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Authors
Inman, Douglas L.
Jenkins, Scott A.
Masters, Patricia M.

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Douglas L. Inman
Coastal Morphology Group
Integrative Oceanography Division
Scripps Institution of Oceanography
dinman@ucsd.edu

Scott A. Jenkins
Coastal Morphology Group
Integrative Oceanography Division
Scripps Institution of Oceanography
sjenkins@ucsd.edu

Patricia M. Masters
Coastal Morphology Group
Integrative Oceanography Division
Scripps Institution of Oceanography
pmasters@ucsd.edu

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MODELING PLATFORMS, TERRACES AND COASTAL EVOLUTION

Terraces and their associated platforms and sea cliffs are the wave-cut and wave-built features associated with the land-water interface of seacoasts and lake shores. Along ocean coasts, they are the primary signature of the stillstands in water level during the transgressions and regressions of Pleistocene and Holocene epochs. The mechanics of terracing are fundamental to understanding the evolution of today's coastlines with their platforms, sea cliffs, barriers, spits, and capes. Coastal evolution models must incorporate processes that treat sediment transport and deposition as well as the abrasion and cutting of bedrock formations. This can be accomplished by coupled models, one treating the mobile sediment and the other the bedrock cutting.

Background

Early studies of terraces, platforms, and sea cliffs include the work of de Beaumont (1845), Cialdi (1866), Fisher (1866), and Gilbert (1885). Gilbert's study of the active topographic features along the shores of the Great Lakes, supplemented by the visually distinct sea levels of the Pleistocene fossil shores of Lake Bonneville in

Utah, provided the most detailed insight into the formation of platforms and terraces. He describes the wave-quarried hard rock platforms as *wave-cut terraces* backed by sea cliffs and the depositional features comprised of littoral drift as *wave-built terraces*. He also studied the terrace relations to changing lake level. Emery (1960), Shepard (e.g., 1963), and others used this nomenclature with *marine terrace* as a more general term for wave-cut and wave-built terraces along ocean coasts.

However as pointed out by Trenhaile (1987), platforms may not be wave-cut but formed by other processes such as solution. He prefers *shore platform* as a more general term for rock surfaces of low gradient within or close to the intertidal zone. He uses the term *wave-cut terrace* to refer to the specific category of platform formed by waves (Trenhaile, 2002). Sunamura (1992) classifies shore platforms developed during the present sea level as (a) sloping, (b) horizontal, and (c) plunging cliff. A more descriptive nomenclature for the latter two would be (b) step platform and (c) submerged platform. Generally types (a) and (b) develop from cliff recession, with the step in platform (b) caused by differential erosion of rock strata. Plunging cliff platforms have sea cliffs that extend below the present water surface before joining a submerged platform. The submerged platform is a remnant feature from rapid sea level rise and/or land subsidence. In what follows we will discuss numerical modeling of wave-cut terraces. These features consist of rock platforms backed by sea cliffs that were formed during the present stillstand in sea level as well as relic terraces now found on the continental shelf buried under Holocene sediment (Figure 1).

The present configuration of coastlines and their associated terraces and sea cliffs retain vestiges of the previous landforms from which they have evolved. Coastal evolution is a Markovian process where the present coastal features are dependent on the landforms and processes that preceded them (Inman and Nordstrom, 1971). This means that modeling coastal evolution must move forward in time from past known conditions and be evaluated by the present before proceeding to the future. Thus paleocoastlines with their wave-cut terraces become time and space markers for modeling coastal evolution.

Numerical modeling of landforms

Physical models have provided insights and guidance to many of the processes leading to coastal evolution (e.g., Inman, 1983; Sunamura, 1992). Generally these efforts are limited by the uncertainties between laboratory experiments and the time and space scales of the landforms they represent. These uncertainties are

