EXTERNAL CONTROLS ON MODERN CLASTIC TURBIDITE SYSTEMS: THREE CASE STUDIES

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ABSTRACT: Three case studies are used to exemplify the wide variety of controlling factors that combine to influence the development of modern turbidite systems, and how these vary with location and time. For example, Cascadia Basin in the Pacific Ocean off western North America, which is underlain by the Cascadia Subduction Zone, exhibits the dominant tectonic control of earthquake triggering for turbidity currents, the increased sediment-supply effects of the Mt. Mazama catastrophic volcanic eruption in 7626 yr B.P., the glacial climatic and sea-level lowstand control on rapid turbidite-system growth rates, and the recent anthropogenic control that reduces sediment supply rates. Lake Baikal in Russia shows how the rift-basin tectonic setting controls the number and type of sediment input points, the amount of sediment supply, and the consequent types of turbidite systems developed along different margins of the Baikal basin. Pleistocene glacial climatic changes, without changes in lake base level, causes increased sediment input and the rapid growth rate of Baikal turbidite systems that is three to five times greater than that during the Holocene interglacial climate. The Ebro turbidite systems in the northwest Mediterranean Sea exhibit control of system types by the Messinian salinity-crisis lowstand, of channel locations by oceanographic current patterns, and of sediment-supply increase by glacial climatic changes as well as recent decrease by anthropogenic changes.

Both active-margin and passive-margin settings have some common controls such as climatic and sea-level changes, and develop similar types of turbidite systems such as base-of-slope aprons, submarine fans, and deep-sea or axial channels. Each margin also has specific local controlling factors, for example the volcanic events in Cascadia Basin, glacial climatic without erosional base-level control in Lake Baikal, and the Messinian extreme lowstand in the Mediterranean Sea. Comparison of modern turbidite systems points out new insights on external controls such as importance of: (1) earthquakes for triggering turbidity currents on active tectonic margins, (2) equal or greater Pleistocene climatic control compared to lowered base level for sediment supply, (3) direct glacial sediment input that results in doubled proximal channel size, (4) greatly reduced deposition rates in drained compared to ponded turbidite basins, (5) importance of ocean currents on location of turbidite systems and channel development, and (6) anthropogenic effects from river damming during the last century that sometimes reduces present sediment supply to turbidite systems by orders of magnitude.

KEY WORDS: Cascadia Basin, Lake Baikal, Ebro, external and local controls, turbidite systems

INTRODUCTION

Modern marine, seismic stratigraphic, and outcrop studies agree that three fundamental controlling factors for turbidite systems are tectonic setting, sediment supply, and interplay of climate and sea level (e.g., Nelson and Nilsen, 1984). Debates have focused on whether tectonic control or control of base-level erosion by lowering sea level, or climatic factors dominate. Modern marine research in active and passive margins shows that the majority of present-day turbidite systems on the sea floor were deposited during Pleistocene time, suggesting a dominant control by the Pleistocene high-frequency climatic and sea-level cycles (Nelson and Nilsen, 1984). Seismic stratigraphic studies have postulated that the different stages of one sea-level cycle (i.e., lowering and rise) control changes in the turbidite systems (e.g., Posamentier et al., 1988). From extensive studies of turbidite outcrops, tectonic controls often are indicated as the dominant control for turbidite system development (e.g., Pickering et al.,
Examining the interplay between the common external controls on the development of present-day turbidite systems provides analogues that help our understanding of the controls through past geologic time and that help resolve debates about climatic, sea-level, or tectonic controls on turbidite systems. Our three basin examples in this paper do not, however, offer a review of external controls that is complete enough to relate architectural elements in ancient turbidite systems to specific external controls. The purpose of this paper is to combine our observations of many years of research on turbidite systems in three present-day basin settings. Each of these settings (active and passive tectonic margins, and deep-riptide basin settings has various types and scales of modern turbidite systems (e.g., aprons, fans, channels) (Nelson, 1983; Nelson et al., 1991). The turbidite systems in the three basins illustrate common fundamental tectonic, sediment-supply, and climate-sea-level controlling factors that are important in each system. Our studies also show that in addition to the common controls, each system has site-specific controls that are significant. Both common and site-specific controls combine in each system to determine characteristics of the turbidite systems. Cascadia Basin has been selected as an example because: (1) the generation of turbidites is controlled mainly by the tectonic factor of earthquakes during the Holocene, (2) the amount of sediment supply and turbidite system growth rate are controlled by climatic changes, sea-level lowstands, and volcanic eruptions, and (3) anthropogenic changes have controlled sediment supply in the past century. Our Baikal basin is an example where (1) tectonic control of the rift-basin morphology determines amounts and input points of sediment supply, and turbidite system types (e.g., apron vs. fan), and (2) without significant Pleistocene lake-level changes (Colman, 1998), climatic control can be assessed as an independent factor determining the growth rate of turbidite systems. The Ebro margin provides an example where (1) climate and sea-level lowstand control turbidite system growth rates, except for anthropogenic effects of the last century, and (2) channel development in Pleistocene turbidite systems is controlled by the underlying Messinian sub-aerial drainage patterns and geostrophic ocean currents.

CASCADIA BASIN TURBIDITE SYSTEMS

Tectonic and Morphologic Control

The unique Holocene tectonic-paleoseismic and volcanic history of Cascadia Basin, in addition to the thorough analysis of glacial and interglacial (Pleistocene-Holocene) turbidite systems, provides an ideal place to define the interplay of tectonic, volcanic, sediment-supply, climate-sea-level, ocean-current, and anthropogenic controls (Fig. 1). Cascadia Basin is underlain by the Juan de Fuca and Gorda Plates. The tectonic control of this convergent margin is generated by the Cascadia Subduction Zone fault, which underlies and determines the morphology of the continental margin of North America from Vancouver Island to the Mendocino Triple Junction (Fig. 1). This active tectonic margin contains a variety of turbidite systems, including Nitinat Fan, which drains south into Cascadia Channel, and Astoria Fan, which partially drains laterally into Cascadia Channel. The Nitinat Fan has sediment supplied by multiple erosional canyons, whereas Astoria Fan is fed by the fault-controlled Astoria Canyon, which supplies Columbia River sediment (Fig. 1) (Carlson, 1967; Carlson and Nelson, 1969). Cascadia Channel is a tectonically controlled deep-sea channel that has eroded through the Blanco Fracture Zone and feeds into Tufts Fan (Fig. 1) (Griggs and Kulm, 1970; Carter, 1988; Nelson et al. 2000a; Normark and Reid, 2003). To the south of these large turbidite systems, smaller canyons associated with local rivers are found feeding from a narrower shelf. These include the Rogue base-of-slope apron, Trinidad and Eel Canyons, which terminate in plunge pools feeding...
Mount Mazama eruption occurred in 7626 yr B.P. and is recorded in the Greenland ice cores as one of the major Quaternary volcanic events (Zdanowicz et al., 1999). The initial plinian eruption of 50 km³ covered about 1 x 10⁶ km² of the Columbia River drainage and was 100 times greater than the Mt. Saint Helens eruption (0.5 km³) of 1980 (Fig. 3) (Nelson et al., 1988). The second phase of fiery avalanche deposits filled the Rogue and other river valleys with volcanic debris for up 75 km from the mountain. Finally, the mountain formed a collapse caldera that contains the famous Crater Lake in the Cascade Mountains of Oregon. As a result, large amounts of volcanic and forest debris washed from the Columbia and Rogue River drainages into the sea and then eventually were resedimented as woody tuffaceous turbidites for hundreds of kilometers along turbidite-system channels (Figs. 3, 4B).

