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Rethinking turbidite paleoseismology along the Cascadia subduction zone

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ABSTRACT

A stratigraphic synthesis of dozens of deep-sea cores, most of them overlooked in recent decades, provides new insights into deep-sea turbidites as guides to earthquake and tsunami hazards along the Cascadia subduction zone, which extends 1100 km along the Pacific coast of North America. The synthesis shows greater variability in Holocene stratigraphy and facies off the Washington coast than was recognized a quarter century ago in a confluence test for seismic triggering of sediment gravity flows. That test compared counts of Holocene turbidites upstream and downstream of a deep-sea channel junction. Similarity in the turbidite counts among seven core sites provided evidence that turbidity currents from different submarine canyons usually reached the junction around the same time, as expected of widespread seismic triggering. The fuller synthesis, however, shows distinct differences between tributaries, and these differences suggest sediment routing for which the confluence test was not designed. The synthesis also bears on recent estimates of Cascadia earthquake magnitudes and recurrence intervals. The magnitude estimates hinge on stratigraphic correlations that discount variability in turbidite facies. The recurrence estimates require turbidites to represent megathrust earthquakes more dependably than they do along a flow path where turbidite frequency appears limited less by seismic shaking than by sediment supply. These concerns underscore the complexity of extracting earthquake history from deep-sea turbidites at Cascadia.

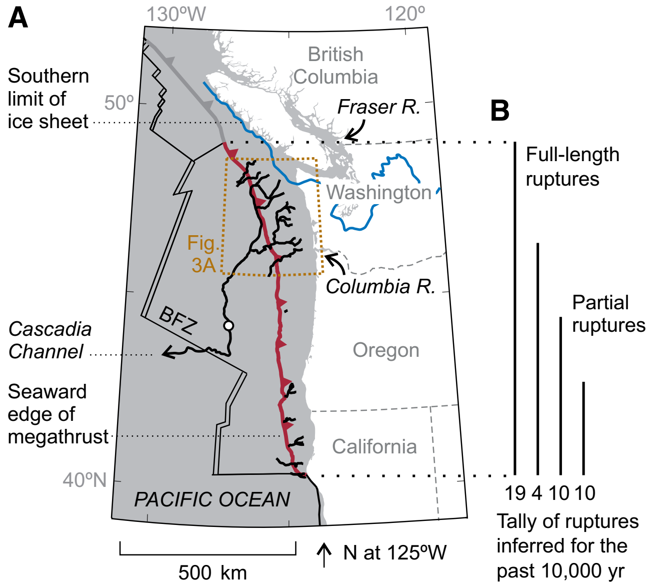

Figure 1. A: Index map. Submarine canyons and channels are in black. Dot along Cascadia Channel locates core sites 6609-24 and M9907-22, M9907-23, and M9907-25. BFZ—Blanco Fracture Zone; R.—river. B: Summary of earthquake history postulated by Goldfinger et al. (2012).

INTRODUCTION

Twenty-first century earthquakes are projected to take millions of lives (Holzer and Savage, 2013). Efforts to reduce the losses employ estimates of earthquake sizes and recurrence intervals. Paleoseismology has improved such estimates by extending earthquake histories thousands of years into the past.

Turbidite paleoseismology is based on observations that earthquakes are among the triggers for sediment gravity flows that evolve downslope into turbidity currents, and that shaking may cause slopes to fail in the same few minutes at sites widely separated along fault strike, a coincidence not expected of other potential triggering mechanisms (Talling, 2014). If turbidites indicative of earthquakes can be positively identified and correlated, their geographic extent would provide a measure of earthquake size, and their repetition would represent earthquake recurrence intervals. Settings shown to be conducive to turbidite paleoseismology include lakes in Switzerland and Chile (Strasser et al., 2013; Moernaut et al., 2014). Less favorable settings include parts of the continental slope off Sumatra, where great earthquakes rarely trigger turbidity currents (Sumner et al., 2013).

Interpretations of deep-sea turbidites are guiding hazard assessment at the Cascadia subduction zone, which extends 1100 km along the North American Pacific coast (Fig. 1). The study of turbidite paleoseismology began there with a confluence test for seismic triggering of turbidity currents (Fig. 2A). Holocene sequences of deep-sea turbidites were found to be similar above and below a confluence of deep-sea channels, and this similarity was ascribed to abyssal merger of turbidity currents that had been triggered simultaneously in different submarine canyons (Adams, 1990). Today, deep-sea turbidites provide the main basis for a proposed 10,000 yr Cascadia history that specifies 19 full-length ruptures and a similar number of shorter southern ruptures (Goldfinger et al., 2012) (Fig. 1B). This inferred history underpins tsunami scenarios (Priest et al., 2010), fault-energy budgets (Goldfinger et al., 2013b), and giant earthquake probabilities (Kulkarni et al., 2013).