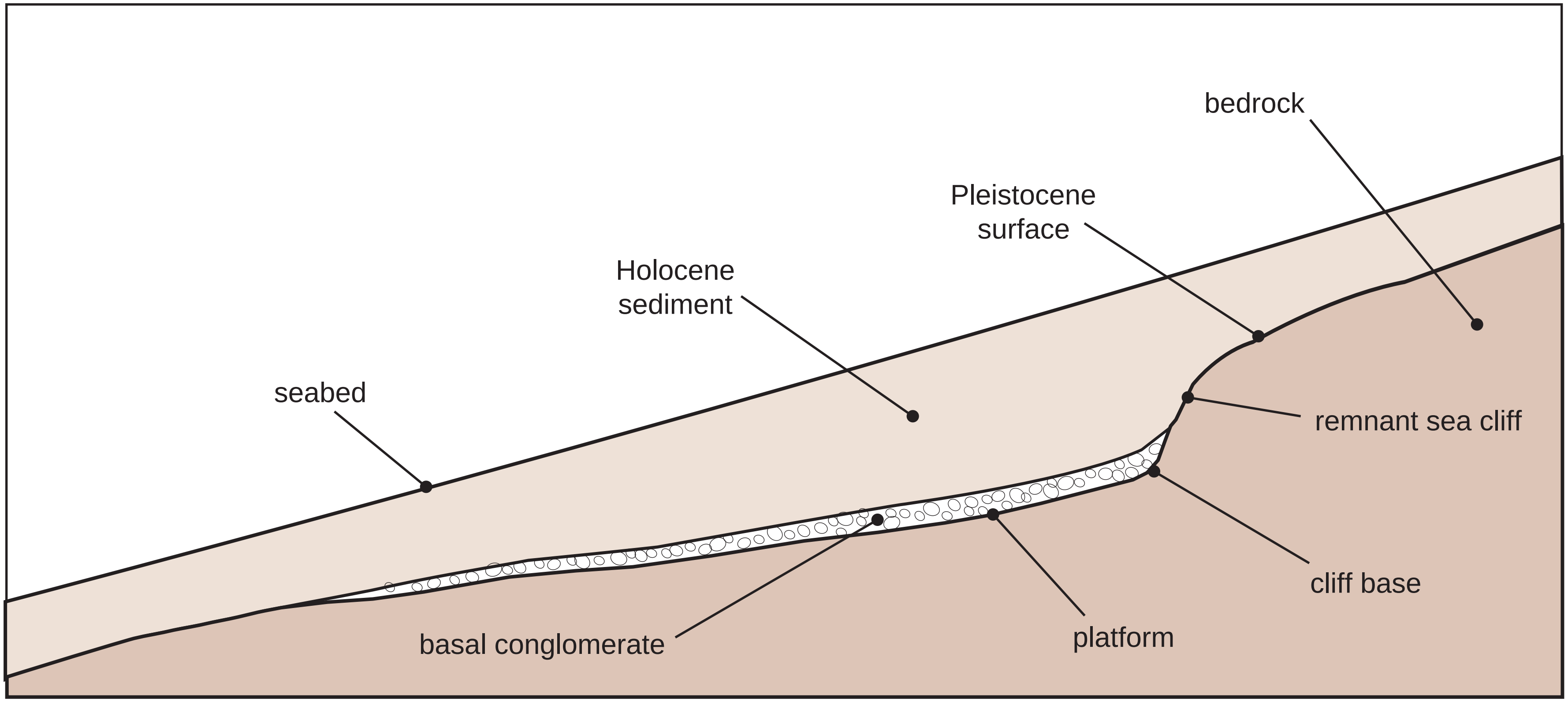

Figure 1. Illustration of wave-cut terrace notched into the bedrock and now found on the shelf by seismic profiling below a cover of Holocene surface sediment.

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circumvented by numerical models where the temporal and spatial scales of the landforms are applied to the laws governing geomorphology.

Numerical modeling of landform evolution is a rapidly expanding field driven by the need to understand the environmental consequences of climate change and sea level rise. Numerical modeling has been enabled by the revolution in computational power, graphical representation, and ever expanding digital databases of streamflow, wave climate, sediment flux, and landform topography (Inman and Masters, 1994). Several 2-dimensional models have been developed for the formation of wave-cut and wave-built terraces at various sea levels. Storms *et al.* (2002) describe a process-response model for the development of barrier beaches during sea level rise, and Trenhaile (2002) developed a model for the formation of rock platforms during changing sea level.

