CHAPTER 5

Eustatic Control of Submarine Fan Development

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Abstract

Global changes in sea-level control both siliciclastic and calciclastic turbidity-current deposition in the deep sea. On modern active and passive margins, growth of submarine fans occurred mainly during the Pleistocene glacials (low sea-level). During interglacials (high sea-level), most fans were dormant. In the rock record, the occurrence of most turbidites and winnowed turbidites closely correlates with lowstands of sea-level. Sea-level fluctuations appear to have been the primary control on fan growth throughout the Phanerozoic. In most cases, tectonism appears to be of secondary importance.

Introduction

This chapter reviews studies that document global lowering of sea-level as the primary factor in the generation of both siliciclastic and calciclastic turbidity currents as well as the cause of vigorous contour currents in the deep sea [1–3]. We used the global sea-level curve of Vail, Mitchum, and Thompson [4], now referred to as the coastal onlap curve [5], as our standard reference because of its coverage of the entire Phanerozoic. Also, the “Vail curve” is in good agreement with most previously published curves (Fig. 1). Our studies show that the duration of maximum sea-level lowering is more important to our thesis than the rate of rise or fall [12]. Global changes in sea-level are primarily controlled by tectonism and glaciation; however, glaciation is considered to be the only mechanism capable of causing relatively rapid (> 1 cm/1000 yr) fluctuations in sea-level [13]. The relative effects of tectonism and glaciation on sea-level fluctuations are illustrated in Figure 2. Long-term gradual fluctuations in global sea-level appear to be controlled primarily by changes in mid-oceanic ridge volume (spreading rate) as well as by subsidence of continental margin and sediment compaction. Short-term rapid fluctuations in sea-level appear to be related to glaciation.

Glacio-Eustatic Control of Submarine Fan Development

Sedimentation and growth of most modern submarine fans have been controlled during the last few million years by Plio-Pleistocene glacio-eustatic sea-level fluctuations. During the relatively short (5,000 to 20,000 years) interglacial phases such as the Holocene, recession of continental glaciers caused the sea-level to rise to or above its present level. Such high stands move the locus of river sedimentation from the vicinity of the shelf break to as much as several hundred kilometers inland across the continental shelf. The great width and low gradient of the shelf generally restrict river deposition to deltas on the innermost shelf, and large amounts of terrigenous sediment that are needed to build submarine fans cannot reach the continental slope or rise. Hence, fan development is temporarily halted during such high sea-level stands. In contrast, during glacial phases such as the Wisconsin Glacial, sea-level is lowered 40 to 150 m below the present level. Most continental shelves become emergent, and rivers discharge their sediment loads directly into the heads of submarine canyons at or near the shelf break. Thus, large quantities of terrigenous sediment are continuously transported to the deep sea via turbidity currents and related mass-gravity flows, and submarine fan development is rapid.

Such glacio-eustatic control of fan sedimentation has been documented in detail for the Amazon Deep-Sea Fan and the adjacent continental margin off northeast Brazil.
Sediment cores show that although terrigenous sediments accumulated rapidly and continuously throughout the Wisconsin Glacial (Y Zone), this sedimentation was abruptly halted at the beginning of the Holocene (~11,000 yr B.P.) when sea-level quickly rose in response to rapid deglaciation (Fig. 3). Sea-level rise moved the locus of Amazon River sedimentation from the shelf break inland by as much as 350 km to its present location. The great shelf width and low gradient plus strong longshore currents have confined Amazon River sediments to the estuary and innermost shelf during the Holocene. The Amazon Fan has been inactive during this time and received only a thin (<1 m) veneer of pelagic sediment (Fig. 3).