In this paper, we reappraise deep-sea turbidites as guides to Cascadia earthquake hazards. We bring together data from legacy cores off the Washington coast that previous paleoseismological studies overlooked. We draw on physiography, stratigraphy, and sedimentology in disputing the confluence test and in questioning the turbidite basis for influential estimates of earthquake size and recurrence.

PHYSIOGRAPHY

Cascadia's largest network of deep-sea channels originates in submarine canyons that notch Washington's continental shelf (Figs. 1–3[1]). The upper canyons debouch onto a lower continental slope ribbed with Pleistocene anticlines (Adam et al., 2004). The northern thalwegs from Nitinat, Juan de Fuca, and Quillayute Canyons drain into Juan de Fuca Channel, which heads at the apex of Nitinat Fan and descends its eastern edge (Fig. 3A). Southern thalwegs emanating from Quinault, Grays, and Willapa Canyons merge on the lower slope. Their shared outlet reaches an abyssal confluence with Juan de Fuca Channel at the head of Cascadia Channel, which drains southward between Nitinat and Astoria Fans and continues westward through the Blanco Fracture Zone. The network is

[1]Figure 3 is provided as an oversize insert.

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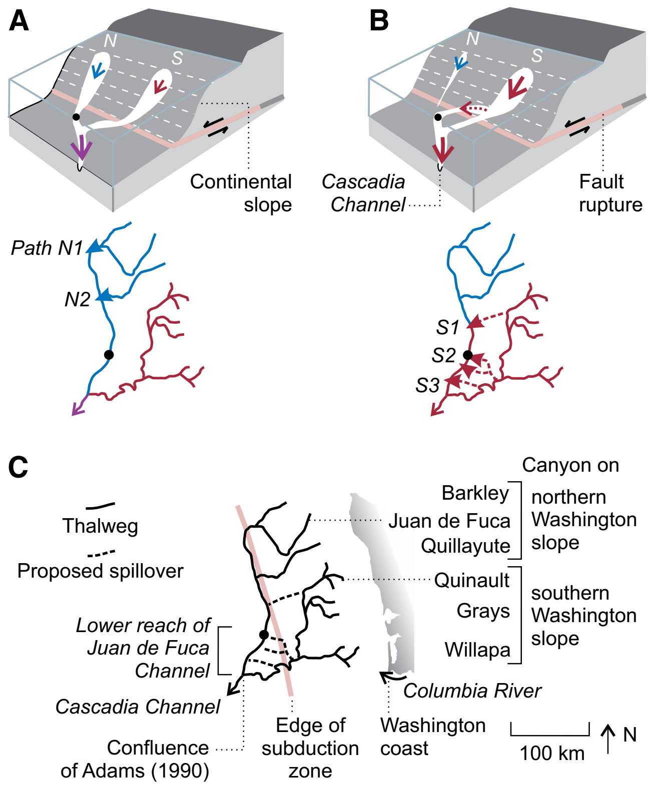

Figure 2. Contrasting views of turbidity current paths from tributaries to Cascadia Channel that originate on northern (N) and southern (S) Washington continental slope. Black dot denotes core sites M9907-11, M9907-12, 29-28, and 6705-2. A: Flows initiated at the same time either merge or closely follow one another below a single confluence at the head of Cascadia Channel. Turbidites cored along lower Juan de Fuca Channel are monitors of shaking off northern Washington (Adams, 1990, p. 574; Goldfinger et al., 2012, p. 87–88). B: Flows initiated off southern Washington predominate, and reach lower Juan de Fuca Channel by way of spillovers (dashed paths S1, S2, and S3). Shaking off northern Washington produces few if any turbidity currents in lower Juan de Fuca Channel or in Cascadia Channel. C: Skeletal index map.

a palimpsest, shaped during Pleistocene glaciations and selectively overwritten in the Holocene (Barnard, 1978, p. 110).

Turbidity currents were not always confined to the network's thalwegs. Spillover paths to lower Juan de Fuca Channel are marked by abyssal plunge pools and sediment waves west of the Columbia River (Fig. 3A), a source of Pleistocene hyperpycnal flows (Normark and Reid, 2003). An upper reach of Cascadia Channel transmitted Holocene flows that overtopped its banks (Griggs and Kulm, 1970).

