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3. North-South Variability in the History of Deformation and Fluid Venting across Hydrate Ridge, Cascadia Margin[1]

Joel E. Johnson,[2,3] Chris Goldfinger,[3] Anne M. Tréhu,[3]
Nathan L.B. Bangs,[4] Marta E. Torres,[3] and Johanna Chevallier[3]

ABSTRACT

Hydrate Ridge is an accretionary thrust ridge located on the lower slope of the central Cascadia convergent margin. Structural mapping based on two-dimensional and three-dimensional multichannel seismic reflection profiles and gridded bathymetry coupled with deep-towed sidescan sonar data and Ocean Drilling Program (ODP) biostratigraphy suggests that seafloor fluid venting patterns are likely controlled by the seaward-vergent (SV) structural style at northern Hydrate Ridge (NHR) and by the dominantly landward-vergent (LV) structural style at southern Hydrate Ridge (SHR). North-south structural variability across Hydrate Ridge is coincident with the seafloor authigenic carbonate distribution, which varies from aerially extensive authigenic carbonate crusts at NHR to a minor focused occurrence of authigenic carbonate at SHR. The older stratigraphy exposed at the seafloor at NHR (>1.6–1.7 Ma) has likely been subjected to a longer history of sediment compaction, dewatering, and deformation than the younger slope basin strata preserved at SHR (1.7 Ma to recent), suggesting the extent of carbonates at NHR may result from a longer history of fluid flow and/or more intense venting through a more uplifted, lithified, and fractured NHR sequence. Furthermore, recent work at SHR shows that the major seafloor fluid venting site there is fed by fluid flow through a volcanic ash–bearing turbidite sequence, suggesting stratigraphic conduits for fluid flow may be important in less uplifted, LV-dominated portions of Hydrate

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[2]Present address: University of New Hampshire, Department of Earth Sciences, 56 College Road, James Hall, Durham NH 03824, USA. joel.johnson@unh.edu
[3]College of Oceanic and Atmospheric Science, Oregon State University, Corvallis OR 97331, USA.
[4]University of Texas, Institute for Geophysics, 4412 Spicewood Springs Road, Austin TX 78759, USA.

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Ridge. In addition, the variability in structural style observed at Hydrate Ridge may have implications for the distributions and concentrations of fluids and gas hydrates in other accretionary settings and play a role in the susceptibility of accretionary ridges to slope failure.

INTRODUCTION

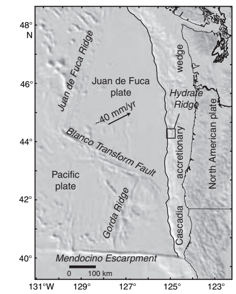
On the Cascadia continental margin offshore central Oregon, Hydrate Ridge (Figs. **F1, F2**) has been the focus of numerous geologic and geophysical investigations for nearly two decades. During the mid-1980s, its location within the lower slope of the accretionary wedge initially prompted investigations of seafloor fluid flow and the dewatering processes associated with accretionary wedge deformation and development and resulted in one of the first discoveries of chemosynthetic biological communities (Suess et al., 1985; Kulm et al., 1986; Ritger et al., 1987). By the early 1990s this early work was supplemented by Ocean Drilling Program (ODP) drilling (Fig. **F2;** Sites 891 and 892), during which gas hydrates were first recovered (Westbrook, Carson, Musgrave, et al., 1994), and detailed structural investigation (MacKay et al., 1992; Goldfinger et al., 1992, 1996). Subsequent work, including numerous sea-floor observation and sampling expeditions since the late 1990s (e.g., Suess et al., 1999, 2001) and more recently a gas hydrate–dedicated ODP leg (Tréhu, Bohrmann, Rack, Torres, et al., 2003; and **Tréhu et al.,** this volume) (Fig. **F2;** Sites 1244–1252), focused on the surface and shallow subsurface gas hydrate system, seeking to characterize the distribution, concentration, and behavior of gas hydrates in an active margin setting.

