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Bottom instrumented tripods: History, applications, and impacts

D.A. Cacchione[a,*], R.W. Sternberg[b], A.S. Ogston[b]

[a]*CME (Coastal and Marine Environments), 2945 Granite Pointe Drive, Reno, NV 89511-5366, USA*
[b]*School of Oceanography, University of Washington, Box 357940, Seattle, WA 98195-7940, USA*

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Abstract

Instrumented bottom tripods have provided important data on sediment transport processes on continental shelves and in estuaries for four decades. Since the initial deployment in a tidal channel in Puget Sound, WA, in 1965 numerous tripods have been constructed to investigate bottom boundary layer and sediment dynamics worldwide. Tripod data have led to new understanding of near-bottom wave and current flows in the coastal ocean, and have been crucial to the development of shelf circulation and sediment transport models. Calculations of bottom stress, bottom roughness, and sediment flux that resulted directly from tripod data have been compared to bottom boundary layer model results. Where these have differed, new or revised model components have been developed to improve the skill of the models. The many discoveries that have been made from tripod experiments include dense, near-bottom fluid mud layers that transport large quantities of suspended sediment offshore into deeper regions of the continental shelf. This process has been linked to the seaward progradation of subaqueous deltas and to the boundaries of mid-shelf mud deposits off rivers with high fine-sediment discharge.
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1. Introduction

Advances in our understanding of geological processes in the oceans have often been led by new data that are obtained with emerging technologies. An example of an instrument development that has had major impacts on our understanding of the seafloor might include the Precision Graphic Recorder or PGR in early bathymetric surveys of the 1960s that revealed a rugged ocean floor filled with oceanic ridges, rift valleys, deep-sea trenches, and abyssal plains (Knott, 1962). Later in the 1990s multi-beam sonars mounted on ships provided imagery that unveiled spectacular details of the shapes and distributions of submarine canyons, gullies, and sediment waves along continental margins (e.g., Gardner et al., 2003). The development of instrumented measurement systems that are deployed on the seabed for field investigations of marine sediment transport is also an excellent example of this axiom. The frames on which the instruments are mounted have generally been three-legged, and so this class of measurement systems is often referred to as instrumented bottom tripods (hereafter, "tripods"; Fig. 1). The tripod configuration offers stability without significant flow interference near the seafloor so that current and other measurements are representative of open flow conditions. Tripods are self-contained, fully submerged structures that can rest stably on the seafloor, and on which are attached various

*Corresponding author. Fax: +1 775 853 9465.
E-mail addresses: dcacchione@charter.net (D.A. Cacchione), rws@ocean.washington.edu (R.W. Sternberg), ogston@ocean.washington.edu (A.S. Ogston).

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Fig. 1. USGS GEOPROBE tripod being readied prior to deployment in San Francisco Bay, CA in 1996. Tripod is constructed from stainless steel tubing, and is about 2.8 m tall (to base of float), and about 2.5 m between footpads. Identified on the photo are: recovery float on top of the line bucket (#1), pressure cases for electronics (#2), acoustic release (#3), pressure sensor (#4), LED transmissometer (#5), electromagnetic current meters (EMCM; #6), vane and nozzle sampling system (#7), Optical Backscattering Sensor (OBS; #8), and lead footpads with plastic base (#9). LED transmissometer (#5) and optical backscattering sensor (OBS; #8) are used to measure suspended sediment concentrations. Four electromagnetic current meters (EMCM; #6) in a vertical stack measure two orthogonal horizontal components of current speed (which is used to determine horizontal velocities at 4 levels near the bottom). The nozzle sampler is directed into the flow by the attached vane (#7). Up to 16 water samples containing suspended particulate matter are collected in one-liter plastic (Teflon) bags contained within the black cases attached to the upper level of the tripod.

instruments, data logger, power supply, and recovery system. Other frames such as quadrapods and single-masted towers have also been used, but tripods have been the predominant structural shape. In this paper, the history and important contributions that tripods and related instrumented bottom systems have made in furthering our understanding of sediment transport in the coastal ocean and in estuaries are examined.

Up until the 1960s a commonly accepted premise was that the seafloor beyond the shoreface was essentially a relict surface, formed during the last glacial low stand and little changed by modern processes, essentially a "Pleistocene museum" (Cacchione and Drake, 1990). Much of our knowledge about sediment processes in the coastal oceans came from geological bottom samples and bottom photographs. These earlier data provided a static view of the seabed with no direct information about active changes to the sediment surface or the causes for the changes. Measurements of flows due to surface waves and currents were obtained at levels well above the seabed, using current meters lowered from ships or attached to anchored moorings. Early investigations of near-bottom processes in shallow water revealed the complexities of this environment (Mosby, 1947 and 1949; Lesser, 1951).

Studies in laboratory flumes and rivers prior to the 1960s had documented that bottom sediment could be mobilized by hydrodynamic stresses acting on the bed (Shields, 1936; Hjulstrom, 1939). These studies aided the development of a variety of semi-empirical equations that were used to estimate entrainment and flux of marine sediment without direct observations necessary to validate their utility in the marine environment. Oceanic conditions in coastal waters are a mixture of various processes that combine to create turbulent flows and shear stresses within bottom boundary layers (BBL) that act on sediment particles comprising the seabed. The dynamics of bottom flows and stresses caused by surface and internal waves, and by tidal, wind-forced, and density-induced currents are quite different than those found in unidirectional and steadier flows in rivers and laboratory channels. Many unanswered questions remained about the validity of applying experimental results and theory from channelized flow and sediment-transport investigations to the shallow marine environment.

