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Comment on "Late Holocene Rupture of the Northern San Andreas Fault and Possible Stress Linkage to the Cascadia Subduction Zone" by Chris Goldfinger, Kelly Grijalva, Roland Bürgmann, Ann E. Morey, Joel E. Johnson, C. Hans Nelson, Julia Gutiérrez-Pastor, Andrew Ericsson, Eugene Karabanov, Jason D. Chaytor, Jason Patton, and Eulàlia Gràcia

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Introduction

Goldfinger *et al.* (2008) conclude that in the northern San Andreas fault and Cascadia margins, Holocene turbidites (i.e., deposits of turbidity currents) were triggered by earthquakes. However, their conclusion falters because of (1) selective data sets that were used for establishing seismicity as the sole triggering mechanism of turbidites, (2) flawed sedimentological concepts and criteria that were applied for interpreting turbidites, and (3) faulty methodologies that were employed for correlating turbidites over long distances. This same turbidite (i.e., sedimentological) theme has also been published previously by Goldfinger *et al.* (2003a,b, 2006, 2007). As with the recent article in *BSSA*, their previous publications on the subject matter were published in journals that are concerned primarily with geophysical topics. As a result, critical sedimentological conclusions, which are an integral part of the articles by Goldfinger *et al.*, have not been subjected to a rigorous scrutiny. Therefore, I would like to comment on the following three issues.

Triggering Mechanisms

Along the Washington–Oregon–California margin, potential triggering mechanisms of sediment failures and related turbidity currents are (1) earthquake (Adams, 1990), (2) tectonic oversteepening (Greene *et al.*, 2006), (3) tsunami (Adams, 1990; Geist, 2005), (4) cyclone (Adams, 1990; Shanmugam, 2008a, fig. 4), (5) ebb tidal current (Puig *et al.*, 2003), (6) submarine volcanic activity (Davis *et al.*, 2002), (7) sediment loading (Adams, 1990), and (8) gas hydrates (Chapman *et al.*, 2004). The link between gas-hydrate decomposition and mass movements on the Norwegian margin was discussed by Mienert *et al.* (2005). In the Cascadia margin, a total of 40 cyclones along the Oregon coast were reported for the 1984–2006 period (Moritz and Moritz, 2006). A total of 24 tsunamis were reported along the Oregon coast for the 1868–1994 period (Table 1). Cyclones and tsunamis are powerful agents of sediment failures (Shanmugam, 2008a). On the outer continental shelf of the Gulf of Mexico, for example, the 2005 category 5 hurricane Katrina not only destroyed 46 petroleum platforms (Minerals Management Service [MMS], 2006) but also triggered major mass flows. Such mass flows commonly transform into turbidity currents downslope (Talling *et al.*, 2007). Furthermore, the transport of coastal sand into the deep ocean by ebb tidal currents and related sediment flows has been documented in southeast Australia (Boyd *et al.*, 2008). In an objective scientific analysis, Goldfinger *et al.* should evaluate all applicable, empirical data sets and should consider alternative mechanisms before advocating earthquake as the primary triggering mechanism of turbidity currents.

Sedimentological Concepts and Criteria

Goldfinger *et al.* (2008, figs. 3–6) interpreted turbidites (with interbedded hemipelagites) as the principal depositional facies. The implication of their interpretation is that the entire Washington–Oregon–California margin was inundated by nothing but the omnipresent turbidity current at the time of deposition. Such a marine setting is rather bizarre because the world's oceans are influenced by a multitude of processes that can transport and deposit sands and muds (Shanmugam, 2007). In fact, the Washington–Oregon–California margin has been subjected to (1) mass movements (McAdoo and Watts, 2004; Greene *et al.*, 2006), (2) normal, southward-flowing California Current (Hickey, 1992), (3) local, counterclockwise California Counter Current (Robinson *et al.*, 2007), (4) anomalous, northward-flowing El Niño Current (1997–1998) over shelf and slope in waters off xOregon (Huyer *et al.* 2002), (5) deep-marine tidal currents in Eel Canyon (Puig *et al.*, 2003), (6) baroclinic currents (Kunze *et al.*, 2002), (7) cyclone-induced bottom flows (Moritz, 2004; Shanmugam, 2008a), and (8) upwelling-influenced flows (Hickey, 1997). In light of these oceanographic data, a realistic interpretation of Holocene deposits must take into consideration all these processes that operate in the Pacific