During the Holocene, in contrast to the typical thin sand turbidites, thick (~ 30–100 cm) tuffaceous turbidites deposited in Cascadia Basin channels after Mount Mazama volcanic glass was transported to canyon depocenters, mixed with Columbia and Rogue Canyon sands when Cascadia Subduction Zone earthquakes triggered turbidity currents, and deposited as tuffaceous turbidites (Figs. 3–5) (Nelson et al., 1968; Nelson et al., 1988; Nelson et al., 2000b). Correlation of the initial marker bed containing ash shows that overbank suspension flows, rich in volcanic glass, deposited thin-bedded turbidites on interchannel areas of the proximal inner and middle Astoria Fan (Figs. 3, 4). Correlative tuffaceous turbidites also reveal that poorly sorted, high-matrix (20%) and wood-rich deposits of the canyon mouth evolved 150 km downstream to well sorted, low-matrix (5%) graded sands with a nearly complete Bouma sequence of vertical sedimentary structures (Fig. 4B) (Carlson and Nelson, 1969; Nelson, 1976).

Climatic, Sea-Level, and Sediment-Supply Controls

In the mid-1960s to 1970s extensive morphologic and coring (several hundred piston cores) studies were conducted on all Cascadia turbidite systems (Carlson, 1967; Nelson, 1968, 1976; Carlson and Nelson, 1969; Griggs, 1969; Griggs and Kulm, 1970; Duncan et al., 1970a; Duncan et al., 1970b). Excellent Mazama ash biostratigraphic, lithologic, and compositional marker beds permitted definition of the glacial late Pleistocene lowstand (> 12,750 cal. yr BP) and interglacial Holocene highstand deposits (< 12,750 cal. yr BP) (Nelson et al., 1968; Duncan et al., 1970a; Duncan et al., 1970b; Gutierrez-Pastor et al., this volume). Astoria Fan was the first location in which a pattern of thick sand beds (10–50 cm) deposited during glacial sea-level lowstand time (i.e., lowstand fans) was observed (Fig. 4A) (Nelson, 1968, 1976). Pleistocene turbidity currents mainly bypassed to outer-fan lobes, where the highest sand/shale ratios are found (Fig. 5). In contrast, during the Holocene interglacial highstand time of warmer climate and significant Pacific Northwest forestation, turbidite deposition was confined to channel floors and, except for tuffaceous turbidites, consisted mainly of thin turbidite sand beds (1–4 cm) and thick mud turbidites (~ 50 cm) in Cascadia Channel (Figs. 4A, 5) (Griggs and Kulm, 1970; Nelson, 1976; Nelson et al., 2000b).

Holocene Paleoseismic Control on Turbidite Deposition

Beginning in the late 1980s, and still continuing, onshore studies from Vancouver Island to northern California have completed thousands of high-resolution AMS ¹⁴C and tree-ring ages to correlate the onshore paleoseismic record of co-seismic drowned trees and marine tsunami sand layers in brackish-water lagoonal muds (Fig. 1) (A.R. Nelson et al., 1995; A.R.
Nelson et al., 2004; A.R. Nelson et al., 2006; Atwater and Hempill-Haley, 1997; Kelsey et al., 2002; Kelsey et al., 2005; Witter et al., 2003). The youngest, AD 1700 great earthquake of Cascadia has been correlated with a sand deposit in Japan from a 3–5 m setup transoceanic Cascadia-derived tsunami (Satake et al., 1996; Satake et al., 2003).

During the past decade, all of the previous archive cores and sixty new cores have been restudied to determine the Holocene turbidite paleoseismic history of the Cascadia Subduction Zone fault (Adams, 1990; Nelson et al., 2000b; Goldfinger et al., 2003; Goldfinger et al., 2008; Gutierrez Pastor et al., this volume). During this investigation, hundreds of high-resolution AMS 14C ages, hemipelagic sedimentation-rate ages, physical-property signatures (i.e., density, velocity), magnetic susceptibility, color scans, and mineralogic studies of volcanic glass and heavy minerals have been undertaken to correlate 18 Holocene turbidites that were deposited during the past 10,000 cal. yr BP in major channel systems of the Cascadia Basin.

The oldest turbidite containing Mazama ash has provided an excellent marker bed for paleoseismic research (Fig. 4A, see layer A) (Nelson, 1976; Nelson et al., 1968; Nelson et al., 2000b; Gutierrez Pastor et al., this volume). The first occurrence of the Mazama turbidite (~ 7200 cal. yr BP) in submarine fan, deep-sea channel, and base-of-slope apron turbidite systems in Cascadia Basin permits us to correlate 13 post-Mazama Holocene turbidites that were synchronously triggered by great earthquakes of the Cascadia Subduction Zone (Adams, 1990; Nelson et al., 2000b). Because multiple tributary canyons upstream had the same 13 post-Mazama turbidites as those downstream below the canyon confluence in Cascadia Channel (i.e., they were not additive), Adams (1990) first suggested that the 13 turbidites had to be synchronously triggered by great earthquakes of Cascadia Subduction Zone.

Our new results indicate that most of the 18 Holocene earthquakes, like the AD 1700 event, ruptured the full Cascadia margin (Nelson et al., 2000b; Goldfinger et al., 2003; Goldfinger et al., 2008; Gutierrez Pastor et al., this volume). The stratigraphic correlation of turbidite events, in addition to their age correlation with extensive Cascadia coastal and Japanese transoceanic tsunami deposits, suggests that the turbidite record mainly monitors great earthquakes (≥ Mw 8.0) similar to the ~ 300 second Sumatra 26 Dec. 2004 event (Table 1) (Nelson et al., 2005; Atwater et al., 2004; Goldfinger et al., 2008).

Two lines of evidence support the hypothesis that the turbidite paleoseismic record mainly monitors great earthquakes in the Cascadia Subduction Zone, whose ~ 1000 km ruptures and shaking of the margin generated turbidites from failed walls in multiple canyons along the margin. The Japanese find that > Mw 7.4 earthquakes are required to trigger turbidity currents (Shikih et al., 2000). Similarly, we have monitored turbidite deposition in Mendocino Channel in 1986 and 1999 before and after two Mw 7.2 earthquakes in the Mendocino Canyon head that did not produce turbidite deposits (Nelson et al., 2000b).