The advent of instrumented tripods in the early 1960s led to major advances in our understanding of flow and sediment processes in the coastal oceans. Beginning in the mid-1960s, instrumentation was placed on tripods to obtain time-series records of the response of bottom sediments to local hydrodynamic forcing close to the seabed. Modern tripods contain numerous sensors that measure current speed and direction at multiple levels near the seafloor, and also remotely sense currents at numerous levels above the tripod (up to 100s of meters from the seafloor). Measurements obtained with tripods dispelled the notion that the shelf floor was a passive surface, and proved that bottom and suspended sediments were actively transported by waves and currents along and across continental shelves. Based on tripod data, sediment entrainment and flux could be calculated from direct measurements of hydrodynamic forcing and sediment response at a wide variety of geographic locations and geological settings in the coastal oceans. These new data guided the development of analytical and numerical marine sediment transport models, and provided validation of model predictions. For example, model predictions of bottom stresses within combined wave-current shelf BBL have been compared to bottom stresses estimated from tripod measurements at a large number of locations (e.g., Wiberg and Smith, 1983, Grant et al., 1984, Cacchione et al., 1987a). The stress estimates from models and tripod data for the current-dominated part of the BBL in general showed close agreement, lending confidence and validation to the model predictions (Cacchione and Drake, 1990; Lyne et al., 1990).

New instrumentation on tripods has continued to evolve rapidly over the past four decades, providing ever-increasing variety and accuracy of data collected with these systems. This review of tripods only skims the growing list of these types of systems, and is not meant to document all of them or their contributions. The emphasis here is on the general historical development of tripods in the USA, using some specific examples (largely from the west coast) to indicate the impacts that these systems have had on the topic of marine sediment transport.

2. Methods

A few basic principles about sediment transport must be kept in mind when assessing measurement systems like tripods for the shallow marine environment. Six of the most important parameters in the mechanics of sediment transport are sediment size, sediment concentration, fluid velocity, bottom stress, bed roughness (including biogenic roughness), and geotechnical properties (e.g., cohesion) of the sediment. Both resuspension and flux of sediment are largely controlled by these parameters. Therefore, in order to provide useful information for understanding sediment transport, tripods must be designed to obtain data related to each of these variables. Most tripod data that have been obtained to date have focused on sediment size and concentration, bed roughness, and bottom flow (or stress). To date, sediment properties like cohesion have been difficult to measure in situ, especially if time-series data are desired, and typically these properties are estimated from bottom samples.

Tripods obtain time-series measurements at specific locations in order to capture sediment response to time-varying hydrodynamic forcing. They have been used to investigate sediment movement related to the entire spectrum of fluid processes from turbulence, surface and internal waves, tides, and low-frequency currents. Beginning in the early 1970s, there was already evidence that bottom sediment on shelves was mobilized and transported mainly during storms (Smith and Hopkins, 1972). Long-term tripod deployments have provided data that document storm-driven transport, as well as dramatic seasonal changes in sediment transport and other energetic events (Sherwood et al., 1994; Ogston et al., 2004).

Tripods operate over a range of water depths across the shelf from about 10–200 m, and are typically deployed and recovered using deck equipment on research vessels. Tripods can be released from a lowering line or wire using an acoustic release or pelican hook, or the lifting line can be slipped free of the tripod by releasing one end from the vessel. Tripods are usually recovered either by activating a tripod-mounted acoustic release to free a recovery float with recovery line that is housed in a container on the tripod, or by bottom dragging for a deployed bottom line attached to the tripod-lifting point. The latter technique is often used in shallow water depths. In some instances tripods that are deployed in generally calm, shallow regions with good visibility can be recovered using divers. Acoustic beacons attached to the tripod frame have been used to aid in relocation.

Occasionally tripods have returned with considerable biofouling. Tripods recovered in productive waters like that in Massachusetts Bay off New England at times had limited data sets because of the fouling (see Downing, 2006). Other mishaps such as damage to tripods hitting the side of the ship during launch or recovery, damage caused by fishing operations, or failure of the acoustic release to free the recovery floats have been responsible for occasional loss of data. In some cases tripods that failed to release recovery floats have been located

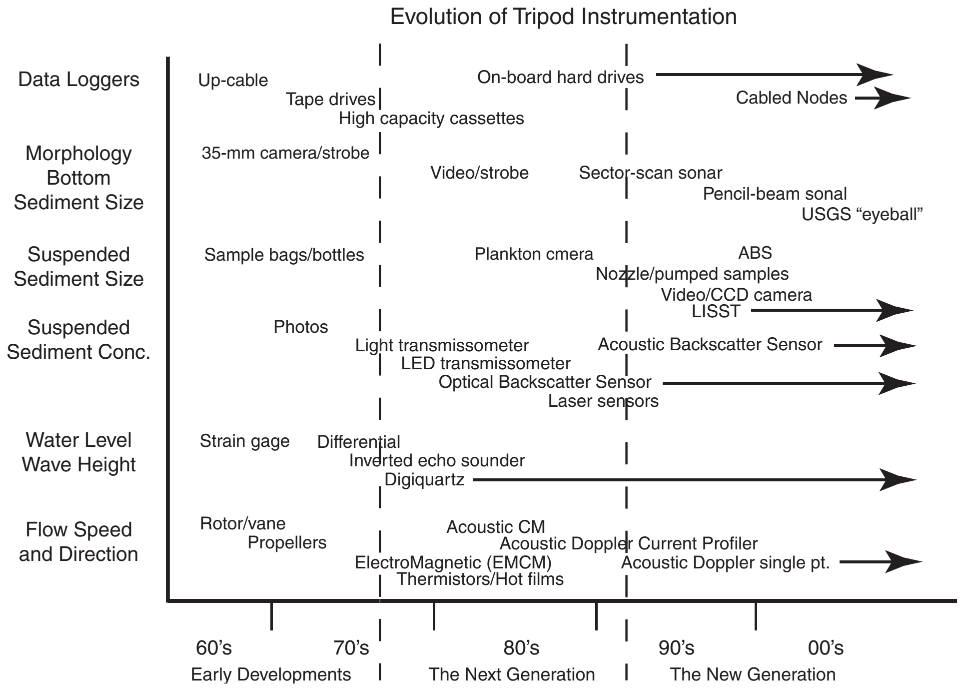

Fig. 2. Graphic showing chronological development of some of the important instruments that have been used on tripods. Most of the instruments are discussed in the text.

using underwater sonar ranging devices or acoustic pingers installed on the tripods and recovered using ROV operations, drag hooks, or fishing nets.

