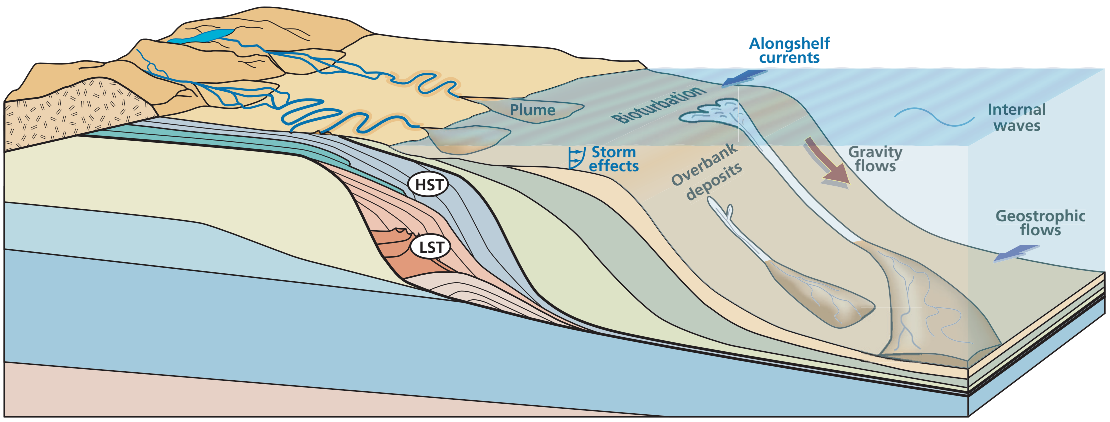
Source-to-Sink (S2S)



Introduction
S2S Questions

1. Executive Summary

Erosion sculpts the landscape, and redistribution of the sediment creates the alluvial plains, coasts, deltas, and continental shelves upon which most of the world's population lives and derives much of its energy and water. This transfer of sediment and solute mass from source to sink plays a key role in the cycling of elements such as carbon, in ecosystem change caused by global change and sea-level rise, and in resource management of soils, wetlands, groundwater, and hydrocarbons. Although the source to sink system has been studied in its isolated component parts for more than 100 years, significant advances in our predictive capability require physical and numerical modeling of fluxes and feedbacks based on data from integrated field studies. The Source-to-Sink Initiative is an attempt to quantify the mass fluxes of sediments and solutes across the Earth's continental margins by answering the following questions:

1) How do tectonics, climate, sea-level fluctuations, and other forcing parameters regulate the production, transfer, and storage of sediments and solutes from their sources to their sinks?
2) What processes initiate erosion and transfer, and how are these processes linked through feedbacks?
3) How do variations in sedimentary processes and fluxes and longer-term variations such as tectonics and sea level build the stratigraphic record to create a history of global change?

The Source-to-Sink Initiative will consist of focused investigations on active convergent continental margins that produce large amounts of sediment deposited in adjacent, closed basins. A suite of inter-connectable numerical and physical-process models with shifting boundaries will be used to test hypotheses concerning process connections and to predict the behavior of these source to sink systems on time scales ranging from individual events to millions of years. Forcing and boundary parameters measured in the field will drive the models, and observations of system variables will allow comparison with model predictions. In this way model results will help to interpret data and data will help test the conceptual understanding embedded within the models.

Processes in the Source-to-Sink system

Rates and mechanisms of sediment production, transport, and accumulation will be monitored using high-resolution digital elevation models, new dating and tracer techniques using cosmogenic isotopes and optically stimulated luminescence, and field acoustic and optical velocimeters for measuring sediment velocity and concentration. High-resolution documentation of the spatial structure of the sedimentary record will be obtained through swath mapping and CHIRP, combined with sediment coring, which will involve new logging tools such as GRAPE and FMS. Experimental work in laboratory settings will allow for the testing of hypotheses under strictly controlled conditions, in which forcing and boundary parameters can be systematically varied.

> "The source to sink system contains most of our energy resources and potable water, and as a result most of Earth's human population lives along the source to sink path"

Following community-wide discussions, the Fly River and adjacent Gulf of Papua (Papua New Guinea) and the Waipaoa River System on the east coast of New Zealand's North Island were chosen for focused research. Selection was based on the ability of the various study areas to address primary scientific objectives, the presence of a strong forcing that produces strong signals, active sedimentation spanning the various source to sink environments, active sediment and solute transfer among environments, system closure to sediment transfer, a high-resolution stratigraphic record, advantageous background data and scientific infrastructure, manageable logistics, small anthropogenic influence, and societal relevance. After five years the two focus areas will be re-evaluated, at which time focus priorities may change.

Differences between the two focus areas are noteworthy. The Fly River and Gulf of Papua constitute one of the few modern examples of a developing foreland basin, and the Waipaoa drainage basin reflects growth of a terrain by volcanism and vertical uplift. The Fly/Gulf System experiences a tropical environment, whereas the Waipaoa is subtropical/temperate. Because of differences in oceanographic environments, the Gulf of Papua possesses both siliciclastic and carbonate sedimentary environments, whereas the Waipaoa margin contains only siliciclastic sediments. The Fly drainage basin (75,000 km^2) experiences relatively constant discharge, the main perturbations being linked to ENSO-related droughts, and it is practically unaffected by human activity, although recent mining on the Ok Tedi has provided a sediment spike that can be monitored farther downstream. In contrast, the Waipaoa system (2000 km^2) is strongly affected by seasonal variations in discharge and (particularly) by tropical cyclones; and for the past 100 years it has been affected by the impacts of European landuse and (to a lesser extent) by dam construction.

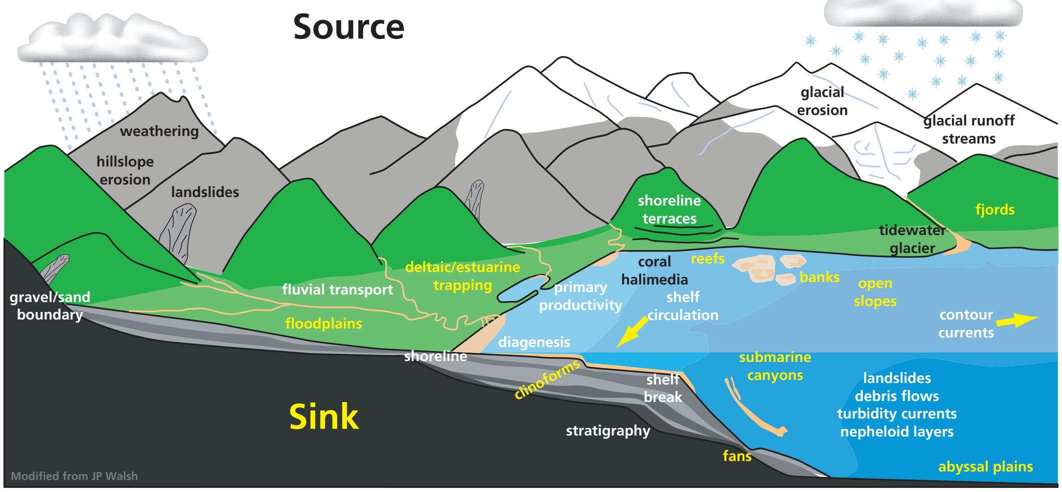


Figure 1. A simple schematic showing the dispersal system. The color of the lettering is coded: sources are indicated by black text, sinks are yellow, processes are shown in white italics, and locations in white regular typeface.

The Source-to-Sink Initiative will be a decadal effort, with initial studies focusing on delineating the sedimentary fluxes in the source areas and their near-term and long-term fates. International collaboration with scientists from New Guinea, Australia, and New Zealand will provide local expertise, access to local facilities (such as ships and on-land facilities), and help disperse research costs. Scientific results will be disseminated through workshops and the MARGINS website, as well as through more traditional scholarly venues.

The integrated approach fostered by this study should pave the way for greater coherence and direction in future studies in sedimentary geology that will go far beyond the scope of source to sink or MARGINS.

2. The Source-to-Sink System

When landscapes are eroded, the resulting sediment and dissolved constituents pass through a connected suite of geomorphic environments, ultimately to be deposited or precipitated on an adjacent flood plain, marine shelf or abyssal plain. This journey from source to sink represents the return limb of a mass flux loop that begins when rock is first exposed to subaerial erosion by tectonic processes such as crustal thickening or volcanic processes. The suite of connected environments through which the journey takes place is the source to sink system (Figure 1).

The connected environments of the source to sink system are separated by dynamic boundaries that shift in response to changes in sediment fluxes and accommodation (Table 1).

Unit:	Boundary:
Terrestrial upland	
	Transition from gravel-bed to sand-bed streams
Terrestrial lowland	
	Coast (shoreline, estuaries, and deltas)
Continental shelf	
	Shelf-slope break
Continental slope	
	Slope base
Continental rise and abyssal plain	

Table 1. The connected environment units and their dynamic boundaries in the source to sink system (cf. Figure 2).

Scope of the Source-to-Sink Initiative

Each environmental unit, which is inter-linked with other units by the flux of sediment through the boundaries, may produce sediment through erosion or act as a sediment sink through deposition, either temporarily or permanently (Figure 2). The erosion and deposition occur at spatial and temporal scales that vary over at least four orders of magnitude, making system behavior especially difficult to predict.

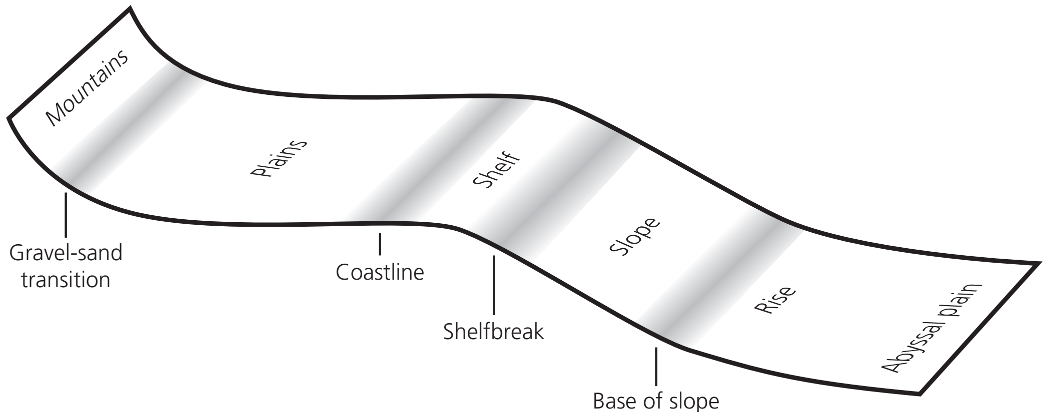


Figure 2. Hypsometric configuration of the various environmental units and boundaries in the source-to-sink concept

The source to sink system is a particularly important historical archive of past and present global change. Yet, whether we look at landscape morphology or the stratigraphy that records its erosion, we see the integral effect of many events over time. Thus, our ability to tell the story of individual events from landscape morphology or from the stratigraphic record remains poor. We see the book of time, and perhaps chapters in the book, but we are only rarely able to read individual pages. Yet it is at the page level that the story truly unfolds. Sometimes an event is global and so large, such as the K-T impact event, that it leaves not only footprints, but also calling cards. But the stratigraphic record is more likely to be an unclear succession of event-related deposits that are recorded in ways we cannot yet read, because it is created by internal and external perturbations that constantly propagate through the system. Similarly, the inverse record, i.e. the eroded landscape, shows the same effects of events and their integral effects over time, and it too remains difficult to interpret.