Studies of late Quaternary climatic fluctuations (see references in [16]) have revealed that warm interglacial intervals (and accompanying high sea-level stands), such as the Holocene, tend to be relatively short (10,000 to 20,000 years) and occur with a periodicity of about 100,000 years (see sea-level curve in Fig. 3). During the remaining 80,000 to 90,000 years of each cycle, the glacial mode is predominant as ice gradually builds up on the continents and sea-level fluctuates between 40 and 150-m below the present level. The generalized sea-level curve (based on published oxygen-isotope curves) shows sea-level fluctuations during the last complete glacial/interglacial cycle. During this period, sea level was at or near its present level only during the Holocene (0 to 11,000 yr B.P.) and at the beginning of the last interglaciation (~120,000 to 127,000 yr B.P.).

The generalized core log in the center of Figure 3 summarizes the sediment lithology observed on the Amazon Fan and adjacent continental margin during the last glacial/interglacial cycle. During the period from 120,000 to 11,000 yr B.P., sea-level was low and turbidity flows continuously deposited sandy turbidites and silty hemipelagic clays across the fan at rates of 25 to greater than 150 cm/10² yr. It was during this and previous glacial phases that the fan was actively growing. The core log shows that during the high sea-level stands (1 to 11,000 and 120,000 to 127,000 yr B.P.), only pelagic biogenic (foraminiferan marl) sediments accumulated on the fan at rates of less than 5 cm/10² yr. Hence, during these interglacial high sea-level stands, the Amazon Fan was temporarily inactive.

Glacio-eustatic sea-level fluctuations have also controlled sedimentation on most other modern deep-sea fans during the Plio-Pleistocene, especially fans on passive margins with wide shelves. The Bengal and Indus Fans, the two largest modern fans, both show an abrupt cessation of terrigenous deposition during the Holocene ([17]; V. Kolla and G. Griep, personal communication). Recent D.S.D.P. results from the Mississippi Fan ([18]; Bouma and Coleman, Chapter 36 of this volume) show a sedimentation regime similar to that observed for the Amazon Fan; i.e., slow pelagic deposition (3 to 30 cm/10² yr) during the Holocene (Z Zone) and Late Interglacial (X Zone), and rapid (up to 1200 cm/10² yr) turbidity-current deposition during the Wisconsin (Y Zone) Glacial. In general, sediment cores from deep-sea fans, continental rises, and abyssal plains throughout the Atlantic and Indian Oceans show lithostratigraphic relationships that are similar to those shown in Figure 3 and which demonstrate that downslope deposition of terrigenous sediment is largely controlled by glacio-eustatic sea-level fluctuations [17]. The right side of Figure 3 shows examples of sedimentation rates on four modern fans during the last glacial/interglacial cycle.

Two notable exceptions to this sedimentation pattern are the Congo and Magdalena deep-sea fans, which have continued to receive turbidity flows and mass-transport deposits throughout the Holocene [19,20]. In these cases, the continental shelf is exceptionally narrow and the submarine canyon that feeds the fans extends across the entire shelf directly into the river mouth. Hence, sediments are discharged directly into the canyon even during the present high sea-level.
In summary, glacio-eustatic sea-level fluctuations are apparently the most important factor controlling sedimentation and growth of most modern deep-sea fans on passive margins, and at least some fans on active margins as well. It is difficult to evaluate the effects of glacio-eustatic fluctuations on fan development prior to the Pliocene because the occurrence, timing, and magnitude of glacial cycles are largely unknown. However, when major periods of glaciation did occur (Fig. 2), they probably had a profound influence on deep-sea fan development.

Eustatic Control of Ancient Submarine Canyons and Fans

Global changes in sea-level appear to control the origin of submarine canyons and fans. The following hydrocarbon-bearing submarine canyon and fan deposits appear to have originated during periods of low sea-level: 1) the Pennsylvanian (Atokan) Red Oak Sandstone in Oklahoma; 2) the early Permian Cook Channel of the Jameson Field in Texas; 3) the Upper Cretaceous Woodbine-Eagle Ford Interval in Texas; 4) the Paleocene sequence of Forties and Montrose Fields in the U.K., North Sea; 5) the Paleocene Balder Field in the Norwegian North Sea; 6) the Paleocene Cod Fan in the Norwegian North Sea; 7) the early Eocene Yoakum Channel in Texas; 8) the early Eocene sequence of Frigg Field in the border of U.K. and Norwegian North Sea; 9) the late Oligocene Lower Hackberry Sandstone in Texas; 10) the late Oligocene Puchikiren Formation in Austria; 11) the late Miocene Stevens Sandstone of southeastern San Joaquin Valley in California; 12) the late Miocene Puente Formation of Wilmington Field in California; 13) the early Pliocene Repetto Formation of Ventura Field in California; and 14) the Pleistocene Mississippi Canyon in Louisiana. The relationship of Tertiary and Quaternary hydrocarbon-bearing submarine canyon and fan deposits to global sea-level stands are shown in Figure 4 (see references in [2]).