Major improvements in underwater instrumentation spurred development of more complex and diverse tripod systems over the past four decades. The evolution of instrumentation that has been used on tripods is shown diagrammatically in Fig. 2. Many of the new instruments have made major increases to the quality and quantity of tripod data. Some of the newer instrument developments that have significantly improved the quality and accuracy of data collected in the BBL include acoustical sensors to measure flow velocities; optical, acoustic and laser-based sensors to measure particle sizes and concentrations in suspension; and high-resolution pressure sensors to measure surface waves and tides over a wide range of seafloor depths and locations (Fig. 2).

3. Tripod evolution

A brief history of tripod development and applications are presented in this section. The historical picture has been subdivided into three eras: early 1960s–mid 1970s; mid 1970s–mid 1980s; and mid 1980s to present. This breakdown is somewhat arbitrary, but it is partly related to the number of tripods in each period, the evolution of instrument systems (Fig. 2), and the corresponding advances in sediment-transport research (Fig. 3). A chronological list of various tripods and their origin would be vast, as many variations of BBL tripods have been developed throughout the world, with differing scientific purpose. Although the focus here is on US tripods that were designed to study small-scale sediment transport processes, other measurements systems have made significant contributions to understanding benthic sediment dynamics (e.g., Green, 1996; also see summary by Sternberg, 2005).

3.1. Early tripod developments—the first decade

The first tripod was assembled at University of Washington (UW) by Sternberg and Creager (1965) to investigate the BBL and sediment transport in tidal channels within Puget Sound. This earliest tripod (Fig. 4a) was constructed out of aluminum pipe and was tethered to a research vessel with a lifting line and underwater electrical cable. The initial experiment was to obtain measurements of

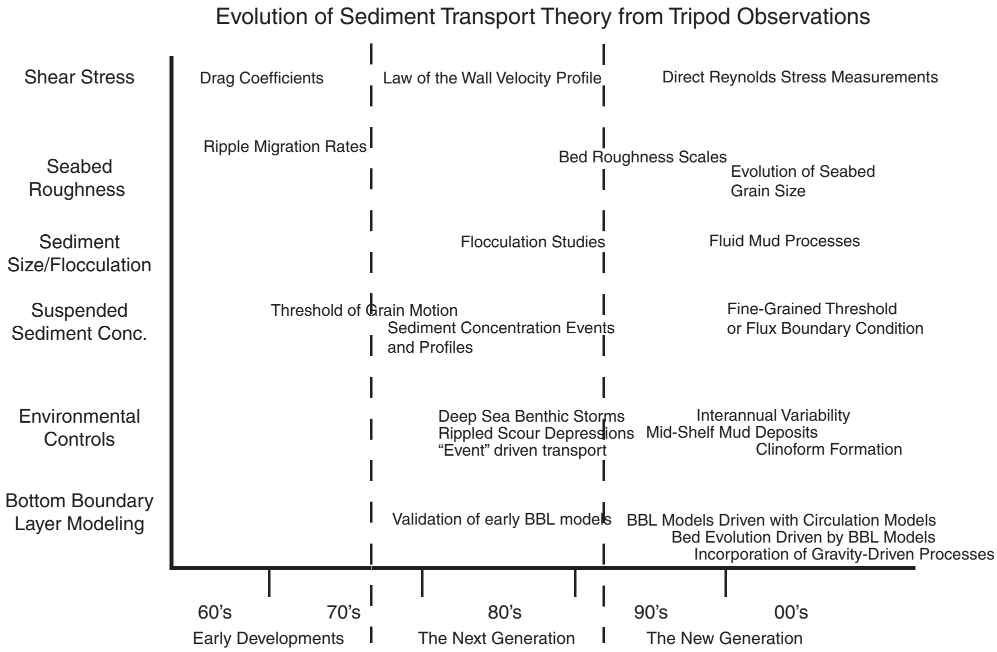

Fig. 3. Important discoveries made by tripods over nearly five decades since the 1960s. This list is not exhaustive, and is meant to indicate some of the significant contributions that tripod experiments have made to the field of sediment dynamics.

near-bottom flows and video images of the seabed to determine if formulae that predicted boundary shear stress and drag coefficients from velocity profiles and ripple migration based on near-bottom flow velocities could be applied in tidal channels. In November 1964 the tripod was deployed over about 3 days from a small vessel anchored in a channel in lower Puget Sound, WA where the mean water depth was about 23 m (Sternberg, 1968). The velocity profile data spanned the 3-day period and enabled computations of the magnitude of bottom stress τ and bottom drag coefficient C_d through several tidal cycles. Useable sediment transport data were limited to a 40-min period when both the current and video instruments operated satisfactorily (the sensor performance was limited by fouling from kelp). Based on the analysis of these data, it was determined that formulae derived from laboratory and river experiments predicted both sediment resuspension and sand ripple migration rates reasonably well in the tidal channel (Sternberg, 1968). This work marked a major milestone in the use of tripods for sediment transport investigations.

During the latter part of the 1960s and into the early 1970s the UW tripod was used at other locations to investigate velocity profiles near the seabed and the validity of the "law of the wall"

$$\frac{\bar{u}}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_o}\right) \tag{1}$$

for turbulent tidal flows over rough bottoms (Sternberg, 1972). $\bar{u}$ is mean current speed at level z above the bottom; u_* is friction velocity ($\tau = \rho u_*^2$); κ is von Karman's constant ~0.4; and z_o is hydrodynamic roughness. The UW tripod measurements contributed to many important advances in marine sediment transport that included: estimates of bottom drag coefficients C_d over a rippled bottom (Sternberg, 1972); threshold flow conditions for resuspension of sandy bottom sediment (Sternberg, 1971); and field evaluation of bed-load equations (Kachel and Sternberg, 1971).

