

Introduction: Exploring the deep sea and beyond: Contributions to marine geology in honor of William R. Normark

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All men by nature desire knowledge.
Aristotle (384 BC–322 BC), *Metaphysics*

We shall not cease from exploration.
And the end of all our exploring will be to arrive
where we started and know the place for the first time.
T.S. Eliot (1888–1965), *Little Gidding*



Bill Normark, May 2006.
Photo taken in Italy.

A volume in honor of William R. Normark, known to all of us as simply Bill, is an appropriate contribution to the memory of a great scientist, an extraordinary mentor, and an unrivaled friend. Editors and authors were energized by the opportunity to craft such a volume: to us Bill was a friend, a colleague, and an insightful peer always ready to share new ideas. For some of us Bill was a mentor, an inspiration, and an unmatched role model. The variety and creativity reflected by these manuscripts revisit Bill's broad interests in earth sciences. His holistic approach to science and his natural talent for synthesizing large data sets made Bill the prototype of the modern scientist. Integration across disciplines, scientific rigor, and masterful syntheses together represent the "core" of Bill's legacy. This volume embodies Bill's ideas of exploring nature with every available tool while keeping his mind open to surprises around each corner. Throughout his career, targeted exploration remained the most effective scientific method to apply to revealing the ocean's secrets. This volume collects scientific contributions from recognized experts in different fields. Contributions are from marine geology, sedimentology, tectonics, seafloor geomorphology, and overarching earth sciences. Before we go into the details of the notable contributions collected in this volume, we briefly retrace Bill Normark's scientific life and his many achievements below. The history of Bill's career and the evolution of his scientific methods and interests provide necessary context for the structure of this volume in his honor.

BILL'S CAREER AND ACHIEVEMENTS

William R. Normark passed away on January 12, 2008, at his home in Sunnyvale, California, after staunchly fighting cancer for nearly eight years.

A proud Wyoming native, Bill moved to the West Coast to attend Stanford University for his undergraduate studies in 1961 where he earned his Bachelor of Science degree in geology in 1965. After graduating from Stanford, Bill headed to Scripps Institution of Oceanography (SIO) for his PhD. Bill's first cruise at Scripps was with pioneering marine geoscientist Francis Parker Shepard. Shepard invited incoming students to go to sea with him before classes started. The cruise sailed directly up the coast to core the Monterey Fan and map in detail the now famous Shepard Meander. After earning his PhD, Bill spent four years at the University of Minnesota, where he started his pioneering work on density-driven underflows using the natural laboratory of Lake Superior. His famous work on Lake Superior gravity-driven underflows was the vehicle through which he was introduced to Gary Parker. Gary provided Bill with an insightful review of his very innovative paper (Normark, 1989); the two would never forget the experience, working together again on documenting and numerically demonstrating the recurrence of cyclic steps across deep sea-scapes decades later (Fildani et al., 2006). The contributions from Gary Parker's group (Eke et al., this volume) and of Svetlana Kostic (this volume) are a natural follow-up to that great collaboration. Even though Bill enjoyed skiing to work during the long winters of Minnesota, the distance from the ocean and his passion for pure research made the "call" from the West an irresistible one for a marine explorer like him. Bill moved back to California in 1974 and began his distinguished career at the U.S. Geological Survey in Menlo Park.

Bill was best known for his work on the character and depositional patterns of turbidite fan deposits, including work on the Navy, Laurentian, Delgada, Monterey, Hueneme, Mississippi, and Amazon fans. His work was informed by and applied to ancient turbidite successions, leading to a productive collaboration with the Italian turbidite school, including Emiliano Mutti (University of Parma) (Mutti and Normark, 1991), and Gian Gaspare Zuffa (University of Bologna). Notably, his long-continuing collaboration with David Piper of the Geological Survey of Canada led to a series of seminal papers about the architecture, sediment type, and growth patterns of fan deposits, both ancient and modern (Normark and Piper, 1991).

Bill served on several Ocean Drilling Program (ODP) advisory panels, was the Joint Oceanographic Institution/U.S. Science Advisory Committee's Distinguished Lecturer for 1995/96, and participated in ODP Leg 155 (Amazon Fan). During much of Bill's career, he served on editorial boards of high profile journals, including *Geology*, the *Journal of Sedimentary Petrology* (now *Journal of Sedimentary Research*), *Marine Geology*, and the *Giornale di Geologia*. He was AAPG Distinguished Lecturer in 1986–87.

Bill was the primary author of at least 90 peer-reviewed papers among the more than 230 total papers (and some 150 presentations) that carry his name. He participated in more than 60 USGS research cruises, about half as chief (or co-chief) scientist. Bill was a recipient of the Department of Interior Meritorious (1986) and Distinguished (2002) Awards; he also received the Michael J. Keen Medal (2003) from the Geological Association of Canada for contributions to the field of Marine Geoscience and the Francis P. Shepard Medal (2005) from SEPM for Excellence in Marine Geology, and was elected a Fellow of the American Geophysical Union in 2006.

