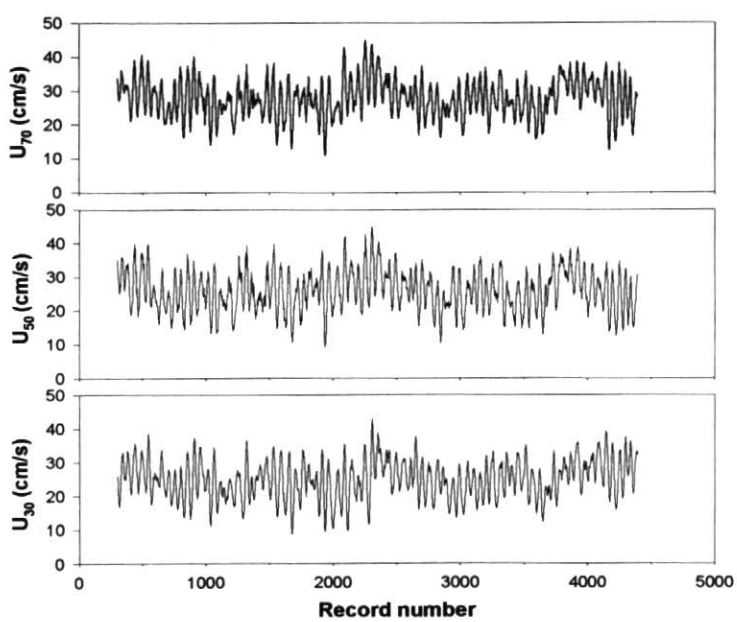

Figure 4 The instantaneous velocity at 0.3, 0.5 and 0.7 m above the seabed recorded by the EMCM array on RALPH in a 1996 deployment on Sable Island Bank.

remarkably linearly over large ranges of concentrations for sediment of relatively uniform grain sizes. However, separating grain size effects from concentration effects and the more sensitive response to mud than sand by OBS continue to be problematic for this type of sensor. An array of 6 OBS mounted on the GSC instrumented platform RALPH is shown in Figure 3, and Figure 5 shows the profile of mean suspended sediment concentration that can be measured by this type of OBS arrays. Figure 5 shows that the peaks of mean concentration recorded at different heights are well correlated and that the suspended sediment concentration decreases with the height above the seabed.

Current and Suspended Sediment Profilers

The critical shortcomings of the EMCM and OBS arrays are that they are intrusive, they cannot be placed very close to seabed, and they are incapable of measuring high-resolution vertical profiles. These problems were solved by the development of acoustic backscatter sensors (ABS) and acoustic Doppler current profilers (ADCP). Acoustic backscatter sensors (see Fig. 6) detect the intensity of backscattered acoustic signals and convert it into suspended sediment concentrations. ABS have two advantages over optical sensors: there are no strong absorption peaks for transmission in the water column, and the much slower propagation speed of sound allows the backscattered signal to be range-gated so that suspension profiles can be measured with a single sensor at a fixed height. ADCP determine current velocities by using the Doppler shift of the backscattered acoustic signal.