An ability to predict the quantitative behavior of the source to sink system is important for a variety of societal reasons. The source to sink system contains most of our energy resources and potable water, and as a result most of Earth's human population lives along the source to sink path. Sediment eroded in uplands represents a significant loss of agricultural productivity even as it replenishes eroding coastlines. Yet we are presently unable to anticipate how perturbations in one part of the system will affect another. Would, for example, a 50% increase in sediment yield over the next century reverse coastal zone erosion, or would the sediment be sequestered on floodplains, leading to increased flood risk up river? Would the increased sediment yields from a large magnitude earthquake in the headwaters of a fluvial system disrupt shipping in its lower reaches, and if so, over what duration? Questions like these

Societal relevance

Archive of global change

Predictability

require accurate quantitative methods for predicting system behavior over an intimidating range of time and space scales. To better explore these questions, as well as to provide the page-by-page reading of the geologic record needed to predict future energy resources, we need improved quantitative methods for predicting bed characteristics and architecture that exist in the subsurface. Stratal patterns arising from the interplay of changing sea level, sediment supply, and accommodation can be crudely predicted from first-generation conceptual and numerical models, but more physically based, coupled landscape-seascape models are needed if we are to predict stratal geometries from reconstructed ancient landscapes and climates.

> "We see the book of time, and perhaps chapters in the book, but we are only rarely able to read individual pages. Yet it is at the page level that the story truly unfolds"

This problem is compounded by the historic disciplinary divisions between geomorphologists who examine erosion and production of sediment on land, the oceanographic community, which examines transport and deposition of marine sediments, the stratigraphic community, which examines the longer-term record, and the modeling community, which establishes the physical basis for construction of the sedimentary record. Some of these divisions, notably between oceanographers and geomorphologists, occur specifically at the environmental boundaries listed above, which remain grossly understudied.

The over-arching NSF-MARGINS approach is critical, for only by encouraging an interdisciplinary community to interact in solving broad problems at selected field sites can we develop quantitative, 3D, field-tested models that are able to predict the response of a sedimentary system and its deposits to perturbations of variable temporal and spatial scales, such as climatic and tectonic variability, and relative sea-level change.

3. What Do We Need to Know about the Source-to-Sink System?

The key scientific issues impeding better predictive capabilities for the source to sink system were identified at two MARGINS Source to Sink Workshops and a MARGINS Workshop to define the concept of a Community Sediment Modeling Environment. Similar issues also were identified by an NSF Geology/Paleontology Panel convened in 1999 to suggest key problems and major thrusts for the next decade. The scientific issues are contained within three questions:

Key scientific issues

Forcing parameters

Question 1: *How do tectonics, climate, sea level fluctuations, and other forcing parameters regulate the production, transfer, and storage of sediments and solutes from their sources to their sinks?*

To better manage the landscapes on which we live, we need to model linked continental margin systems so we can predict quantitatively the response of these systems to perturbations (both natural and anthropogenic). We need to decipher how input signals (e.g., individual storms, floods, or landslides) are filtered or amplified along a dispersal system.

For example, it is postulated that sediment delivery to the continental slope occurs primarily at low stands of sea level (Jervey, 1988; Posamentier et al., 1989; Lawrence, 1993) with a consequent order of magnitude increase in sedimentation rates compared to high stands. This increase also has been interpreted to result in frequent hyperpycnal flows that may feed deepwater submarine fans and slope aprons (Mulder and Syvitski, 1995). However, there is no dynamic model linking sediment delivery and storage in large rivers on the coastal plain to sediment delivery and storage in the sea. How exactly, for example, does the sediment transfer vary as a function of sea level? Rivers can erode and transport massive amounts of sediment from the montane system, independent of sea level, but the site of ultimate sediment accumulation (particularly on passive margins) depends on sea level. A definitive answer to this issue requires an improved understanding of the leads and lags in river response to perturbations, and further observations and models linking the coastal plain with the subaqueous margin. Monitoring of present-day sediment fluxes and comparison of accumulation rates over longer geologic time scales by examination of the stratigraphic record can address this question.

As another example, there are fundamental uncertainties as to how sediment is partitioned between the floodplain, shelf, and slope during major flood events. The bulk of sediment carried by most modern rivers is suspended mud (Milliman and Syvitski, 1992), yet the stratigraphic record abounds with examples of sand-dominated fluvial and shelf deposits, much presumably transported as bed load or bed-material load. Were these ancient dispersal systems fundamentally different from today, or is there a combination of forcing parameters that yields sandy deposits from otherwise mud-laden rivers? What controls the proportion of mud deposited in a floodplain versus carried through a river system and deposited on a muddy shelf? Synchronous monitoring of sediment transport in different parts of a source to sink system is required to address these questions.

Process initiation and linkage

***Question 2**: What processes initiate erosion and sediment transfer, and how are these processes linked through feedbacks?*

Erosion and transport agents are well known, but processes that initiate erosional events are often less well understood, even though they can have significant scientific and societal impact. Moreover, feedback mechanisms can either increase or decrease the impact of a particular event.

To cite one example, terrestrial and submarine landslides, generated by both earthquakes and floods, are dominant agents of sediment transfer and morphological evolution, as well as constituting widespread hazards in mountains and in marine environments (the latter by generating tsunamis, rupturing pipelines, and disrupting communication cables). Presently, however, we have limited ability to anticipate landslides and predict their rate of occurrence. What, for example, is the relative importance of earthquake-driven landslides versus those triggered by floods? To help prepare for landslides and lessen their impacts, we need to understand more thoroughly the processes that cause slope failure and landslides, particularly distinguishing flood-caused versus earthquake caused. While the study of individual landslide genesis is crucial, it must be complemented by a more integrated approach of landsliding in the context of the margin system. This would

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allow for evaluation of how, for instance, incisional events that start at the shoreline propagate through the landscape (e.g., Westcott, 1993), triggering submarine landslides seaward, and fluvial rejuventation landward, as the perturbation is transmitted through the dispersal system. Incision at the shoreline may be initiated by migration of tidal inlets in a barrier system, by landward migration of a sediment failure at the continental shelf-slope break, by sea-level changes, and also potentially by storms and earthquakes. These processes operate at a variety of time-scales. Sediment failure in the shelf, for example, can be driven by sediment loading during progradation of an individual mouth bar, such as those that cause growth faults, and by movement of salt and overpressured shales (Bhattacharya and Davies, 2001). Collapse of sediment at the shelf edge can also generate tsunamis that may cause coastal erosion that can in turn affect associated rivers. A complete understanding of landslides, therefore, requires understanding how the dispersal system is linked to the source of sediment and specifically how depositional or erosional events in one part of the system may destabilize the landscape elsewhere by triggering waves of erosion or sedimentation.

Question 3: *How do variations in sediment processes and fluxes and longer term variations such as tectonics and sea level build the stratigraphic record to create a history of global change?*

The stratigraphic record is our main source of information about the history of the Earth's surface over geologic time, as well as the repository of major reserves of groundwater and hydrocarbons. If the record is deconvolved correctly, it allows us to reconstruct the history of sea level, climate, and tectonics and better predict the properties and occurrences of reservoirs in the subsurface. But the fidelity of the stratigraphic record is imperfect, often distorted and containing gaps over a wide spectrum of time scales (Barrell, 1917). Our reconstruction of past events is only as good as our understanding of the processes by which they are recorded in sediments. Moreover, recognizing that the modern depositional environment of the shelf reflects the recent past as well as the present, we need to know more about its evolution, particularly since the last glacial maximum (LGM). Our ability to find the next generation of sediment-hosted resources, for example, will be limited by our ability to predict the locations of potential reservoir bodies in the subsurface. Understanding the formation of the stratigraphic record is truly a source to sink problem, from the generation of the signal carrier (the sediment) to the partitioning of fluxes among the whole suite of margin environments. Integrated studies of sediment production and accumulation over a time interval for which key controls (e.g., sea level) are relatively well understood is a crucial step toward developing reliable interpretive and predictive stratigraphic tools.

Reconstructing the record of global change

In terms of global change, the various environments of the continental margin are also major reactors in many geochemical cycles, particularly those of Si, Ca, P, and C. Carbon (both organic and inorganic) cycling has important relevance to climate-change modeling. Margin environments are critical sites for CO_2 sequestration via weathering reactions in source areas as well as by carbonate deposition in the shallow and deep ocean environments. Quantification of weathering rates, organic carbon and inorganic carbonate production, reactive surface area, and particle fluxes will provide critical information for carbon-cycle models and evaluation of global-change scenarios. Carbonate reefs and platforms are particularly sensitive to environmental perturbations such as changes in sediment discharge, changes in salinity, sea-surface temperature, fertilization by nutrients (anthropogenic and weathering by-products), sea-level change, and topography (James and Kendall, 1992). The dynamics of many carbonate systems are fundamentally linked to input of sediment and nutrients from upstream terrestrial sources. By choosing a mixed clastic-carbonate system, it is possible to test hypotheses on the relative importance of the factors that control the stability of carbonate systems, such as investigating the relative importance of El Niño-type phenomenon versus changes in river-discharge.

The sedimentary wedge that characterizes many continental margins is built from depositional systems that relate to the specific environments that comprise source to sink. Localized delta depocenter progradation and along-shelf sediment transport turn sediment point sources into broad continental shelves and provide sediments to replenish coastlines. To understand how such processes affect margin architecture, we must acquire observations and develop stratigraphic models that combine knowledge about deltaic sedimentation, and shelf and slope depositional processes with tectonism and sea-level variation. River avulsions and delta lobe switching are linked processes, but there is significant debate as to the importance of allocyclic controls, such as sea level change, versus autocyclic controls, such as super-elevation of a channel above the floodplain (Blum and Tornqvist, 2000).

S2S and continental margins

The shoreline is a dynamic boundary that records the complex interplay between relative sea-level perturbations, physiography and sediment supply. As such, margin sediments often are contained within an expanded section from which both terrestrial and marine signals can be obtained. Qualitative models have predicted that the shoreline is farthest seaward when the rate of sea-level drop is a maximum (e.g., Posamentier et al., 1988). Recent morphodynamic experiments have suggested that this result may not always be the case. A combination of morphodynamic and numerical studies linking moving boundaries (e.g., the shoreline) will help direct future data acquisition to test model predictions, and will yield new insights to help mitigate future hazards in coastal environments in response to such events as rising sea level.