Table 1
Tsunami Events that Affected the Oregon Coast Region 1 during 1868–1994

Tsunami Event	Date (mm/yyyy)	Origin of Event	Affected Community
1	04/1868	Hawaii	Astoria
2	08/1868	Northern Chile	Astoria
3	08/1872	Aleutian Islands	Astoria
4	11/1873	Northern California	Port Orford
5	04/1946	Aleutian Islands	Bandon
6	04/1946	—	Clatsop Spit
7	04/1946	—	Depoe Bay
8	04/1946	—	Seaside
9	11/1952	Kamchatka	Astoria
10	11/1952	—	Bandon
11	05/1960	South Central Chile	Astoria
12	05/1960	—	Seaside
13	05/1960	—	Gold Beach
14	05/1960	—	Newport
15	05/1960	—	Netarts
16	03/1964	Gulf of Alaska	Cannon Beach
17	03/1964	—	Coos Bay
18	03/1964	—	Depoe Bay
19	03/1964	—	Florence
20	03/1964	—	Gold Beach
21	03/1964	—	Seaside
22	05/1968	Japan	Bewport
23	04/1992	Northern California	Port Orford
24	10/1994	Japan	Coast

Region 1 includes all of Oregon's coastal counties: Clatsop, Coos, Curry, Douglas (coastal section), Lane (coastal section), Lincoln, and Tillamook. The lower estuarine Columbia River is also included in Region 1 (Clatsop County). Data were compiled from the Oregon Coast Hazards Assessment (see the Data and Resources section).

Ocean (i.e., uniformitarianism). Paradoxically, modern turbidity currents have never been documented using relevant empirical data. Although Parsons *et al.* (2003, p. 839) claimed that "in fact, one of us (JDP) has personally observed (via an ROV) a dilute turbidity current associated with internal wave resuspension in the Eel Canyon," they did not provide the crucial supporting evidence for (1) sediment gravity as the driving force of the flow downslope, (2) Newtonian fluid rheology, and (3) turbulent flow state (i.e., Reynolds number), which are the physical properties that define turbidity currents (Dott, 1963; Sanders, 1965; Middleton and Hampton, 1973; Mulder and Alexander, 2001; Shanmugam, 2006a; Talling *et al.*, 2007).

In turbidity currents, deposition occurs through suspension settling. As a result, normal grading would develop irrespective of differences in their triggering mechanisms (e.g., seismicity versus tsunami). This is because physical features preserved in a deposit directly represent the physics of sediment movement that existed at the final moments of deposition (Middleton and Hampton, 1973), which is the basic tenet of process sedimentology (Shanmugam, 2006a). Process sedimentological interpretations of sedimentary deposits must be based on (1) objective descriptions of lithofacies on sedimentological logs (1:20 scale) with Wentworth grain-size class on the abscissa, (2) detailed documentation of sedimentary structures, (3) detailed hydrodynamic explanation of sedimentary structures, (4) quantification of lithofacies, and (5) quantification of depositional facies. Surprisingly, Goldfinger *et al.* (2008) did not provide even the very basic Wentworth scale for grain-size reference (see their figs. 3–6). Furthermore, their casual use of grain-size nomenclature, such as "sand" and "VFS" for very fine sand (their fig. 5), is confusing because the textural term "sand" represents (1) very fine sand (0.0625–0.125 mm), (2) fine sand (0.125–0.25 mm), (3) medium sand (0.25–0.50 mm), (4) coarse sand (0.50–1.0 mm), and (5) very coarse sand (1.0–2.0 mm).