ABS and ADCP were being developed at several institutes in the mid-1980s and their potential was just being realized (Huntley and Drapeau, 1986). Since then, ABS technology has been widely applied in sediment transport studies (*e.g.,* Hanes *et al.,* 1988; Vincent *et al.,* 1991; Lynch *et al.,* 1994). Figure 7 shows the high-resolution profiles of suspended sediment concentration of several data bursts recorded by a 1 MHz ABS mounted at a height of 1.3 m on an instrument platform. Furthermore, attempts have also been made to use ABS for *in situ* measurements of grain size profiles (Hay and Sheng, 1992) and bed elevation changes (*e.g.,* Li *et al.,* 1999a). In contrast, further development and application of ADCP have been relatively limited. Cheng *et al.* (1999) at the United States Geological Survey (USGS) developed the broad-band ADCP and used it to measure velocity profiles in South San Francisco Bay, California. Examples of high-resolution velocity profiles measured by this broad-band ADCP are shown in Figure 8. In Canada, a pulse-to-pulse coherent Doppler system has been developed at Memorial University of Newfoundland (Zedel and Hay, 1995) which can measure both velocity and suspended sediment concentration profiles. Given the promising potential and importance of simultaneous, high-resolution measurements of velocity and suspension profiles using combined ABS and ADCP (Huntley and Drapeau, 1986), it is surprising that there has been no known field effort to obtain simultaneous measurements from ABS and ADCP and to use these to estimate the suspended load transport rate. Besides the encouraging development of the ABS techniques (Hay and Sheng, 1992), laser technology has also been tried for particle sizing (Agrawal and Pottsmith, 1994). However, we are still far from being able to obtain accurate measurements of grain size profiles in the water column.

Sensors For Bedform Dimension and Migration Measurements

A sound understanding of bedform development and accurate information on

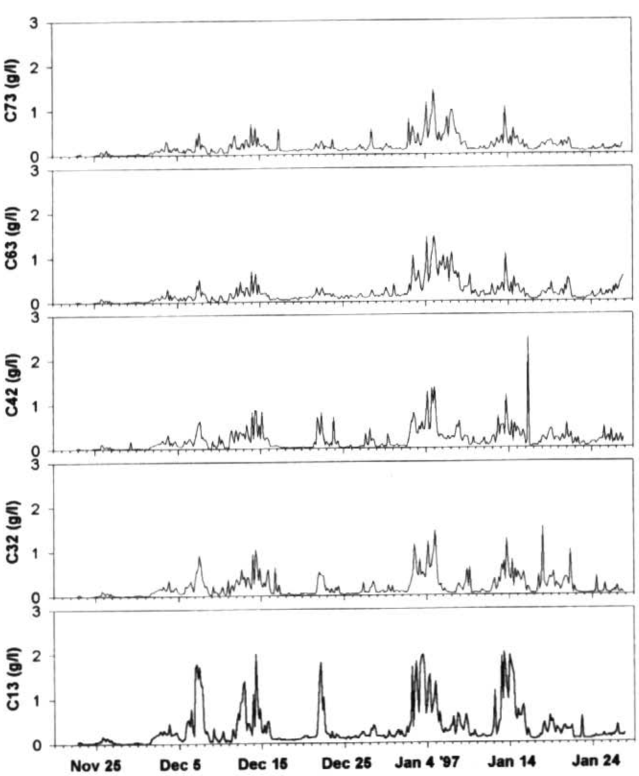

Figure 5 Profiles of mean suspended sediment concentration measured by the OBS array on an instrumented tripod (courtesy of D.A. Hepworth, C.T. Friedrichs, and L.D. Wright of Virginia Institute of Marine Science).

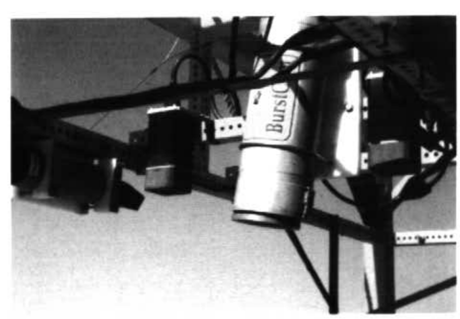

Figure 6 Photograph showing the Mesotech 2.2-MHz acoustic backscatter sensors (rectangular cylinders) and the 675-kHz Imagenex Sector Scanning Profiler (far-left cylinder with a flat head) mounted on the GSC-instrumented platform RALPH.