STRATIGRAPHY

Data Sources and Syntheses

Cascadia turbidite paleoseismology has roots in sedimentological studies that were unconcerned with earthquakes. Three of these studies defined deep-sea stratigraphy off the Washington coast, in the south near the head of Cascadia Channel (Griggs, 1969), in the north on upper Nitinat Fan (Carson, 1971), and along the continental slope (Barnard, 1973). We draw on this coverage more fully than did Adams (1990) and Goldfinger et al. (2012), who used data from one-quarter of the legacy cores in Figure 3 and overlooked the legacy cores off northern Washington.

Supporting information for Figure 3 includes an extended explanation (Table DR1 in the GSA Data Repository[2]), a core list (Table DR2), volcanic-ash data (Table DR3), notes on inferred flow paths (Table DR4), and logs of cores on Nitinat Fan and the Washington slope (Figs. DR1 and DR2). An index map to cores keys them by source (Fig. DR3). Figure DR4, showing plunge pools west of Willapa Bay, includes EM 122 multibeam bathymetry and acoustic backscatter data derived from Holbrook et al. (2012). Figure DR5 schematically relates findings in Figure 3 to the confluence test of Adams (1990).

North-South Stratigraphic Contrasts

Holocene stratigraphy off Washington differs between north and south, both on the continental slope and on the adjacent abyssal plain. The differences involve numbers of successive turbidites and abundance of reworked Mazama ash. Erupted sometime between 7500 and 7800 yr ago, Mazama ash was delivered to the sea by the Columbia River (Peterson et al., 2012) and to the deep sea by turbidity currents (Nelson et al., 1968). Offshore, the ash serves as a tracer of Columbia River sediment (Fig. 3D), and its lowest stratigraphic occurrence provides a widely used stratigraphic datum (Figs. 3A, 3B).

Off northern Washington, post-Mazama turbidites are few and volcanic ash contents are low (Figs. 3A, 3D). Core logs and supporting analyses (Carson, 1971; Barnard, 1973; Goldfinger et al., 2012) are available for 11 sites within or near Juan de Fuca Canyon and upper Nitinat Fan: 63-18, 63-19, 63-20, 39-8, 39-9, 29-23, 39-26, 39-27, M9907-5, 29-25, and 39-7. The cores at all these sites show six or fewer post-Mazama turbidites. At M9907-5, where the likely number is between 3 and 6, Goldfinger et al. (2012, p. 42–43) counted 13 by positing, implausibly, that turbidites high in the piston core overlie the uppermost turbidites of the associated gravity core (details in Table DR4, path N1). No reported ash content exceeds 10% at any of the 11 sites. Only from site 63-17, between Quillayute and Quinault Canyons, did a sample from the northern Washington slope yield an ash content of 10%–35%.

Off southern Washington, post-Mazama turbidites are comparatively numerous, and reworked Mazama ash is widely abundant. These characteristics prevail on the slope west and south of Quinault Canyon, and along channels on the adjoining abyssal plain: the lower reaches of Juan de Fuca Channel, the nearby outlet from southern canyons, and Cascadia Channel (Fig. 3). Some of the sequences contain a dozen or more post-Mazama turbidites (yellow numerals, Fig. 3A), and in many sequences the maximum volcanic ash contents exceed 35% (Figs. 3A and 3B; individual analyses from five slope cores, Fig. 3D). Superimposed on these shared properties is pronounced variability in turbidite thickness, grain size, and bedding, and in the thickness of intervening hemipelagic clay, near the head of Cascadia Channel (Fig. 3C).

SEDIMENTOLOGY

Sediment Supply to Submarine Canyons

These north-south contrasts in deep-sea stratigraphy parallel trends in Holocene sediment supply on the Washington continental shelf. In the north, the Holocene transgression isolated Juan de Fuca Canyon from sediment of the Fraser River (Williams and Roberts, 1989). Reworking of glacial drift on the ocean floor accounts for much of the Holocene deposition in the Strait of Juan de Fuca and on the adjoining continental shelf (Herzer and Bornhold, 1982; Hewitt and Mosher, 2001). From the south, by contrast, Columbia River detritus has produced a mid-shelf silt of Holocene age that exceeds 20 m in thickness west of Willapa Bay and thins to the northwest (Fig. 3A). Upper reaches of Willapa and Quinault Canyons indent this mid-shelf silt (Nittrouer et al., 1979; Wolf et al.,

[2]GSA Data Repository item 2014286, Tables DR1–DR4 and Figures DR1–DR5, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

1999), and Quinault Canyon is known to receive modern shelf sediment during storms (Carson et al., 1986).