Eustatic Control of Winnowed Turbidites

In modern oceans, thermohaline-induced bottom currents are commonly known as contour currents because of their tendency to flow parallel to bathymetric contours [21, 22]. Contour currents are capable of erosion, transportation,
dissolution, and redeposition of vast quantities of sediment, and some portions of the continental rise appear to be largely constructed of such deposits (e.g., Western North Atlantic). Theoretically, contour currents should be more vigorous during global lowstands of sea-level. This should cause major winnowing of turbidites. To test this hypothesis, Shanmugam and Moiola [1] plotted ages of winnowed turbidites on the global sea-level curve of Vail, Mitchum, and Thompson (Fig. 5). This plot (Fig. 5) shows a strong correlation between winnowed turbidites and relative lowstands of sea-level.

**Eustatic Control of Calciclastic Turbidites**

Reworked neritic fossils in central Pacific pelagic sediments (Fig. 6) have been attributed to erosion of shallow-water carbonates during periods of low sea-level [23]. The presence of shallow-water-derived limestone clasts in these deep-sea pelagic sediments can only be explained by downslope transportation from shallow-water carbonate platforms by debris flows and associated turbidity currents. Furthermore, these data (Fig. 6) imply a possible lowstand of sea-level in the Late Cretaceous (Campanian-Maastrichtian) that has not been previously recognized. Similar to these Cenozoic and Mesozoic examples, Shanmugam and Moiola [3] showed that the following calciclastic turbidites of the Paleozoic age also correlate with low sea-level: 1) the late Permian (Guadalupian) Pinery and Rader Limestones in west Texas; 2) the Pennsylvanian (Atakan) Dimple Limestone in Texas; 3) the late Mississippian (Meramecian) Rancheria Formation in New Mexico and west Texas; 4) the early Devonian Rabbit Hill Limestone in Nevada; 5) the early Middle Ordovician Cow Head Breccia in Newfoundland; 6) the early Ordovician Hales Limestone in Nevada; and 7) the early Cambrian Sekwi Formation in Northwest Territories. These data suggest that deep-sea carbonate sediments of turbidity-current origin also tend to form during relative low sea-level stands.

**Effects of Tectonic Setting on Fan Development**

Effects of active and passive margins are generally reflected in associated submarine fans. Active margins tend to produce small sand-rich fans, whereas passive margins develop large mud-rich fans (Table 1). Tectonic activity may disrupt normal fan growth on active margins (Stow and others, Chapter 4 this volume), but fans may continue to grow without tectonic interruptions on passive margins. The relationship between tectonic setting and type of fan is less clear for ancient fans when compared with modern fans. For example, the Eocene Hecho Group in Spain and its mud-rich, highly efficient submarine fan is associated with an active margin setting. An explanation for this apparent discrepancy may be found in the modern fans and the timing of their development.

Modern fans of both active (e.g., Astoria, Navy, Coronado, and Monterey) and passive (e.g., Bengal, Indus, Amazon, and Mississippi) margins were all active during the Pleistocene Glacials (low sea-level), but most were either dormant or relatively inactive during the Holocene and previous interglacials (high sea-level). The development of a submarine fan, therefore, is controlled primarily by fluctuations in sea-level, and not by tectonic setting.