The Storms *et al.* (2002) model uses energy and mass flux balances to solve for incremental changes in the cross-shore profiles of mobile sediment in the Caspian Sea. On the other hand, the Trenhaile model uses a force-yield criterion to calculate the incremental erosion of steep, rocky submarine slopes. The latter model does not balance the budget of energy flux and, for certain selections of model parameters, requires a greater expenditure of energy in cutting rock than is available in the incident waves. This deficiency can be overcome by the energetics based rock cutting model of Hancock and Anderson (2002). Developed for the formation of strath terraces in the Wind River valley during the Quaternary, the model includes sediment transport, vertical bedrock cutting that is limited by alluvial cover, and lateral valley-wall erosion. When reformulated for wave-forcing and sea level change, their approach is applicable to wave-cut terraces.

Architecture of a coastal evolution model

Here, we describe the broad outlines of a 3-dimensional coastal evolution model developed under funding from the Kavli Institute (Inman *et al.,* 2002). 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 (see entry on *Littoral Cells*).

The Coastal Evolution Model (Figure 2) consists of a Littoral Cell Model (LCM) and a Bedrock Cutting Model (BCM), both coupled and operating in varying time and space domains determined by sea level and the coastal boundaries of the littoral cell at that particular time. The LCM accounts for erosion of uplands