Tsunami marine sand deposits provide the second line of evidence that suggests that Cascadia turbidites result mainly from great earthquakes. Sumatra earthquakes show that the Mw ≥ 9 earthquake of 28 March 2005 created only small local tsunamis compared to the earlier Mw ≥ 9.2 earthquake in December, 2004, which created extensive large tsunamis in Sumatra and large transoceanic tsunamis in Thailand, Sri Lanka, India, and Africa. The Cascadia onshore and transoceanic Japanese tsunami records are comparable to the Sumatra 2004 and 2005 tsunami records because great earthquakes of ~ Mw 9 appear to be responsible for the tsunamis with 3-5 m setup and several-kilometer runups on the coast (Table 1). The age correlation of the Cascadia onshore tsunami and turbidite paleoseismic records (Satake et al., 1996; Goldfinger et al. 2003; Goldfinger et al., 2008; Atwater et al., 2004) (i.e., this is not a correlation of tsunamis generating turbidites), in addition to correspondence of the Sumatra, Cascadia, and Japanese tsunami records (Table 1), imply long fault rupture length and support the hypothesis that mainly great earthquake ruptures of ~ 1000 km generate the
FIG. 4.—Lithology and stratigraphy at representative locations on Juan de Fuca Plate region of Cascadia Basin. ~ 550 yr frequency of the Holocene turbidite deposition in the Juan de Fuca Plate area in AD 1700 (Nelson et al., 1995; Goldfinger et al., 2008), there may be an interplay of local earthquake and storm triggering of turbidity currents to account for the more frequent turbidites (~ 34 to 133 yr) on the Gorda Plate compared to those on Cascadia Plate (~ 550 yr).

Late Holocene Sea-Level, Ocean-Current, and Anthropogenic Controls

The calculations of Holocene sediment budget for the Columbia River not only show the typical shift of the sediment depocenter to the shelf where the highstand sea level, but also show that the river sediment is mainly dispersed toward the north by geostrophic ocean currents (Fig. 6; Table 2). This contrasts with the Pleistocene lowstand sea level, when the sediment was mainly dispersed toward the south, thick turbidite sand beds were deposited on the outer Astoria Fan, and the Fan deposition is 300 to 2000 m thick (Figs. 4A, 5, 6) (Shipboard Scientific Party, 1973; Nelson et al., 1987). Consequently, the external controls on the Columbia River sediment dispersal system have resulted in rapid Pleistocene lowstand submarine-fan growth in one direction by turbidity currents and Holocene sea-level-highstand deposition on the continental shelf in the opposite direction by geostrophic ocean currents (Fig. 6; Table 2).

During the past century, anthropogenic effects have added a significant new control on the sediment supply to Cascadia Basin. Because the Columbia River system has more dams than any other river in North America, most of the sediment load is now trapped and does not reach the river mouth to feed the turbidite systems. By utilizing the Holocene to Pleistocene stratigraphic datum (Fig. 4A), the pre-dam Holocene sediment load of the Columbia River is calculated to be about 20 million metric tons of sediment per year (Table 2) (Wolf et al., 1999b; Sternberg, 1986). Since the advent of dams, measurements indicate that the present sediment load has been reduced to about 5 million metric tons of sediment a year (Sherwood et al., 1990).

LAKE BAIKAL TURBIDITE SYSTEMS

Setting

Lake Baikal is located in central Siberia in Russia along the active Baikal Rift Zone, which separates the Siberian Platform to the northwest from the Mongolian fold belt to the southeast (Fig. 7) (Hutchinson et al., 1992). The Lake is divided into three half-graben rift segments, the North, Central, and South Basins, all of which are bounded by border faults on the western side (Fig. 8) (Hutchinson et al., 1992). The lake is the deepest in the world at 1637 m and is about 600 km in length and 50 to 100 km in width. The lake level, unlike sea level, appears to have had little fluctuation related to the glacial–interglacial periods of the Pleistocene and Holocene times (Colman, 1998) and therefore the turbidite systems have no erosional base-level control. However, extensive Pleistocene ice fields and valley glaciation were developed, mainly in the mountains around the northern edges of the lake (Fig. 7). The climatic changes and glaciations have had a significant impact on grain size and sediment supply to the turbidite systems (Nelson et al., 1995; Back et al., 1998; Back et al., 1999).
Tectonic Control of Turbidite System Type

The tectonic setting controls the drainage systems, number and types of sediment input points to Lake Baikal, volume of sediment supply at input points, and consequent basic types of turbidite systems. The fault-bounded western margin of the lake mainly drains to the exterior basins of the Lena and Kirenga Rivers, which carry sediment away from the lake (Figs. 7, 9A) (Back et al., 1999; Nelson et al., 1999). Only the drainage of the border-fault scarp itself supplies restricted amounts of sand and gravel from multiple, short stream input locations to local Gilbert fan deltas on the western side of the lake, which in turn feed local base-of-slope sand-rich aprons on the lake floor (Figs. 8, 9) (Nelson et al., 1995; Nelson et al., 1999; Colman et al., 2003). Shallow slopes of the southeastern ramp margins (hanging wall) of the lake basins, conversely, feed finer-grained sediment, in greater volumes, from larger drainage basins into two different types of channelized turbidite sublacustrine fan systems: (1) small (15–20 km) laterally fed sand-rich fans sourced by local rivers, which commonly originated from glaciated valleys (Figs. 7, 9C) and (2) large (> 65 km) axially fed, elongate silt-rich fans sourced by regional exterior drainage of the Selenga River (Figs. 7–9). Lake Baikal thus provides an ideal example to show that the coarser-grain-size sediment supply of small rivers results in coarser-grained sand turbidites of the “sand-rich fans” and that the finer-grain-size sediment supply of large rivers results in finer-grained silt turbidites of the “mud-rich fans” (Nelson, 1983; Nelson et al., 1995).

The half-graben morphology of the rift basin establishes the basic control for the amount and type of sediment supply, which in turn determines the different type of turbidite systems in Lake Baikal. Steep border-fault slopes (footwall) along half-graben basins provide multiple small sources of gravel and sand to feed nonchannelized, small (< 10 km diameter) sublacustrine base-of-slope sand-rich aprons on the lake floor (Figs. 8, 9) (Nelson et al., 1995; Nelson et al., 1999; Colman et al., 2003). Shallow slopes of the southeastern ramp margins (hanging wall) of the lake basins, conversely, feed finer-grained sediment, in greater volumes, from larger drainage basins into two different types of channelized turbidite sublacustrine fan systems: (1) small (15–20 km) laterally fed sand-rich fans sourced by local rivers, which commonly originated from glaciated valleys (Figs. 7, 9C) and (2) large (> 65 km) axially fed, elongate silt-rich fans sourced by regional exterior drainage of the Selenga River (Figs. 7–9). Lake Baikal thus provides an ideal example to show that the coarser-grain-size sediment supply of small rivers results in coarser-grained sand turbidites of the “sand-rich fans” and that the finer-grain-size sediment supply of large rivers results in finer-grained silt turbidites of the “mud-rich fans” (Nelson, 1983; Nelson et al., 1995).

These same relationships related to tectonic control of morphology, sediment supply, and development of turbidite system
types also are shown in other rift lakes (Scholz et al., 1990) and in models of ancient rift-basin turbidite systems (e.g., Prosser, 1993). The similarity of modern and ancient turbidite system types related to rift tectonic settings thus provides a way to predict the expected type of turbidite system architecture in ancient systems. For example, the typical turbidite systems on the border-fault margin of an ancient rift basin are most likely to start as sand-rich aprons.