In this paper we integrate our recent work on

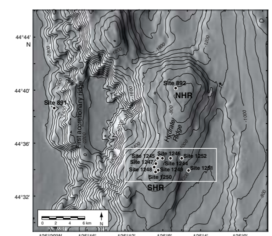
1. The history of deformation, constrained by structures interpreted from seismic reflection data and core biostratigraphy;
2. The record of fluid venting, as imaged on sidescan sonar data;
3. The surface and subsurface gas hydrate distribution, constrained by seafloor observations and ODP coring; and
4. Records of slope failure, interpreted from piston cores and ODP cores in the Hydrate Ridge region.

Together, these data suggest that variability in structural style may strongly influence the distribution and concentration of fluids and gas hydrates in the subsurface and the susceptibility of accretionary ridges to slope failure.

F1. Cascadia margin bathymetry and topography, p. 12.



F2. Hydrate Ridge bathymetry and locations of ODP drill sites, p. 13.

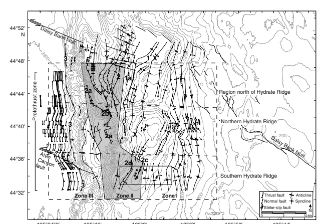


GEOLOGIC SETTING

The Cascadia accretionary wedge evolved in response to the oblique subduction of the Juan de Fuca–Gorda plate system (Fig. **F1**) and is composed of folded and faulted abyssal plain turbidites and hemipelagic clays as well as the recycled products of these uplifted sediments as slope basin fills (Kulm and Fowler, 1974; Westbrook, Carson, Musgrave, et al., 1994; Tréhu, Bohrmann, Rack, Torres et al., 2003). The Quaternary portion of the accretionary wedge is widest off the Washington and northern Oregon margins, coincident with accretion of the thick Pleistocene Astoria and Nitinat Fans (Carlson and Nelson, 1987), and narrows to the south. The active accretionary thrust faults and folds of the lower slope are characterized by mostly landward-vergent (LV) thrusts on the Washington and northern Oregon margins and seaward-vergent (SV) thrusts on the central and southern Oregon margin (Seely, 1977; MacKay et al., 1992; Goldfinger et al., 1992, 1997; MacKay, 1995). Virtually all of the incoming section in the LV province is accreted to the margin above a deep décollement, whereas a shallower décollement in the SV portion of the margin results in accretion of the upper two-thirds of the incoming stratigraphic section and subduction and/or underplating of the lower one-third (MacKay et al., 1992). In addition to the SV and LV thrust faults and folds that comprise the Cascadia accretionary wedge, nine west-northwest-striking left-lateral strike-slip faults also cut across the lower slope of the wedge (Goldfinger et al., 1997). These faults form as antithetic Riedel shears (R′) in the lower plate as a result of dextral shear of the forearc during oblique subduction and propagate upward into the accretionary wedge through time. The outermost accretionary wedge abuts a steep slope break that separates it from the Eocene oceanic basalt Siletz Terrane that underlies the continental shelf off the central Oregon to southern Washington margins (Snavely, 1987; Tréhu et al., 1994). Above this oceanic basement terrane is a moderately deformed Eocene through Holocene forearc basin sequence (Snavely, 1987; McNeill et al., 2000).

In the central Oregon portion of the margin discussed here (the Hydrate Ridge region), a transition zone exists between the northern LV province and the southern SV province, yielding a narrow zone of mixed vergence, both along and across strike, which is coincident with the location of two of the nine left-lateral strike-slip faults (Goldfinger et al., 1996; Johnson, 2004) (Fig. F3). Structurally, Hydrate Ridge is a composite thrust ridge, formed from both SV and LV structures (discussed below). The morphologic expression of Hydrate Ridge on the seafloor is asymmetric along its length; northern Hydrate Ridge (NHR) lies at a shallower water depth (~600 m) than southern Hydrate Ridge (SHR) (~800 m).

F3. Structure map of the Hydrate Ridge region, p. 14.