Improvements to instrumentation and structure came quickly to the UW tripod. The successes of the first tripod generated enthusiasm to obtain quantitative data about the effects of waves and currents on bottom sediment at other locations in the coastal ocean. The next version was designed for unattended operation on the open continental shelf in water depths to 200 m and for durations of 1 month or more (Fig. 4b; Sternberg and Creager, 1965; Sternberg et al., 1973). The redesigned frame was

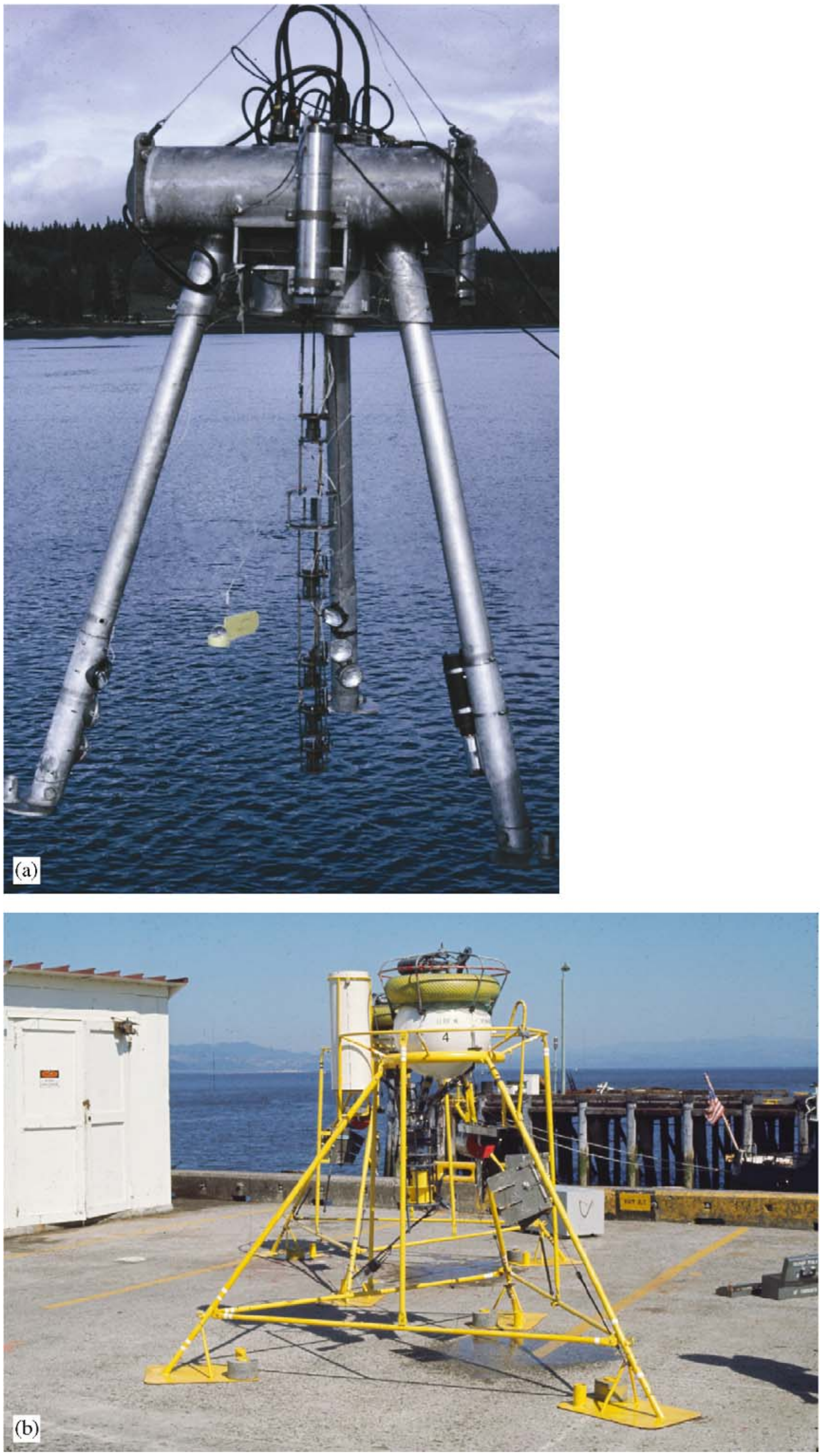

Fig. 4. (a) The deployment of original tripod developed at UW (Sternberg and Creager, 1965). Note the stack of small rotor current sensors inside the legs, and the temperature sensor attached to the bottom of one leg (right leg in photo). (b) Second tripod constructed at UW for shelf sediment transport experiments (Sternberg et al., 1973). Rotor and vane current sensors are visible near the center inside the frame.

weighted with large footpads attached to the base of each leg to minimize sinkage into the sediment. The tripod used strip charts to record time-series current and pressure data (Sternberg et al., 1973). The electronics and strip-chart recording systems were placed in an anodized cast aluminum sphere (51 cm diameter) in which a plastic port was installed at the bottom for a camera. The sphere was mounted within the frame about 2 m above the tripod base (Fig. 4b). The sensors included a current rotor and vane (for current speed and direction) at 1 m above the tripod base, pressure transducer (for water level and wave heights), and a 35-mm camera and underwater strobe (mounted on a leg). This newly configured tripod was used in a variety of locations and experiments throughout the 1970s and 1980s. Important results derived from the tripod data included wave-induced resuspension criteria for sandy bottom sediment on the continental shelf off Washington (e.g., Sternberg and Larsen, 1975 and 1976; Sternberg, 1986).