4. Methods of Investigation

To address these questions, Source-to -Sink will proceed as a focused modeling and field investigation of landscape and seascape evolution, and of sediment transport and accumulation in two primary field areas where the complete source to sink system can be analyzed. Deciphering the transfer of a signal of an event through a complete and natural source to sink dispersal system will require strong process-based analyses, predictive models, and examination of environmental linkages to other segments of the dispersal system. At present, for instance, we cannot quantitatively delineate how the segments respond to changes in water discharge or sediment loading. Answers to such questions require us to examine controls on the rates and processes of floodplain and clinoform sedimentation within a holistic modeling of the environment.

Signal transfer through a system can be investigated as a "forward" or an "inverse" problem, or both. The forward problem asks: what are the effects of variable sedimentary processes on the signal transferred between a succession of environments and on the signature imparted to the preserved strata? In contrast, the inverse problem asks: what signatures in the stratigraphic record can be used to interpret sediment source dynamics in order to deduce the role of climate, tectonics, and sea-level variation in its formation? The answer to the forward problem may range from significant transfer of a pulse through segments of the dispersal system (top option in Figure 3) to complete attenuation of the pulse along the dispersal system, such that locally generated signals (e.g., from sediment dynamics) are recorded in the lower segments of the system (middle option in Figure 3). The time scales for these two questions generally fall into one of three time categories: short term (present to 7 ka BP), medium term (7 to 18 ka BP), and long term (>18 ka BP), corresponding to sea-level conditions of highstand, transgression, and last glacial lowstand, respectively.

At present, we have little predictive ability to address the forward problem and thus limited criteria for the inverse problem be-

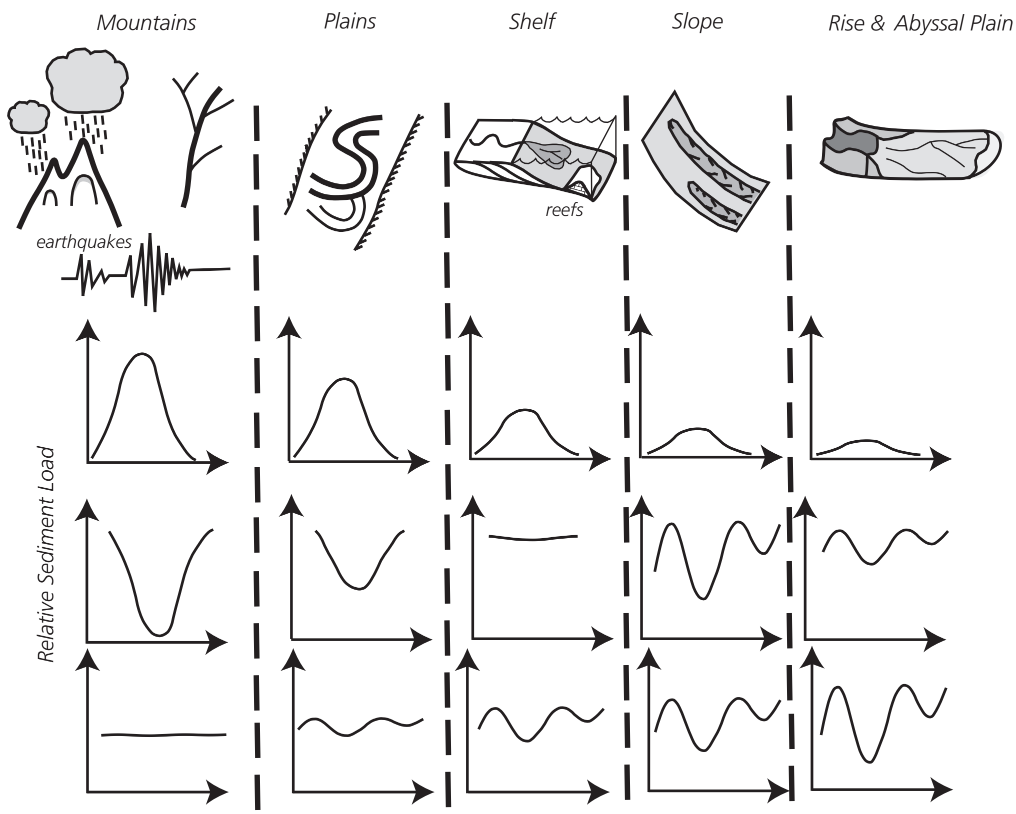


Figure 3. Several scenarios might explain how a sediment discharge "signal" varies through the morphodynamic segments of sediment dispersal systems. Three scenarios are displayed and can be viewed from a "forward" modeling perspective or an "inverse" modeling perspective, as discussed in the text. The time scale is shown as arbitrary, but needs to be defined in order to identify the processes responsible for impacts on the signal transitions. The first row of graphs shows a strong uplands input that progressively attenuates downstream, but is still visible in the marine record. This might be the case in the Waipaoa basin. The second row shows a negative signal (e.g. the El Nino signal in the Fly system) damping completely downstream and being replaced with a signature driven by tidal, shelf or deep-water transport dynamics. A third scenario shows that even without variations in source sediment (e.g., Fly during many years), local processes can lead to significant temporal variation in sediment flux. The two focus sites have strong signals generated, but little is known about how the signals are transferred.

Signal transfer in the S2S system

cause of the incomplete nature of the stratigraphic record. Progress can only be made through a well-structured, nested research plan involving collaborative efforts of individuals from disparate backgrounds integrating whole systems, and including all morphodynamic segments present in those systems. By selecting a well-chosen pair of focus sites we ensure that the potentially enormous scope of source to sink questions can be directed towards a tractable solution.

Model development within the S2S initiative

Developing quantitative and physical models for the source to sink System is integral to the strategy of the initiative. Models will be used to help define key questions and to test various hypotheses. Model predictions will help guide aspects of field programs and field observations will validate/verify model output. Finally, models will allow us to generalize our observations, and thus extend our understanding to other regions. A new generation of numerical modules predicting the transport and accumulation of sediment in landscapes and sedimentary basins over a broad range of time and space scales is a high priority of the Source-to-Sink Initiative. The models should be based on algorithms that mathematically describe the processes and conditions relevant to sediment transport and deposition in a complete suite of earth environments, and contain the optimum algorithms, input parameters, feedback loops, and processes to better predict behavior of the complete system (Syvitski et al., 2002). The general program of investigation for each selected site will include:

1) Assessment of available data and its appropriateness for building first-order computational and physical models;
2) field investigation of sediment production, transport and accumulation, and associated mechanics and rates;
3) second-order model building/testing to illuminate mechanisms of sediment transport and stratigraphy generation under various controls; and
4) stratigraphic documentation at appropriate spatial concentration to provide desired temporal resolution.

Monitoring and modeling of active processes are examples of work that should occur throughout the course of the proposed studies. This will include high-resolution digital elevation models (DEMs) and swath imaging of both landscapes and seascapes. Monitoring of the fluxes throughout the system, can be compared with measurements in the changes between surfaces surveyed before and after major events to determine system response. For example, successive high-resolution surveys of the seafloor before and after a major storm event can be used to determine how the shelf responds, where erosion occurs and where deposition occurs. This can be compared with rates and magnitude of changes in coeval landscape and seascapes. This can also be linked to the relative scale of changes in the floodplain. Documentation of the stratigraphy can proceed in phases by working through the different storage elements of the morphodynamic segments, and by investigating the temporal resolution initially from the finest-scale deposits of the past thousand years and later to longer, deeper records that extend back to millions of years. Both monitoring and modeling can be greatly enhanced by capitalizing on existing data and measurements taken in selected study sites.

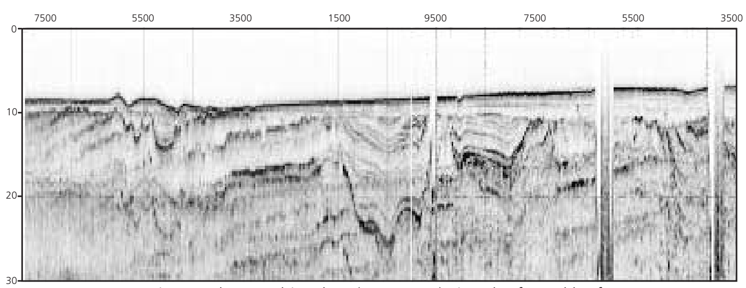
5. New Technologies and Opportunities for Source-to-Sink Research

For each of the segments of the source to sink system, recently developed technology offers unprecedented opportunities for new insight. Several of these key innovative technologies are explained below in their relation to Source-to-Sink scientific objectives.

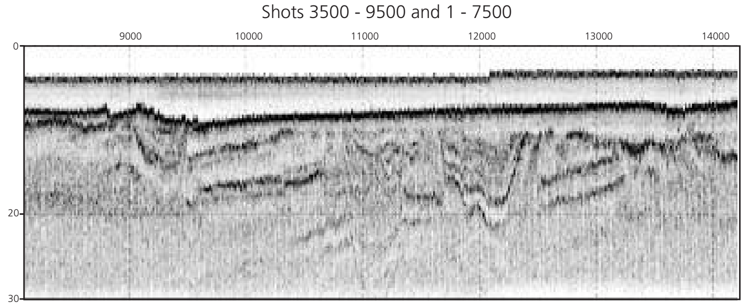
- High-resolution DEMs, radar interferometric DEMs (broad coverage, lower accuracy) and laser-altimetry (LIDAR, narrow coverage, high accuracy, very-high resolution) permit the finer-scale mapping of fluvial dispersal systems (flow routing), calibrating transport laws, and documenting surface evolution. Programs such as goCad and ARCVIEW can be used to measure volumetric differences in degrading landscapes and aggrading seascapes. These differences can be used to measure mass balances among linked systems.
- Precision positioning (e.g., DGPS) allows us not only to define our position within a few centimeters (Xu et al., 2000), but also permits the reoccupation of study sites, so that short- and medium-term changes can be studied.

Technology in the S2S initiative

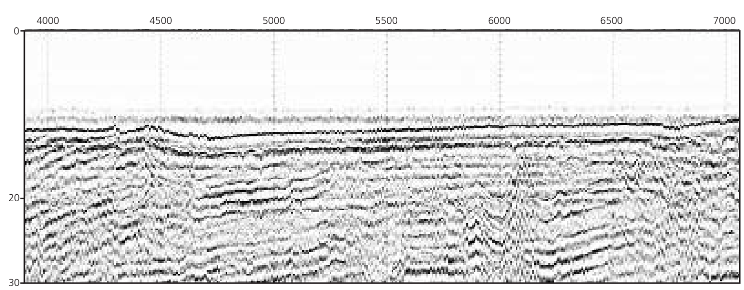
* all vertical scales two-way travel time in milliseconds



Scripp's Subscan Chirp data (May 2001) Lines l16f1 and l16f2
Shots 3500 - 9500 and 1 - 7500



SIS-1000 Chirp (Nov, 1999) Line l105f1 Shots 8100-14200



Huntec Boomer (Nov, 1999) Line l105f1 shots 3900 - 7100

Figure 4. Geophysical images acquired offshore South Carolina's Grand Strand, illustrating the improved resolution and penetration of the Subscan CHIRP system (top), relative to standard CHIRP data (middle), and a Huntec boomer (bottom). Resolution increases from several meters in the Huntec record to considerably less than 1 meter in the Subscan record.