Pleistocene Climatic Control of Turbidite System Growth

Once the basic types of turbidite systems have been established by the tectonic control of basin morphology, Pleistocene glacial climatic and sediment-supply changes have determined the growth rate of all of the turbidite system types in Lake Baikal (Nelson et al., 2000a). The restricted growth rates, low sedimentation rates, and thin-bedded mud and silt turbidites are characteristic of the Holocene interglacial climate (Fig. 10; Table 3). In contrast, rapid growth rates, high sedimentation rates, thick sand turbidites, and oversized fan channels are characteristic of Pleistocene glacial climates (Figs. 10, 11; Table 3) (Nelson et al., 1995; Escutia et al., 2000). As sediment supply decreased during final glacial recession (Back et al, 1998; Back et al., 1999), fan lobes backstepped and thinner and finer-grained turbidites were deposited on the Tompuda Fan (Fig. 12; Table 3) (Nelson et al., 1995).

Sediment always has direct access down the steep border-fault basin walls to the lake-floor turbidite systems during

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**Table 1.—Comparison of tsunami records and earthquake rupture lengths from Cascadia, Japan, and Sumatra subduction zones.**

<table>
<thead>
<tr>
<th>SUBDUCTION ZONE</th>
<th>RUPTURE LENGTH (km)</th>
<th>HEIGHT m &gt; MSL</th>
<th>ONSHORE INUNDATION km from shore</th>
<th>TRANS-OCEANIC LOCAL TSUNAMI</th>
<th>SITES STUDIED</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASCADIA</td>
<td>~ 1000</td>
<td>&gt; 5.5</td>
<td>&gt; 10 upriver</td>
<td>X (Japan)</td>
<td>~ 70</td>
</tr>
<tr>
<td>1700 AD</td>
<td>~ 1000</td>
<td>1–5</td>
<td>2</td>
<td>X</td>
<td>7</td>
</tr>
<tr>
<td>JAPAN</td>
<td>~ 1000</td>
<td>&gt; 5</td>
<td>&gt; 3</td>
<td>X</td>
<td>~ 33</td>
</tr>
<tr>
<td>JAPAN</td>
<td>100–200</td>
<td>&lt; 4</td>
<td>&lt; 0.5</td>
<td>X</td>
<td>~ 33</td>
</tr>
<tr>
<td>SUMATRA 04</td>
<td>~ 1300</td>
<td>5–22</td>
<td>&gt; 2</td>
<td>X</td>
<td>~ 25</td>
</tr>
<tr>
<td>SUMATRA 04</td>
<td>~ 1300</td>
<td>3–12</td>
<td>&gt; 1</td>
<td>X (Sri Lanka)</td>
<td>~ 15</td>
</tr>
<tr>
<td>SUMATRA 04</td>
<td>~ 1300</td>
<td>3–11</td>
<td>1.5</td>
<td>X (Thailand)</td>
<td>~ 15</td>
</tr>
<tr>
<td>SUMATRA 04</td>
<td>~ 1300</td>
<td>5–9</td>
<td>?</td>
<td>X (Africa)</td>
<td>5</td>
</tr>
<tr>
<td>SUMATRA 05</td>
<td>~ 330</td>
<td>3–5</td>
<td>&lt; 1</td>
<td>None</td>
<td>X</td>
</tr>
</tbody>
</table>


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**Fig. 6.—Sea-level lowstand Pleistocene and highstand Holocene reversal of Columbia River sediment dispersal system.** The lowstand dispersal to Astoria Fan is shown by the high sand:shale ratios in Figure 5, and the highstand dispersal to the Washington continental shelf is shown by the Holocene sediment budget of Table 2. (Modified from Nelson and Maldonado, 1990.)
glacial or interglacial times, because of (1) the lack of significant lake-level variations (Colman, 1998) and (2) restricted lakeshore shelf development to trap sediment (Figs. 8, 9) (Nelson et al., 1995; Colman et al., 2003). Consequently, in Lake Baikal only glacial climatic changes have increased sediment supply and grain size. Thus climate alone controls turbidite-system growth rates that are comparable to those in marine basins that have climatic and sea-level controls (Figs. 4A, 10; Table 3) (Nelson et al., 1995; Nelson et al., 2000a). The Lake Baikal example isolates Pleistocene climatic change as a major factor controlling sediment supply, in contrast to the conceptual idea that lowered sea level and erosional base level of drainages mainly control sediment supply and turbidite-system growth rate (Posamentier et al., 1988).

**EBRO TURBIDITE SYSTEMS**

*Setting and Control of Turbidite Systems by the Extreme Messinian Lowstand*

The Ebro turbidite systems are associated with the Ebro River drainage system, which derives sediment from the Pyrenees Mountains and the Ebro Basin of north-central Spain (Fig. 13). The Ebro Delta enters the northwestern Mediterranean Sea and has successively fed a number of Pleistocene submarine canyons and channel–levee complexes along this passive continental margin (Figs. 13, 14) (Nelson and Maldonado, 1988). These channels, which are oldest in the northeast and are progressively younger toward the southwest, have drained into Valencia Valley, a deep-sea channel that bypasses sediment 200 km downstream into the Valencia Fan on the Balearic Abyssal Plain (Fig. 13). The subaerial drainage system, formed during the Messinian desiccation in the Mediterranean Sea, exerted control on the late Pleistocene Ebro turbidite systems (Escutia and Maldonado, 1992). For example, the Pleistocene Valencia Valley now follows the pathway of a Messinian subaerial valley (Fig. 15). In the slope, the 20-km-wide and 500-m-deep Messinian Ebro Canyon, but not the younger adjacent Pleistocene canyons, rapidly filled with Pliocene deep-water clays when the Mediterranean refilled. This thick, rapidly deposited Pliocene mud in the deeply eroded Messinian Ebro Canyon now is unstable (Figs. 14, 15) (Nelson and Maldonado, 1990; Escutia and Maldonado, 1992). The result is a central Ebro margin segment that is underlain by the mud-filled Messinian Canyon, and now is dominated by sediment failures and three wide gullied canyons (Fig. 14). These sediment failures from the gullied canyons prevent the develop-

### Table 2.—Minimum estimated Columbia River sediment discharge per year during the past 5000 years (modified from Wolf et al., 1999b).