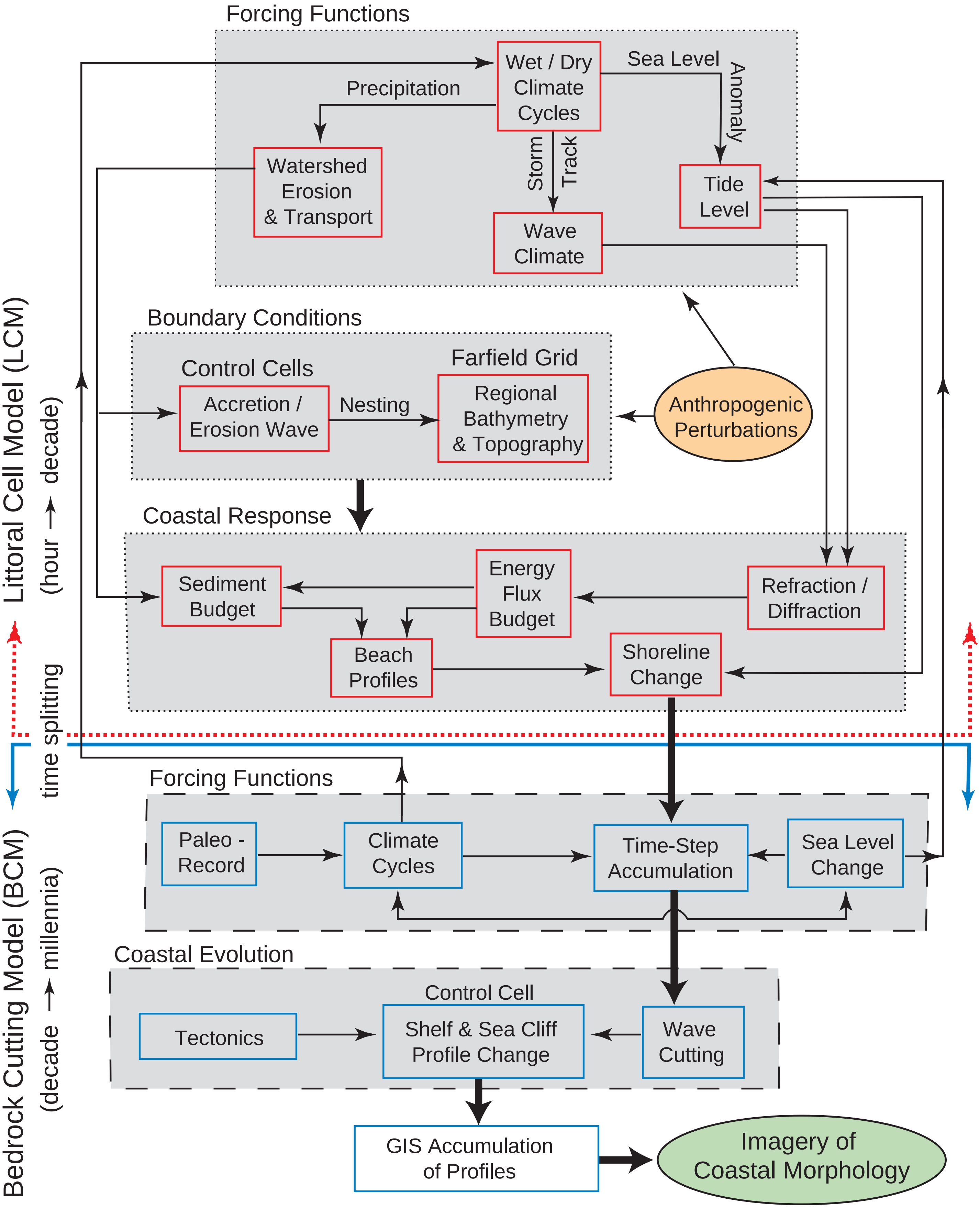

Figure 2. Architecture of the Coastal Evolution Model consisting of the Littoral Cell Model (above) and the Bedrock Cutting Model (below). Modules (shaded areas) are formed of coupled primitive process models.

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by rainfall and the transport of mobile sediment along the coast by waves and currents, while the BCM accounts for the erosion of bedrock by wave action in the absence of a sedimentary cover. During stillstands in sea level along rock coasts, the combined effect of bottom erosion under breaking waves and cliffing by wave runup carves the distinctive notch in the shelf rock of the wave-cut terrace (Figure 1).

In both the LCM and BCM, the coastline of the littoral cell is divided into a series of coupled control cells (Figure 3). Each control cell is a small computational 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 with similar sets of coupled control cells.