bedform dimensions are the foundation to the modelling of bottom boundary layer dynamics and sediment transport. These parameters directly control the near-bed velocity structure, the partition of skin friction from form drag, and sand resuspension processes. Time-lapse optical imaging has been and still is the conventional method for measuring bedforms and other seabed micro-topographies (*e.g.*, Wilkinson *et al.*, 1985; Amos *et al.*, 1988; Boyd *et al.*, 1988; Wright *et al.*, 1991; Drake and Cacchione, 1992; Li *et al.* 1997). However, sediment suspension often reduces the transparency of the water column and constrains the use of optical techniques. Because of this, many researchers have used acoustic devices for bedform measurements. The first such instrument was a diver-operated, track-mounted sonar system used for nearshore wave ripple measurements (Dingler and Inman, 1976). A similar, but more advanced and remotely operated system was developed in Canada and used for bedform monitoring on beaches (Greenwood *et al.*, 1993). Though these tracking systems were capable of accurate bedform measurements and worked well in sediment suspension, they could not yield information on the 3-D nature of many bedforms and their coverage of the seabed was also spatially limited.

More recently, high-frequency rotating sidescan sonar systems have been developed for imaging the seabed. Hay and Wilson (1994) use a customized Simrad Mesotech rotating sidescan sonar on an instrumentation platform to measure bedforms on the crest of a nearshore bar. The sidescan sonar was mounted 50 cm above the seabed and driven by a step-motor. The system provided continuous circular seabed images of 10-m diameter, which can be used to detect the occurrence of ripples and megaripples. On the latest GSCA instrumented platform, RALPH (Heffler, 1996), two Imagenex model 881 sector scanning sonars are incorporated: one as a sector scanning profiler (SSP, Fig. 6), and the other as a sector scanning imager (SSI). The profiler has a pencil beam transducer that rotates around a horizontal axis to produce bathymetric profiles along a 5-m line of the seabed for bedform height and seabed scour measurements. The imager has a fan-beam transducer much like a miniature sidescan. This transducer rotates around a vertical axis to record 270° fan-shaped seabed images of up to 40 m in diameter to show 2-D bedform patterns. The applications of this system on Sable Island Bank have produced exciting data on the height and wavelength of small and large-wave ripples (Li *et al.*, 1999a). Two example images from these Imagenex sonars are shown in Figure 9.

Instrumented Platforms

Our current understanding of shelf sediment transport would not have been possible without the development and continued improvement of multi-parameter instrumented platforms. This type of platform was pioneered in the 1960s by Sternberg and Creager (1965) and adapted by others in the 1970s and 1980s. The well-known systems include: the GEOlogical PROcesses Bottom Environmental (GEOPROBE) tripod developed at the west coast USGS (Cacchione and Drake, 1979) and its precursor on the east coast (Butman and Folger, 1979); the Benthic Acoustic Stress Sensor (BASS) tripod developed at Woods Hole Oceanographic Institution (Williams, 1985); the tripod systems of Virginia Institute of Marine Science (VIMS tripod, Wright, 1989); and the Sediment Transport And Boundary Layer Equipment (STABLE) tetrapod system (Humphery and Moores, 1994).

In Canada, the GSC instrumented tripod RALPH has been significantly advanced and successfully applied in shelf as well as nearshore sediment transport studies in the last 15 years (*e.g.*, Amos *et al.*, 1988; Boyd *et al.*, 1988; Forbes and Drapeau, 1989; Li *et al.*, 1997). The earlier version of RALPH was a tripod system and was equipped with a limited number of sensors (Heffler, 1984). Recently, RALPH has been upgraded to a 3 m x 3 m x 2 m quadrapod (Fig. 10).

