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Facing the Coastal Challenge: Modeling Coastal Erosion in Southern California

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Abstract

Erosion due to natural and human activities poses a challenge to the future of California's coast. A process-based coastal evolution model is being developed to evaluate the past, present, and future rates of erosion of the southern California coast and present this dynamic environment in a visual format. The model consists of a mobile sediment transport component and a bedrock cutting component, both coupled and operating in varying time and space domains determined by sea level and boundaries of the littoral cell. We will utilize retrospective data from geomorphology, tectonics, sea level, climate, and paleoecology to investigate erosional and depositional processes and rates of change. Correlating the earlier shorelines with past climate conditions and time-stepping the ancient coastlines forward to the modern coastline will serve to validate the model. The model then will project the future evolution of the coastline using three scenarios: a most likely change, a minimum change, and a maximum change based on climate projections and possible human interventions. Our goals are to make this modeling technology and 3D visualization accessible to coastal planners and to advance public understanding of coastal evolution.

Introduction

The coast exists at the interface of the land, the sea, and the air. Due to its natural beauty and mild climate, this highly dynamic environment attracts dense populations and urbanization. Over 34 million people now live in California and about 80% of them live within 50 km of the coast (Resources Agency, 2001). Population projections are that the state will grow by 32.8% in the next 20 years (California Dept. of Finance, 2001). The recreational spending at California's beaches was estimated at $61 billion in 2001, including $15 billion/year in tax revenues (CDBW and SCC, 2002). The economic value of the coast in tourism alone is double the state's agricultural output (CDFA, 2000) which is the highest in the nation. Not reflected in these numbers is the value of property and infrastructure.

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About 85% of the California coast is eroding due to climatic conditions and human interventions (Resources Agency, 2001). The southern California coast in particular is facing grave challenges to the preservation of beaches as dams and hardening of the watersheds reduce sand moving to the coast. In addition, global warming is projected to raise sea level about 50 cm by the end of this century, an increase of 3 times the rate of sea level rise in the last century (IPCC, 2001). By the year 2100, atmospheric CO_2 concentrations may increase the frequency and amplitude of El Niño events (Collins, 2000) as well as interannual variability (Timmermann et al., 1999). Regional climate modeling indicates significant changes in temperature, precipitation, and snow will affect California once atmospheric CO_2 concentrations exceed the pre-industrial level by two-fold, perhaps as early as 2050 (Snyder et al., 2002). Thus, climate change will affect the coast in terms of sea level rise and increased storminess, both having adverse impacts on our beaches.

Working with these demographic and climate trends over long time scales will improve future projections of the state of the coast. To this end, we have initiated a study of the evolution of the southern California coast. Our project analyzes and models the eroding coast of the Southern California Bight from Point Conception to the Mexico border (Figure 1). The model is designed to predict coastal morphology as it evolves with time, changing sea level, and human interventions. With this longer perspective and understanding of the science behind coastal erosion, we can aim for more adaptive responses to our coastal challenges.

Geological Setting

California's coast was shaped by the collision of tectonic plates resulting in crustal compression and consumption (Inman and Nordstrom, 1971; Davis, 1996). This type of coast is characterized by narrow shelves bordered by deep basins and ocean trenches. The rock portion of the shore consists of a wave-cut platform backed by sea cliffs and coastal mountains. Sand beaches form on the platform during the low waves of the summer. Strong winter storms carry the sand seaward and erode the inner platform and sea cliff. The following summer of low wave energy will move the sand shoreward and rebuild the beach. The gently sloping wave-cut platform provides a "perch" for the beach, and a relatively small reservoir of sand is required to reform the beach each summer (Figure 2). Rapid sea level rise will submerge the platform and increase the amount of sand necessary to form a beach. Most southern California beaches are sand limited. Consequently, the beaches will be lost during rapid sea level rise.

It is this functional connection among the wave-cut platform, the sea cliff, and the beach that will be the focus of our modeling effort. However, neither the past nor the future can be exactly like the present because the condition of the coast always depends in part upon previous events and conditions. Coastal evolution is an example of a Markovian process because the present coastal features are dependent on the land forms that preceded them as well as the processes that formed them (Inman and Nordstrom, 1971). This means that modeling coastal evolution must