Flow Paths to the Lower Juan de Fuca Channel

These congruent patterns in turbidite stratigraphy and sediment supply cast doubt on a longstanding assumption about the provenance of Holocene turbidites in lower Juan de Fuca Channel, on the abyssal plain off southern Washington (location in Fig. 2C). Adams (1990) and Goldfinger et al. (2012) assumed that these turbidites represent flows that originated in canyons off northern Washington (paths N1 and N2; Fig. 2A; Table DR4). This routing requires flows that deposited few turbidites and little Mazama ash on upper Nitinat Fan to have produced numerous turbidites and abundant Mazama ash farther downstream (Fig. 3A).

It is unlikely that numerous flows from northern canyons would have bypassed all core sites off northern Washington. Juan de Fuca Canyon is lined with dozens of slumps (Carson and McManus, 1969) that subsequent Holocene flows have not removed. In contrast, on the southern Washington slope, erosive flows are evidenced by a scarcity of slumps and by the presence of unconformities in canyon thalwegs (at 53-19, M9907-13, and 63-08), and these features coexist with Holocene turbidites about as numerous and ash-rich as those in lower Juan de Fuca Channel (Figs. 3A and 3B).

We therefore propose that Holocene flows from canyons off the southern Washington slope spilled into lower Juan de Fuca Channel (Fig. 2B, paths S1–S3). The most important of the proposed paths would enable flows from upper Quinault Canyon to reach the abyssal plain as far north as site 48-8, the northernmost known occurrence of numerous ash-rich turbidites in Juan de Fuca Channel. This path, S1, is evidenced by stratigraphy and appears consistent with heavy-mineral assemblages.

Holocene flows using path S1 are evidenced by 8 post-Mazama turbidites and abundant ash at 53-14, on the lower slope midway between upper Quinault Canyon and Juan de Fuca Channel. To account for these turbidites, westward discharge from the upper canyon would continue directly across an outside bend at the canyon outlet and would rise ~200 m from there to pass through a saddle in an anticlinal ridge (Fig. 3A). The upper portions of turbidity currents are known to diverge from canyons or channels at outside bends (Piper and Normark, 1983). Off California, split flows have exited Monterey Canyon 150 m above its floor more than 12 times in the past 3000 yr (Fildani et al., 2006), and flows have overtopped a wall 280 m high at an outside bend of Eel Canyon (Lamb et al., 2008).

Holocene turbidite sand of lower Juan de Fuca Channel contains heavy-mineral assemblages consistent with sources on upper Nitinat Fan or Vancouver Island (Goldfinger et al., 2013a). However, such assemblages are also known from volcanic rocks of the Olympic Mountains (Carson, 1971, p. 81) and from surficial sand on the inner shelf north of Grays Harbor (Venkatarathnam and McManus, 1973). Furthermore, assemblages derived from Vancouver Island may be available for reworking, both along path S1 in Pleistocene turbidites derived from the Cordilleran ice sheet and along lower Juan de Fuca Channel in slide debris (Fig. 3A; Fig. DR4).

Turbidite Facies and Fine-Scale Correlation

Facies variations impede stratigraphic correlation among cores near the head of Cascadia Channel (Fig. 3C). The uniformly thin, sand-poor turbidites in Juan de Fuca Channel at site 6705-2 contrast with the thick, sandy turbidites along the southern thalweg at 6705-4 and 6705-5. The core sites nearest the head of Cascadia Channel, 6705-6 and 6508-K1, show elements of both.

It has been proposed that sandy units several centimeters thick correlate among cores taken hundreds of kilometers apart in mostly unconnected channels and basins along the Cascadia subduction zone (Goldfinger et al., 2012). In Pleistocene deposits, turbidite correlations this fine have been made along a North Atlantic levee (Hesse, 1995), but are statistically precluded by variable facies on Nitinat Fan (Carson and McManus, 1971). Facies variability also impedes fine correlations among Holocene turbidites near the head of Cascadia Channel (Fig. 3C) and between lower Juan de Fuca Channel and lower Cascadia Channel (Atwater and Griggs, 2012, their figure 5).

PALEOSEISMOLOGY

Confluence Test

The confluence test of Adams (1990) asks whether turbidity currents off Washington were triggered regionally by earthquakes or locally by other means (Fig. 2A; Fig. DR5A). The regional earthquake hypothesis fails if the numbers of post-Mazama turbidites differ greatly among thalweg sites above and below the head of Cascadia Channel. In the test design, flows from northern canyons aggrade lower Juan de Fuca Channel sites 6705-2 and 6705-6; flows from southern canyons register on the slope at 53-18 and downstream at 6705-5; and flows from both north and south reach the confluence site 6508-K1 and are capable of reaching Cascadia Channel sites 6509-15 and 6609-24 (Figs. 1A, 3A, and 3B). Citing similarities in turbidite counts among these 7 sites, Adams (1990) concluded that each of 13 post-Mazama earthquakes shook the entire region, north and south.