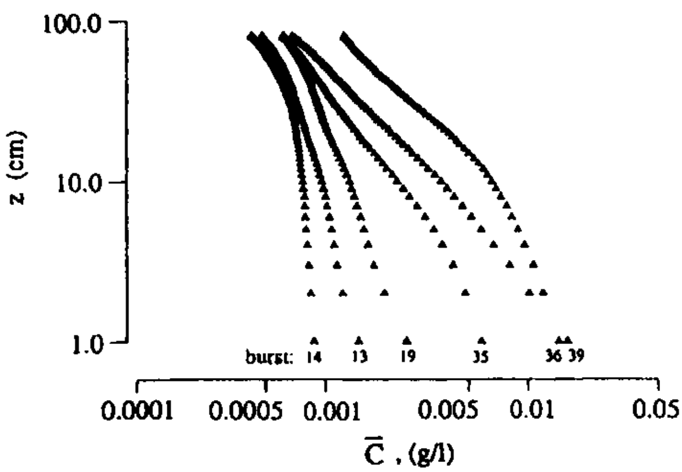

Figure 7 High-resolution profiles of suspended sediment concentration of several data bursts recorded by a 1-MHz ABS (courtesy of Dr. J.J. Williams of Proudman Oceanographic Laboratory).

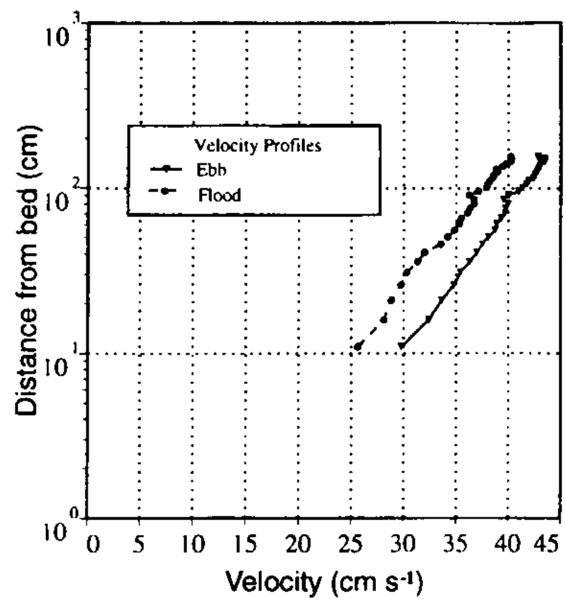

Figure 8 High-resolution velocity profiles measured by a broad-band acoustic Doppler velocity profiler (ADCP; courtesy of Dr. Ralph Cheng of the United States Geological Survey).

Besides the conventional pressure transducer, compass, and roll/pitch sensor, the main elements on the upgraded RALPH platform (Heffler, 1996) include an array of four Marsh-McBirney EMCMs, six OBS sensors situated within 1.36 m of the sea floor, four Mesotech 2.2 MHz ABS sensors all mounted at 1.5 m above the seabed at various horizontal locations, and an underwater digital video camera. The latest addition of devices to RALPH are the two 675 kHz Imagenex sector scanning sonars as described in the previous section. The profiles and "side-scan" images generated by these sonars provide accurate data on bedform height and wavelength (see Fig. 9). Sensor sampling, programming, and data logging are controlled by Onset Tattletale computers. Overall, the upgraded RALPH system now has 23 sensors, seven computers, and 2.5 Gbyte data storage capacity. This upgraded RALPH platform was recently deployed several times on Sable Island Bank, Scotian Shelf, and has produced several long-term data sets of bbl dynamics and sediment transport under storm conditions (Li *et al.*, 1999a).

Multibeam Mapping

The multibeam bathymetric mapping technology measures the slant-range travel time of echo sounder signals travelling from the sonar transducer to the seabed and refracted back to detect seafloor depth (Courtney and Shaw 2000). This technology provides high-resolution, 100% bathymetric coverage of the seabed. The application of the multibeam bathymetric mapping technology to sediment transport studies is just beginning. For example, Li *et al.* (1999b) are applying this method to the study of the morphodynamics and migration of sand ridges and associated large-scale bedforms on Sable Island Bank. Similarly, Taylor *et al.* (1999) used multibeam bathymetric surveys to delineate bedforms, their geometry, and implications for sediment transport pathways on Milne Bank, Prince Edward Island. On the west coast, Mosher and Hamilton (1998) also use this technology to study the morphology, structure, and stratigraphy of the offshore Fraser delta and adjacent Strait of Georgia. In general, multibeam mapping technology has three applications to sediment transport studies: characterizing morphology, bedform distribution and regional sediment transport patterns; estimating migration of large-scale bedforms through repetitive mapping; and using multibeam maps for planning other surveys and selecting sites for instrument deployment.

