Abstract

The past occurrence of great earthquakes in Cascadia is now well established by both the coastal (Atwater and Hemphill-Haley, 1997; Kelsey et al., 2002, 2005; Nelson et al., 2000) and turbidite event paleoseismic records (Goldfinger et al., 2003a,b; Goldfinger et al., 2008, 2009; 2011a, 2011b). Consequently, attention has turned to magnitude, recurrence intervals, and segmentation of the margin. Segmented and whole margin ruptures should leave distinctly different stratigraphic records in both the coastal marshes and the offshore turbidite record. The turbidite event stratigraphy shows a clear record that the northern 660 km of the Cascadia Basin has operated as one segment for at least the past ~10,000 years, though smaller localized events that did not trigger turbidites may have occurred. Along the southern Cascadia margin, a series of smaller events suggests segmented ruptures occur there, supported by the apparent presence if similar events in coastal Bradley lake. Similar work now underway along the northcoast segment of the San Andreas Fault suggests that a long-term earthquake record is also recorded there in the turbidite record (Goldfinger et al., 2007). Key to the definition of an earthquake record from these turbidite sequences is event correlation along the margins using multiple proxies.

In the course of both offshore paleoseismic investigations, we have been using physical property signatures to aid in event correlation. Recently, we have found that it is possible to correlate individual turbidites from site to site using high resolution physical property data such as Gamma density, P-wave velocity and magnetic susceptibility. These continuous data are routinely collected from offshore cores. The magnetic and density “fingerprints” of each turbidite are a reflection of grain size distributions within each turbidite Goldfinger et al., 2011a). It is the sequence of coarse units that we are correlating over large distances, using the same techniques used in the oil industry to “fingerprint” formations and track them through prospect fields. While
such correlations are common stratigraphic tools, and are a staple of the oil industry, we did not expect that individual turbidites would correlate as well as they do over such large distances. Even more surprising than successful local correlations between cores, we also found that individual events can be correlated not only within channels, but between separate channels that never meet. This is a startling observation, since turbidites in separate channels should have little in common. Some correlated events are as much as 500 km apart, yet they share basic characteristics such as event size, number of coarse sandy pulses, and even subtle details of the shape of the physical property signatures (proxies for grain size distribution), for which we do not know the cause.

This project addresses this remarkable correlation property of earthquake generated turbidites in Cascadia (and perhaps elsewhere). Why is this important to earthquake investigations? Our working hypothesis is that given the separation of the channels, the sometimes differing geology, and differing canyon/channel morphologies through which the turbid flows passed is that the turbidite deposits have recorded information about the original earthquakes, resulting in the correlations we see. Recent numerical and physical models suggest that the basic properties of turbidity currents are relatively well modeled by simple techniques, and that the governing principles may allow the initial perturbation to be recorded by the final deposit. Our hypothesis is that multiple coarse pulses in the turbidites, correlated over some distance, may reflect the rupture of multiple segments or asperities during an earthquake, that is, the source-time function of the earthquake (Goldfinger et al., 2004, 2008, 2011a).

In this project, we proposed a simple laboratory test of this hypothesis. We generated turbidity currents in flume tanks, and triggered these currents with a set of inputs that simulated several input scenarios. We input initial perturbations similar to those expected from several recent great earthquakes, such as the 1906 NSAF earthquake, and the 2004 Sumatran earthquake, as well as generic signals and simulations of storm generated hyperpycnal flows. We used calibrated simulated sediment material that was color coded by grain size, and used photographic techniques to extract detailed grain size plots of each turbidite deposit. We then compared the input sources to the turbidite deposits. We found that there is an excellent correlation between the input perturbations and the recovered grain size profiles of the deposits, reflecting considerable detail of the input source. We successfully simulated input perturbations of single and multiple input energy peaks of varying lengths and flow hydrographs, as well as simulated hyperpycnal flows, with consistent results across a range of timing variations, and a range of scaling variations.

We conclude that turbidite records may offer information about the original earthquakes, or other input sources, and that this is a possible explanation for the unusual correlation of isolated paleoseismic sites in Cascadia. If correct, turbidites under ideal conditions may record enough source information to be considered “paleoseismograms” recording information about paleo-rupture sequences on large fault systems. Data from turbidites found in land-locked inlets and sub-alpine Cascadia lakes are consistent with this experimental result.