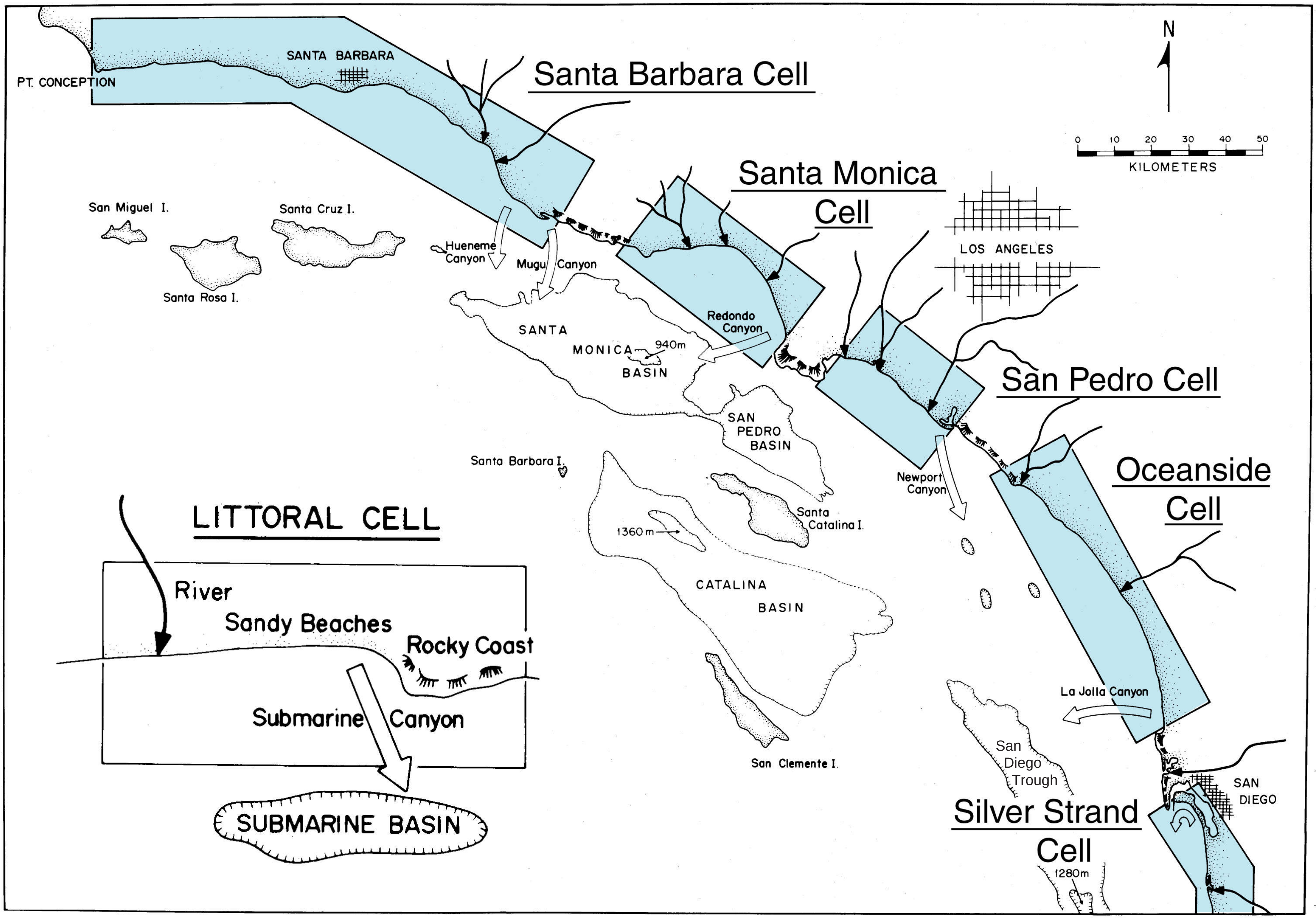

Figure 1. The five littoral cells along the southern California coast. Each cell contains a complete sedimentation cycle. Most sand is brought to the coast by streams, carried along the shore by waves and currents, and lost through submarine canyons to offshore basins [after Inman and Frautschy, 1965].