Modelling Developments

Since the developments of 1-D and 2-D sediment transport models at the GSC in the early 1980s (Martec Ltd., 1982, 1983), there have been some moderate advances in shelf sediment transport modeling. The original 1-D model SED1D has been re-evaluated, upgraded, and calibrated based on advances in combined-flow bottom boundary layer theory and newly available data of *in situ* sediment transport measurements (Li and Amos, 1995, 2001). For given input data of wave, current, and seabed conditions, the upgraded model, SEDTRANS, applies the combined wave-current bottom boundary layer theories to derive the nearbed velocity profile and bed shear stresses, and then calculates sediment transport for currents or combined waves and currents over either cohesive or non-cohesive sediments. The prediction of the friction factor (f_{cw}) and combined wave-current shear stress (τ_{cw}) has been upgraded according to the more recent combined-flow boundary layer theory of Grant and Madsen (1986). Other key

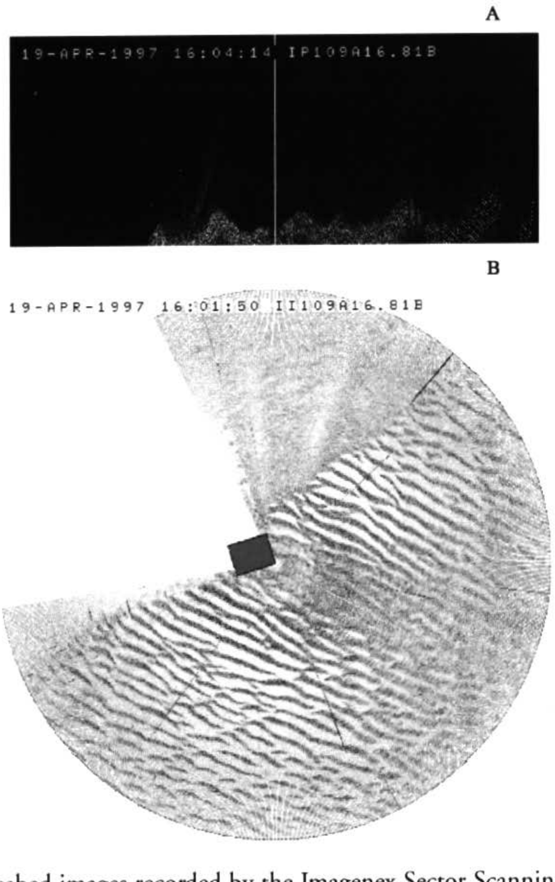

Figure 9 Example seabed images recorded by the Imagenex Sector Scanning sonars. (**A**) the vertical profile of the seabed scanned by the sector scanning profiler. The length of the image is about 5 m and the vertical height is about 130 cm. The white band indicates the bedforms with a maximum height of 18 cm. (**B**) the 270^0 image recorded by a sector scanning imager. The image has a 40 m diameter and displays large wave ripples of 1 m average wavelength.