Background

Cascadia offshore paleoseismology has been greatly aided by the great similarity of turbidite structure in individual deposits along strike. This has allowed us to use traditional oil industry techniques in use since the 1920’s to correlate individual deposits between our core sites. We have found that it is possible to correlate individual turbidites from site to site using high resolution physical property data such as Gamma density, P-wave velocity and magnetic susceptibility. These continuous data are routinely collected from offshore cores. The magnetic and density “fingerprints” of each turbidite are a reflection of grain size distributions within each turbidite. While these techniques are similar to the oil industry, the scale is quite different.
spatially (the entire subduction zone in our case) and because the Cascadia deposits in many cases have no stratigraphic continuity between sites. The typical signature consists of 1-3 coarse fining upward sandy pulses (partial Bouma sequences), capped by the fining upward silty tail, indicating final waning of the turbidity current. It is the sequence of pulses that we are correlating over large distances, using the same techniques used in the oil industry to “fingerprint” formations and track them through prospect fields. While such correlations are common stratigraphic tools, and are a staple of the oil industry, we did not expect that individual turbidites would correlate as well as they do over such large distances. Even more surprising than successful local correlations between cores, we also found that individual events can be correlated not only within channels, but between separate channels that never meet. This is a startling observation, since turbidites in separate channels should have little in common. Some correlated events are as much as 500 km apart, yet they share basic characteristics such as event size, number of coarse sandy pulses, and even subtle details of the shape of the physical property signatures (proxies for grain size distribution), for which we do not know the cause.

Significance of a Probable Earthquake Record at Effingham Inlet, Western Vancouver Island

Geoscientists and oceanographers of the Canadian Institute for Ocean Sciences (IOS) in Sidney, British Columbia on Vancouver Island, have recently begun investigating the recurrence pattern of great earthquakes and tsunamis along the Canadian Cascadia margin using annually laminated sediments from anoxic coastal fjords, which show variable disturbances possibly related to paleo-seismic events (Dallimore et al., 2005, 2009). These sediment records are excellent geochronological archives of sediment disturbance events, providing in some cases annual event timing resolution when tied to known volcanic deposits such as the Mazama ash datum. The varying thickness of diatom/terrigenous mud varves in sediment cores from these anoxic basins can be interpreted in terms of annual changes in surface productivity and freshwater input within the inlet. Similarly, the occurrence of un laminated mud units (homogenites) intercalated amongst the laminated sediments can be interpreted in terms of oceanic and climatic changes (Dallimore et al., 2005; Hay et al., 2009; Chang et al., 2003; Chang and Patterson, 2005). However, the sedimentary record also contains massive and graded mud units considered to arise from debris flows and turbidity currents and these units, some of which were probably initiated by seismic events, including a previously unrecognized major sediment disturbance event about 4500 y BP which may be earthquake/tsunami related.

A large (50 cm) massive unit has been found in the most recent sediments of Effingham Inlet as well as other inlets farther to the north on the central mainland B.C. coast and is correlated to the large (magnitude 7.3) central Vancouver Island earthquake that occurred in June 23, 1946 (Dallimore et al., 2005). Liquefaction of sediments, resulting in significant terrestrial and submarine slumps and slides, were initiated on both coasts of Vancouver Island by the seismic shaking associated with this earthquake, which was one of the most damaging in British Columbia’s history (Rogers, 1980). This regionally recognized event bed provides a rare modern analogue of the nature of coastal marine sediment disturbance resulting from a large (M~7) earthquake and hence provides a proxy for the identification of other large earthquakes expressed in the sediment record.

The paleoseismic events at Effingham are interpreted as such because they all have a wall rock signature from the surrounding highlands, and because they show characteristics more closely resembling true turbidites than other disturbance events attributed to climate events in the core. The clear link to the 1946 earthquake is, while much larger than the other events, similar in character to the events suggested as Cascadia great earthquakes (Dallimore et al., 2005). As a preliminary test of the Effingham record, we compared 11 candidate events interpreted as Cascadia earthquakes to possible correlatives in offshore turbidite records. (Data from the upper 4 events have not been collected, as this section is a “freeze core” and cannot be removed from its
storage freezer, creating some difficulties for magnetic measurements). Six of these comparisons are shown in Figure 1. We show magnetic and density traces, and radiocarbon ages for Effingham and Cascadia Channel cores for these events. A strong stratigraphic signature common to both onshore and offshore cores is apparent, as is a good correspondence in $^{14}$C ages. (Four of the other five correlations are somewhat generic in profile, and not particularly diagnostic (though all are compatible in age), and one is a relatively poor match). We were startled to find that not only