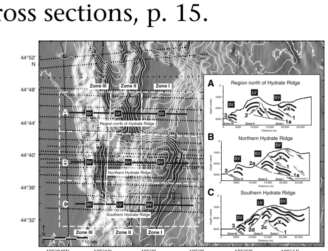


STRUCTURAL HISTORY

Mapping

Structural mapping (Goldfinger et al., 1992, 1996, 1997; MacKay et al., 1992; MacKay, 1995; Johnson, 2004) (Fig. F3) using multichannel seismic reflection profiles from an ODP site survey conducted in 1989 (seismic lines shown in Fig. F4) and insights from mapping within the three-dimensional (3-D) seismic survey on SHR (Tréhu, Bohrmann, Rack, Torres, et al., 2003; Chevallier, 2004) reveal the variability in structural styles across the Hydrate Ridge region (Fig. F3). Based on correlations between various structures and strata and their relative position in the wedge, the Hydrate Ridge region can be divided into three strike-parallel zones (I, II, and III) across the wedge from Hydrate Ridge to the deformation front (Fig. F3). A summary of the structural vergence variation and schematic cross sections along three dip transects (north of Hydrate Ridge, NHR, and SHR) are shown in Figure F4. Assuming a steady-state model of westward wedge growth through time, Zones I, II, and III also indicate the relative timing of major accretionary wedge growth (major deformation is oldest in Zone I and youngest in Zone III). However, because deformation on structures across the wedge has likely continued throughout the Pleistocene, we cannot as-

F4. Summary of the structural vergence variation and schematic cross sections, p. 15.



sume that deformation across these three zones is completely steady state. For this reason, we use the geometries and timing constraints (from ODP biostratigraphy) of the major faults and the common stratigraphic packages associated with each fault to infer the relative order of thrusting through time.

Age Constraints from Drilling

Using the biostratigraphic results from ODP drilling at Sites 891 (Shipboard Scientific Party, 1994a; Zellers, 1995), 892 (Fourtanier and Caulet, 1995), 1244 (Shipboard Scientific Party, 2003a), and 1245 (Shipboard Scientific Party, 2003b) (Fig. F2), we can constrain the timing of deformation in the Hydrate Ridge region. These sites were chosen because they lie within the three different structural zones: Site 891 in Zone III, Site 892 and 1244 in Zone I, and Site 1245 in Zone II (Figs. F2, F3). The sediments at both Sites 891 and 892 represent an uplifted and accreted abyssal plain section (Shipboard Scientific Party, 1994b, 1994c). At Site 1244, sediment cored beneath the slope cover was also accreted material of similar age (1.7–1.6 Ma) as Site 892 and thus is likely the equivalent facies. Given the above, the folding and thrusting of the accreted material at Sites 892 and 1244 (Zone I) most likely occurred after the deposition of the youngest abyssal plain deposits recovered at these sites. Based on comparison of the core biostratigraphies at these sites, the youngest age of the abyssal plain sediments at Sites 892 and 1244 is 1.7–1.6 Ma. Therefore, deformation of Zone I postdates 1.7–1.6 Ma. Currently, uplift and erosion of NHR has exposed this 1.7- to 1.6-Ma and older abyssal plain stratigraphic package at the seafloor, whereas at SHR less uplift resulted in the burial of the accreted abyssal plain sediments beneath younger overlying slope basin sediments (Tréhu, Bohrmann, Rack, Torres, et al., 2003). Because the age of the youngest sediments deformed by the frontal thrust in Zone III cannot be well determined at Site 891, we use the range of 0.30–0.25 Ma given by Westbrook (1994) for the timing of uplift of the first accretionary ridge (Fig. F2).

The above age relationships imply that because Zone I of Hydrate Ridge lies farther east in the accretionary wedge and contains older deformed sediments than the first accretionary ridge (Zone III), the difference in age of deformed sediments at Sites 892 and 1244 (Zone I) and the timing of uplift of the first accretionary ridge at Site 891 (Zone III) can be used to determine the maximum time between accretion of Zones I and III. Thus, Zone I was incorporated into the wedge sometime after the early Pleistocene (1.7–1.6 Ma). Assuming steady-state growth of the wedge, the major period of uplift of Zone I was likely completed by the late Pleistocene (0.30–0.25 Ma), the earliest age of the first accretionary ridge uplift (Zone III deformation). Because the wedge normally builds westward with continued accretion, the uplift of the first accretionary ridge at the deformation front initiates a time when shortening, previously taken up on structures to the east, was beginning to be accommodated on the first accretionary ridge frontal thrust. For this reason, we suggest that most of the uplift of Hydrate Ridge (Zone I deformation) was completed by the time ridge one or Zone III deformation was initiated.