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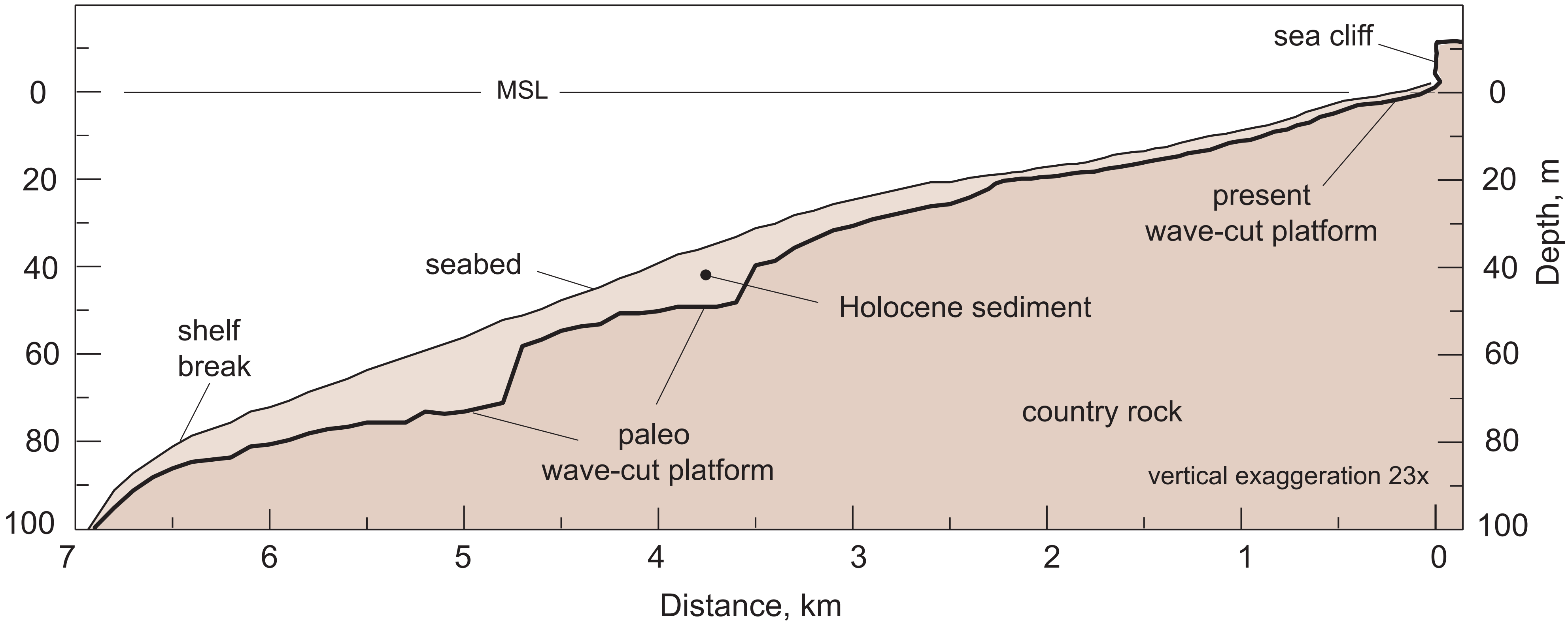

Figure 2. Generalized seismic profile relative to present mean sea sevel (MSL) across the continental shelf of the northern part of the Oceanside littoral cell (Figure 1). The sea cliff and adjoining platform are known as the terrace.

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move forward in time from past known conditions and be evaluated by the present before proceeding to the future. Beginning with paleo-coastal conditions provides a more comprehensive understanding and scale for coastal evolution as well as furnishing a necessary calibration in support of the main thrust of developing reliable predictions of future coastal evolution.

Sea Level and Paleoclimate

The position of the paleocoastline changed from near the present 50 m depth contour to the position of the modern coastline over the span of 12,000 years. Mean sea level (Figure 3) becomes the moving surface where forcing by waves, tides, and weather operates. The model addresses sequential time intervals over the past 12,000 years (Holocene) forward to the present and 200 years into the future. The rate of sea level rise varied widely since the last glaciation with three known periods of stillstand, one associated with the Younger Dryas cold climate about 12 thousand years before present (ka), one about 8.2 ka, and the modern stillstand. Paleo wave-cut platforms are notched into the shelf and are now found by seismic (subbottom) profiling beneath the cover of surface sediment. The two paleo-platforms provide relatively precise time and depth markers for model calibration. Waves and weather for driving the model will be based on the oceanic and atmospheric circulation that paleoclimate records indicate prevailed at that time. Also, the low sea level during the Younger Dryas event exposed large areas of offshore banks and caused significant modification in the shoaling patterns of waves and currents of the bight.

Littoral Cell

The model is functionally based on a geographic unit known as a littoral cell. A littoral cell is a coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. The universality of the littoral cell makes the model easily adaptable to other parts of the world by adjusting the boundary conditions of the model to cells characteristic of different coastal types (e.g., Inman, in press).

We apply our coastal evolution model to the Oceanside littoral cell first because it has been studied extensively and is tectonically the most stable of the five cells of the Southern California Bight (Figure 1). The computational area for the Oceanside littoral cell extends for 130 km in an on-offshore direction from the mountains of the coastal watersheds, rising to elevations of about 2000 m, seaward to the San Diego Trough in water depth of about 1200 m. The cell extends 84 km along the coast from Dana Point south to Point La Jolla. The sediment sources for the cell are the soil eroded from the watersheds that is carried to the coast by streams and the erosion of sea cliffs by wave energy. The sand moves along the coast as a river of sand powered by wave action. Scripps and La Jolla submarine canyons cut across the shelf and intercept the river of sand. The sand is transported episodically down the submarine canyons by turbidity currents and deposited on the floor of San Diego Trough. Longshore transport and loss down the Scripps-La Jolla submarine canyons