The previously overlooked cores off northern Washington confound this venerable result (Fig. 2B; Fig. DR5B). Regional seismic triggering fails a rerun confluence test in which post-Mazama turbidites are few off northern Washington (range of 0–6) but numerous off southern Washington (range of 8–14; Fig. 3). The test design also fails if Holocene flows from northern canyons rarely reached lower Juan de Fuca Channel.

Earthquake Size

Geologic dating usually lacks the time resolution to show whether a long fault broke as a whole during the seconds or minutes of a single earthquake, or whether it ruptured piecemeal in a series of lesser earthquakes distributed across days, years, or even decades (Nelson et al., 1995). The 10,000 yr earthquake history proposed by Goldfinger et al. (2012) seemingly overcomes this ambiguity, because it includes 19 full-length ruptures but no instance of serial rupture (Fig. 1B). This inference of long ruptures hinges, however, on centimeter-scale turbidite-bed correlations in which each correlated bed represents a pulse of seismic shaking that was felt during the same few minutes along hundreds of kilometers of the subduction zone (Goldfinger et al., 2012, p. 135–136). Correlation this exact does not accord with the variable turbidite facies noted above, and it would not be expected of earthquake motions that vary along fault strike, of slope failures that lag the shaking, or of tributaries of unequal length that issue flows at different times (Atwater and Griggs, 2012, p. 13–17).

As interpreted by Goldfinger et al. (2012), Holocene turbidites of the lower Juan de Fuca Channel help define rupture length by representing megathrust rupture off northern Washington. If, however, these turbidites reflect spillover from canyons off southern Washington, they do not reliably show whether the fault broke north of those canyons.

Earthquake Recurrence

Submarine mass movements need not correspond dependably with earthquakes (Völker et al., 2011; Goldfinger et al., 2012, p. 138; Sumner et al., 2013). Off northern Washington, Holocene turbidites from Juan de Fuca Canyon compare to less than one-third of the 19 Holocene ruptures posited to have extended beneath it (Figs. 1B and 3A). Conversely, off southern Oregon, turbidites outnumber megathrust earthquakes at a locality where the region's most recent megathrust earthquake (A.D. 1700) predates three turbidites of unknown cause (Goldfinger et al., 2013c, p. 2141).

In the earthquake history of Goldfinger et al. (2012), the Cascadia plate boundary breaks twice as often off northern California and southern Oregon as off Washington and British Columbia (Fig. 1B). This estimate requires one-to-one correspondence of turbidites and earthquakes off Oregon and Washington (Goldfinger et al., 2012, p. 92, 112), in contrast with the likely turbidite deficit off northern Washington and the observed surplus off southern Oregon.

CONCLUSIONS

Holocene turbidity currents have partly overwritten a Pleistocene channel network off Washington. The resulting turbidite stratigraphy reflects latitudinal differences in Holocene sediment supply to canyon heads and probable Holocene spillover from canyons on the southern Washington slope. The stratigraphy has provided important estimates of earthquake magnitudes and recurrence intervals, but these estimates hinge on simplifying assumptions about flow paths, stratigraphic correlation, and record completeness. The way forward requires renewed attention to sediment supply, flow initiation, downstream pathways, and uncertainty in turbidite correlations.

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REFERENCES CITED

Adam, J., Klaeschen, D., Kukowski, N., and Flueh, E., 2004, Upward delamination of Cascadia Basin sediment infill with landward frontal accretion thrusting caused by rapid glacial age material flux: Tectonics, v. 23, TC3009, doi:10.1029/2002TC001475.

Adams, J., 1990, Paleoseismicity of the Cascadia subduction zone: Evidence from turbidites off the Oregon-Washington margin: Tectonics, v. 9, p. 569–583, doi:10.1029/TC009i004p00569.

Atwater, B.F., and Griggs, G.B., 2012, Deep-sea turbidites as guides to Holocene earthquake history at the Cascadia Subduction Zone—Alternative views for a seismic-hazard workshop: U.S. Geological Survey Open-File Report 2012-1043, 58 p., http://pubs.usgs.gov/of/2012/1043/.