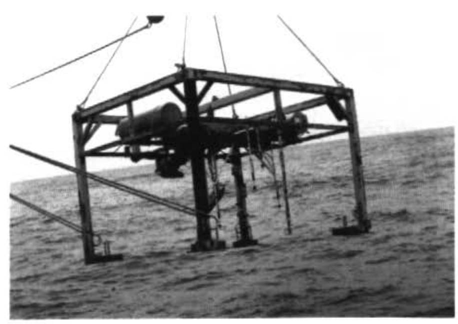

Figure 10 Photograph of RALPH, the upgraded GSC-instrumented platform for boundary layer dynamics and sediment transport research.

developments incorporated into the SEDTRANS model include: 1) tested critical shear stresses for the various sediment transport modes under the combined waves and currents; 2) an explicit combined-flow ripple predictor to provide time-dependent bed roughness prediction; 3) the vertical profiles of velocity and suspended sediment concentration and the integration of their product through depth to derive the suspended-load transport rate; and 4) rigorous calibration of the model using measured sediment transport rates over fine and medium sands to reduce the difference between the predicted and measured transport rates from more than one order of magnitude to less than a factor of five.

As for regional predictions, a 2-D, time-dependent model SED94 has been developed (Anderson, 1995). This 2-D model applies SEDTRANS at each point on a rectangular grid at successive points of time, and a finite-difference scheme is used to account for the net erosion or accretion at each grid point. These upgraded models have been applied successfully to predicting sediment transport on the Scotian Shelf and the Queen Charlotte Islands shelf in western Canada (Amos and Judge, 1991; Amos *et al.*, 1995; Li *et al.*, 1997).

Besides these models developed at GSC, other models have also been developed and applied for predicting sediment transport/dispersion in estuaries and harbours. For instance, a shear dispersion boundary layer transport model called bblt has been developed by Fisheries and Oceans Canada (Hannah *et al.*, 1998) for predicting dispersion of drilling wastes from offshore hydrocarbon operations. The hydrodynamics and sediment transport model Mike21, developed by the Danish Hydraulic Institute, has also seen applications in coastal sediment transport studies (*e.g.*, Baird and Associates, 1990).

CONCLUDING REMARKS

This review indicates that shelf sediment transport studies in Canada first started with surficial geology and bedform mapping in the 1960s and 1970s. These quickly advanced to field measurements of hydrodynamics and sediment transport using current meters and simple instrumented tripods in the early 1980s. Shelf sediment transport models were also developed in the early 1980s but only saw some sparse applications. An earlier state-of-the-art review by Hodgins *et al.* (1986b) showed that the central problems to further advancing shelf sediment transport studies were poor understanding of the dynamics of the wave-current boundary layer, the effects of bedform development on boundary layer dynamics, and the lack of reliable *in situ* hydrodynamics and sediment transport measurements.

Significant technological advances have occurred since the mid 1980s. Although electromagnetic current meters and optical backscatter sensors continue to be the popular choices for measuring velocity and sediment concentration, various acoustic sensors are now more widely applied in shelf sediment transport studies. For seabed scouring and bedform measurements, the recently developed sector scanning sonar systems have produced exiting data and hold great potential. These advanced sensors are generally incorporated on instrumented platforms, such as RALPH, to be used in long-term field deployments on continental shelves. The multibeam mapping technology has just begun to be applied to shelf sediment transport research, and it should provide high-resolution information on bedform distribution and the morphodynamics and migration of large scale bedforms on continental shelves. Recent advances in combined-flow bottom boundary layer theory and newly available field data have been used to upgrade and calibrate shelf sediment transport models.

The second companion paper in the next issue (Li and Heffler, in press) will discuss the principal scientific advances in shelf sediment transport studies in Canada, focussing mainly on the results from the Scotian Shelf. It is shown that the technological advances, discussed in this article, have led to much improved understanding of the wave-current boundary layer dynamics. Explicit sediment transport thresholds and ripple predictors for combined waves and currents have been proposed and tested. A combination of several techniques has shed new light on the morphology and dynamics of sand ridges on outer-shelf sand banks. Sediment transport models have been significantly upgraded and calibrated based on advances in combined-flow bottom boundary dynamics and new *in situ* sediment transport measurements. And these improved models have been applied to predict regional sediment transport patterns at several sites on Canadian continental shelves. Projections of future research directions will also be made based on the contents of both articles.

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