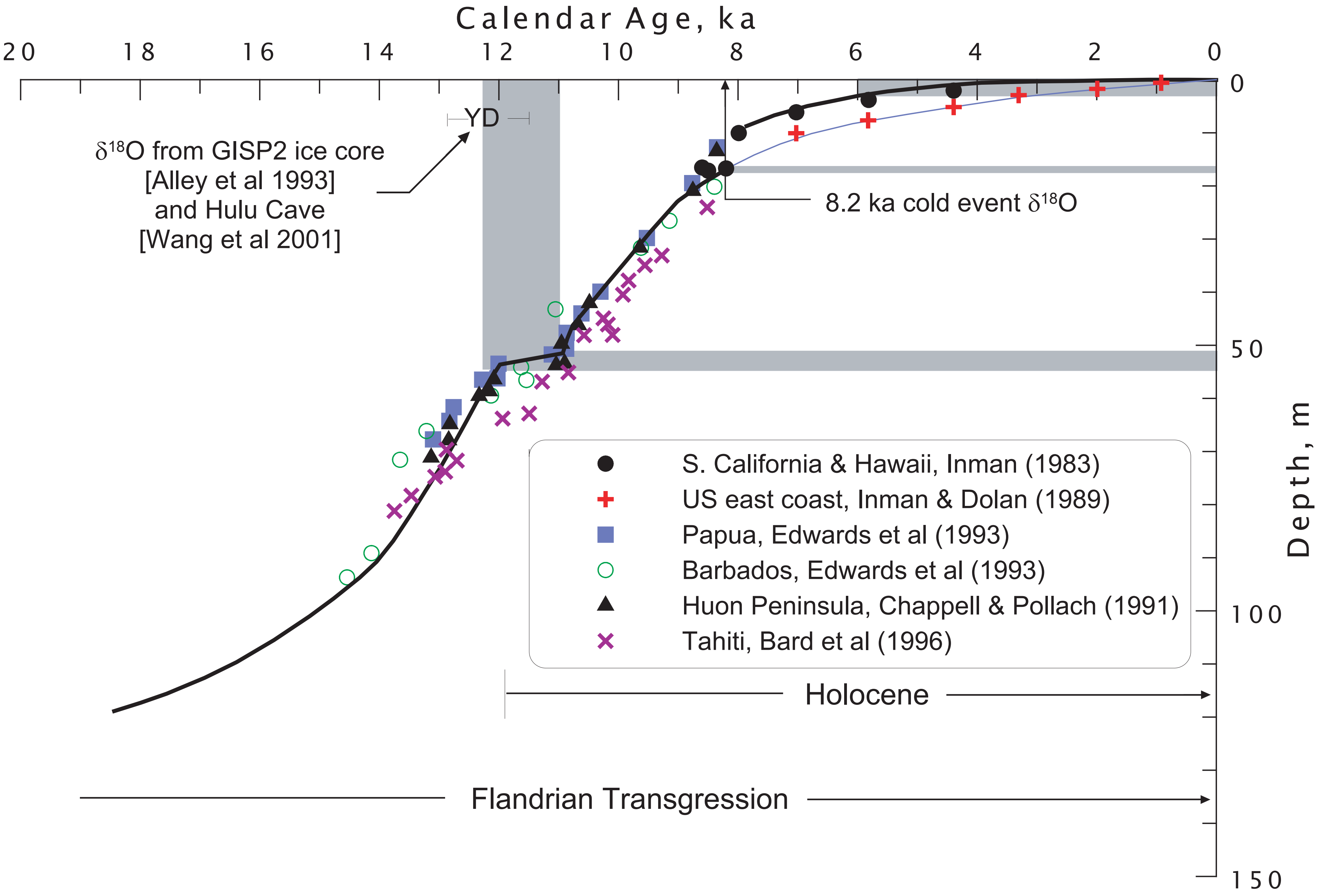

Figure 3. Sea level during the Flandrian transgression with stillstands associated with the Younger Dryas (YD), the 8.2 ka cold event, and the last 6 ka.

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is about 200,000 m^3/yr. Of this quantity, about 10%-20% is from sea cliff erosion and the rest is from streams and uplifted marine terraces (Inman and Masters, 1991; CDBW and SCC, 2002).