<table>
<thead>
<tr>
<th>GEOGRAPHIC AREA</th>
<th>VOLUME (km²)</th>
<th>DRY BULK DENSITY (metric tons/m³)</th>
<th>WEIGHT (metric tons/yr)</th>
<th>CORRECTION FACTOR (2)</th>
<th>CORRECTED WEIGHT (metric tons/yr)</th>
<th>% COLUMBIA R. BUDGET</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA/OR MID/OUTER SHELF</td>
<td>48.500</td>
<td>1.41</td>
<td>13,677,000</td>
<td>-3.5%</td>
<td>13,198,305</td>
<td>65.87</td>
</tr>
<tr>
<td>WASHINGTON SLOPE *</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1,300,000</td>
<td>6.49</td>
</tr>
<tr>
<td>WASHINGTON CANYONS *</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1,255,000</td>
<td>6.27</td>
</tr>
<tr>
<td>N. CASCADIA BASIN</td>
<td>2.612</td>
<td>0.85</td>
<td>444,040</td>
<td>-3.2%</td>
<td>429,830</td>
<td>2.15</td>
</tr>
<tr>
<td>CASCADE CHANNEL</td>
<td>5.757</td>
<td>0.85</td>
<td>978,690</td>
<td>-3.8%</td>
<td>941,499</td>
<td>4.70</td>
</tr>
<tr>
<td>ASTORIA CANYON FLOOR</td>
<td>0.873</td>
<td>0.96</td>
<td>167,529</td>
<td>-2.9%</td>
<td>162,670</td>
<td>0.81</td>
</tr>
<tr>
<td>NORTHERN OREGON SLOPE</td>
<td>3.493</td>
<td>0.96</td>
<td>670,656</td>
<td>-2.9%</td>
<td>651,206</td>
<td>3.25</td>
</tr>
<tr>
<td>NORTHERN ASTORIA FAN</td>
<td>3.287</td>
<td>0.85</td>
<td>558,879</td>
<td>-3.0%</td>
<td>542,112</td>
<td>2.71</td>
</tr>
<tr>
<td>CENTRAL ASTORIA FAN</td>
<td>7.809</td>
<td>0.85</td>
<td>1,327,530</td>
<td>-36.2%</td>
<td>846,964</td>
<td>4.23</td>
</tr>
<tr>
<td>SOUTHERN ASTORIA FAN</td>
<td>14.138</td>
<td>0.85</td>
<td>2,403,460</td>
<td>-70.8%</td>
<td>701,810</td>
<td>3.50</td>
</tr>
<tr>
<td>TOTAL OFFSHORE COLUMBIA RIVER SEDIMENT PER YEAR **</td>
<td>20,017,110</td>
<td></td>
<td></td>
<td></td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

* Washington slope and canyons from Sternberg (1988)
** not including inner-shelf, shoreline, and estuarine sediments

(1) Dry bulk density numbers were derived mainly from sediment water content and textural data of Carlson (1967), Griggs (1969), Nelson (1968), and Nittrouer (1978) converted to dry bulk density values with the formulas of Hamilton (1970) and Lambe and Whitman (1969). In addition, cores taken in 1998 on the Washington and Oregon shelf along N–S and E–W transects had measurements of density that were taken by the core sediment loggers.

(2) Correction factors account for the autochthonous organic carbon and carbonate carbon contents measured in sediment cores from the different physiographic areal compartments: the shelf sediment factor is from Nittrouer (1978); N. Cascadia Basin and Cascadia channel factors are from Griggs (1969); Astoria Canyon floor and northern Oregon slope factors are from Carlson (1968); Astoria Fan factors are from Nelson (1968). The large central and southern Astoria Fan correction factors are derived from Holocene clay-mineral analyses of Duncan et al. (1970b), which show that about 33% of clays in the central Astoria Fan and about 68% of clays from the southern Astoria Fan are from non–Columbia River sources.
ment of turbidite systems along this central segment of the margin because the recurrent deposition of mass-transport deposits destroys incipient turbidite systems on the basin floor below the canyons (Figs. 13, 14) (Nelson and Maldonado, 1988; Nelson et al., 1991).

In contrast, Pleistocene canyons that feed channel–levee complexes develop in adjacent areas of the slope where there is no evidence for underlying Messinian canyons. The channel systems 1 to 4 extend from canyon mouths to the Valencia Valley without developing typical radiating fan morphology or outer-fan-lobe deposits (Figs. 13, 14). The lack of submarine-fan-lobe deposition in this case apparently is caused by the continuous steep drainage gradients along the channels that connect into the Valencia Valley, where the gradient is controlled by the underlying Messinian subaerial valley (Fig. 15) (Escutia and Maldonado, 1992). Typical fan gradients in sand-rich fans change from 1:25 to 1:100 in proximal fans to 1:500 downstream in distal fans (Nelson and Nilsen, 1984). In the Ebro channels, however, the gradients never change significantly along the entire channel length, gradi-

Pleistocene Clastic, Sea-Level, and Ocean-Current Control on Sediment Supply

The Messinian, Pliocene, Pleistocene, and Holocene seafloor reflection surfaces as well as sedimentation rates can be used to estimate the Ebro River sediment supply to highstand deltaic and lowstand turbidite systems (Figs. 15–17) (Nelson, 1990). The continuous sea-level highstand conditions during the Pliocene, similar to the Holocene highstand, resulted in a low discharge of Ebro River sediment (~ 6.5 million metric tons/yr) and a sediment drape across the margin that was deposited at rates of ~ 24–40 cm/ky (Fig. 16; Table 4) (Nelson, 1990). In contrast, sediment supply increased by a factor of two to three during the Pleistocene, the margin prograded rapidly seaward for 80 km, and deposition occurred at rates of 101–165 cm/ky on the outer shelf and slope (Fig. 17; Table 4). On the basin floor, however, sedimentation rates in the turbidite channel systems and Valencia Valley remained anomalously low (21–26 cm/ky) compared to typical Pleistocene turbidite-system rates (~ 100 cm/ky or more) (Fig. 18). These low rates resulted because turbidity currents drained along Valencia Valley, which follows the relict subaerial Messinian pathways, and then currents bypassed sediment eastward to be broadly dispersed in Valencia Fan (Figs. 13–16) (Nelson and Maldonado, 1990; Escutia and Maldonado, 1992).

Throughout high to low Pleistocene sea levels, geostrophic ocean currents have dispersed sediment to the southwest and there has been a progressive southwestward progradation of Ebro prodeltas, canyons 1 to 4, and turbidite systems (Figs. 13, 14) (Nelson and Maldonado, 1990). During the late Pleistocene...
The sedimentation rates verify the importance of sea-level control on the successive change in location of depocenters, in direction of sediment dispersal, and, in part, in the amount of sediment supply (Figs. 13, 17; Table 4). Pleistocene climatic change and resultant deforestation alone, however, appear to be mainly responsible for the more than doubled sediment supply during the glacial climates (Table 4) (Nelson, 1990). The importance of climatic change and deforestation for controlling sediment supply of sea level, the main depocenters progressively shifted shoreward and sedimentation rates decreased greatly, from 175 cm/ky on the upper slope during the early transgression to 106 cm/ky on the outer shelf and then to 63 cm/ky on the mid-shelf during the late transgression as the river sediment discharge dropped to less than half by Holocene time (~ 6.2 million tons/yr) (Fig. 17; Table 4) (Nelson, 1990). Maximum sedimentation rates occur in active depocenters such as the present Holocene delta (370 cm/ky) or the youngest Pleistocene number 1 channel–levee complex (750 cm/ky), where deposition rates are more than an order of magnitude greater compared to average Ebro prodeltaic (38 cm/ky) or turbidite system rates (21 cm/ky) during the Pleistocene (Fig. 17) (Alonso and Maldonado, 1990; Nelson, 1990).

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Table 3.—Comparison of Pleistocene and Holocene sand–silt bed content in all basins of Lake Baikal.