VOLUME CONTRIBUTIONS

The ideal venue for this collection of work in honor of Bill's memory is *Geosphere*, which demonstrates applications of new technologies in earth science, including deep-sea exploration, and advocates new ways of doing and reporting science in a provocative yet rigorous way. The range of papers reflects the broad scope of Bill's interests and scientific impact. We trust it is a suitable memorial to a remarkable scientist and dear friend, and we are convinced that these contributions will be of high import to the broader scientific community.

While all the manuscripts are well integrated and amenable to a broad audience, there are affinities that help loosely cluster them by methodology and/or topic.

Contributions from Paull et al. and Macdonald et al. have the typical deep-sea exploration and fresh discovery flavor that always inspired Bill. The two contributions from Paull et al. are a natural follow-up to the latest collaboration that Bill and Charlie Paull undertook using the AUV (autonomous underwater vehicle) developed at the Monterey Bay Aquarium Research Institute. The AUV is able to produce unprecedented high-resolution images and has been used to detail the seafloor of the Monterey Canyon and its tributaries. Here, the processes governing large-scale bedform formation have been the center of animated debates in recent

years. By using the AUV and in situ measurements, Paull et al. offers stunning new imagery and thought-provoking hypotheses of these bedforms that will keep the community on its toes for a while to come.

Macdonald et al. present a frontier data set from the deep reaches of the Atlantic Ocean. A series of large-scale erosional scours are described from four modern deep-water canyon/channel systems along the northeast Atlantic continental margin. Regional-scale geophysical data indicate that most scours occur in zones of rapid flow expansion, such as canyon/channel termini and margins. These large features on the seafloor are imaged with a state-of-the-art AUV. Four distinct scour morphologies are identified: spoon-shaped, heel-shaped, crescent-shaped, and oval-shaped. Isolated scours are shown to coalesce laterally into broad regions of amalgamated scours that may be several kilometers across. The combined morpho-sedimentological data set is used to consider some of the putative mechanisms for scour genesis.

The contributions from Kostic, Eke et al., and Talling et al. belong more to the numerical, experimental, and process-based investigation that Bill always found insightful and key to fully understanding natural processes and testing natural hypotheses.

Kostic offers a fundamental numerical description of an increasingly recognized seafloor feature in submarine cyclic steps. She outlines submarine cyclic steps in the context of sediment waves of various origins and clarifies the physics and the key parameters governing their formation, migration, and architecture. Furthermore, this contribution finally clarifies the frequent terminology confusion between net-depositional cyclic steps and sediment waves in general.

The Eke et al. article presents numerical modeling of breaching as a mechanism for generating continuous turbidity currents. The term "breaching" refers to the slow, retrogressive failure of a steep subaqueous slope, forming a turbidity current directed down slope. They model a breach-generated turbidity current using a three-equation, layer-averaged model that has its basis in the governing equations for the conservation of momentum, water, and suspended sediment of the turbidity current. The model is applied to establish the feasibility of a breach-generated turbidity current in a field setting, using a generic example based on the Monterey Submarine Canyon.

Talling et al. offer an interesting perspective on sediment-flow rheology in deep water, arguing that submarine flows are volumetrically the most important process for moving sediment across our planet. As they describe, long

run-out submarine flows are often thought to be either fully turbulent dilute suspensions called turbidity currents or dense debris flows with high yield strength whose base was lubricated by high pore fluid pressure. They also present a third type of flow that potentially deposits very large volumes of sediment into the deep ocean. They argue that this third type of flow comprises a thin layer of sand-laden muddy fluid with low yield strength, where sand and mud deposition occurs from a laminar plug.

Covault et al., Chiocci and Casalbore, and Piper et al. focus on the processes that sculpt the continental margins, linking them to broader causes such as relative sea-level fluctuations and tectonism (i.e., margin tectonic setting, volcanism, and paleoseismicity).

Covault et al. quantify twenty submarine canyon-and-channel longitudinal profiles across various types of continental margins on the basis of relative convexity or concavity and according to their similarities to best-fitting mathematical functions. Profiles are clustered into convex, slightly concave, and very concave groups, each of which generally corresponds with a continental margin type and distinct depositional architecture. Their results show that longitudinal-profile shape provides a basis for classifying deep-sea sedimentary systems, linking them to the geomorphic processes that shape continental margins.

Chiocci and Casalbore elaborate on the pioneering work done by Chiocci and Normark (1992) on submarine gullies off the west coast of Italy with newly acquired multibeam bathymetry and high-resolution seismic-reflection profiles. The imagery strongly support the early interpretation based on relatively low-resolution 2D seismic-reflection data. Their model links relative sea-level fluctuations and terrestrial processes (river development and catchment basins) to processes sculpting the continental slope of the Tyrrhenian margin offshore western Italy.