Figure 1. Preliminary correlations between Cascadia Channel core M9907-23PC and core MD02-2494 from Effingham inlet, western Vancouver Island, From Goldfinger et al., 2011). Each plot shows the magnetic susceptibility record (blue) from an Effingham Inlet (inner basin) turbidite, and a magnetic susceptibility or Gamma density record from our 1999 cores in Cascadia Channel in purple. These events were interpreted as seismites by Dallimore et al., 2005b, based on wall rock signature from the adjacent Fiord walls (shown in gray), and by comparison to the historical turbidite triggered by the1946 Vancouver Island earthquake. The records show a striking similarity in general size, number of sandy pulses (magnetic and density peaks) and in some cases, detailed trends. Radiocarbon ages are also first order compatible, but have separations of 100-200 years in some cases. Offshore ages are the OxCal combined ages in Appendix 10b of Goldfinger et al (2011) with 2σ ranges. The combined age data and stratigraphic correlation suggest that the Effingham turbidites and Cascadia Basin turbidite signatures are recording the same earthquakes. Effingham data from Dallimore et al. (2009).

could these event fingerprints be found in offshore cores, but in the Effingham cores interior to Vancouver Island. We believe that this evidence lends strong support to an earthquake “signature” as the common link between the onshore and offshore cores.

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investigations? Our working hypothesis is that given the separation of the channels, the
sometimes differing geology, and differing canyon/channel morphologies through which the
turbid flows passed, the only factor in common is the original earthquake itself. If so, then it is
possible that the turbidite deposits have recorded information about the original earthquakes,
resulting in the correlations we see (Goldfinger et al., 2004, 2008, 2011). At first glance, this
would certainly seem to be an outrageous hypothesis. It is difficult to imagine that a chaotic
event such as a turbidity current could record anything useful. However, reviews of the literature
and a previous small pilot experiment suggest otherwise. Recent numerical and physical models
suggest that the basic properties of turbidity currents are relatively well modeled by simple
techniques, and that the governing principles may allow the initial perturbation to be recorded by
the final deposit. Our hypothesis is that multiple coarse pulses in the turbidites, correlated over
some distance, may reflect the rupture of multiple segments or asperities during an earthquake,
that is, the source-time function of the earthquake.

In this project, we proposed a simple laboratory test of this hypothesis. We generated
turbidity currents in flume tanks, and triggered these currents with a set of inputs that
simulated several input scenarios. We input initial perturbations similar to those expected
from several recent great earthquakes, such as the 1906 NSAF earthquake, and the 2004
Sumatran earthquake, as well as generic signals and simulations of storm generated
hyperpycnal flows. This report includes a brief description of the methods and results from a
series of such experiments.

Theoretical Basis

Particle-driven gravity currents have received considerable attention during recent years
(see the review of Huppert, 1998). Studies have adopted both experimental and theoretical
approaches to elucidate the physical processes which control these flows (e.g. Bonnecaze,
Huppert and Lister, 1993; Hallworth, Hogg & Huppert 1998). There are many examples of
particle-driven flows in natural and industrial settings. These include volcanic ash flows (Sparks
et al. 1997), turbidity currents in the ocean (Simpson 1997) and the particle-laden plumes arising
from water-injection dredging (Hallworth et al. 1998). Particle-driven gravity currents are
dissimilar from those driven by compositional difference in fluids because the suspended
particles, which contribute to the excess density, sediment to the underlying boundary as the flow
evolves. Thus the density difference is progressively reduced and the flow eventually ceases,
leaving a deposit of particles on the boundary. In almost all of the analytical work to date it has
been assumed that the suspension of particles possess a single settling velocity. However in many
situations this is a considerable simplification and in virtually all real situations there is a range of
particle sizes, and hence settling velocities. For example, it has been noted that the presence of a
small fraction of fine particles has a marked effect on the propagation of the particle-driven
current at late stages (Harris, et al. 2001). Also, in many geological situations, there will be a
large range of different classes of particles. For instance, pyroclastic flows involve particle size
ranges from tens of centimeters to microns. Similarly, turbidities comprise significant fractions of
sand, silt and clay particles, the settling velocity of which differs by many orders of magnitude.
Observations of long-runout turbidite deposits have indicated that a single event may lead to a
segregation of grain sizes, as discussed recently by Wynn et al. (2002). The proximal regions
comprise coarse grains in a wedge-shaped deposit which are overlain by a layer of finer particles.
Conversely the distal deposits are primarily composed of the finer grained sediment.