Figure courtesy of Neal Driscoll, Scripps Institution of Oceanography.

- Similarly, swath-mapping—particularly the new interferometric swath sonar system—and the CHIRP seismic profiler allow marine geologists and geophysicists to achieve horizontal and vertical resolutions of less than 15-20 cm, thus providing unprecedented ability to define fine-scale bathymetry and stratigraphy (Figure 3). Together with DGPS, these new technologies allow us to document the change in seafloor morphology and stratigraphy with time.
- Enhanced coring (e.g., wire-line coring that can be obtained through the Ocean Drilling Program) can continuously sample long sections of unconsolidated sediments in diverse environments. New and established logging tools and geophysical processing (e.g., GRAPE, FMS, magnetic susceptibility, and the multispectral scanner), moreover, allow continuous acquisition of downhole physical properties data.
- Acoustic, electromagnetic, and optical devices have been developed to measure velocity, concentration and grain size of sediment particles in transport, and high-speed video imaging, particle-image velocimetry used in monitoring physical experiments can provide valuable constraints on conceptual, analytical and numerical models.
- Laboratory experimental facilities, such as those recently developed for experimental stratigraphy, allow for the testing of hypotheses under strictly controlled conditions in which forcing and boundary parameters can be systematically varied.
- Recently developed experimental facilities (e.g., large-scale tanks and flumes, Paola et al., 2000) enable unprecedented physical modeling studies to be posed, especially if constrained by good field data, as is a central aim of Source to Sink (Figure 5). This is particularly important because most previous modeling studies have been purely 2D (e.g., Jervey, 1988; Lawrence, 1993; Wehr, 1993).

Methods and facilities

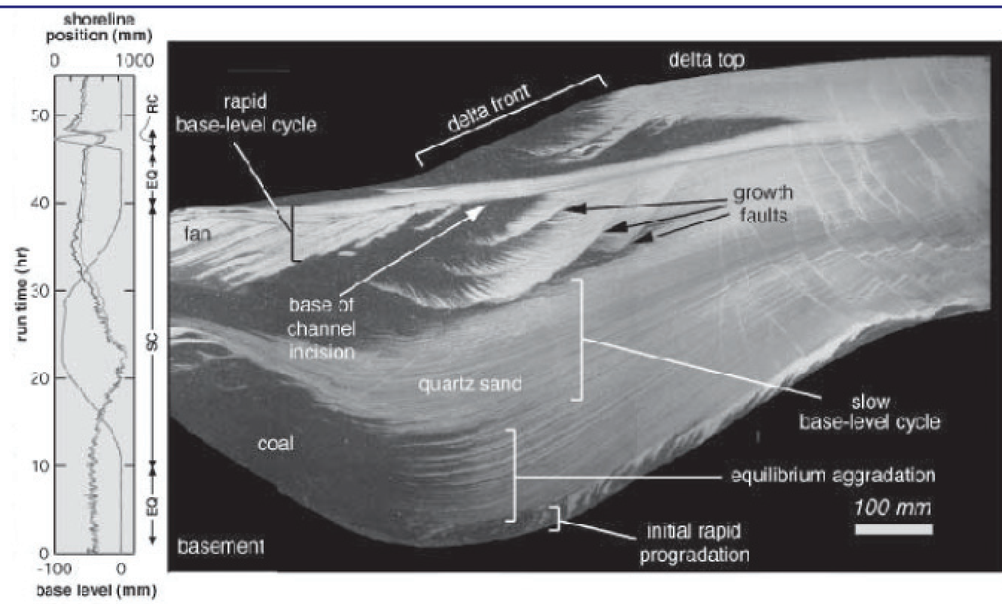


Figure 5. Experimental run illustrating the complex interplay between base level, shoreline position, and accomodation. Illustration courtesy of Chris Paola, University of Minnesota.

6. Selection of Focus Sites

Through discussion at various workshops and working groups, there was general agreement about the criteria considered essential in the selection of a Source-to-Sink study area. Other criteria were considered important, although perhaps not mandatory:

6.1 Critical Criteria

- Strong forcing that produces strong signals, some of which may be transferred between environments - Areas experiencing rapid uplift and vigorous atmospheric forcing (e.g., heavy rainfall, frequent storms) yield large amounts of sediment, often during catastrophic events. Because they tend to erode and store less sediment on their flood plains, smaller mountainous rivers tend to have particularly high sediment yields (Milliman and Syvitski, 1992). As a result, more than 65% of the sediment presently discharged to the global ocean comes from rivers draining southern Asia and the high-standing islands in Oceania. Rivers draining the high-standing islands in the East Indies and the Philippines alone are estimated to discharge about more than half of the southern Asian fluvial sediment load (Figure 6).
- Active transfer among environments within a generally closed system - Because larger watersheds tend to store more sediment and to modulate the effect of individual events, it is preferable to study systems in which the source drains moderate- to small-sized basins (e.g., 10^3-10^5 km in area). In this way the transfer and fate of sediment within the study area can be quantified, allowing a mass-balance calculation.
- High-resolution stratigraphic record — a long record better allows delineation of various-scale events as well as larger changes in climate and sea level. A high-resolution stratigraphic record extending back to glacial stage 5e (125 ka BP), for example, would allow us to delineate the stratigraphic response to glacial-interglacial cycles and eustatic sea-level fluctuations.
- Must have sufficient background data to allow the formulation of an optimal integrated systems study — quantitative data concerning rainfall, stream flow, sediment discharge, the oceanographic environment as well as a general understanding of the sedimentary sinks facilitate the formulation of an effective field study. Aerial photographs, digital models, and remotely sensed data also would be extremely helpful.
- Local scientific infrastructure — access to the entire study area, from source to sink, is necessary. Access to local ships and land support systems (e.g., shallow-water boats, field camps) would provide the opportunity to reach areas otherwise inaccessible and also allow us to study the impact of episodic events, such as floods and storms.

6.2 Other Important Criteria

* Analogs with ancient sedimentary environments - Sites whose environments and/or sedimentary deposits can be linked to geological formations clearly would enhance the uniformitarian aspects of the study.

* Presence of carbonate environments - By virtue of their usually forming within the environment in which they are deposited, carbonate sediments offer unique paleo-environmental and

Focus site selection criteria

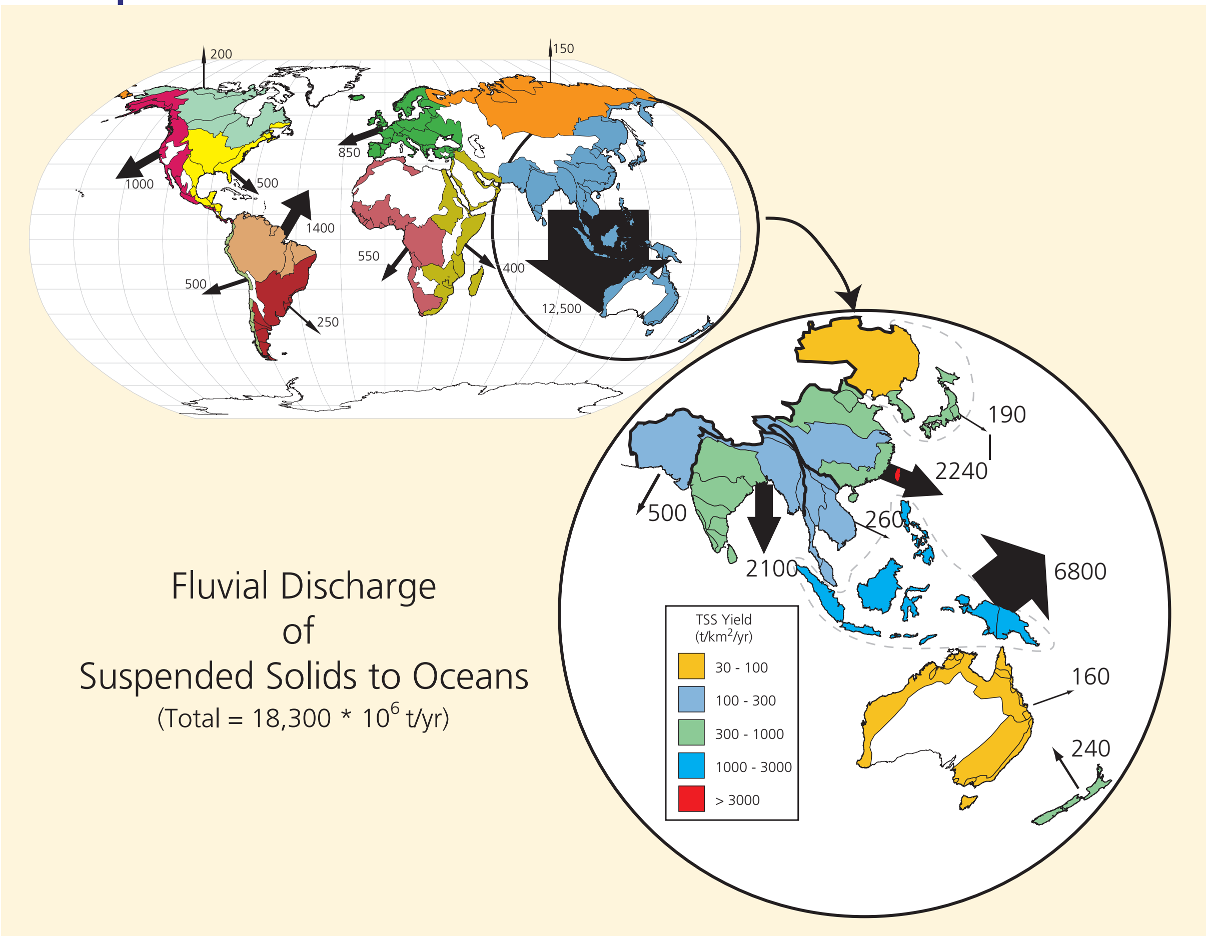


Figure 6. Calculated fluvial discharge of suspended solids to the global ocean (upper left). Of the approximately 2/3 of the global load emanating from southern Asia, more than half comes from high-standing islands in the East Indies and the Philippines. Illustration after Milliman and Farnsworth (in preparation).

geochronologic constraints as well as chemical signals, sea-level information, and other insights. While mixed siliciclastic-carbonate deposits are common in the geologic record, the factors that control the dominance of one system relative to the other are only qualitatively understood (James and Kendall 1992). By supporting a field focus site in which there are mixed siliciclastics and carbonates, this research will help bridge another gap between deep specialist divisions in our community. Bridging this division is particularly important in protecting and managing the world's carbonate reef communities, which are so strongly affected by changes in siliciclastic sedimentation.