Model Architecture

The Coastal Evolution Model (CEM) consists of a Littoral Cell Model (LCM) and a Bedrock Cutting Model (BCM), both coupled and operating in varying time and space domains (Figure 4) determined by sea level and the coastal boundaries of the littoral cell at that particular sea level and time. At any given sea level and time, the LCM accounts for erosion of uplands by rainfall and the transport of mobile sediment along the coast by waves and currents, while the BCM accounts for the cutting of bedrock by wave action in the absence of a sedimentary cover. During stillstands in sea level, the combined effect of bottom erosion under breaking waves and cliffing by wave runup carves the distinctive notch in the shelf rock known as a wave-cut terrace (Figure 2).

In both the LCM and BCM, the coastline of the littoral cell is divided into a series of coupled control cells (Figure 5). Each control cell is a small coastal unit of uniform geometry where a balance is obtained between shoreline change and the inputs and outputs of mass and momentum. The model sequentially integrates over the control cells in a down-drift direction so that the shoreline response of each cell is dependent on the exchanges of mass and momentum between cells, giving continuity of coastal form in the down-drift direction. Although the overall computational domain of the littoral cell remains constant throughout time, there is a different coastline position at each time step in sea level. For each coastline position there exists a similar set of coupled control cells that respond to forcing by waves and current. Time and space scales used for wave forcing and shoreline response (applied at 6 hour intervals) and sea level change (applied annually) are very different. To accommodate these different scales, the model uses multiple nesting in space and time, providing small length scales inside large, and short time scales repeated inside of long time scales.

Progress in Model Development

The LCM (Figure 4, upper) has been used to predict the change in shoreline width and beach profile resulting from the longshore transport of sand by wave action where sand source is from river runoff or from tidal exchange at inlets (e.g., Jenkins and Inman, 1999). More recently it has been used to compute the sand level change (farfield effect) in the prediction of mine burial (Jenkins and Inman, 2002; Inman and Jenkins, 2002). Time-splitting logic and feedback loops for climate cycles and sea level change were added to the LCM together with long run time capability to give a numerically stable couple with the BCM.

The BCM (Figure 4, lower) is a new effort to model the erosion of country rock by wave action during transgressions, regressions, and stillstands in sea level. Because bedrock cutting requires the near absence of a sediment cover, the boundary