Submarine debris flows and related turbidity currents have been reported to travel over 1500 km from their triggering point on the northwest African margin (Talling *et al.*, 2007). During their long journey, debris flows commonly undergo flow transformations into turbidity currents (Hampton, 1972; Fisher, 1983; Talling *et al.*, 2007). Because of flow transformations, the final process of deposition (e.g., turbidity current) reveals nothing about the process of transport (e.g., mass flow) nor about the triggering mechanism (e.g., seismicity), which may occur thousands of kilometers away from the site of deposition. Such real-world complexities make it impossible to distinguish turbidites that were triggered by earthquakes from those that were triggered by nonseismic events (e.g., meteorological cyclones, slope-failure generated tsunamis, etc.). In spite of these practical challenges, Goldfinger *et al.* (2008) relied on sedimentological criteria, which were developed by Inouchi *et al.* (1996), Nakajima and Kanai (2000), and Shiki *et al.* (2000), for distinguishing seismoturbidites (i.e., seismicity-triggered turbidites) from other types. Nakajima and Kanai (2000, table 2) proposed (1) amalgamated beds, (2) normal grading, (3) inverse grading, and (4) grain-size breaks as the criteria for recognizing seismoturbidites. These features, which simply reflect flow dynamics at the time and site of deposition, reveal nothing about a particular type of triggering mechanism (e.g., seismicity versus tsunami).

Sedimentological problems associated with distinguishing tsunami-related deposits from other triggering mechanisms are colossal (Shanmugam, 2006b; Bridge, 2008). This is partly because tsunami-related deposition in deep-water environments occurs in four progressive stages: (1) the triggering stage, (2) the tsunami stage, (3) the transformation stage, and (4) the depositional stage (Shanmugam, 2006b, fig. 1). During the transformation stage, a reversal in transport direction occurs. Nonetheless, Nakajima and Kanai (2000) did not take into consideration such process-related complications in developing their criteria for seismoturbidites. The term seismoturbidite was introduced for deposits of mass flows (Mutti *et al.*, 1984). Mass flows represent debris flows but not turbidity currents. Ironically, seismoturbidites are not turbidites at all.

In an observational science such as physical sedimentology (Allen, 1985), one must always maintain a clear distinction between description and interpretation. Nevertheless, Goldfinger *et al.* (2008, p. 868) first described Holocene deposits using the Bouma (1962) turbidite notations (e.g., Ta, Tb, and Tc divisions) and then interpreted these deposits as turbidites, which is circular reasoning. More importantly, there is no theoretical (Sanders, 1965; Van der Lingen, 1969), experimental (Leclair and Arnott, 2005), or observational (Shanmugam, 2002, 2006a) basis for validating the Bouma Sequence. As a result, the Ta division has been variously ascribed to (1) low-density turbidity currents (Bouma, 1962), (2) antidune phase of the upper flow regime (Harms and Fahnestock, 1965), (3) bed load (Sanders, 1965), (4) grain flows (Stauffer, 1967), (5) pseudoplastic quick bed (Middleton, 1967), (6) density-modified grain flows (Lowe, 1976), (7) high-density turbidity currents (Lowe, 1982), (8) upper-plane-bed conditions under high rates of sediment feed (Arnott and Hand, 1989), and (9) sandy debris flow (Shanmugam, 1996). In addition, four other processes have been proposed for massive sand intervals: (1) quasi-steady concentrated density currents (Mulder and Alexander, 2001), (2) sand injections (Duranti and Hurst, 2004), (3) contour currents (Rodriguez and Anderson, 2004), and (4) slumping (Chang and Grimm, 1999). Given these uncertainties, it would be helpful if Goldfinger *et al.* could explain the physics and hydrodynamics of the process that emplaced the basal (Ta) division in their cores with supporting sedimentological details but without using the Bouma turbidite notations.