- Societal relevance - The results of the investigations at the two study sites should help document the impact of anthropogenic activities on the environment. What is the effect on landscape evolution, for example, of deforestation or farming, or the effect on water quality or stream flow by dam construction? Landslides and tsunamis are perhaps two extreme examples of events that can have extreme impact on both the sedimentary environment and human communities inhabiting those environments.

- Significant differences between two sites - By choosing two sites with different climatic regimes, hydrography, sediment sources, oceanographic forcing and stratigraphic architectures, we can better differentiate the qualitative and quantitative impact of these different environmental controls. Where possible, drainage basins should have significant differences in land-use activities and histories. Where perturbations have occurred - and most drainage basins throughout the world have been affected by anthropogenic activities - it is preferable that the changes be quantifiable and should not overwhelm the natural processes.

6.3 Assessment of Candidate Sites

Candidate sites

More than twenty sites were considered within the community as possible candidates for a source to sink study. Candidate areas ranged from Belize to Alaska and to Papua New Guinea. Nearly all candidates, however, failed to meet one or more of the critical criteria. The Mississippi River, for example, suffered both its very large size (which tends to dampen the down-basin effect of even very large events) as well as the fact that it contains more than 30,000 dams of various sizes, which collectively greatly control the fluvial regime. On the other hand, because of its arid and dammed drainage basin, the Brazos River presently supplies relatively small amounts of modern sediment to its dispersal system. Consequently there is little or no sediment transport to the more distal shelf and offshore segments of its system, despite an otherwise excellent offshore seismic and core subsurface data set that extends back to the Pleistocene.

The two sites that appeared to satisfy all or at least the most critical criteria were the Fly River/Gulf of Papua in Papua New Guinea, and the Waiapoa dispersal system in New Zealand. Two adjacent areas (the Markham River in PNG and the South Island of New Zealand) were considered reasonable alternative sites that should be reevaluated after the first five years of the Source-to-Sink program have been completed.

6.4 Candidate Sites

6.4.1 Fly River/Gulf of Papua (New Guinea)

The Gulf of Papua (GoP) and, in particular, the Fly River system provide a unique opportunity to study a major river system that remains in a nearly pristine condition (Figure 7). The Fly River (drainage basin area 75,000 km^2) rises in the fold and thrust belt of central New Guinea, where mountains locally reach elevations of 4000 m. The basin receives up to 10 m of rain in its headwaters and mean annual Fly River runoff approaches 2 m/yr. The two major tributaries to the Fly, the Ok Tedi and Strickland, join the Fly along a broad flood plain less than 20 m above sea level (Figure 8).

Most of the Fly's sediment load comes from the mountains, with natural loading dominated by landslides. The natural sediment load of the Fly River delta is estimated to be 85 x 10^6 t yr^{-1} (Pickup et al., 1981), 90% of which is fine-grained. Mass wasting and (to a lesser extent, ENSO variations) may cause significant fluctuations in this load. During El Niño periods, the normally high levels of Fly River discharges of water, solutes and particulates decrease to negligible levels, creating a decadal signal whose propagation can be studied through the diverse segments of the dispersal system.

Unlike most rivers, the Fly system has experienced little deforestation or agricultural development and has no dams or artificial levees. The one major anthropogenic perturbation to the system has been the Ok Tedi gold and copper mine, begun in 1985 and by 2010 predicted to have introduced 1.7 x 10^9 t to the watershed. The large influx of sediment in the Fly offers a unique opportunity to examine a large sediment signal, with a distinctive chemical composition, which can be exploited to document and model sediment transfer processes through the entire system. While the vast majority of the sediment thus far has remained within the Ok Tedi and upper Fly rivers (G. Parker and W.

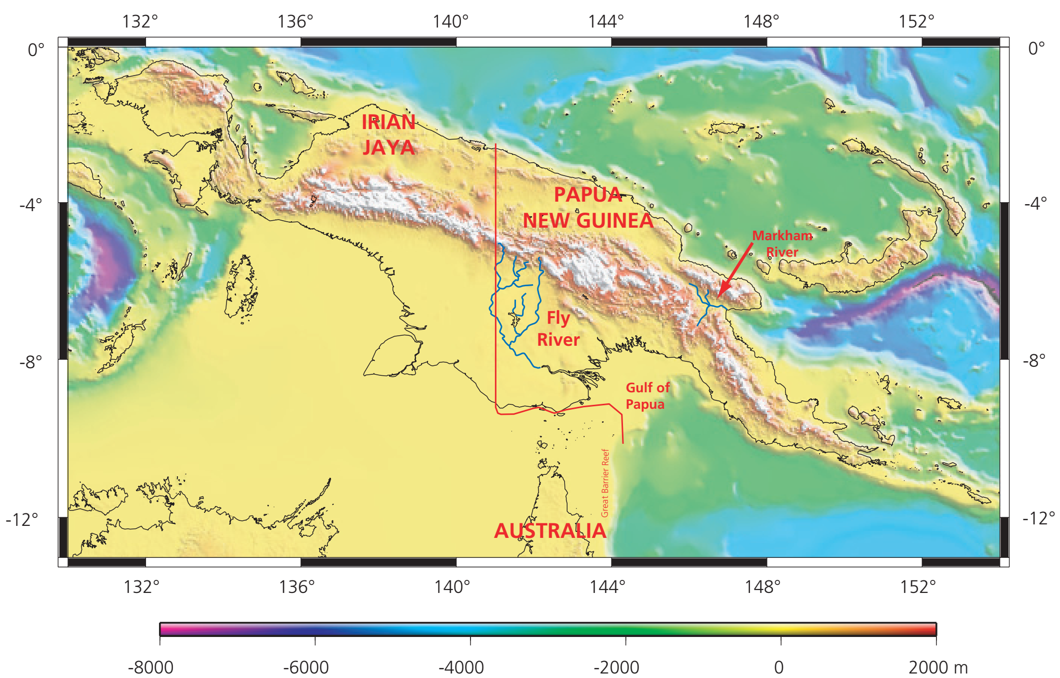


Figure 7. Location map showing the Fly River, Gulf of Papua, and Markham River in Papua New Guinea.

Dietrich, unpublished report), it will produce a strong, long-duration signal that differs from short-term stochastic introduction associated with natural loading events.

As a result of mining activities, there are currently nine flow and suspended-sediment gauging stations along the Ok Tedi-Fly system, some of which go back to the early 1980's. Detailed topographic maps using high-resolution aerial photographs and repeat infrared surveys also have documented changes in morphology and vegetation. Using differential GPS, a high-resolution network of benchmarks has been established on the Fly and Ok Tedi, resulting in a high-quality river profile in very flat terrain. Numerous cross-sections have been established for repeat surveys. The Ok Tedi and Fly floodplains have been topographically mapped through a combination of aerial photography, laser profiling and ground surveying. The extensive data already collected and the established precipitation and hydrologic program in the Fly greatly increase the opportunity and possibility of obtaining accurate sediment budgets through the system.

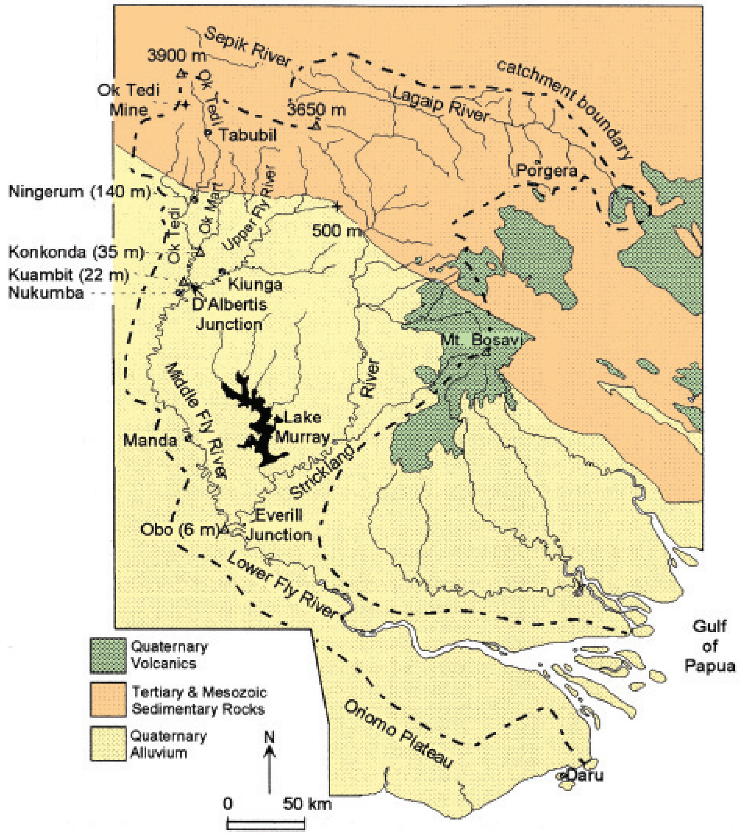


Figure 8. Fly River watershed, also showing Ok Tedi mine, Strickland River and present-day estuary, and adjacent Gulf of Papua. Modified from Dietrich et al (1999).

The Fly River delta has the classic funnel-shaped geometry of a tide-dominated system (Galloway, 1975), and has been used as the end-member example in delta classification, although in terms of our knowledge about the different delta types, we know the least about tide-influenced deltas (Bhattacharya and Walker, 1992). Local tides range from about 3.5 m at the mouth to 5 m at the apex (meso- to macro-tidal). Strong tidal currents cause fluid muds to be deposited on the floors of distributary channels, which are hypothesized to represent the staging area for distribution to the offshore shelf clinoform (Dalrymple et al., in press). The continental shelf contains an actively growing mud-dominated clinoform similar in scale to those associated with other major rivers (e.g., Amazon, Ganges- Brahmaputra, and Changjiang), and which represents the dominant stratigraphic unit of continental margin architecture around the world (Driscoll and Karner, 1999). Sediments become progressively finer in the offshore direction as wave and current velocities diminish. Simulta-

Fly River

Low human impact

Fly River sediment productivity

neously, benthic organism abundance increases, and the interbedded physical structure is replaced by homogenous, bioturbated muds (Harris et al., 1996). A preliminary sediment budget over a ^{210}Pb timescale (100-yr) indicates that modern sediments are partitioned in the following fashion: Delta Front 24 ± 12x10^6 metric tons/yr, Prodelta 22 ± 6x10^6 metric tons/yr, Distal Delta 0.9 ± .2x10^6 metric tons/yr, which collectively represents about 55% of the Fly's average annual load (Figure 9). An additional 2% is estimated to be transported southward into the Torres Strait, and some may be sequestered in the extensive mangrove forests that line the GoP coastline. The "missing" Fly sediment is hypothesized to move northeastward along the GoP shelf (Harris et al., 1993), where it mixes with sediments supplied by the Kikori, Purari and other rivers and accumulates on the shelf, probably on clinoform deposits that extend along the 50-m isobath. High sediment accumulation rates (> 1 cm/yr) are known to occur in this region. Geochemical evidence also suggests some terrestrial sediment is escaping the shelf into Pandora Trough, but the magnitude of this loss is unknown. The GoP also provides an excellent locality for Source-to-Sink research, including its long marine sedimentary history of foreland-basin evolution (3000 m since the Jurassic).