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,

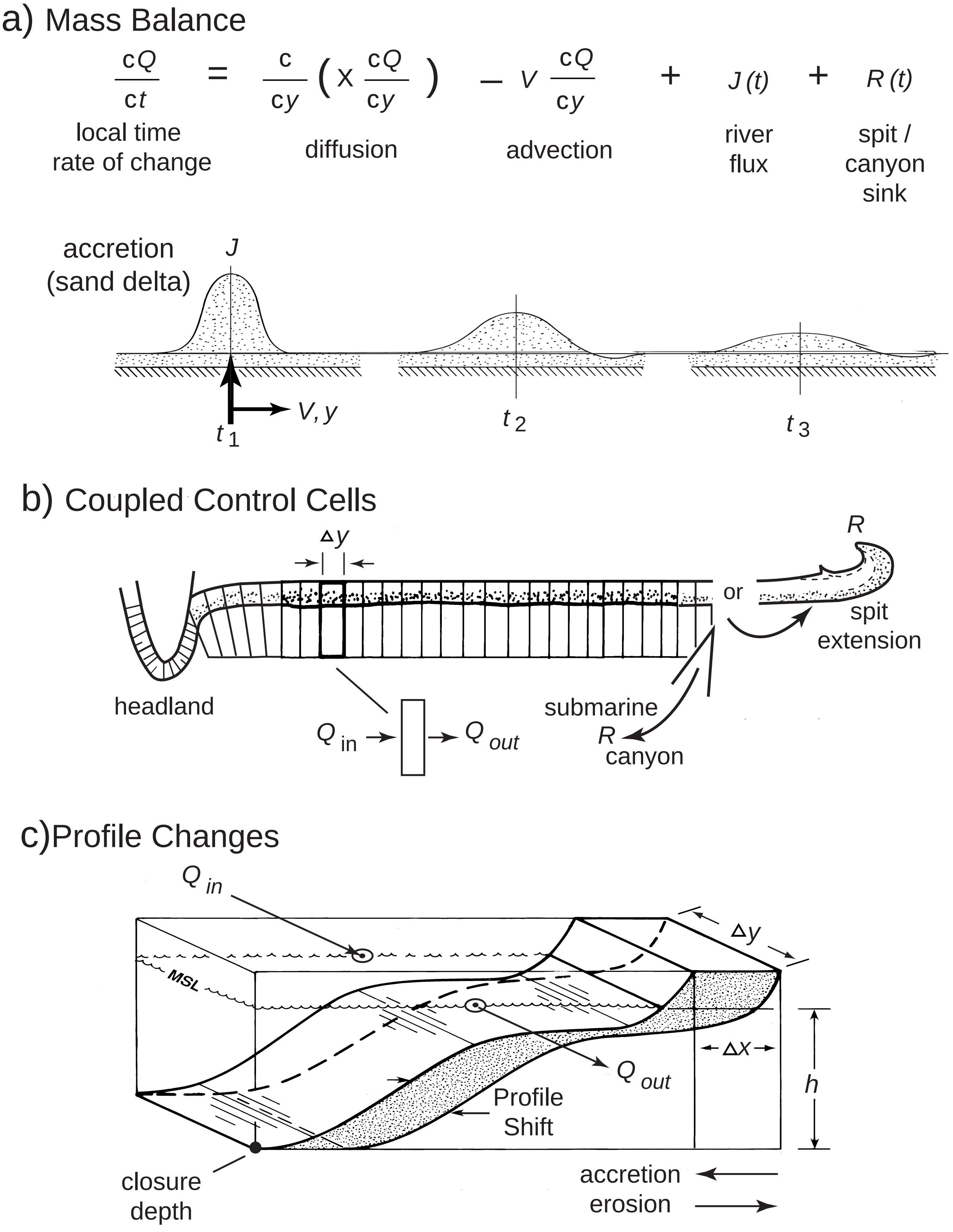

Figure 3. Computational approach for modeling shoreline change [after Inman et al., 2002].

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providing small length scales inside large, and short time scales repeated inside of long time scales.

The LCM (Figure 2, 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). It has also been used to compute the sand level change (farfield effect) in the prediction of mine burial (Inman and Jenkins, 2002).

Bedrock erosion

The BCM (Figure 2, lower) models the erosion of bedrock by wave action during transgressions, regressions, and stillstands in sea level. Because bedrock cutting requires the near absence of a sediment cover, the boundary 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. Time-splitting logic and feedback loops for climate cycles and sea level change are imbedded in LCM together with long run time capability to give a numerically stable couple with the BCM.

Bedrock cutting involves the action of wave energy flux to perform the work required to notch the country rock, abrade the platform, and remove the excavated material. Both abrasion and notching mechanisms are computed by wave-cutting algorithms. These algorithms provide general solutions for the recession of the shelf and sea cliff. The recession is a function of the amount of time that the incident energy flux exceeds certain threshold conditions. These conditions require sufficient wave energy flux to remove the sediment cover, and a residual energy flux that exceeds the erodibility of the underlying bedrock. The erodibility is given separate functional dependence on wave height for platform abrasion and wave notching of the sea cliff.

The erodibility for platform abrasion increases with the 1.6 power of the local shoaling wave and bore height, commensurate with the energy required to move the cobbles in the basal conglomerate that abrade the bedrock platform (Figure 1). As a consequence, recession by abrasion is a maximum at the wave breakpoint and decreases both seaward and shoreward of that point. In contrast, the erodibility of the notching mechanism is a force-yield relation associated with the shock pressure of the wave bore striking the sea cliff (Bagnold, 1939; Trenhaile, 2002). The shock pressure is proportional to the runup velocity squared, and its field of application is limited by wave runup elevation. Wave pressure solutions (Havelock, 1940) give a notching erodibility that increases with the square of the wave runup height above water level.

An example of terrace cutting by the BCM is shown in Figure 4 where a constant sea level rise of 100 cm/century over a continental shelf sloping 2% was interrupted by a 1000 year stillstand. The wave cutting was driven by a two decade continuous wave record reconstructed for the southern California shelf by wave monitoring (Inman *et al.,* 2002). This data was looped 170 times to provide forcing over the 3400 year long simulation. Inspection of the figure shows that the shelf slope receded about 15 m during the periods of rapid sea level rise. During the 1000-year stillstand, a wave-cut 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 along the California coast (Inman *et al.,* 2002). However, models of terrace cutting at paleo-sea levels will always require input of proxy wave climate appropriate for the location being modeled as well as the proper erodibility coefficients for the bedrock at that location (see entries on *Climate Patterns in the Coastal Zone*, and *Energy and Sediment Budget of the Global Coastal Zone*).