<table>
<thead>
<tr>
<th></th>
<th>Pleistocene</th>
<th>Holocene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment rate all basins (cm/ky)</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td>Net sand % all basins</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>Net sand % north basin</td>
<td>5x Holocene</td>
<td></td>
</tr>
<tr>
<td>Turbidite bed thickness (north basin)</td>
<td>3x Holocene</td>
<td></td>
</tr>
</tbody>
</table>

ply is indicated by the observation that human deforestation of the Iberian Peninsula also more than doubled the Ebro sediment supply (Table 4). Beginning with Roman civilization 2000 years ago, pollen assemblages changed abruptly from pines of the Pyrenees and oaks of the Ebro Basin to grasses in the Pyrenees (like the Pleistocene) and grapes and grains in the Ebro Basin (Nelson, 1990). This change of vegetation showed deforestation, whether caused by Pleistocene climatic change or humans, can more than double the Ebro sediment supply.

**Anthropogenic Control on Sediment Supply**

During the past 2000 years, humans have controlled sediment supply to the Ebro margin system: first, by deforestation, which more than doubled river sediment discharge and shelf deposition rates to equal those of Pleistocene time; and second, by construction of river dams, which then reduced sediment discharge to less than 1% of normal Holocene discharge (Table 4) (Nelson, 1990; Palanques et al., 1990). Similar anthropogenic reductions in sediment discharge from the Nile, Po, and Rhone Rivers suggest that during the past century there has been a significant loss of river sediment supply for deltaic progradation and turbidite-system growth in most of the Mediterranean Sea. As a result, the Ebro Delta now has a net recession of 1 cm/yr for the delta shoreline compared to a net progradation of 4 cm/yr prior to the development of dams (Nelson and Maldonado, 1990).

**EXTERNAL CONTROLS OBSERVED IN INDIVIDUAL BASINS**

**Cascadia Basin**

The tectonic setting and resulting drainage basins for sediment supply, continental-margin morphology, and Cascadia Basin floor gradients provide the basic control for the types of turbidite systems that developed in Cascadia Basin (Fig. 1). Similar erosional canyons have cut through the accretionary folds of the continental slope and have fed each Cascadia turbidite system (Fig. 1). The multiple tributary canyons that join to form Cascadia Channel, and the tectonic lineament of the channel, are factors that control the development of this deep-sea-channel type of turbidite system (Fig. 1) (Carter, 1988). The tectonic lineament and steep downstream gradients at the base of the Mendocino Escarpment also result in the single channel-levee complex that follows the escarpment. Similarly to other systems, the narrow margin, which has a lower continental slope steeper than 5 degrees in southern Cascadia Basin, apparently causes the plunge-pool and sediment-wave turbidite systems at the mouth of the Trinidad and Eel canyons (Fig. 2) (Lee and Talling, 1998). Without the specific tectonic controls of tectonic lineaments or steep continental slopes, the general tectonic control on drainage-basin size, morphology, and amount of sediment supply mainly controls the type of Cascadia Basin turbidite systems. For example, the larger sediment supply causes the formation of downstream channel levees and lobes in the Eel Turbidite System compared to the absence of the lobe deposits in the Trinidad and Mendocino turbidite systems (Figs. 1, 2) (Nelson et al., 2000b). Large or coalescing drainages result in a large sediment supply to form the Astoria and Nitinat submarine fans, respectively, whereas the small river drainage of the Rogue River results in the small Rogue Apron.
Cascadia Basin shows the direct control that earthquake activity can have on timing, periodicity, and cycles of Holocene turbidite deposition. This control undoubtedly has persisted throughout the Pleistocene history of turbidite systems. However, the controls of glacial climatic change and lowered sea levels of the Pleistocene resulted in strong turbidity currents that eroded channels, and the record of earthquake controls cannot be confirmed during glacial times. Consequently during the Quaternary, three main epochs of dominant controls for the development of turbidite systems are evident in Cascadia Basin. During the epoch of glacial times of lowered sea level, thick, sandy, and possibly more frequent turbidites are widespread throughout the turbidite systems (Figs. 4A, 5 Pleistocene). During the epoch of interglacial times of high sea levels, the reduced sediment supply restricted turbidite deposition mainly to the channel floors, and the triggering of turbidity currents by great earthquakes is evident (Fig. 5 Holocene). During the last century and the present epoch of human civilization, the sediment supply from the Columbia River to Cascadia Basin has been reduced by 75%, and these effects on turbidite systems remain to be seen. Any of these three main epochs of varying dominant controls (i.e., tectonic, climatic-sea-level, and anthropogenic) on turbidite systems can be interrupted by increased turbidite deposition caused by catastrophic volcanic eruptions such as that of Mt. Mazama during the mid-Holocene (Figs. 3–5).

Lake Baikal

The rift-basin tectonics of Lake Baikal control the organization of river drainages, the basin morphology, the distribution of sediment input points to the Lake, and the amount and grain size of sediment supply. These factors in turn establish the type and location of turbidite systems on the lake floor. For example, the multiple small drainages of the border-fault scarp on the western lake margin result mainly in development of base-of-slope aprons, whereas sand- and mud-rich fans are fed from larger river drainages on the eastern ramp margin of the lake basin (Figs. 8, 9).

The glacial climates and increased glaciation of the drainage basins during the Pleistocene also influenced sediment supply and determined the growth rates of the turbidite systems in Lake Baikal (Fig. 7). During glacial times, thick sandy turbidites were deposited rapidly compared to the interglacial time of the Holocene, when a condensed section of mud and silt turbidites was deposited slowly (Fig. 10; Table 3). Because there were no significant lake-level changes between the late Pleistocene glacial and Holocene interglacial times (Colman, 1998), climatic change alone, and not erosional base level, controlled the increased Pleistocene sediment supply and high growth rates of the Lake Baikal turbidite systems (Fig. 10; Table 3). The abnormally large inner-fan channels fed by valley glaciers that reached the canyon heads again substantiates the control of ice-sheet sediment sources on turbidite systems (Fig. 11) (Escutia et al., 2000), as does the backstepping of submarine fan lobes associated with the final recession of the valley glaciers (Fig. 12) (Back et al., 1998; Back et al., 1999).
Similarly to Cascadia turbidite systems, the Pleistocene climatic change, coupled with sea-level lowstands, may be equally important in having caused tripled sediment supply to turbidite systems and 80 km of progradation of the Ebro continental margin (Fig. 16; Table 4). Both the Ebro and the Cascadia systems also show not only that sea-level change results in a change of the main sediment depocenters from deep-sea turbidite systems to shelf mud blankets, but also that the sediment dispersal systems change to opposite directions between lowstand to highstand sea-level conditions when geostrophic ocean currents become important (Figs. 6, 13).

An unusual site-specific controlling factor for the Ebro turbidite systems was the Messinian desiccation of the Mediterranean Sea, which resulted in the erosion and enlargement of the subaerial Ebro Canyon and a main basin-floor drainage valley (Fig. 15) (Escutia and Maldonado, 1992). The subaerial canyon was filled by muddy Pliocene transgressive and highstand deposits (Nelson and Maldonado, 1990). These muds became unstable during the Pleistocene, resulting in wide, gullied Pleistocene submarine canyons and mass-transport apron deposits below on the basin floor (Fig. 14) (Nelson et al., 1991). The Messinian subaerial valley has controlled the eastward Valencia Valley pathway on the abyssal sea floor as well; however, the fundamental control on the subaerial Messinian and later Pleistocene Valencia Valley is an original fault lineament from the aborted rift system (Figs. 13, 15, 16) (Escutia and Maldonado, 1992; Nelson and Maldonado, 1990).