Finally, the Fly River-dominated GoP can be distinguished by its close proximity

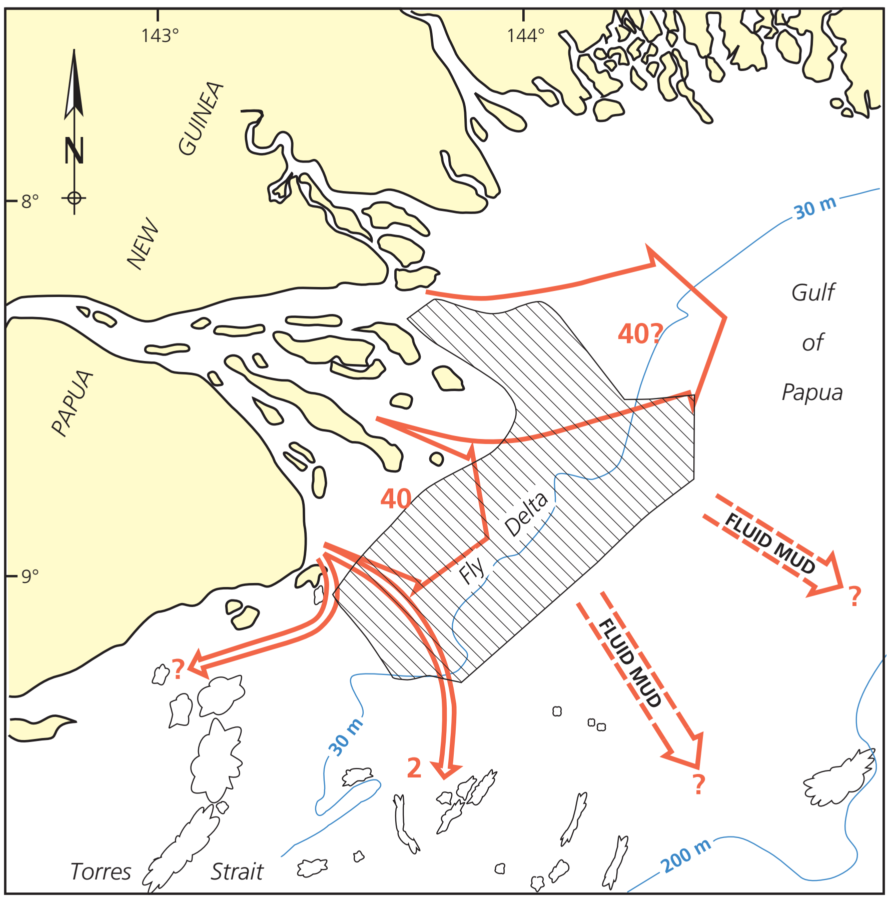


Figure 9. Schematic diagram showing transport pathways for Fly River sediment dispersal. According to this model, floodplain sedimentation is zero and nearly half of the annual load moves alongshore and offshore to the northeast. Modified from Harris et al. (1993).

to extensive coral reefs and Halimeda banks that extend northward from the Great Barrier Reef, thus providing a unique opportunity to study the carbonate- siliciclastic transition (Wolanski et al., 1984).

Scientists from Papua New Guinea and Australia have been investigating the terrestrial and marine portions of the dispersal system for more than 20 years. In particular, recent and ongoing flow and sediment monitoring on the Fly River (http://www.Ok-Tedi.com) provide essential flux data as well as (ultimately) insights as to the impact of a major anthropogenic activity (the Ok Tedi mine). Project TROPICS (Tropical River-Ocean Processes In Coastal Settings) has recently studied the fate of solutes and particulates entering the Gulf of Papua over Holocene time scales (http://www.aims. gov.au/pages/research/projects/ project05/tropics/tropics.html). The US-NSF RiOMar program is planning to collaborate with Source-to-Sink investigations in the examination of carbon pathways through this wet-tropical system.

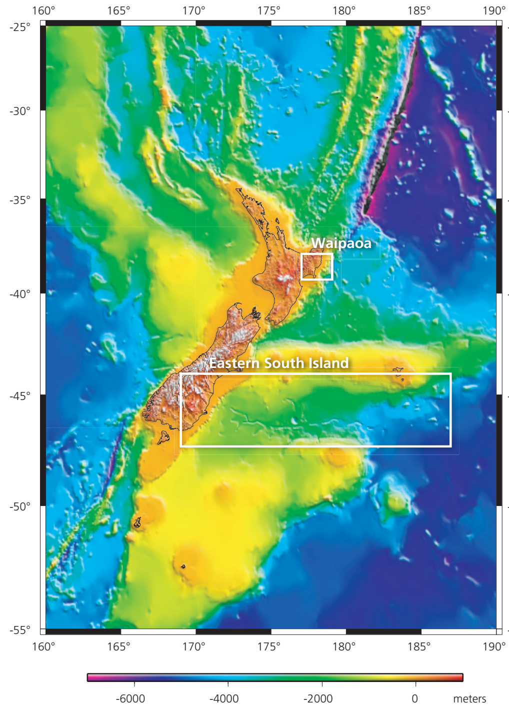


Figure 10. Location map showing the Waipaoa dispersal system and the eastern South Island dispersal system.

New Zealand
Focus Site

6.4.2 Waipaoa Dispersal System (New Zealand)

The Waipaoa River margin provides an opportunity to investigate the signal transfer of high-magnitude perturbations during the late Quaternary (ENSO driven changes in precipitation, cyclonic storms, and large-scale destruction of forests from major volcanic eruptions and historical land-use practices) across a relatively closed, small-scale, sedimentary system. The system (Figure 10) is compact (~2570 km^2 source, ~900 km^2 sink), has a point-source discharge to the ocean, and is virtually closed under present highstand conditions (i.e. sediment budgets can be balanced from upland to shelf).

The setting is within the zone of active deformation associated with the Hikurangi subduction margin, and encompasses the 2200 km^2 Waipaoa and 370 km^2 Waimata river basins, which drain the eastern flanks of the Raukumara Range (Figures 10, 11). These drainage basins are positioned above a major tectonic plate boundary and are underlain by deformed Cretaceous and Early Tertiary mudstones and argillites, early Cretaceous greywacke, and a thick forearc sequence of Miocene-Pliocene mudstone and sandstone. Subduction has induced rapid uplift (~4 mm y^{-1}) in the ranges at the head of Waipaoa River (Berryman et al., 2000), where there has been 120 m of downcutting in the last 15 kyr, much of which was accomplished in the late Pleistocene and early Holocene. Rainfall across the basin is primarily controlled by topography, with a mean annual rainfall of 1470 mm from a gauging station 48 km upstream from the coast.

Waipaoa River

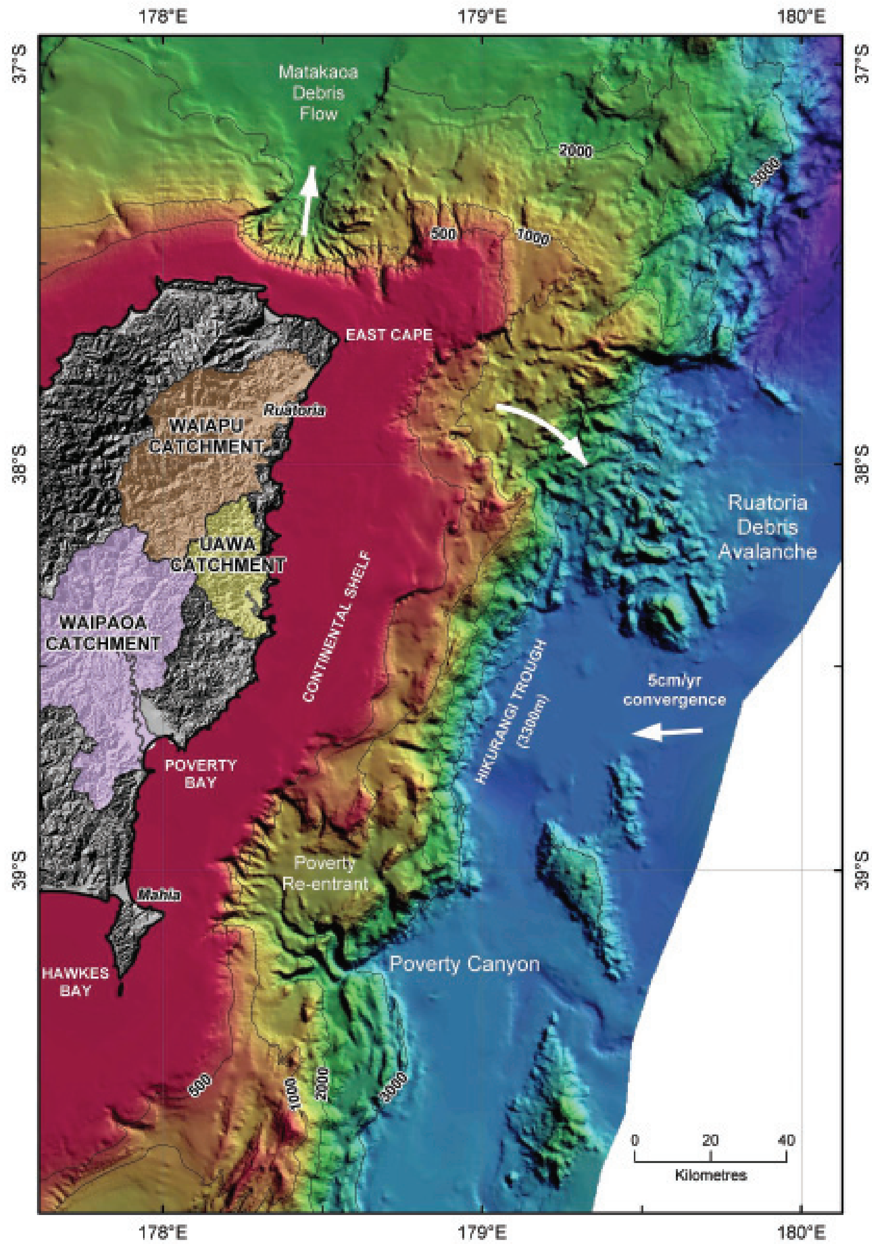


Figure 11. Topography and bathymetry of the Waipaoa, Waiapu, and Uawa Rivers in the eastern North Island of New Zealand, showing the onshore and offshore dispersal parts of the Waipaoa dispersal system. From Orpin et al., 2002.