3.2. *The next generation of tripods—late 1970s–mid-1980s*

Sparked by the successes of the UW tripod experiments, other tripods appeared during the mid-1970s–mid-1980s. Scientists at US Geological Survey (USGS), Virginia Institute of Marine Sciences (VIMS), and National Oceanic and Atmospheric Administration (NOAA) independently constructed tripods for BBL and sediment transport experiments in estuaries and on continental shelves. (Personal note: the lead author and USGS colleague, D. Drake made a valuable visit to R. Sternberg at UW in 1975 to discuss tripod design and handling.) USGS tripods were rugged systems designed for handling on large research vessels and for unattended, long-term (1–6 months) deployments in a variety of shelf environments. USGS GEOPROBE tripods (Fig. 1, modern version) have been in use since they first appeared in 1976 (Cacchione and Drake, 1979). GEOPROBE tripods have been outfitted with a sequence of new instrumentation over the three decades of use, but their basic design has remained unchanged. Similar tripod systems were developed and used over about the same time period at more than 210 locations by USGS scientists in Woods Hole, MA (Butman et al., 1979).

Other instrumented systems that appeared during this period included an early tripod used in experiments off New Jersey (Lesht et al., 1976), a quadrapod deployed off New Zealand (Carter et al., 1976), and a tripod constructed by Canadian scientists (Heffler, 1979). All of these systems were used primarily in various field experiments to investigate sediment processes on continental shelves.

GEOPROBE tripods were the first to use a vertical array of spherical electromagnetic current sensors in order to estimate current-induced shear stresses in the BBL using Eq. (1) (Cacchione and Drake, 1979). Solid state electromagnetic current meters only 4 cm in diameter provided long-term measurements of near-bottom wave and current velocities with minimal biofouling (Cacchione and Drake, 1979). Other solid-state current sensors also were introduced during this period. Small heated thermistor sensors mounted on a tripod that was deployed on the shelf off Oregon provided current data in the lowermost region of the BBL that were used to estimate C_d (Chriss and Caldwell, 1982). Benthic acoustic sensor systems (BASS) were the first tripods to use acoustic current meters for measurement of currents at specific levels above the bed. BASS tripods were developed at Woods Hole Oceanographic Institution in the early 1980s, and were intended for handling on large research vessels at all ocean depths (Williams, 1985). Acoustic Doppler current profilers (ADCPs) were installed on tripods in the late 1980s, and made it possible to obtain detailed vertical profiles of current velocity over hundreds of meters above the seabed. Once adapted to tripods, ADCPs greatly expanded the vertical measurement domain, and linked water column dynamics to BBL processes.

During this period other instrumentation emerged that provided important data on sediment parameters in the BBL. A major advance in measurement of suspended sediment concentrations initially came from use of optical sensors: optical backscattering sensors (OBS; Downing et al., 1981) and LED transmissometers (Bartz et al., 1978). OBS were rather small robust sensors that could operate in turbulent nearshore environments. They provided time-series data over a large range of suspended sediment concentrations. Transmissometers were also used to obtain suspended sediment concentration measurements in regions with lower turbidity. Later, particle characteristics such as size and shape were measured on some tripods with special camera systems that were modified to obtain images of suspended materials (e.g., Kranck and Milligan, 1992). Still and video cameras with underwater strobe lighting were incorporated on tripods to obtain images of the seabed. Important data were collected with these camera systems on physical bottom roughness (wave and current ripples, biogenic structures, etc.) and on types and numbers of benthic organisms (e.g., Nichols et al., 1989).

Tripod capabilities were greatly improved during this period with the utilization of digital data loggers and controllers. Tripods were equipped with new digital systems that greatly expanded data storage capacity while offering large reduction in size and power requirements. Strip chart recorders were replaced in the mid-1970s by high capacity (~4 Mb), rapid-recording cassette tape drives (Cacchione and Drake, 1979). In the 1980s solid-state recording devices such as miniaturized computer hard drives created a quantum jump in tripod data collection. Small, low-power computers were installed to control data sampling (often set to measure high-frequency wave and turbulent motions), and to record hundreds of megabytes of rapidly sampled, time-series data throughout the experimental duration (e.g., Grant et al., 1984).

The emergence of tripods during the 1970s and 1980s was contemporaneous with major advances in conceptual and theoretical modeling of shallow marine sediment transport. Important laboratory work by Jonsson (1966) and others on wave BBLs and friction factors provided background and impetus for development of 1-D BBL models that dealt with combined flows of waves and currents (Smith, 1977; Grant and Madsen, 1979; Fredsoe, 1984). These models provided methods to calculate bottom stresses, velocity and suspended sediment concentration profiles for combined wave-current flows. The models required inputs of near-bottom wave and current data, which were provided by tripods. Model predictions were tested by comparison to tripod-based results, and the models were modified to improve their skill.

3.3. Tripods—the new generation

Newly designed tripods emerged during the mid- to late 1980s equipped with many of the new instruments shown in Fig. 2. Most of the tripods that were originally constructed before the mid-1980s like GEOPROBE and BASS were updated with new instruments and recording systems. Improvements in battery power enabled longer sensor "on-times" for increased data collection and longer deployments. Advances in computer miniaturization provided gigabytes of data-logging capacity that allowed high-frequency sampling for waves and turbulence over longer periods of time. However, in this new generation, biofouling of sensors remains a key limitation in deployment duration.

Single-point acoustic Doppler velocimeters (ADVs) became the preferred current sensor on the newer tripods, largely owing to their accurate and rapid sampling capabilities, and relatively low power usage. ADVs can be sampled at frequencies up to about 20 Hz, providing data on turbulent velocity fluctuations near the bed. These data can be used to compute turbulent Reynolds stresses, which could be compared with stress estimates obtained from other techniques (Shaw and Trowbridge, 2001; Shaw et al., 2001; Sherwood et al., 2006). High frequency, pulse-coherent acoustic Doppler profilers (PC-ADPs) have recently been adapted to some tripods, allowing for direct measurement of low-frequency current profiles in vertical bins of 5 cm or less over vertical distances of about 2 m above the bed (Lacy and Sherwood, 2003). These data can be used to make high-confidence estimates of current-induced bottom stresses from Eq. (1). The newest PC-ADPs provide direct measurements of near-bottom wave velocities, and in combination with the bottom current measurements can be used to estimate combined wave-current bottom stresses. In addition, algorithms to convert acoustic backscatter intensity data from ADCPs and PC-ADPs into estimates of suspended sediment concentrations have been developed (Thorne and Hanes, 2002). This technique can be used to calculate a detailed profile of suspended sediment concentration from tens of centimeters to tens of meters above the bottom.