Barnard, W.D., 1973, Late Cenozoic sedimentation on the Washington continental slope [Ph.D. thesis]: Seattle, University of Washington, 255 p.

Barnard, W.D., 1978, The Washington continental slope; Quaternary tectonics and sedimentation: Marine Geology, v. 27, p. 79–114, doi:10.1016/0025-3227(78)90075-0.

Carson, B., 1971, Stratigraphy and depositional history of Quaternary sediments in northern Cascadia Basin and Juan de Fuca Abyssal Plain, northeast Pacific Ocean [Ph.D. thesis]: Seattle, University of Washington, 249 p.

Carson, B., and McManus, D.A., 1969, Seismic reflection profiles across Juan de Fuca Canyon: Journal of Geophysical Research, v. 74, p. 1052–1060, doi:10.1029/JB074i004p01052.

Carson, B., and McManus, D.A., 1971, Analysis of turbidite correlation in Cascadia Basin, northeast Pacific Ocean: Deep Sea Research and Oceanographic Abstracts, v. 18, p. 593–604, doi:10.1016/0011-7471(71)90125-2.

Carson, B., Baker, E.T., Hickey, B.M., Nittrouer, C.A., DeMaster, D.J., Thorbjarnarson, K.W., and Snyder, G.W., 1986, Modern sediment dispersal and accumulation in Quinault submarine canyon—A summary: Marine Geology, v. 71, p. 1–13, doi:10.1016/0025-3227(86)90030-7.

Fildani, A., Normark, W.R., Kostic, S., and Parker, G., 2006, Channel formation by flow stripping; large-scale scour features along the Monterey East Channel and their relation to sediment waves: Sedimentology, v. 53, p. 1265–1287, doi:10.1111/j.1365-3091.2006.00812.x.

Goldfinger, C., et al., 2012, Turbidite event history—Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone: U.S. Geological Survey Professional Paper 1661-F, 170 p., http://pubs.usgs.gov/pp/pp1661f/.

Goldfinger, C., Beeson, J.W., Nelson, H., Patton, J.R., Morey, A.E., and Galer, S., 2013a, Cascadia seismoturbidites: A landlubber critiqued: American Geophysical Union 2013 Fall Meeting, abs. S21C–2420.

Goldfinger, C., Ikeda, Y., Yeats, R.S., and Ren, J., 2013b, Superquakes and supercycles: Seismological Research Letters, v. 84, p. 24–32, doi:10.1785/0220110135.

Goldfinger, C., Morey, A.E., Black, B., Beeson, J., Nelson, C.H., and Patton, J., 2013c, Spatially limited mud turbidites on the Cascadia margin: Segmented earthquake ruptures?: Natural Hazards and Earth System Sciences, v. 13, p. 2109–2146, doi:10.5194/nhess-13-2109-2013.

Griggs, G.B., 1969, Cascadia Channel: The anatomy of a deep-sea channel [Ph.D. thesis]: Corvallis, Oregon State University, 183 p.

Griggs, G.B., and Kulm, L.D., 1970, Sedimentation in Cascadia deep-sea channel: Geological Society of America Bulletin, v. 81, p. 1361–1384, doi:10.1130/0016-7606(1970)81[1361:SICDC]2.0.CO;2.

Herzer, R.H., and Bornhold, B.D., 1982, Glaciation and post-glacial history of the continental shelf off southwestern Vancouver Island, British Columbia: Marine Geology, v. 48, p. 285–319, doi:10.1016/0025-3227(82)90101-3.

Hesse, R., 1995, Long-distance correlation of spillover turbidites on the western levee of the Northwest Atlantic Mid-Ocean Channel (NAMOC), Labrador Sea, *in* Pickering, K.T., et al., eds., Atlas of deep water environments: Architectural style in turbidite systems: London, Chapman and Hall, p. 276–281.

Hewitt, A.T., and Mosher, D.C., 2001, Late Quaternary stratigraphy and seafloor geology of eastern Juan de Fuca Strait, British Columbia and Washington: Marine Geology, v. 177, p. 295–316, doi:10.1016/S0025-3227(01)00160-8.

Holbrook, W.S., Kent, G., Keranen, K., Johnson, P., Trehu, A., Tobin, H., Caplan-Auerbach, J., and Beeson, J., 2012, Cascadia fore arc seismic survey: Open-access data available: Eos (Transactions, American Geophysical Union), v. 93, p. 521–522, doi:10.1029/2012EO500002.

Holzer, T.L., and Savage, J.C., 2013, Global earthquake fatalities and population: Earthquake Spectra, v. 29, p. 155–175, doi:10.1193/1.4000106.