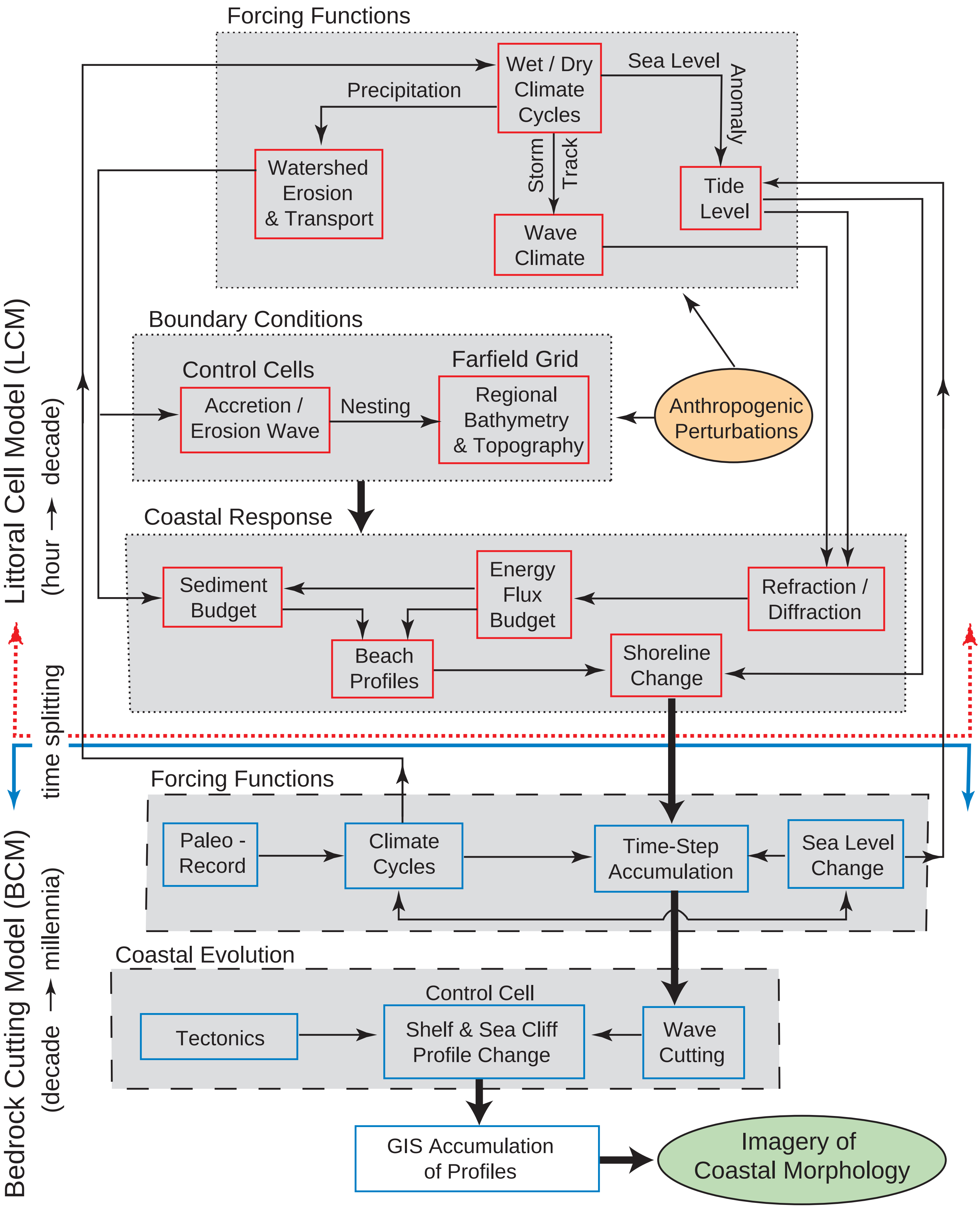

Figure 4. Architecture of the Coastal Evolution Model consisting of the Littoral Cell Model (above) and the Bedrock Cutting Model (below). Modules (shaded areas) are formed of coupled primitive process models.

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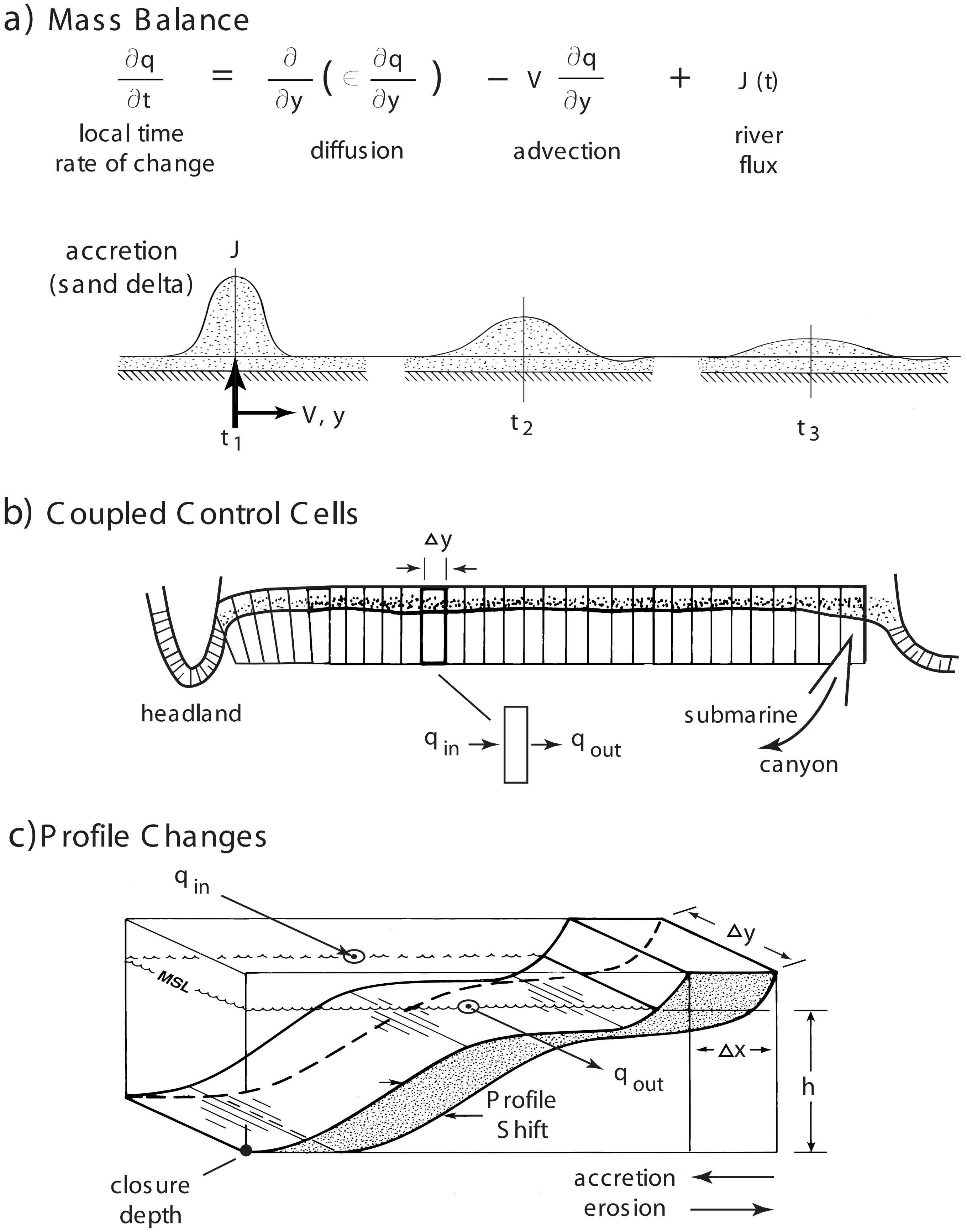

Figure 5. Computational approach for modeling shoreline change [after Inman and Masters, 1994].