Flows of particle-laden fluid give rise to distributions of deposited particles. Numerical
models can now simulate the variation of the deposit vertically and with streamwise distance (e.g
Harris et al., 2002). The deposit comprises contributions from each class of particles. Not only
can such models predict the total thickness of each class, but also the variation of the composition
of the deposit with depth, and its deposition with time.
Recent model results suggest that at early times, flow is similar to a compositionally driven current in which the density difference between the current and the ambient fluid remains constant. At later times, particle sedimentation begins to significantly reduce the overall concentration. At these times, the general characteristics of the current are as if the current were monodisperse, composed of particles with the average settling velocity. The effects of a distribution of settling velocities is only noted at much later times and it is the variance of the initial distribution, relative to the square of the mean settling velocity, which governs its magnitude (Harris et al., 2002; Gladstone et al. 1998; Bonnecaze et al., 1996). Details of the modeling methods are given in Harris et al. (2002).

Thus the composition in both the vertical and streamwise direction may be computed from a single, initially well-mixed intrusion of a polydisperse (range of grain sizes) suspension. Model predictions are in accord with field observations of turbidite deposits. It seems that the limits of both numerical models, which generally do not consider spanwise flow, and of physical experiments, which are in confined tanks, do not seriously compromise simulations. This may be because most turbidites are channelized flows to begin with, simulating the experimental boundary conditions. In our work, we have indeed found that turbidites have been highly confined flows. Several of our 2002 cores that were either taken as controls, or simply missed their targets, show a rapid dropoff in turbidite sedimentation away from channels.

Numerical modeling is beginning to resolve the depositional pattern in time and space based on sediment grain size and density. Until very recently, models generally considered only a constant grain size, and neglected much of the internal dynamics of the turbidity current. More recent work now can handle multiple grain sizes, or a continuum of grain sizes, though the “box model” approach still usually neglects the internal dynamics of the turbid flow. This is more due to the success of simple models than to limits of the technique or computing. The depositional patterns based on more complex fluid dynamic models do not seem to significantly improve on the relatively simple ones that ignore most of the flow details. This indicates that the governing processes of deposition are more sensitive to the particle size distribution and settling velocities than to processes within the turbid flow. This modeling result may help explain why details of the time history of flow initiation might be preserved in the deposited stratigraphy: because time and the grain size distribution are the most important parameters. We suggest that time is probably the most important factor, as suggested by our simple experiment, and that there may not be a limiting time interval that cannot be reflected in the resulting deposit. If so, it may be possible to record some details of seismic energy input that takes place over a span of seconds to a one or two minutes typical of the Mw 8-9 earthquakes known to occur in the Cascadia and San Andreas systems.

No modeling approach, physical or analytical that we are aware of has addressed the issue of interest in this project; that is the preservation of a time history of short duration in the turbidite record.

**Investigations Undertaken**

Our tasks for this project included following:

**A Pilot Experiment**

Prior to this project, we conducted a simple unscaled physical experiment to test our working hypothesis with a real, if grossly imperfect model. Figure 2 shows an image of the experimental results. We initiated debris flows in one end of a small tank, using a bimodal sediment load consisting of medium sand colored black, and fine sand-silt sized silica particles colored yellow for easy identification. Density driven true turbid flow was not possible in this small experiment due to the short length of the tank, so the deposit would more correctly be called a debrite or debris flow deposit. We found that with two input pulses separated in time by
5 minutes, two upward fining graded deposits were left, one from each sediment input. Somewhat surprising was that the layers were graded reasonably well, even with a very short runout distance of less than a meter. When we reduced the time interval of the two pulses, we recorded virtually the same stratigraphy, two fining upward sequences, with less fine fraction between the two pulses. The final run was done with two pulses separated by only 2 seconds. Both pulses were well recorded as before. A subsequent run was done with three pulses with a time separation of about 1 second. Again, all three were recorded in the sediment, with less fine fraction between the three layers, and an overlying fine “tail”.