During highstands and fluctuations of the Pleistocene sea level, the strong westward geostrophic currents have resulted in
Fig. 15.—Isobath map of the Messinian surface in seconds (contour interval 0.1 s) outlining the Messinian subaerial drainage pathways. Proximal to distal seismic profiles across the Messinian subaerial valley and Pleistocene Valencia Valley are shown as uninterpreted (A, B, C) and interpreted (A’, B’, C’) cross sections. The Pleistocene surface deep-sea channel of Valencia Valley overlies and follows the subsurface Messinian subaerial valley (modified from Escutia and Maldonado, 1992).
the progressive development of submarine canyons from northeast to southwest along the continental slope and the asymmetric progradation of the margin toward the southwest (Figs. 13, 14) (Nelson and Maldonado, 1990). Within historical times, the anthropogenic changes of deforestation have equaled the effects of the deforestation from Pleistocene climatic change by increasing sediment supply threefold (Table 4). During the last century, however, river dams have now reduced the sediment supply to less than 1% of normal Holocene sediment supply (Table 4) (Palanques et al., 1990).

COMMON EXTERNAL CONTROLS

The tectonic setting provides fundamental control for the morphology of the hinterland drainage basins, turbidite basin morphology and basin-floor gradients, sediment supply, basin sediment input points, turbidite-system locations, and turbidite-system types. The relations of tectonic setting, drainage basins, sediment-input points, and amount of sediment supply are particularly evident in the Baikal Rift setting (Fig. 9). In the Cascadia and Ebro Basins, the line source of canyons with large sediment supplies and drainage along fault lineaments results in deep-sea channels. On a smaller scale, axial channels develop and drain along faults on the rift-basin floors of Lake Baikal and other modern and ancient rift systems (Fig. 8) (Scholz et al., 1990; Nelson et al., 1995; Nelson et al., 1999; Prosser, 1993).

Tectonic control on basin-floor gradients helps determine present-day, and most likely ancient, turbidite-system depositional rates during sea-level lowstands. The Ebro turbidite systems exhibit the lowest average sedimentation rates (Fig. 18). The low rates result because turbidity currents drain downstream into Valencia Valley. The Valley follows steep river-channel gradients inherited from the underlying Messinian subaerial drainage systems that follow faults from the rifted basement (Figs. 13–18) (Escutia and Maldonado, 1992). In contrast, sedimentation rates are an order of magnitude greater than Ebro rates in turbidite systems that are in ponded-basin settings like Navy Fan in a California borderland basin and Mississippi Fan in the Gulf of Mexico (Fig. 18). Apparently, the drainage gradient of the turbidite basin appears to control deposition rates because the amount of sediment supply and size of the turbidite system (i.e., the small Navy Fan or the large Mississippi Fan) are not related to deposition rates (Fig. 18).

As expected, we find that the external control of increased sediment supply and of the main growth phase of turbidite systems occurs during low stands of sea level (Figs. 4A, 5, 6, 10, 13, 27; Tables 3, 4). In contrast, significantly reduced sediment supply and development of hemipelagic-clay condensed sections takes place during high stands such as the Pleiocone, the Pleistocene interglacial times, and the Holocene. A caveat is that if the canyon head feeding a turbidite system extends into the present shoreline and intersects littoral-drift sediment supplies, systems such as Mendocino Channel or Var Fan remain active during sea-level high stands (Fig. 1) (Mulder et al., 1998). Another exception is active tectonic areas, like Cascadia, where although turbidite deposition is generally restricted during high stands, the earthquake triggering of turbidity currents and catastrophic volcanic eruptions result in some thick turbidite deposition in channel floors (Figs. 4A, 5) (Nelson et al., 2000b).

Turbidite deposits, whether from Lake Baikal, with a subarctic climate, or Ebro system, with a Mediterranean climate, show the importance of Pleistocene glacial climatic control as an independent factor for increasing sediment supply compared to tectonic activity or lowering of sea level. In Lake Baikal, even though this is an extremely active tectonic basin, during glacial climatic epochs sediment supply, deposition rates, sand percent, and turbidite bed thickness increased three to five times with no change in base level (Table 3). Even in the Mediterranean Ebro system, which did not have as extensive changes in hinterland glaciation as Baikal, sediment supply increased two to three times during deforestation of glacial cycles, just as it has done during deforestation by humans, when there have been no changes in base level (Table 4).

The importance of climatic change increasing sediment supply also helps to explain the anomalously high deposition rates in Pleistocene turbidite systems compared with older pre-Pleis-
tocene systems, which may be controlled more by tectonic and sea-level changes rather than climate (Nelson and Nilsen, 1984). However, there is a caveat that high-resolution chronologies are difficult to obtain and thus accurately constrain sedimentation rates in ancient systems. The climatic effects from the high frequency and high amplitude of sea-level lowering as well as increased sediment supply help clarify why the majority of present-day submarine fans formed during the Pleistocene. Prior to the Pleistocene, the smaller number of fans and lower sedimentation rates may have resulted because of the reduced scale and frequency of sea-level lowering as well as less rapid changes in climate, forestation, and sediment supply. The absence of basin-level control in Lake Baikal and the formation of the majority of submarine fans on the present-day sea floor during the extreme Pleistocene climatic changes also suggests that mainly these climatic changes, and not lowered erosional base level in drainage systems, were the main control on the growth of turbidite systems during the Pleistocene.

The Cascadia and Ebro turbidite systems also exhibit the recent anthropogenic control caused by damming of river systems during the past century; this now greatly reduces sediment supply for many systems compared to that earlier in the Holocene (Tables 2, 4). However, prior to the dams on the Ebro River, the anthropogenic effects of deforestation, overgrazing, and desertification had greatly increased sediment supply to the Ebro system (Table 4) (Palanques et al., 1990). These anthropogenic effects causing increased sediment supply still exist for many other rivers that do not have dams, such as the Eel River in Cascadia Basin (Schymiczek and Suchsland, 1987).

The Cascadia, Baikal, and Ebro deepwater basins all provide information about dominant external controls that determine basic types of turbidite systems in both active tectonic and passive-margin settings. Cascadia Basin shows that a large sediment supply, such as the Columbia River, results in large submarine fans (e.g., Astoria Fan), even in a subduction-zone trench setting (Fig. 1) (Shipboard Scientific Party, 1973; Nelson et al., 1987). In contrast, if the sediment supply is small as with the Rogue River, a base-of-slope Rogue Apron without channels is formed (Fig. 1) (Wolf et al., 1999b). Similarly in Lake Baikal, small drainages and a number of small sediment input points on the border-fault margin control development of base-of-slope aprons, just as the limited sediment supply controls the development of the Rogue Apron (Figs. 7–9). If the sediment supply to canyons is intermediate between that of large submarine fans like Astoria and small aprons, then small sand-rich fans develop like those on the ramp margin of Lake Baikal (Figs. 8, 9).