Sector-scanning high-frequency sonars are now used on tripods to obtain detailed images of seabed morphology and their temporal scales of change, in addition to providing information on the acoustic character of surface sediment (Cacchione et al., 1999). Narrow-beam ("pencil-beam") sonars have also been used on tripods to measure bed elevation over short transects at repeated time intervals. These data measure small-scale changes to seabed features such as ripple heights and wavelengths. Although optical instruments continue to be standard sensors for measuring suspended sediment concentration, high-frequency acoustic backscatter sensors (ABS) are also now used to profile suspended sediment concentrations within the bottom few meters (e.g., Thorne et al., 1993). The most recent versions of ABS can also provide information on sizes of suspended sediment in coarser-grained sediment suspensions (Thorne et al., 1993). Measurements of suspended sediment concentration in fine-grained suspensions using acoustic methods have met with some success, although issues remain with calibration using natural concentrations.

More recently, laser diffraction instruments have been used to collect time-series measurements of particle size distributions and concentrations of suspended materials at single levels above the bottom (Agrawal and Traykovski, 2001; Mikkelsen and Perjup, 2001) and particle-settling velocity has been measured using video systems (Sternberg et al., 1999). Suspended sediment concentration profiles are used to compute size-dependent suspended sediment flux when combined with velocity profile measurements from ADPs (Betteridge et al., 2002). A new instrument that has been recently developed to measure bed sediment size distributions is the USGS "eyeball" camera system. It provides detailed close-up images of the bed sediment from which grain size distributions can be calculated using image-analyzing software (Rubin et al., 2004).

Advances in flow and sediment transport models continue to be based on new findings obtained from tripod measurements. Improvements to shelf BBL models based on tripod experimental data include incorporation of settling velocities for flocculated suspended sediment dynamics associated with downslope, gravity-driven, dense bottom layers that are maintained by energetic near-bottom wave stresses (Traykovski et al., 2000). Numerical 3-D process-based sediment transport models are also being used to investigate seabed evolution. The generation of bottom morphology and the formation of sedimentary strata in shallow marine environments are important objectives for the new models. Integration of 1-D BBL models into larger-scale 2-D and 3-D shelf circulation and sediment transport models has made significant advances in our understanding of sedimentary processes in the oceans (Niedoroda et al., 1995; Harris and Wiberg, 2002).

4. Tripod experiments

Tripods have played a major role in a number of multi-institutional, multi-disciplinary field programs commencing with the Coastal Ocean Dynamics Experiments (CODE) in 1981–82. Examples of tripod deployment locations from a variety of experiments and institutions are illustrated in Fig. 5. During CODE both GEOPROBE and BASS tripods collected data that were used to estimate bottom stresses and roughness scales at several sites on the northern California shelf. The results were compared with 1-D BBL model predictions to evaluate model performance, and results indicated

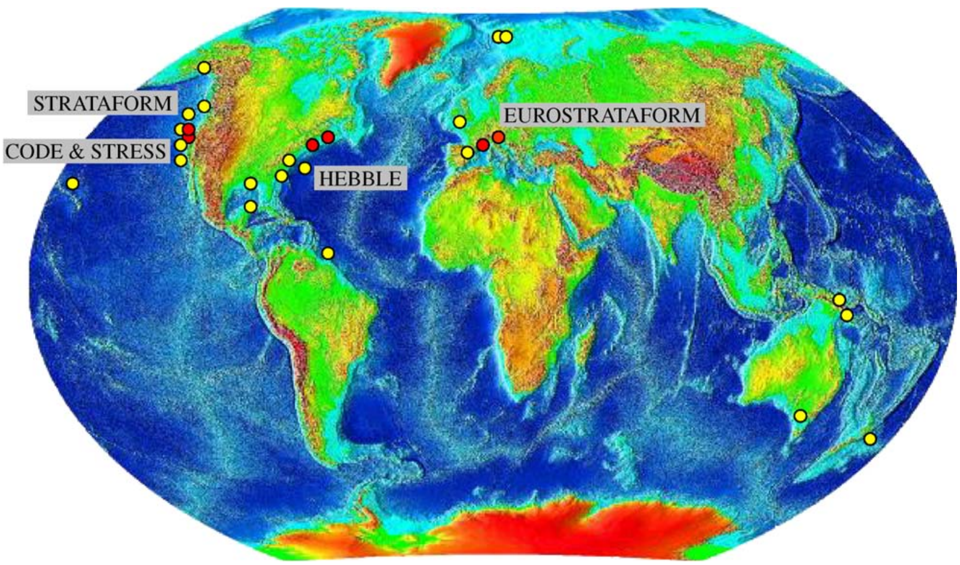

Fig. 5. Locations of many tripod experiments over the past four decades. Repeated deployments in a region (>5) are shown by red dots. Major multi-institutional tripod experiments are named and are described in text.

that model predictions of combined wave-current stresses on the shelf were generally accurate and useful (Grant et al., 1984; Cacchione et al., 1987a). In addition, during CODE the GEOPROBE tripod obtained the first quantitative data within rippled scour depressions (RSDs) on the inner shelf (Cacchione et al., 1984).

The BASS tripod, having been successfully deployed at several shelf locations, was one of the first tripods used in the deep ocean during high-energy benthic boundary layer experiments (HEBBLE; Nowell and Hollister, 1985) to obtain measurements of flow and suspended sediment concentrations within the deep western Atlantic boundary current (Grant et al., 1984). These data confirmed the occurrence of deep benthic "storms" that caused resuspension and along-isobath transport of large amounts of deep-sea fine sediment (Gross and Williams, 1991).