While this unscaled debris flow experiment obviously ignores scaling factors, and did not generate true turbidity currents, it did faithfully record our crude input pulses that were spaced closely together in time.

This project is a logical next step, to test a more realistic scenario with realistic inputs and scaling parameters to test the hypothesis that turbidites may record significant details of the perturbing event that triggered the turbidity currents that deposited them.

Figure 2. Unscaled experiment showing stratigraphy developed with multiple pulse input of mixed sand/silt suspension. Grey sand forms a basal layer and is not part of the experiment. Colored layers are a mixture of sand sized black particles, and silt sized yellow particles. In this run, input was made with three pulses with ~ 2.0 second time separation. Three pulses, shown with red arrows, are repeated in the stratigraphy as three fining upward units within a single amalgamated deposit. Inset shows an approximation of the grain size distribution based on image analysis (light pixels are finer grained, method of Parsons et al., 2002).

Results

The literature of turbidity currents is replete with turbidite tank experiments, however in nearly all cases, the goal is to zero out input heterogeneity and investigate the
hydrodynamics of the currents, and sometimes the depositional patterns (map, temporal or 3D). Our goal was essentially the opposite, to control input heterogeneity, and create quantifiable input heterogeneity that would convolve with hydrodynamic effects to deposit sediment in a receiver basin. Rather than assume that hydrodynamics control deposition patterns, our intent was to test this assumption and generate a variety of source inputs which could be compared to the resulting deposits.

We first constructed a prototype system to test various mechanisms to generate turbidity currents in which we could control the input flow to simulate a variety of input sources. An initial sediment source mixing box with controllable output flap was discarded as the mechanisms were prone to clogging with sediment, and because of the difficulty of keeping a variety of grain sizes in suspension. The prototype system consisted of a 114 liter transparent walled tank (~ 30 U.S gallons), a slurry pump capable of pumping sand silt slurry at rates from 0.1-6 gpm, and a half-round PVC slanted tube to simulate a submarine canyon. The receiver basin was a transparent container within the tank, with fluted walls designed to reduce flow near the basin walls and therefore expand sediment deposition near the walls for better sampling and visual observations. We tested a variety of sediment grain sizes and compositions for suitability for both the experiment design and scaling considerations. Figure 3 shows grain size plots for some of the materials we tested for use. Selected grain size analyses were performed with the laser diffraction method using a Beckman-Coulter LS 13-320 laser counter (Blott and Pye, 2006). For the prototype experiments we primarily used commercially available calibrated sediments representing very fine sand, silt and clay grain size fractions. We looked for materials with consistent grain size peaks, with as narrow a range as practicable, and available in distinct colors that could be analyzed visually. We tested the commercial silicon materials products SilcoSil 250, SilcoSil 53, Aluminum oxide 220 and 280, silicon carbide 180, fine beach sand, and kaolin. The numbers in these materials refer to “grit” sizes, as some of them are sandblasting materials.

![Figure 3](image.png)

**Figure 3.** Laser diffraction grain size results for a variety of candidate materials.

For very fine sand fraction, we used aluminum oxide sand available in a range of grain sizes for sandblasting applications. 180 grit AlO₂ had a median grain size of ~ 76, and
AlO2 220 was 95 microns, in the middle of the range for very fine sand (62.5-125 microns). Both of these were suitable for this experiment (Figure 3). Silt material (3.9-62.5 microns was well represented by kaolin and SilcoSil 53, with median grain sizes of 19 and 15 microns respectively, however their grain size peaks were low enough that settlement in the tank took an impractically long time. We instead used SilcoSil 250, which had a rather broad grain size distribution, mainly concentrated between 50 and 150 microns. While this seemed non-ideal at first glance, it proved to be an ideal material, with obvious deposition consistently overlying the very fine sand, even though the coarse fraction of the SilcoSil 250 was actually mixed with the very fine sand. The finer end of the SilcoSil 250 extended to the finest silt, at the boundary with clay material, providing ample fine material to drive the turbid flow.

Using this arrangement we tested a number of combinations of SilcoSil 250 and AlO2 180 with kaolin and without until we arrived at proportions that allowed reasonable settling times and provided good visual distinctions between grain size fractions. We then did a series of input runs to simulate a variety of input sources, including 1) single pulse and multiple pulse “impulsive” inputs, that is inputs with sharp input flow ramps simulating a landslide or earthquake input 2) gradual waxing and waning hydrograph ramps, simulating a hyperpycnal flow; 3) inverted impulsive flows, with gradual starting flow increase, with abrupt shutoff. We also varied the time between individual pulses from 15 minutes to as short as 30 seconds to simulate complex heterogeneous flow hydrographs. An example of these experiments is shown in Figure 4.