Both Cascadia and Ebro systems verify that if multiple tributary canyons with a large sediment supply drain into a tectonically controlled channel pathway, an extensive deep-sea channel drains, and bypasses sediment to detached abyssal-plain fans like Valencia Fan or Tufts Fan (Figs. 1, 13, 14, 15, 16) (Carter, 1988; Normark and Reid, 2003). When tectonic lineaments and morphologic setting of the basin results in small turbidity currents draining from one part into another part of the basin, connecting channel–levee systems such as Mendocino Channel and the North Baikal Basin axial channel develop without fan deposits (Figs. 1, 8, 9, 13, 14).

Both the Cascadia and Ebro marine systems show that another external control of geostrophic ocean currents together with sea-level change can influence the location of the lowstand turbidite system and highstand shelf depocenters. During the Pleistocene along the Ebro margin, the southwest geostrophic currents have caused the asymmetric southwest progradation and successive development of submarine canyons and channel
systems (1 to 5) (Figs. 13, 14) (Nelson and Maldonado, 1988; Alonso and Maldonado, 1990). Both lowstand shelf-margin deltas and slope canyons, as well as the transgressive and regressive sediment packages of intermediate sea levels, have progressively developed toward the southwest because of the geostrophic currents (Farran and Maldonado, 1990; Nelson and Maldonado, 1990). In both Cascadia and Ebro margins, there are opposite sediment dispersal directions between lowstand turbidite systems and highstand shelf mud blankets (Figs. 6, 13). During the lowstand, turbidity currents transport sediment eastward or southward in the Ebro and Cascadia systems, respectively, whereas during the high stands geostrophic ocean currents transport sediment westward or northward in the Ebro and Cascadia systems, respectively (Figs. 6, 13).

Although this study focuses on the late Quaternary external controls on turbidite systems on the present-day sea floor, we can observe some significant changes in external controls prior to the Pleistocene glacial and interglacial controls. In Cascadia Basin, no turbidite systems were present prior to the Pleistocene climatic changes (Shipboard Scientific Party, 1973; Nelson et al., 1987). On the Ebro margin, during the continuous sea-level high stand of the Pliocene, only a mud drape without turbidite systems was deposited over the Ebro margin, and the sediment supply from the Ebro River was nearly the same as during the Holocene highstand time (Figs. 6, 13). During the lowstand, turbidity currents transport sediment eastward or southward in the Ebro and Cascadia systems, respectively, whereas during the high stands geostrophic ocean currents transport sediment westward or northward in the Ebro and Cascadia systems, respectively (Figs. 6, 13).

Both active and passive tectonic-margin settings have some common external controls such as the tectonic setting, which determines the morphology of the basin, or the Pleistocene high-frequency climatic cycles and sea-level lowstands, which resulted in rapid growth of turbidite systems. Both active-margin and passive-margin settings also develop similar types of turbidite systems such as base-of-slope aprons, submarine fans, and deep-sea or axial channels. Each margin, however, has specific local controlling factors, for example: (1) the volcanic events in Cascadia Basin, which cause unusually thick Holocene sedimentation rates (cm/1000 yr)

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Pleistocene sedimentation rate (cm/1000 yr)</th>
</tr>
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<tbody>
<tr>
<td>1.65–4.8 million yr</td>
<td>6.5** ** Note highstands are equal</td>
</tr>
<tr>
<td>10,000–1.65 million yr</td>
<td>15* Note human &amp; glacial effects are equal</td>
</tr>
<tr>
<td>&lt; = 10,000 yr</td>
<td>6.2**</td>
</tr>
<tr>
<td>1912–1935</td>
<td>0.12</td>
</tr>
</tbody>
</table>

loccene turbidites on channel floors, (2) climatic without lake-level control of sediment supply in Lake Baikal, and (3) the Messinian extreme lowstand in the Mediterranean Sea, which created unusually steep subaerial drainage gradients followed later by the Pleistocene turbidite-system channels.

The main common external controls that determine the types of turbidite systems are size of the drainage basin, morphology of the turbidite basin, amount and type of sediment supply, and characteristics of the sediment input points. The tectonic setting affects the area of the drainage basin, sediment supply, and location of sediment input points. If there is a small volume of sediment supply, only small base-of-slope aprons a few kilometers in diameter form, whether there may be one canyon like Rogue Canyon or multiple sediment input points of a line source and many individual aprons like those along the border fault of Lake Baikal. If a small to medium volume of sand-rich sediment is supplied at a canyon mouth, a sand-rich fan tens of kilometers in diameter with channels develops, such as those associated with local rivers of the ramp margin in Lake Baikal. If there is a large volume of muddy to sandy sediment supplied at a canyon or deep-sea channel mouth, mud-rich fans hundreds of kilometers in length form. If multiple tributary canyons coalesce and drain along a tectonic lineament, large (several kilometers wide) deep-sea channels such as Cascadia Channel or Valencia Valley extend for hundreds of kilometers. Small (ca. 1 km wide) channels that connect parts of turbidite systems form when there is a small volume of sediment supply that drains for tens of kilometers along local tectonic gradients in turbidite basins. These connecting channels are found as axial valleys draining along faults of the basin plains in Lake Baikal, as channels that connect Ebro canyons to Valencia Valley, and as channels that drain from the Eel plunge pool or along the Mendocino Channel escarpment in Cascadia Basin.

At longer time scales, not studied in depth in this paper, we observe that the tectonic control appears to be the dominant external control that determines the fate of turbidite systems. Examples of this are the Messinian alluvial systems in the Ebro seafloor and pre-mid-Pleistocene shallow-water deltaic systems in the Baikal Basin. The interplay of high-frequency climatic and sea-level cycles are the main common external controls that determine the formation and growth rates of the Pleistocene turbidite systems. Turbidite systems were not formed in the Cascadia and Ebro marine basins until the presence of glacial climatic cycles. The climatic changes, vegetation changes, and increase in sediment supply appear to be the dominant control on the growth of Lake Baikal turbidite systems and together with sea-level changes resulted in the formation of the Cascadia and Ebro systems. The main effect of Pleistocene sea-level changes are to allow sediment access to canyon heads at lowstands and limiting sediment access at highstands. This becomes most important when there are wide shelves and geostrophic ocean currents that transport sediment away from canyon heads. As a result, at highstands of sea level, if canyon heads do not intersect shoreline sediment supplies, condensed hemipelagic sediment units are deposited over the turbidite systems, whereas thick turbidite sand beds are deposited during lowstands. An exception to this sea-level and climatic control is found in Cascadia Basin, where earthquake triggering of turbidity currents and catastrophic volcanic eruptions result in turbidite deposits that are limited mainly to channel floors.

The turbidite-system links to the combination of common and specific external controls that determine their development provide the potential to assess: (1) resources such as petroleum reservoirs in turbidite deposits, (2) environmental changes, such as the recent anthropogenic effects on sediment supply and the consequent rapidly eroding Mediterranean deltas, and (3) geologic hazards, such as the paleoseismic history of the Cascadia Subduction Zone.

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