The conventional wisdom that tectonic uplift usually increases sediment supply and, thus, submarine fan growth may not be valid. In order for a fan to develop, a large supply of unconsolidated sediment is required to generate the major turbidity currents that form the fan. Such volumes of sediment are seldom produced by initial tectonic uplift.
because the uplifted land is a lithified mass. Initial erosion of the uplifted land mass does not produce large quantities of sand- to clay-sized sediment. Because of the lack of sand- to clay-sized sediment, the major turbidity currents needed to develop submarine fans cannot be generated. The coarse debris from initial erosion must first be broken into a finer size by fluvial and shallow-marine processes before it can be transported by turbidity currents to deep-sea fans. This important aspect is often overlooked in advocating tectonics as a causal factor for submarine fan growth.

Shelf and related environments are major areas of sediment accumulation where delta, offshore bars, storm deposits, sand ridges, and sand waves develop. The shelf is a “transit lounge” for sand- to clay-sized sediments that are bound for deep-sea fans during lowstands of sea-level. As a generality, passive margins with wide shelves should develop large-scale fans, and active margins with narrow shelf should produce small-scale fans. In summary, sea-level changes exert primary control on fan development as evidenced by the preferential growth of fans during lowstands of sea-level on both active and passive margin settings. However, tectonics play an important secondary role on fan growth along active margins by limiting shelf width and sediment supply.

Summary and Conclusions

Our studies [1,2] show that major packages of siliciclastic turbidites throughout the geologic record are associated with lowstands of sea-level. This is presumably because of increased exposure and erosion of the shelf plus the discharge of sediment by rivers directly into the heads of submarine canyons (Fig. 7C). As subareal exposure of carbonate platforms eventually results in meteoric cementation [25], most major turbidity currents derived from isolated carbonate platforms should occur during the initial stage of sea-level lowering (Fig. 7H), just prior to prolonged exposure of the platform. At this time, subaqueous carbonate sediments would be unaffected by meteoric cementation, and lowered wave base would result in slope instabilities that would produce slumps, debris flows, and turbidity currents. Such downslope transport apparently correlates with initial lowering of sea-level from the Sangamon highstand in Exuma Sound [26]. Thick deep-water carbonates of the Roncal Unit of the Hecho Group (Cuisian and Lutetian) in northern Spain, which are considered to be analogous to carbonate debris sheets in Exuma Sound, also correlate with a major sea-level low during the Eocene [27]. Combined effects of high carbonate productivity during

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**Table 1. Factors Affecting Fan Development on Active and Passive Margins**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Active Margin</th>
<th>Passive Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Eustatic influence</td>
<td>Low to high</td>
<td>High</td>
</tr>
<tr>
<td>2. Tectonic influence</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>3. Shelf width</td>
<td>Narrow</td>
<td>Wide</td>
</tr>
<tr>
<td>4. Shelf exposure/</td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>sediment availability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Sediment transport</td>
<td>Short distance</td>
<td>Long distance</td>
</tr>
<tr>
<td>6. Fan sediment</td>
<td>Sand-rich</td>
<td>Mud-rich</td>
</tr>
<tr>
<td>7. Fan size</td>
<td>Small (tens of km)</td>
<td>Large (hundreds of km)</td>
</tr>
<tr>
<td>8. Modern example</td>
<td>Navy Fan</td>
<td>Amazon Fan</td>
</tr>
</tbody>
</table>

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**Figure 6.** Correlation of calciclastic turbidites [23] and lowstands of sea-level [24]. Arrow points to a possible low sea-level during Campanian-Maastrichtian time not shown on Vail and Mitchum’s curve [24]. From Shannumag and Moiolli [3].

**Figure 7.** Eustatic model for development of siliciclastic and calciclastic turbidites.
highstands of sea-level and erosion of the platform during lowstands would result in moderate turbidity-current activity from attached carbonate platforms during all phases of sea-level changes (Fig. 7D-F), with perhaps major flows developing during initial lowering of sea-level (Fig. 7E). Development of submarine fans in the deep sea are, therefore, expected to correspond to the timing of major turbidity flows from both clastic shelves and carbonate platforms during lowstands of sea-level.

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References