**Figure 4.** Multiple experimental runs, 30 gallon prototype tank. Image shows the resulting deposit from four simulated turbidites. A: Two pulse impulsive event with 30 seconds elapsed between input pulses. B: Single pulse impulsive event. C: Simulated...
hyperpycnal event, with gradually increasing hydrograph, then gradual decrease. D. Two pulse impulsive event, too compacted by overlying runs for further analysis. Plots at right are four pixel profiles through the deposit at its greatest thickness. Pixel value shows grain size distribution, with while material of silt size (SilcoSil 250) having values of ~ 180-210, and aluminum oxide very fine sand in the tan color, ranging from ~ 100-150. Plots show sharp bases for the impulsive events, and the waxing then waning nature of the simulated hyperpycnal event. 30 second separation between pulses is clearly visible in the image and observable in the data.

Results from the prototype experiment were quite well defined. A variety of flow hydrographs were simulated, and each was clearly discernable in the color coded deposits. Impulsive multipulse runs with time separation as short as 30 seconds were observable in the data, as was the waxing-waning hyperpycnal simulation. Photographic extraction of the grain size distributions were successful in illustrating these relationships with excellent resolution. The initial test runs were supportive of the hypothesis that flow heterogeneity of a variety of types could be recorded in the deposit, overcoming the influence of the hydrodynamics of the flow, and warranted further experiments with better controlled inputs and scaling.

**Larger Scale Experiment**

The experiment was then developed to incorporate more control in both the input methods and the overall scaling of the experiment. A large, ¾ inch thick glass tank was purchased, which was 2 feet wide and tall, and 11 feet long. A Fisher Signet 2551 magnetic flowmeter was plumbed into the input pipe. To ensure that accurate measurements could be taken, a 12 foot pipe was placed before the sensor, to reduce the presence of turbulent flow from the pump system and resulting in a smooth, laminar flow past the sensor for accurate flow rate readings.

**Testing of the system capabilities.**

The capability of the flowmeter was extensively tested to find the maximum flow rate achievable with a sediment laden flow, and the maximum flow rate was found to be around 8 US Gallons per minute. This was an acceptable maximum rate of flow, and allows enough variability within the setup that a variety of flow types and speeds can be created within the range of the apparatus. The original pump system from the initial experiment was improved upon with a two pump system– one pump maintaining the sediment in suspension and the other pumping out the sediment into the delivery tubes and tank. The system was controlled by a y-valve – the position of which was recorded during the experiment.

**Experimental Results**

The first test runs ensured that sediment in its current ratio could travel through the new, larger system into the tank and that sediment flow could be maintained into the receiver basin. A similar setup within the tank was used as in the previous experiment, with the
same configuration of receiver basin and half-round PVC slanted tube. To reduce the effects of the tank itself, the experiment setup was positioned in a central location within this larger tank, and a mesh net was placed behind the receiver basin, to slow down the flow after the initial deposition, eliminating the reflection of the flow from the surrounding glass walls and downslope wall of the receiver basin, which was partially cut away for this purpose.
Figure 5. Example test run from larger tank experimental setup. In this run, three input pulses were introduced into the simulated canyon system. Upper panel shows the slurry flow history for these three pulses. Lower panels show the deposit, and the extracted grain size proxy based on the color coded sediment size fractions. The first pulse was intended to be a hyperpycnal waxing then waning flow, though the rate of change was too great to capture the idealized flow hydrograph, instead it simulated a two pulse event with no time gap, but rather a flow reduction by ~ 50%. The second event was a two pulse event impulsive event.

Extensive testing was conducted to find the optimal configuration for recording turbidite-type deposits within this new tank setup. This testing also contributed to the question of scaling. Tests were made with varying angles of the PVC pipe, varied density of the sediment flow (with the addition of a densifying agent, calcium chloride dihydrate, at a range of ratios), the rate of flow – with higher and lower flow rates, and with a number of receiver basin configurations. While an optimal setup was found within these parameters, it was also found that deposition patterns related to the heterogeneous flow still occurred regardless of changes in any of these parameters. Example runs from the 130 gal. setup are shown in Figure 5. Aside from ‘extreme’ and unrealistic setups, most configurations still produced a measurable turbidite flow and deposit. These initial tests and calibrations indicate that small changes to density, flow rate, slope angle, and other factors, appears to have little effect on the turbidite form and sediment input itself. Further controlled testing of these parameters and their ranges is planned to further analyze and determine what effect scaling changes may have.