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conditions for cutting are determined by the coupled mobile sediment model, LCM. When LCM indicates that the sediment cover is absent in a given area, then BCM kicks in and begins cutting. BCM cutting is powered by the wave climate input to LCM but applied only to areas where mobile sediment is absent. Bedrock cutting involves the action of wave energy flux *ECn* to perform the work required to abrade and notch the country rock. Both abrasion and notching mechanisms are computed by the newly developed wave-cutting algorithms. These algorithms use a general solution for the recession *R* (in meters) of the shelf and sea cliff. The recession is a function of the amount of time Δt that the incident energy flux exceeds certain threshold conditions,

$$R = f_e \int_{\Delta t} ECn\, dt$$

where the threshold condition imposed by Δt is the effective duration of the breaking wave and f_e is a function that varies from 0 to 1 and is referred to as the erodibility. The units of the erodibility are the reciprocal of the wave force per unit crest length (m/N). The erodibility is given separate functional dependence on wave height for the platform abrasion and wave notching of the sea cliff. For abrasion, the erodibility varies with the local shoaling wave height $H_{(x)}$ as

$$f_e \propto H_{(x)}^{1.63} \quad \text{(abrasion)}*$$

Consequently, recession by abrasion is a maximum at the wave breakpoint (at a depth of about 5/4 the breaking wave height, H_b) and decreases in both the seaward and shoreward directions. In contrast, the erodibility of the notching mechanism is a force-yield relation associated with the shock pressure of the bore striking the sea cliff (Bagnold, 1939; Trenhaile, 2002). The shock pressure is proportional to the runup velocity squared, which is limited by wave runup elevation. Wave pressure solutions (Havelock, 1940) give

$$f_e \propto h_r^2 \quad \text{(notching)}$$

where the runup elevation η_r is dependent on the tidal level η_o and the breaking wave height by Hunt's formula,

$$h_r = h_o + \Gamma H_b$$

Here Γ is an empirical constant determined from calibration data.

A simple test of the BCM is shown in Figure 6, where a constant sea level rise of 100 cm/century over a continental shelf sloping 2% was interrupted by a 1000 year

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*$H_{(x)}$ is related to energy flux by $ECn = \rho g H_{(x)}^2\, Cn/8$ where *ECn* is wave energy flux per meter of wave crest length (W/m), ρ is seawater density (kg/m^3), g is gravitational acceleration (m/s^2), and *Cn* is wave group velocity (m/s).