Kulkarni, R., Wong, I., Zachariasen, J., Goldfinger, C., and Lawrence, M., 2013, Statistical analyses of great earthquake recurrence along the Cascadia subduction zone: Seismological Society of America Bulletin, v. 103, p. 3205–3221, doi:10.1785/0120120105.

Lamb, M.P., Parsons, J.D., Mullenbach, B.L., Finlayson, D.P., Orange, D.L., and Nittrouer, C.A., 2008, Evidence for superelevation, channel incision, and formation of cyclic steps by turbidity currents in Eel Canyon, California: Geological Society of America Bulletin, v. 120, p. 463–475, doi:10.1130/B26184.1.

Moernaut, J., Van Daele, M., Heirman, K., Fontijn, K., Strasser, M., Pino, M., Urrutia, R., and De Batist, M., 2014, Lacustrine turbidites as a tool for quantitative earthquake reconstruction: New evidence for a variable rupture mode in south-central Chile: Journal of Geophysical Research, v. 119, p. 1607–1633, doi:10.1002/2013JB010738.

Nelson, A.R., et al., 1995, Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone: Nature, v. 378, p. 371–374, doi:10.1038/378371a0.

Nelson, C.H., Kulm, L.D., Carlson, P.R., and Duncan, J.R., 1968, Mazama ash in the northeastern Pacific: Science, v. 161, no. 3836, p. 47–49, doi:10.1126/science.161.3836.47.

Nittrouer, C.A., Sternberg, R.W., Carpenter, R., and Bennett, J.T., 1979, The use of Pb-210 geochronology as a sedimentological tool: Application to the Washington continental shelf: Marine Geology, v. 31, p. 297–316, doi:10.1016/0025-3227(79)90039-2.

Normark, W.R., and Reid, J.A., 2003, Extensive deposits on the Pacific plate from late Pleistocene North American glacial lake outbursts: Journal of Geology, v. 111, p. 617–637, doi:10.1086/378334.

Peterson, C., Minor, R., Gates, E.B., Vanderburgh, S., and Carlisle, K., 2012, Correlation of tephra marker beds in latest Pleistocene and Holocene fill of the submerged lower Columbia River valley, Washington and Oregon, U.S.A.: Journal of Coastal Research, v. 28, p. 1362–1380, doi:10.2112/JCOASTRES-D-11-00181.1.

Piper, D.J., and Normark, W.R., 1983, Turbidite depositional patterns and flow characteristics, Navy Submarine Fan, California borderland: Sedimentology, v. 30, p. 681–694, doi:10.1111/j.1365-3091.1983.tb00702.x.

Priest, G.R., Goldfinger, C., Wang, K., Witter, R.C., Zhang, Y., and Baptista, A.M., 2010, Confidence levels for tsunami-inundation limits in northern Oregon inferred from a 10,000-year history of great earthquakes at the Cascadia subduction zone: Natural Hazards, v. 54, p. 27–73, doi:10.1007/s11069-009-9453-5.

Strasser, M., Monecke, K., Schnellmann, M., and Anselmetti, F.S., 2013, Lake sediments as natural seismographs: A compiled record of late Quaternary earthquakes in central Switzerland and its implication for Alpine deformation: Sedimentology, v. 60, p. 319–341, doi:10.1111/sed.12003.

Sumner, E.J., Siti, M.I., McNeill, L.C., Talling, P.J., Henstock, T.J., Wynn, R.B., Djajadihardja, Y.S., and Permana, H., 2013, Can turbidites be used to reconstruct a paleoearthquake record for the central Sumatran margin?: Geology, v. 41, p. 763–766, doi:10.1130/G34298.1.

Talling, P.J., 2014, On the triggers, resulting flow types and frequencies of subaqueous sediment density flows in different settings: Marine Geology, v. 352, p. 155–182, doi:10.1016/j.margeo.2014.02.006.

Venkatarathnam, K., and McManus, D.A., 1973, Origin and distribution of sands and gravels on northern continental-shelf off Washington: Journal of Sedimentary Petrology, v. 43, p. 799–811.

Völker, D., Scholz, F., and Geersen, J., 2011, Analysis of submarine landsliding in the rupture area of the 27 February 2010 Maule earthquake, central Chile: Marine Geology, v. 288, p. 79–89, doi:10.1016/j.margeo.2011.08.003.

Williams, H.F.L., and Roberts, M.C., 1989, Holocene sea-level change and delta growth: Fraser River delta, British Columbia: Canadian Journal of Earth Sciences, v. 26, p. 1657–1666, doi:10.1139/e89-142.