Conclusions

Simulated heterogeneous flows into a total of four tank arrangements were achieved, and showed a strong relationship to the deposits across all four setups, and across a range of scaling parameters that is larger than that expected in nature. Simulated hyperpycnal flows, short and long pulse turbidites, multipulse turbidites with simple and complex flow hydrographs were all recreated and recorded within the sediment deposited in the receiver basin. The grain size profiles were successfully extracted from the color coded sediment at very high resolution. With the addition of the flowmeter data, there is also now a much clearer view of the details of the input flow into the tank. With measurements of the changing flow rate at 10 Hz, a highly detailed record of the fluctuations in flow is available, which can be directly compared to the photography of the sediment deposited in the basin (Figure 5). High frequency variability in the flow when the rate exceeds the maximum stable rate (~ 8 gpm) results in a chaotic input, however this chaotic input is buffered by the flow to the receiver basin and is generally not seen in the deposits. There is certainly a frequency limit to variable inputs above which the deposits are not sensitive.

We conclude that heterogeneous simulated turbidity currents leave deposits that closely reflect the low frequency content of flow variability. As seen in natural deposits, hyperpycnal flow hydrographs results in a waxing then waning grain size depositional
pattern. Similarly, impulsive inputs that simulate earthquake, self-failure, delta-front failure or other impulsive sources result in sharp based fining upward sequences that reflect the input flow hydrographs. Multiple input pulses within single flows also result in multiple fining upward sequences reflected in the grain size profiles (Figure 5).

We find at least permissive support for the hypothesis that natural turbidites may in some cases represent elements of the heterogeneity of the source mechanism of complex sources such as earthquakes, as they are known to do for hyperpycnal flows. Earthquake source mechanisms can be complex, and any given site will represent the arrival of different phases as well as the arrival of energy fluctuations from a heterogeneous source. We expect that the initiation of turbidity currents in submarine canyons from earthquakes is a response to these arrivals in sequence from their respective sources at a variety of ranges. Detailed strong ground motion records for major earthquakes are relatively rare however, making the analysis of the site ground motions difficult. The 1999 Chi-Chi Taiwan earthquake was unusually well recorded, with a dense array of strong ground motion instruments. The ground-velocity recordings of the of that event recorded at stations near the ruptured fault trace show a simple, large-amplitude, and long-period pulse following the $S$ wave, which is closely associated with the surface faulting and the rupture process of thrust faulting (Chen et al., 2001). The ~10 second long pulse was interpreted as the superposition of the rupture pulses and sub-events that nucleated at an asperity near and underneath the stations and propagated up-dip and laterally along the fault plane toward the surface stations. This well recorded event is probably representative of ground motions expected at submarine canyon sites during a nearby earthquake. In the Chi Chi case, the thrust mechanism effectively simulates a subduction earthquake or rupture of a splay fault in the accretionary complex.

Further investigation of the source time functions of recent earthquakes for which a turbidite record exists have suggested some support for this hypothesis. For example, seismograms and geodetic analysis (Song et al., 2008) for the 1906 San Francisco earthquake indicate this earthquake was likely included two main rupture patches. Our analysis of core samples including the likely 1906 turbidite in Noyo Channel near the northern end of the NSAF show this event contains two fining upward sand pulses (Goldfinger et al., 2004). Similarly, the 2004 Sumatran earthquake was composed of three distinct rupture patches (e.g. Chlieh et al., 2006). Our cores from the 2004 rupture area collected in 2007 show the uppermost event, interpreted to be the 2004 turbidite, is composed of three fining upward coarse pulses (Patton et al, submitted). Investigations of other events for which good seismologic records and cores exist is ongoing.

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**Non-Technical Summary**
Correlations of turbidites over great distances along the Cascadia margin have demonstrated earthquake origin for many of them in the last 10,000 years. Flume experiments suggest that long-distance correlation using physical property “fingerprints”
may be possible because the turbidites record details of the earthquake that triggered them.