Douglas L. Inman, Scott A. Jenkins and Patricia M. Masters

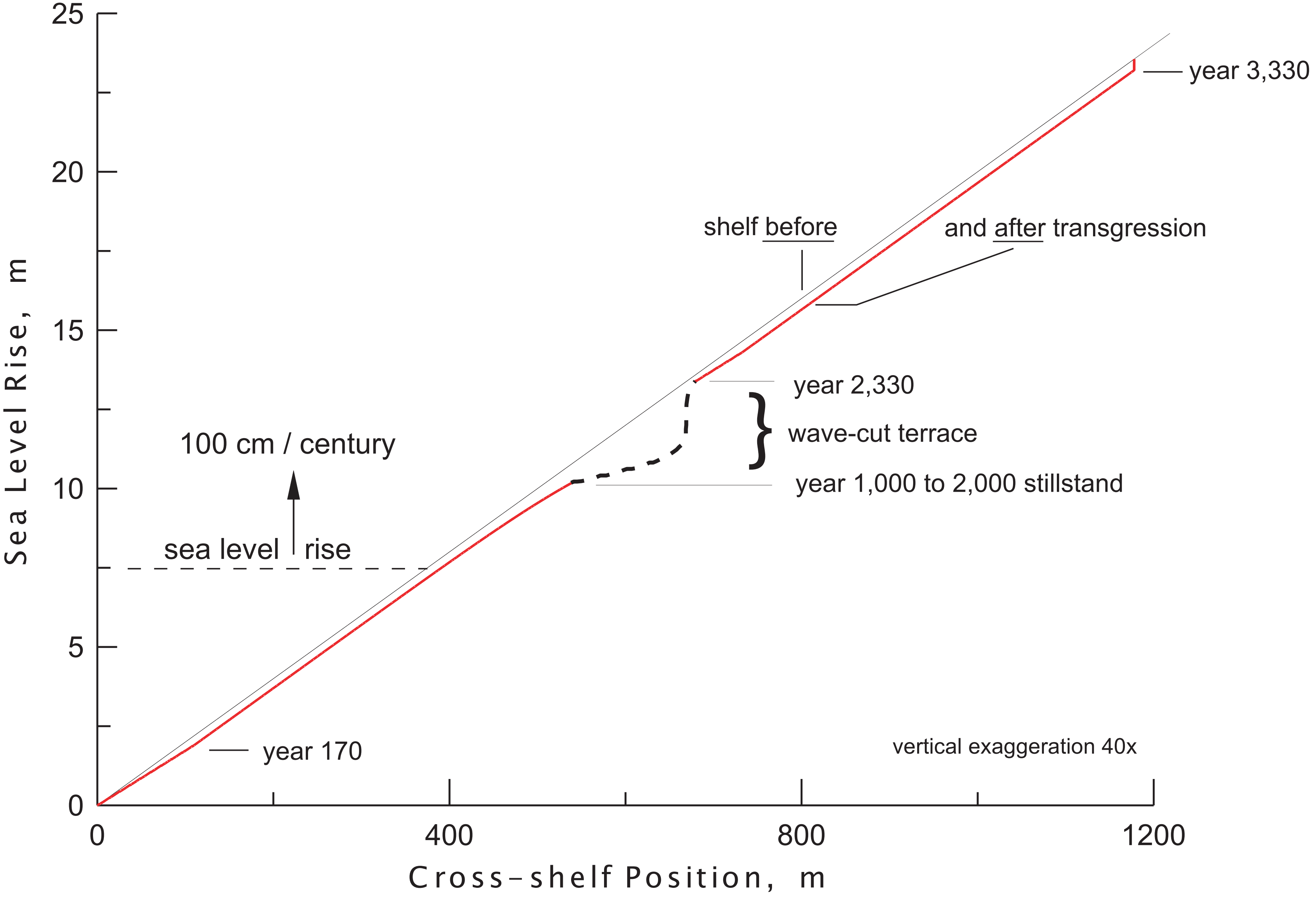

Figure 4. Test of Bedrock Cutting Model (BCM) showing change in initial 2% shelf slope (thin line) due to wave cutting during a transgression/stillstand/transgression sequence (red & dashed line) [from Inman et al., 2002].

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