Several years later during the 1988–89 sediment transport experiments on the shelf and slope (STRESS) in the same region as CODE, BASS and GEOPROBE tripods again obtained BBL data that were used to validate 1-D BBL predictions of current-induced bottom stress, and to improve 1-D BBL models (Wiberg et al., 1994). Based on the tripod data and model results, sediment flux was calculated at a number of shelf locations to document the importance of winter storms in transporting sediment along and across the shelf (Sherwood et al., 1994). The results showed the overriding significance of storm-generated, combined wave and current stresses in shaping and driving the migration of large sand ripples and low amplitude crescentic dunes within RSDs on the inner shelf (Cacchione et al., 1984 and 1987b).

Tripod systems developed at VIMS have been deployed in a variety of environments since the mid-1980s, including estuaries with both strong and weak tidal flows (e.g., Wright et al., 1997), and open shelf regions dominated by strong currents and intense wave energy (Wright et al., 2002). These systems have documented the erosion and transport of sediment caused by storms on the inner shelf, most dramatically off Duck, North Carolina after recovery of a tripod data logger that had washed up on a nearby beach (Wright et al., 1994). Although the tripod measurements showed convincingly that large surface waves controlled the suspension of bottom sediment, the data also documented that the across-shelf transport of the fine sand was controlled by low-frequency flows.

One of the most concentrated and successful deployments of a variety of tripods occurred in 1995–2000 during the multi-institutional experimental program Strata Formation on Margins (STRATAFORM) on the continental shelf and upper slope off the Eel River of northern California (Nittrouer and Kravitz, 1996; Nittrouer, 1999). Tripods from UW, VIMS, WHOI, and USGS (GEOPROBE) were deployed at various times throughout the 5-year period. The UW tripod was maintained on a muddy surface deposit in 60 m water depth for the entire 5-year duration of STRATAFORM (Ogston et al., 2004), while the other tripods were located at various sites on the shelf for shorter periods (Nittrouer, 1999). A number of significant findings have evolved from the integrated tripod measurements including the causes of shelf sand/mud transition zones (Friedrichs et al., 2000), the development and maintenance of shelf clinoforms (Walsh et al., 2004) and generation and maintenance of bed roughness (e.g., Nittrouer, 1999; Wheatcroft, 2000).

Recent benthic tripod observations using the latest generation of instruments has continued to advance our knowledge of BBL and sediment dynamics under a wide range of marine conditions. Fluid muds have been measured on a number of shelves using both tripod-mounted OBS and ABS. Transport of fluid muds is now thought to play an important role in creating fine-grained deposits on deltas. Seaward progradation of the subaqueous Amazon delta is likely caused by this process (Cacchione et al., 1995; Kineke et al., 1996; Kuehl et al., 1996). An instrumented tripod "Gafanhoto" that was originally developed in the late 1980s for obtaining shipboard profiles of suspended sediment concentrations, temperature, salinity, and current has made important contributions to our understanding of gravity-driven flows of fluid muds in several shelf regions offshore of large rivers including the Amazon and Eel Rivers (Sternberg et al., 1991; Kineke and Sternberg, 1995). Gravity-driven mud flows that are maintained by high wave-induced bottom stresses are major factors controlling the distribution and locations of shelf mud deposits (Friedrichs et al., 2000; Ogston et al., 2000; Traykovski et al., 2000).

Tripod measurements have inspired new thinking about the role of high concentrations of suspended sediment on BBL velocity profiles (Friedrichs and Wright, 1997; Wright et al., 2001). Reduced turbulent velocity shear caused by strong density stratification due to high suspended sediment concentrations close to the bed lowers bed shear stress and limits entrainment of bottom sediment (Friedrichs et al., 2000). Shelf tripod experiments have shown that benthic biota can modify sediment response to fluid stresses (Nowell et al., 1981; Wright et al., 1997), and alter bed shear stress through changes in bed roughness (Drake et al., 1992). These findings have led to important modifications of 1-D sediment transport models. Regional numerical circulation and sediment transport models have also benefited from tripod measurements, using the data for model input and to check model predictions (e.g., Harris and Wiberg, 2001).

The latest major deployment of tripods occurred in 2003–05 as part of the European STRATAFORM (EUROSTRATAFORM) program (Nittrouer et al., 2004; Sherwood et al., 2004). Experiments on sediment resuspension and transport on the shelves in the western Adriatic Sea and in the Gulf of Lyons have included numerous tripods from several sources (Sherwood et al., 2004; Fain et al., submitted for publication; Puig et al., submitted for publication; Traykovski et al., submitted for publication). USGS GEOPROBE tripods that were deployed in EUROSTRATAFORM have been substantially upgraded and modified to contain the latest instrumentation and recording systems (Sherwood et al., 2004). An unique bottom system for obtaining time-series measurements of sizes and concentrations of near-bottom suspended particulate matter was also used during EUROSTRATAFORM (Mikkelsen et al., 2005). These latest tripod data will advance our understanding of sediment processes along the transport pathways from the river sources along the eastern Italian and southern French coasts to shelf and deeper depocenters.

5. Discussion

Tripods have made significant contributions to our understanding of shelf sediment transport over the past four decades. Tripod measurements have been collected at many locations on shelves and in estuaries, over a broad range of sedimentary and oceanic conditions. Some (and by no means all) of the tripod deployment locations are shown in Fig. 5. Tripods have provided critical quantitative data that have been used to investigate BBL dynamics and sediment processes, and that have advanced our knowledge of the seabed closest to our coasts. Tripod results have led to new understanding in at least two major topical areas:

1. Bottom boundary layer dynamics
   - Flow measurements close to the seafloor have documented the shape of the velocity profile under combined wave-current flows, and been used to calculate shear stress from a variety of techniques including log profile, turbulent dissipation, and Reynolds stresses (Grant et al., 1984; Shaw and Trowbridge, 2001; Sherwood et al., 2006).
   - Time-dependent variability in bottom flows has been demonstrated for different atmospheric and oceanic conditions. Near-bottom wave velocities and low-frequency bottom currents have been measured during different seasons, storm events, and spring-neap tidal periods at a wide variety of geographic locations on continental shelves. These data have documented the richness and complexity of BBL dynamics including strong bottom currents due to pulsating internal solitons and internal tides (Noble and Xu, 2004), and persistent downslope (offshelf) gravity-driven flows (Traykovski et al., 2000).
   - Bottom drag coefficients and roughness length scales have been calculated from tripod measurements. These parameters have been used in various shelf circulation models (Harris and Wiberg, 2001).
2. Sediment transport
   - Threshold flow and bottom stress conditions for sediment resuspension have been established for a variety of natural sediment conditions on shelves and in estuaries (e.g., Sternberg and Larsen, 1975; Drake and Cacchione, 1989).
   - Transport of flocs and their significant role in shelf sediment transport have been documented at several shelf locations (Sternberg et al., 1999; Geyer et al., 2000; Hill et al., 2000).
   - Sediment flux convergence patterns in both along and across-shelf direction have been observed which are correlated to boundaries of shelf mud deposits (Wright et al., 1999; Ogston et al., 2000).
   - Gravity-driven flows laden with high suspended-sediment concentrations transport large amounts of sediment into deeper sections of the shelf (e.g., Scully et al., 2002). These

flows can originate on the inner shelf as a function of waves, currents, and frontal zone dynamics and can play a major role in the formation of mid-shelf mud deposits (Wright et al., 2002; Guerra et al., 2006).

- Relationships of ripple formation and migration to wave and current bottom stresses have been derived based on tripod current data, sonar and photographic observations (Trembanis et al., 2004).
- Interannual variability of suspended sediment flux shows significant changes in direction, magnitude, and wintertime duration. Dominant physical processes forcing sediment transport include waves, currents, river/sediment discharge, and mesoscale circulation patterns (Ogston and Sternberg, 1999; Ogston et al., 2004; Guerra et al., 2006), each of which varies inter-annually.
- Analytical and numerical models of marine sediment transport have used tripod data as input. The models provide estimates of shear stresses, resuspension rates, bottom roughness, and sediment flux. Calculations of shear stresses, sediment flux, and bottom roughness from tripod measurements of velocity profiles, suspended sediment sizes and concentrations, and bottom morphology have been used to validate model predictions, and to improve the models (Wiberg et al., 1994; Harris and Wiberg, 2001; Pullen and Allen, 2000).

Modern tripods can be deployed for long time periods, limited now mainly by bio-fouling of sensors and available power. Individual tripod deployments exceeding 6 months have been accomplished (e.g., Sternberg et al., 2001). These long deployments capture sediment transport events due to storms and the effects of changes to low-frequency flows (e.g., intrusion of eddies and oceanic fronts onto the shelf).

In recent years, scientists have expressed the need for long-term experiments on shelves and in estuaries in order to address longer-term issues such as inter-annual variability of natural processes and climate change. This interest has led to the emergence of seafloor observatories. Examples include the long-term ecosystem observatory (LEO-15) located on the New Jersey inner shelf. LEO-15 uses a cabled network on the seabed to transmit in real time visual images and measurements of temperature, currents, turbidity, and pressure (Glenn et al., 1998). Future considerations include NEPTUNE, an underwater observatory system that would include fiber-optic/power network of distributed sensors on the scale of an oceanic plate off the west coast of the USA and Canada (Delaney et al., 2001). More recently, a large multi-disciplinary, multi-institutional observatory program, Ocean Research Interactive Observatory Networks (ORION), has been established under the auspices of the US National Science Foundation (NSF), Joint Oceanographic Institutions (JOI), and the Consortium for Oceanographic Research and Education (CORE). These new ventures promise major advances in our understanding of the seafloor, including BBL dynamics and sediment transport. Tripod instrumentation and data analysis developed for sediment transport studies have already been incorporated into the seafloor observatory systems, and extended tripod deployments will likely be an integral part of future underwater observatory experimental programs.

6. Conclusions

Since the initial instrumented tripod appeared in the mid 1960s, these bottom measurement systems have made significant contributions to our understanding of BBL dynamics and sediment transport in the coastal ocean. Tripods can be assembled on ships and in staging areas close to research areas. This mobility has allowed these systems to be deployed in many locations worldwide. Tripod data from many shelf locations have helped to dispel the notion that the seabed beyond depths of tens of meters is placid. In fact, tripod data have been used to demonstrate that during energetic storms, waves and currents actively resuspend bottom sediments across shelves, and transport large quantities of suspended materials both along-shelf and across-shelf into deeper water (Ogston et al., 2004). Tripod measurements have also played a major role in testing predictions from sediment transport models. Where the models have failed to compare favorably to the tripod-based calculations, improvements to the analytical and numerical schemes have been made.

New findings based on tripod experiments have uncovered important sediment processes not previously known. Measurements of fluid mud flows in delta and shelf regions off rivers with high sediment discharge have revised ideas about movement of fine-grained sediment into deeper water (Cacchione et al., 1995; Kineke et al., 1996; Traykovski et al., 2000). Based on limited tripod data sets, it is now thought that in those regions where active fluid-mud transport occurs, much of the seaward transport of fine-grained sediment is accounted for by down-slope movement of fluid muds (Wright et al., 2002).

Continuing advances in instrumentation for measurement of sediment transport parameters and in situ data logging systems have been incorporated in tripods, thus increasing measurement capabilities and accuracies. For example, the use of ADCPs on tripods has enabled measurements of vertical profiles of currents that link the dynamics of the overlying water column to near-bottom flow and sediment processes. This linkage has aided development of numerical sediment transport models that require inputs on water column currents, sea-level fluctuations, and bottom roughness. Coupled with high-resolution side-scan and multi-beam sonar mapping of the seafloor, tripod measurements have been used to investigate features such as RSDs, mid-shelf mud deposits, clinoforms, sand–mud transitions, and sediment bedforms. The merging of multiple measurements systems in field experiments to investigate sediment processes will greatly increase our future capabilities to obtain the necessary data to understand and model generation of shelf sedimentary deposits and changes to seafloor morphology.

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