A remarkable Holocene history of catchment erosion events (mainly storm-induced rainfall) during the past 2 ka has been documented for the east coast of New Zealand from Lake Tutira (Eden and Page, 1998), formed just south of the Waipaoa basin by a large landslide ~6500 ^{14}C years before present (Trustrum and Page, 1992). In the historical period these can be tied with recorded large storms (e.g., Cyclone Bola) that cause extensive landsliding. Periods of abundant storm layers are observed throughout the 2-ka record, which have been hypothesized to correspond with ENSO variations (Eden and Page, 1998), although neotectonic movements also could be important. New Zealand researchers are planning to extend the high-resolution storm record to the lake's origin by coring through the thickest part of the lake sediment in 2003. This 6-ky lake record of erosion events is an unique proxy for river discharge events, and can be used to drive quantitative models of river input to the coastal ocean.

Present-day sediment and nutrient fluxes in the Waipaoa system have been strongly influenced by anthropogenic activities. Although Maori settlers to the area had disrupted the natural vegetation, widespread clearing of the indigenous forest did not commence until after the arrival of European colonists in the late 1820's, and by 1920 the headwaters were cleared; today only ~3% of the basin remains under primary indigenous forest. The destabilized landscape consequently initiated severe hillslope erosion in the Waipaoa River Basin's headwaters, where amphitheater-like gully complexes (up to 0.2 km^2 in area) developed in the highly sheared rocks. Large volumes of fine sediment are delivered to stream channels by gully erosion and shallow landsliding, and the Waipaoa River has a mean sediment concentration of ~1700 mg l^{-1}. The annual average suspended-sediment load to Poverty Bay of 15 $x10^6$ t yr^{-1} (Hicks et al., 2000) ranks amongst the highest measured in New Zealand, and its sediment yield (5900 t km^{-2} yr^{-1}) is very high by global standards (Milliman and Syvitski, 1992). Moderate flows (less than the bank-full discharge of ~1800 m^3 s^{-1}) transport ~75% of the sediment load. As such the Waipaoa is an ideal system to study the effects of heavy landuse on the source to sink system, and may lead to a better ability to predict the longer term consequences of deforestation that is an epidemic land management problem globally. Furthermore, large sediment pulses may be mimicked by natural events common to the area, such as those thought to occur following a major volcanic eruption or neotectonic displacement.

Strong human impact on Waipaoa River system

Fine sediments discharged from the Waipaoa are distributed primarily as hypopycnal plumes and are carried out of Poverty Bay onto the shelf by the baroclinic circulation (which may be intensified during periods of high river discharge). Hyperpycnal flows are though to occur during high discharge events, such as those associated with cyclonic storms (Foster and Carter, 1998). The frequency of hyperpycnal flows during certain times in the past may have been considerably lower, as pre-deforestation discharge was reduced nearly an order of magnitude. Such changes should be reflected in distinct sediment dispersal patterns, offering the potential to examine the effect of changing river discharge on the development of shelf stratigraphy. Study of hyperpycnal flows is of particular economic interest because of their potential importance in delivering coarse sediment into deepwater environments. Much of the global energy exploration budget is focused on attempting to predict the distribution of potential hydrocarbon bearing sandstone reservoirs deposited in deep water environments.

The combination of a broad crescent coast and actively growing anticlines (Lachlan Ariel; Figure 11) on the outer shelf effectively captures sediment on the middle shelf. Post-glacial accumulation rates are high (~1.9m ka^{-1}). A 13 km-wide gap between Ariel and Lachlan anticlines provides an escape route for some sediment, but it is estimated that the off-shelf loss of modern mud is small. Sediment escaping onto the continental slope is likely to be retained within a

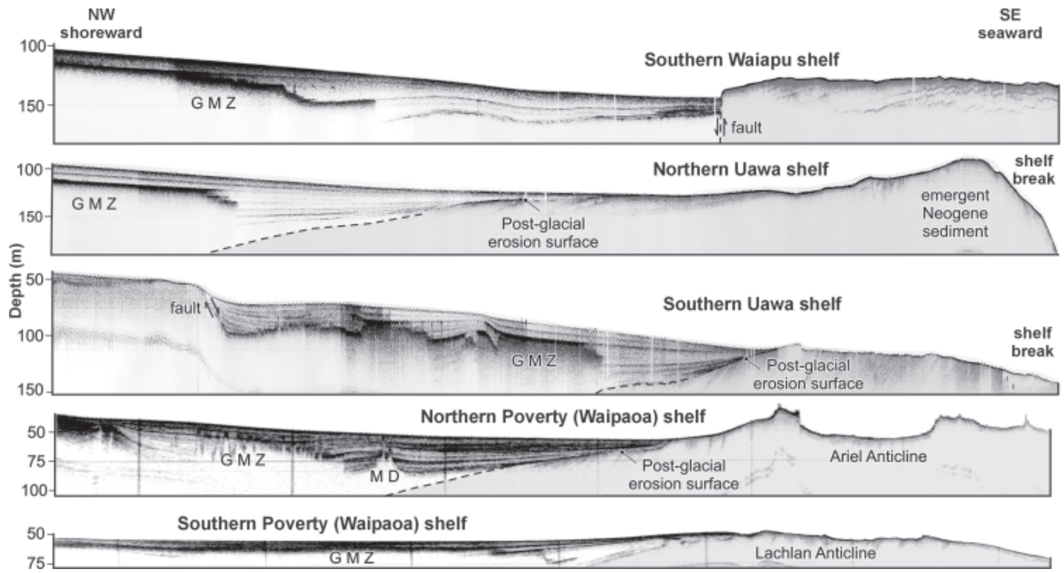


Figure 12. Seismic sections across the mid-shelf at the Waipaoa, Waiapu, and Uawa Rivers, showing mudstone structural highs on the seaward side, trapping Holocene sediments. From Orpin et al., 2002.

Sea level and sediment trapping on Waipaoa shelf

large amphitheater of a (Pliocene?) collapse structure formed by collision of the accretionary prism with a seamount on the subducting Pacific Plate. Given the shelf and slope entrapment of sediment, conditions must be considered favorable for closing the modern Waipaoa budget. The only uncertainty relates to sediment transported into the area by the prevailing along-margin circulation. On the shelf, transport is weak and ephemeral. However, on the outermost shelf and upper slope, sediments come into contact with the southwest-flowing East Cape Current. This flow mainly affects sediment escaping the shelf depocenter and transport rates have yet to be resolved.

During sea-level lowstands, the Waipaoa River presumably reached the shelf edge, although the exact point of discharge is not obvious as the course of the ancestral river has not been traced entirely across the shelf. If discharge was into Poverty Canyon, south of the Ariel-Lachlan gap, sediment within the canyon would be guided to a shallow basin at 3000-3200 m depth that has formed between the base of slope and the left bank levee of Hikurangi Channel. If the lowstand discharged at a gully near the central part of the gap, then sediment would accumulate mainly within the amphitheater of the collapse structure. Whichever is the case, the slope conduits lead into basins where there is a reasonable expectation of closing the budget.

6.5 Differences Between the Two Study Sites

One of the important criteria in study site selection were the differences between the two sites. At first it may appear that the Fly and Waipaoa sites are closely similar, and it is true that both study sites involve documenting the input and fate of sediment from relatively small mountainous rivers in the SW Pacific Ocean. A closer inspection, however, shows many fundamental differences. For example:

These and other contrasting sedimentary considerations provide a wide variety of processes and stratigraphic signatures that will help develop a global understanding for sedimentation, but also will allow greater fundamental insights through comparison of the mechanisms and patterns found in the two areas.

	Fly	Waipaoa
Drainage-basin size	(75,000 km^2), medium	(2000 km^2), small
Terrestrial and marine climates	tropical	sub-tropical
Fluvial database	small	substantial
Seasonal river discharge	steady	episodic
Anthropogenic impact	minimal	considerable
Sediment residence time in drainage basins	long	short
Dominant oceanographic variability	trade winds	cyclonic storms
Shelf sediments	siliciclastic, with reef-derived carbonate facies to the south	siliciclastic
Shelf stratigraphic architecture	clinoform progradation	basin infill

Table 2. Comparison between the two focus areas, Fly River in Papua New Guinea, and Waipaoa River in New Zealand.

7. Implementation Plan

Because the source to sink concept involves a wide range of terrestrial and marine studies, field work and modeling, the entire integrated effort will take at least a decade. The general outline for these various studies is given in Table 3, in which the timelines for various activities are indicated. The sequence of study and relative effort was designed to build on the strengths of each site to yield new understanding in a realistic time frame given the length of the Source-to-Sink Program.

Because both the Fly and Waipaoa rivers are subject to episodic events, the Fly to ENSO variations in precipitation and the Waipaoa to cyclone activity, it is critical that the dispersal system be monitored for the full duration of each study. Onshore and offshore imaging will help define the morphologic and stratigraphic framework and thereby locate targets for detailed imaging and sampling. Onshore sampling and dating would help provide constraints on age of surface exposure and material properties. Box, vibra-, and piston-coring of the preserved stratigraphy will provide age constraints required for sediment budgets as well as lithologic information for geophysical data. Where longer histories are needed, non-Riser drilling will determine the history and rates of incoming material to the sink; the location of these cores will depend greatly

Time (years)	1	2	3	4	5	6	7	8	9	10
1. Monitoring Dispersal System	●	●	●	●	●	●	●	●	●	●
2. Onshore/Offshore Imaging	●	●	●	●	●					
3. Onshore Sampling and Dating		●	●	●	●	●				
4. Sediment Properties/Rates		●	●	●	●	●				
5. Offshore Non-Riser ODP Drilling						●	●	●		
6. Experimental Studies	●	●	●	●	●	●	●	●	●	●
7. Quantitative Modeling	●	●	●	●	●	●	●	●	●	●
8. Alternate Platforms/New Drilling								●	●	●

Table 3. Logical progression of studies within focus sites.

upon data acquired previously by both imaging and sediment sampling. Experimental studies and particularly quantitative modeling will provide insights and predictions about the dispersal system that can be tested; at the same time, modeling can provide directions for the acquisition of seismic and sedimentologic data. Particular attention is being devoted to development of the Community Sediment Model (CSM), whose goal is to produce a unified framework model, analogous on some levels to a Global Climate Model. Alternate platforms and new drilling technology presumably would be applied toward the end of the study, after all the data and model outputs have been evaluated; these final field operations can provide key samples from diverse environments to test model predictions.