Wolf, S.C., Nelson, H., Hamer, M.R., Dunhill, G., and Phillips, L.R., 1999, The Washington and Oregon mid-shelf silt deposit and its relation to the late Holocene Columbia River sediment budget: U.S. Geological Survey Open-File Report 99-173, pubs.er.usgs.gov/publication/ofr99173.

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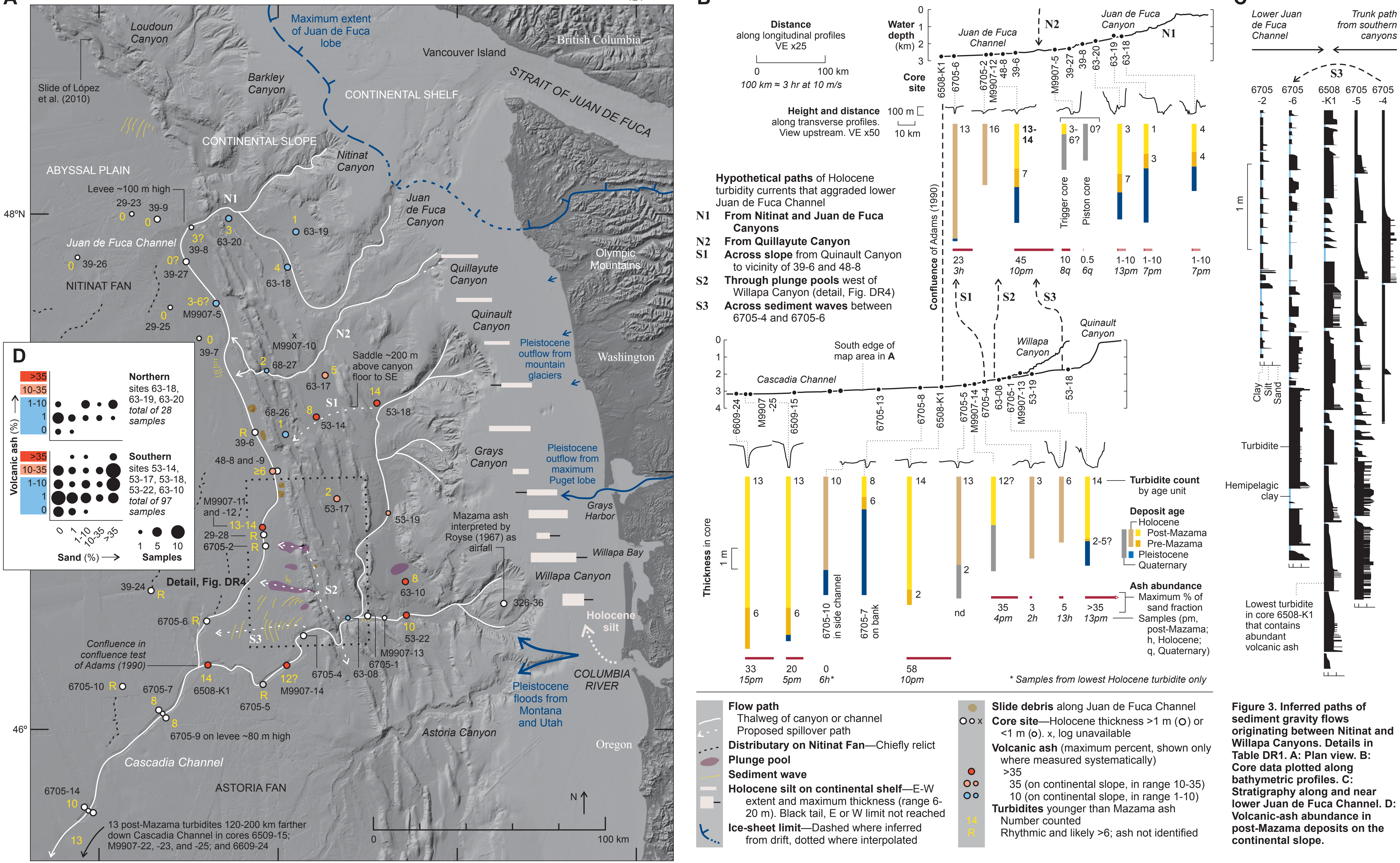

Figure 3. Inferred paths of sediment gravity flows originating between Nitinat and Willapa Canyons. Details in Table DR1. A: Plan view. B: Core data plotted along bathymetric profiles. C: Stratigraphy along and near lower Juan de Fuca Channel. D: Volcanic-ash abundance in post-Mazama deposits on the continental slope.