Piper et al. use a small basin within the Orphan region on the eastern Canadian margin to infer the region's paleosismological record. They distinguish slump-related and other turbidites on the basis of petrographic and sedimentological grounds, and assess the role of earthquakes using geotechnical data. They argue that the available short instrumental seismological record is comparable to the stratigraphic record.

Marsaglia et al. and Preece et al. strive to a more holistic approach to study continental margins and define themselves as "source to sink" studies, an approach pioneered in deep water by Bill with his work on the Cascadia margin and in southern California (Normark and Reid, 2003).

Marsaglia et al. revisit ODP Site 1122 located on the Bounty Fan offshore New Zealand. A

Late Miocene to Pliocene sedimentation hiatus is linked to the tectonic evolution of the Southern Alps of New Zealand. While there is no significant change in sediment provenance across this interval, Marsaglia et al. attribute the hiatus to a combination of decreased sediment supply related to tectonic disruption of the terrestrial fluvial drainage pattern and potentially simultaneous increase in bottom-current strength.

Preece et al. report on the tectonic and climatic controls on the evolution of the Surveyor Fan and Channel system of the Gulf of Alaska. The deep-water Surveyor Fan is dominated by the >700 km long Surveyor Channel, an anomaly in a system with no major fluvial input or shelf canyons. The sediment supply instead was interpreted to have been provided by glacial erosion in the still-active Chugach–St. Elias orogen and glacial transport across the shelf. The change in morphology observed throughout the sequences of the Surveyor Fan allows the authors to characterize the influence that a glaciated orogen can have in shaping margin processes and the sediment pathway from source to sink.

Still in the exploration/new discovery vein but with global climate implications is the effort from Aiello and Ravelo as they report on the Bering Sea Integrated Ocean Drilling Program (IODP) Expedition 323. Sediments of the Bering Sea, derived mainly from biogenic, glacio-marine, and, secondarily, riverine sources, reflect the history of oceanographic changes within the basin and climatic changes on adjacent continents. Expedition 323 recovered cores that reveal the evolution of sedimentation in the Bering Sea over the past five million years, a period that includes globally significant events such as the early Pliocene warm period, the onset of large Northern Hemisphere glaciation, and the Pleistocene glacial–interglacial and millennial-scale climate cycles. Aiello and Ravelo document the regional response and role of the Bering Sea in these global climate change events, and provide a comprehensive view of sediment types and sedimentation processes on this frontier area.

Advancements in methodologies, technologies, and interdisciplinary communication are at



Bill Normark, 1970, collecting box-cores from Navy Fan, offshore California.

the core of contributions from Moore et al., Xu, and Salmi et al.

Moore et al. present an amazing data set of resistivity images from IODP Site U1322 on the Mississippi Fan showing borehole failure as: (1) low resistivity bands interpreted as breakouts and (2) high resistivity bands. While the low resistivity breakouts resemble similar features in other IODP boreholes from southwest Japan and offshore Oregon, the high resistivity features are unknown in other boreholes. Estimates of stress magnitudes based on the overburden stress and the extensional tectonic environment in the Gulf of Mexico predict that the borehole was at failure. This analysis is the first documentation of this incipient stage of borehole failure.

Xu presents a review paper on several key advancements in both technology and science in the field of “currents in submarine canyons” since the 1979 publication of the similarly titled book by Francis Shepard. Precise placement of high-resolution, high-frequency instruments have not only allowed researchers to collect new data essential for advancing and generalizing theories governing the canyon currents, but have also revealed new natural phenomena that challenge the understanding of theorist and experimentalist alike in predictions of submarine canyon flow fields. These new methods

reveal that turbidity currents are frequent in “active” submarine canyons such as the Monterey Canyon. These turbidity currents have maximum speeds of nearly 200 cm/s, which are much smaller than the speeds of turbidity currents recorded from submarine cable breaks, but potentially are still destructive.

Salmi et al. report on the behavior of methane seep bubbles over a pockmark on the Cascadia continental margin. They use a new method to observe time-dependent bubble plumes and associated zooplankton behavior at a methane seep emitted from the northeast Pacific continental shelf in 150 m water depth offshore Grays Harbor, Washington. Instrumentation consisted of a seafloor mooring with an upward-oriented 200 kHz sonar that imaged the lower 100 m of the water column for 33 h during September 2009. Assuming that the fluxes measured by their instrumentation are constant, they conclude that the total flux from one of some twenty active bubble vents at the site could significantly contribute to the global marine flux of methane to the atmosphere.

ACKNOWLEDGMENTS

We would like to thank the contributors for helping us create a highly impactful volume and the reviewers for helping us maintain the much-needed rigor and balance for a product that will honor William R.

Normark’s scientific life. Bridgette Moore and Dennis Harry are thanked for their support throughout the *Geosphere* adventure. Angela M. Hessler and Jacob A. Covault reviewed an early draft of this editorial.

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MANUSCRIPT RECEIVED 20 JANUARY 2011

REVISED MANUSCRIPT RECEIVED 01 MARCH 2011

MANUSCRIPT ACCEPTED 01 MARCH 2011