CSM—Community Sediment Model

Communication and interaction will be cornerstones of the implementation policy, to provide opportunities for increased synergy through collaboration and piggyback research campaigns. A mid-program evaluation will occur in the fifth year to determine whether a course correction is required and, if so, how substantial.

Because, as pointed out earlier, there are considerable differences between the Fly/GOP and Waipaoa sites, actual implementation plans for the two sites will show some differences.

The Fly/GOP focus site is a complete, relatively pristine dispersal system, where we have the opportunity to address processes operating along all source to sink morphodynamic segments. Although sediment production rates in the highlands are large by world standards, the extensive floodplains of the lowland Fly and Strickland rivers appear to damp upland production variations, providing an opportunity to investigate damping mechanisms and the associated stratigraphic record. Because historic measurements along the river are relatively few, we need first to understand how changes in water discharge and sediment loading impact floodplain and shelf-clinoform sedimentary sinks, and how escaping sediments impact carbonate production by coral/algal communities on the shelf and in deeper water. On longer time scales, these sedimentary processes are modified by relative base-level changes (caused by tectonics and eustasy). We can address sediment production and sequestration questions in many of the morphodynamic segments of this system on short (0-7 ka BP), medium (7-18 ka BP), and long (>18 ka BP) time scales.

It is particularly important at the outset of the Fly/GOP research to engage both land and marine scientists. This can be accomplished best by focusing first on fundamental issues addressing sedimentary mechanisms on short time scales, which can be linked most strongly to stratigraphy. Of particular significance on short time scales is the high-amplitude sediment-transfer signal generated by the strong El Niño forcing. Based on this strategy, among the short time-scale problems that can be addressed are (in the downstream direction): siliciclastic sediment production in the uplands, sediment storage and transfer in the floodplain, lobe switching in the delta, clinoform development on the shelf, and carbonate production from the outer shelf to the deep sea. These require monitoring studies to be initiated first as well as collection of baseline morphometry of present landscapes and seascapes through high resolution DEM and seafloor mapping. We may also wish to re-map specific morphometric features following large events, particularly storms and floods, that may occur throughout the duration of the study. This places an even greater importance on the collection of baseline data (e.g., CHIRP data, High resolution DEM's) early in the individual studies.

On medium time scales, research should involve the paleoclimatic record in floodplains and lakes in response to sea-level rise. Shallow coring of the floodplain and lake sediments will accomplish this. Similarly, cores taken at selected sites within the shelf clinoforms can be compared with cores taken from the floodplain to examine the similarities and differences in how these changes are expressed. A significant seismic program also will be required to map subsurface deposits in 3D. Core data are also critical to calibrate lithology, thickness and age of the older strata imaged by these seismic data. These data will also help quantify the reciprocal carbonate and siliciclastic sedimentation offshore. The longer time-scale investigations should involve investigation of channel stacking in the flood plain, through collection of deep cores and possibly GPR or seismic data, as well as offshore seismic data, which will image channel incision of the shelf, and interaction of shelf-slope carbonate and siliciclastic sedimentation over glacial/interglacial cycles. Locations of deeper cores offshore will be selected after processing and preliminary interpretation of seismic data.

These will ultimately result in a complete characterization of a source to sink system in which short-term processes can be extrapolated back to a stratigraphic record of a few million years. Modeling work will be undertaken to simulate this system and test sensitivities to processes at a variety of scales, from short-term stochastic processes such as floods and storms to longer-term processes such as subsidence, tectonics, and sea level. This will allow us to perform a well-calibrated test of the relative importance of allogenic vs. authogenic processes in building the stratigraphic record.

This type of integrated modeling over orders-of-magnitude spatial and temporal scales has never been attempted before, partly because of a lack of well-constrained field examples against which to build the models, as is a key goal of the Source-to-Sink Initiative.

The specific sediment yield for the Waipaoa river ranks among the highest in the world, consequently, even small-scale perturbations in the terrestrial environment should create a strong depositional signal. Because of the small size of the drainage basin, the residence time of sedimentary material within the terrestrial environment is relatively small, and therefore changing discharge conditions should rapidly propagate to the shelf depocenter. As a result, the Waipaoa system represents a sedimentary end-member where the potential for preservation of climatic, geologic, and anthropogenic signals on the shelf is high. Despite this potential, we need to understand how operative marine processes filter the changing discharge conditions to determine the dominant control on the formation of shelf stratigraphy. Thus, a combination of terrestrial and marine observations and modeling should be undertaken to define the terrestrial signals, determine the dominant marine transport processes, and resolve the shelf stratigraphic record.

Differences in implementation between Focus Sites

Episodic and highly concentrated river outflow into an energetic coastal environment ultimately will allow the community to examine the role of marine transport processes in modulating strong signals emanating from the drainage basin. Monitoring and modeling studies will be required to understand the mechanisms of sediment dispersal from Poverty Bay to the open shelf, and the resulting depositional signatures. Near bottom observations are key to understanding present-day sediment dispersal patterns (e.g., instrumented tripods, swath mapping, high-resolution seismic) and will provide realistic constraints for sedimentary models which need to be developed in order to predict dispersal and accumulation patterns beyond the temporal range of these observations.

A large body of research already exists regarding the geologic framework and Holocene environmental conditions in the terrestrial part of the Waipaoa system (e.g., Foster and Carter, 1997; Eden and Page, 1998). Using these present data, process and sampling studies can begin in the uplands and floodplain regions. Information also exists for the offshore part of the Waipaoa system, but data are fewer. Waipaoa studies would build on past and continuing work of New Zealand scientists in three significant areas: 1) Holocene climate record and landscape evolution, as well as mechanisms and patterns of sediment production (Landcare Research; http://www.landcare.cri.nz); 2) flow and sediment discharge monitoring (Gisborne District Council and the National Institute of Water & Atmospheric Research, NIWA); 3) nature and amount of along-margin and off-shelf transport and sediment storage on the continental slope (NIWA; http://www.niwa.cri.nz). These studies represent a significant contribution from New Zealand partners and provide ample opportunities for collaborative efforts to make significant scientific advances toward the Source-to-Sink objectives.

International collaboration

NIWA-US

Ok Tedi Mine group

University of PNG

A combination of methods will be needed to understand better the Waipaoa system. Shallow and deep coring of lacustrine and shelf environments along with chronostratigraphic analyses will be needed to define the inputs and sedimentary architecture. Numerous tephra layers and pronounced textural variations in marine cores off the Waipaoa will enhance our ability to constrain shelf stratigraphy. The erosion of regolith following large magnitude events that generate massive landsliding (e.g., 7.8 magnitude Napier earthquake of 1931) is characterized by an abundance of Tertiary pollen, which thus provides a means for identifying them in the shelf record (Wilmshurst and McGlone, 1996). The chronostratigraphic control afforded by tephrachronology, along with coring and high-resolution seismic studies, will facilitate construction of sediment budgets that can be used to constrain estimates of riverine inputs over the Holocene. Consequently, investigations should focus on the upland source regions, the floodplains, coast, and shelf. Ongoing studies of the continental slope by NIWA, in collaboration with US MARGINS scientists, will help to address the possibility of off-shelf transport, and to close the offshore portion of the dispersal system during the Holocene. Before process and sampling studies can begin, however, geophysical characterization of the shelf needs to be carried out, principally by swath bathymetry and high-resolution seismic profiling, with limited ground-truthing. This would be followed by more detailed sampling and observational studies. During this phase, it will be critical to coordinate closely the terrestrial and marine studies to address how changing terrestrial inputs and the dominant transport processes affect the segregation, dispersal and preservation of strata.

8. International Cooperation

The success of both focus studies will depend greatly on our foreign partners. Without their help in supplying previously acquired terrestrial and marine data, without their assistance in providing field support, such as boats and field camps, and without (particularly in the case of Papua New Guinea) permission to work in their territorial waters, these studies would be impossible.

In the Fly River study we rely on three prime groups for support. The Ok Tedi Mine group have been extremely forthcoming in sharing their hydrologic data from the Fly, and they also have given access to their river boats and even helicopters, the only practical ways in which field operations can be accomplished in the coastal lowlands. The Papua New Guineans themselves, particularly faculty at the University of Papua New Guinea, Port Moresby, have been helpful in obtaining permission to work in the country. Finally, the Australians have had a long-time interest in the Fly River, particularly as it stands at the northern end of the Great Barrier Reef; any change in the fluvial and/or dispersal paths of the Fly River system could have major impacts on the reefs to the south. As such, the Australians have conducted many research programs in the Gulf of Papua. Several Australian cruises, in fact, provided the first opportunities for American scientists to work in Papua New Guinean waters. These various links will be continued in future studies, particularly as the assistance of Ok Tedi and the Australians is critical for us to obtain small-draft boats that can work in river and coastal environments.

The success of any study of the Waipaoa River and adjacent offshore basin depends strongly upon New Zealand scientists. Fluvial data are available from Landcare, while access to New Zealand ships will come from close ties with NIWA (see previous section). The NIWA link to ships of opportunity is particularly critical, since it is our assumption that episodic events, most likely tied to cyclones, have a major effect on both the river and the transport of its sediment to the offshore basins. As US UNOLS ships are scheduled far ahead of any actual cruise, our only opportunity to study these major events and their effects on the dispersal and sedimentary systems most likely could come only from using New Zealand ships. As in the case of Australians, New Zealand scientists will be working as our research partners, and therefore ship costs should be less than if we were forced to lease a third-party ship.

9. Education and Communication

Educational opportunities should be vigorously incorporated within Source-to-Sink. Graduate students are expected to participate through the funded research activities. However, special attempts should be made to extend the terrestrial and marine research efforts to benefit younger and older scientists. Within NSF there are additional resources for undergraduate and post-graduate education. After an initial round of research is approved, plans will be developed for running undergraduate field camps for study of earth surface processes in conjunction with the research activities. Similarly, the opportunity will exist for professional field trips (~2 weeks) by interested scientists, especially university professors and secondary educators.

The MARGINS Office (currently at the Washington University in St. Louis) maintains an active website (www.margins.wustl.edu) that can provide information describing past, present, and future field programs and experiments as well as access to the existing databases. In this way both information of future opportunities and existing data can be accessed quickly, thus providing "instant" communication between geomorphologists, marine geologists, stratigraphers, and modelers.

An NSF-sponsored program entitled Digital Library for Earth Systems Education (DLESE) is a web-based operation that provides the basis by which many of the results by Source-to-Sink participants during the next 10 years. Unique opportunities would be dynamic figures, such as laboratory simulations of mass flows or time-series video observations of the seabed. This "text" would be used for the field camps and field trips, and would be available to anybody through the web. Other means for dissemination of results include Theoretical and Experimental Institutes (TEI), which are basically short courses. Regular sessions at national/international meetings should be planned. And the MARGINS web site will receive materials from Source-to-Sink studies.

Outreach

MARGINS Office and website

DLESE

Theoretical Institutes

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