To date, no one could explain how a suspension turbidity current (Ta) transforms into an upper flow regime traction current (Tb) in forming the vertical (Ta and Tb) sequence. In discussing this fluid dynamical dilemma, Leclair and Arnott (2005, p. 4) acknowledged that "… the debate on the upward change from massive (Ta) to parallel laminated (Tb) sand in a Bouma-type turbidite remains unresolved." In a pragmatic process sedimentological approach, Bouma notations Tb and Tc would be described objectively as parallel laminated and ripple (convolute) laminated divisions, respectively. These traction structures should be appropriately interpreted as products of traction bottom currents, not suspension turbidity currents (Shanmugam, 2008b). The importance of deep-marine tidal bottom currents in the world's submarine canyons and on ocean floors has been discussed elsewhere (Shepard *et al.*, 1979; Egbert and Ray, 2000; Shanmugam, 2003, 2008c). In the Cascadia margin, semidiurnal tidal currents have been documented in Eel Canyon (Puig *et al.*, 2003) and in Astoria Canyon (Bosley *et al.*, 2004). Without considering these empirical data, Goldfinger *et al.* (2008) opted for the (Bouma) model-driven interpretation with a turbidite mind set (Shanmugam, 1997, 2000).

Correlation Methodologies

Goldfinger *et al.* (2008) used ^{14}C dates of forams collected from hemipelagite mud layers for correlating synchronous turbidite events over long distances. There are major problems with this methodology.

1. Goldfinger *et al.* did not explain the criteria for distinguishing the boundary between turbidite mud and overlying hemipelagite mud.
2. Turbidity currents, by nature, are turbulent flows, which invariably cause erosion of the seafloor. Therefore, it is impractical to select turbidite sites that did not undergo erosion.
3. Available radiocarbon dating methods cannot resolve the precise age of a single depositional event that was emplaced in a matter of hours by cyclone-triggered bottom flows.
4. Radiocarbon dates are meaningful in stratigraphic correlations only if a turbidite unit represents a single depositional event. However, the Bouma Sequence represents multiple depositional events in the Annot sandstone in the Peira Cava area, which is the type locality for the Bouma Sequence, French Maritime Alps (Shanmugam, 2002, fig. 17). Multiple depositional events generate amalgamated beds. Amalgamated beds are unsuitable for correlating a single event. Ironically, Nakajima and Kanai (2000, table 2) proposed amalgamated beds as a criterion for recognizing seismoturbidites over long distances.
5. For correlating turbidite units, Goldfinger *et al.* (2008, figs. 4 and 5) used magnetic susceptibility and Gamma density logs as grain-size proxies for normal grading. Similar correlations, based on electrical (wireline) logs, are popular in the petroleum industry. But these methods are inherently flawed because they are based on the erroneous and dated belief that normal grading is unique to turbidites. But the reality is that normal grading has been associated with deposits of (1) sandy debris flows (i.e., sandy debrites) (Marr *et al.*, 2001), (2) cyclone-triggered combined flows (Gagan *et al.*, 1990; Allison *et al.*, 2005, fig. 6), and (3) tsunami-triggered flows (Gelfenbaum and Jaffe, 2003, fig. 9). Without core, one cannot distinguish graded turbidite sand from graded debrite sand using grain-size proxies.
6. The other issue is that not all turbidites are normally graded. Massive turbidite sands, composed of amalgamated units, commonly are uniform in grain size. Such amalgamated turbidite sands cannot be distinguished from sandy slumps, sandy debrites, or sandy injectites on electrical (wireline) logs (Shanmugam *et al.*, 1995, fig. 24). In short, electrical (wireline) logs and grain-size proxies are irrelevant for correlating turbidite units.
7. Finally, Goldfinger *et al.* (2008) applied the confluence test to validate the synchronous triggering of turbidite events by earthquakes. Such a test can be meaningful only if one can assume that the Washington–Oregon–California margin has never been subjected to depositional processes other than turbidity currents and that the margin has never been affected by triggering mechanisms other than earthquakes during Holocene. Such assumptions defy empirical reality.

Concluding Remarks

The model-driven turbidite interpretation, which was popular in the latter third of the twentieth century, is obsolete now. Pragmatic process sedimentological interpretation is the norm. At present, there are no criteria for distinguishing an individual triggering mechanism (e.g., earthquake versus cyclone) from the depositional record (e.g., normal grading). Neither are there tools to measure the precise age of deep-water deposits that may be emplaced in a matter of hours. Until we develop appropriate new tools and relevant new methodologies, the use of grain-size proxies and electrical (wireline) logs for correlating depositional events is inconsequential in discovering the truth.

Data and Resources

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