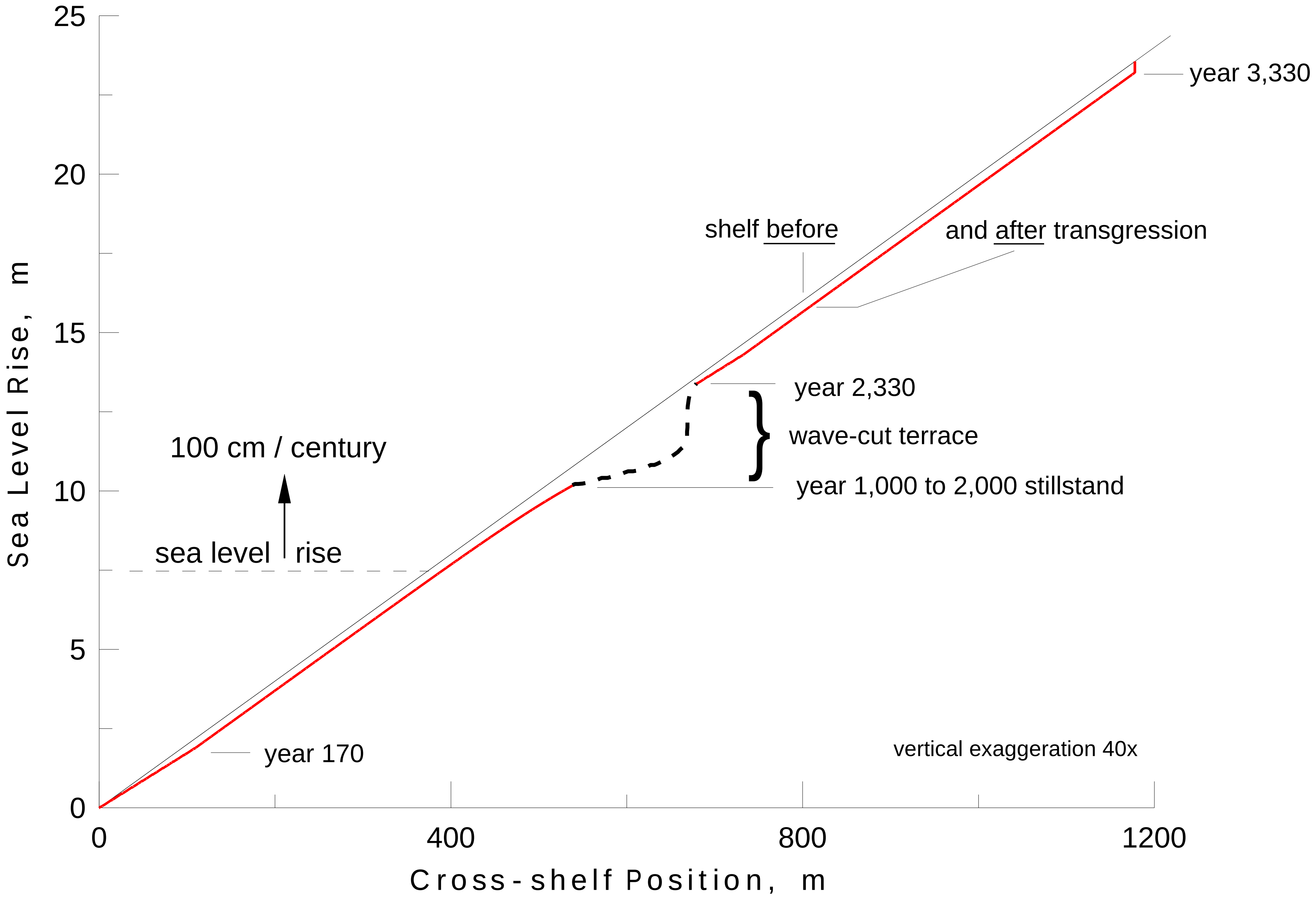

Figure 6. Test of Bedrock Cutting Model (BCM) showing change in initial 2% shelf slope (thin line) due to wave cutting during a transgression/stillstand/transgression sequence (heavy solid & dashed line).

stillstand. The wave cutting was driven by a two decade continuous wave record reconstructed for the shelf of the Oceanside cell from CDIP (2000) wave monitoring. This data was looped 170 times to provide forcing over the 3400 year long simulation. Inspection of Figure 6 shows that the shelf slope receded about 15 m during the periods of rapid sea level rise. However during the stillstand, a terrace was formed with about a 100 m wide wave-cut platform and a 2 m high remnant sea cliff. These dimensions are in approximate agreement with evidence of wave-cut terraces in the subbottom profiles of the shelf where the present 6 ka stillstand has eroded a platform more than 500 m wide (Figure 2). Refinements for the variability of wave climate during the Holocene are now being incorporated into the model.

Conclusions

Modeling the processes that shape California's coast will become more critical in the next few decades. With greenhouse warming, the rate of sea level rise will increase, most likely in the latter half of the century. For every 1^{o} C increase in air temperature globally, sea level rises 10 cm due primarily to thermal expansion and melting of low latitude glaciers (IPCC, 2001; Permanent Service for Mean Sea Level, 2002). The time to rapid sea level increase gives California 20 to 30 years to plan and it is not too early to start the process.

Advance planning is important for several reasons. First, land use planning is the cost-effective way to reduce hazards in the coastal zone (Titus, 2000; Resources Agency, 2001). Engineering solutions can always be instituted down the road, but avoiding hazards requires early planning and can reduce the future need for government assistance. Second, regional climate models indicate that California's hydrological crisis will become more acute with global warming (Snyder et al., 2002; Barnett et al., 2002). It is encouraging that the state is incorporating climate change scenarios in its updated water policy (CDWR, 2003), but choices involving water supply also affect the coast. Dams, particularly in southern California, are the major cause of sand-starved beaches. If increasing the reliability of water supply means building more dams, the coast will suffer. If it were possible to accommodate California's projected population growth with more recycling, conservation, or outside sources (desalination), then additional dams would not be needed. Channelization and hardening associated with urbanized watersheds also restrict sediment flux to the coast.

Foremost, responsible planning for sea level rise will rely on high resolution digital mapping of the coastal zone and underlying geology as well as process-based modeling of coastal evolution. The ultimate decisions on preserving California's beaches will be better informed for undertaking these efforts.

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