The above age constraints imply that the major period of uplift and SV slip along Zone I structures in the NHR and SHR regions occurred sometime after the early Pleistocene (1.7–1.6 Ma) and was mostly completed by the late Pleistocene (0.3–0.25 Ma). Because of the position of

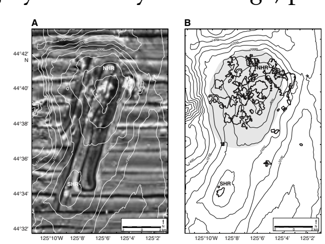
Zone II deformation within the wedge (between Zones I and III), the timing of Zone II accretion into the wedge (LV in the region north of Hydrate Ridge and at SHR and SV at NHR), must have occurred sometime within this same time window (1.7–1.6 to 0.3–0.25 Ma). Through sequential unfolding of biostratigraphically constrained horizons at Site 1245, Chevallier (2004) suggests that initiation of the most eastward LV fold within Zone II began at 1.2 Ma and was completed by 0.3 Ma. Johnson (2004) suggests that this period of LV at SHR was coincident with the period of LV in the region north of Hydrate Ridge and SV at NHR, as all three regions appear to lie within the same location along strike within the wedge (the Zone II region). With steady-state growth of the wedge, this implies that Zone II deformation throughout the region most likely occurred between 1.2 and 0.3 Ma.

These results suggest that the wedge in this region generally advanced westward in a series of three structural phases since the late Pliocene–early Pleistocene (1.7–1.6 Ma): a SV phase (1.7–1.2 Ma), a dominantly LV phase (1.2–0.3 Ma), and a SV phase (0.3 Ma to recent). Superimposed on this structural vergence variation with time is the influence of left-lateral strike-slip faulting (not discussed here), which appears to have resulted in the clockwise rotation of structures during their accretion (Johnson, 2004).

DISTRIBUTION OF FLUID VENTING

Carson et al. (1994) reprocessed GLORIA sidescan sonar data (removing the effect of slope) to map the distribution of authigenic carbonates and gas hydrates in the Hydrate Ridge region. Their results suggest a nearly continuous distribution of diagenetic deposits at or near the seafloor surface across the western flank and southern summit of Hydrate Ridge. Recent higher resolution deep-towed data, groundtruthed with seafloor observations and sampling, are consistent with their early work and add additional coverage across all of Hydrate Ridge and the surrounding region (Johnson et al., 2003). On Hydrate Ridge, these new data show fluid venting manifestations at NHR are more extensive compared to those at SHR (Fig. F5). The observed north-south variability in the underlying structure and history of deformation of the ridge may explain this distribution.

F5. Deep-towed sidescan sonar imagery across Hydrate Ridge, p. 16.



Although the results from the structural mapping and ODP coring reveal the core of Hydrate Ridge (Zone I deformation) was likely accreted to the margin at the same time at both NHR and SHR, more uplift and erosion at NHR has resulted in the exposure of older stratigraphy (>1.7–1.6 Ma) at the seafloor. The existence of duplexed SV thrust faults beneath NHR (Fig. F4) has likely aided not only in its uplift but also in providing multiple deep fluid migration pathways to facilitate the massive fluid expulsion observed at the crest. NHR is also the only location in the Hydrate Ridge region that has undergone deformation through repeated SV wedge building events (Fig. F4). Duplexing is likely more prevalent in SV portions of the wedge in the Hydrate Ridge region than LV ones because the detachment for SV thrusts typically lies several hundred meters above the basement/cover contact (MacKay, 1995). In the SV case, a portion of the incoming abyssal plain section is allowed to be incorporated into the wedge through duplexing from below (resulting in substantial vertical thickening of the accretionary wedge above the basal décollement). In contrast, LV detachments in this region usually lie closer to the basement/cover contact (MacKay, 1995), virtually offscraping all of the incoming section and incorporating it into the wedge dominantly through lateral accretion. At SHR, duplexing is less pervasive, as shortening there during Zone I and II deformation was accommodated on both SV thrust faults and the LV thrust faults and folds west of the crest (Fig. **F4**). This mixing of structural styles presumably results in less net uplift at SHR. Less uplift at SHR has also helped to preserve the cap of younger slope basin sediments that are preserved there and absent from NHR.

HISTORY OF FLUID VENTING

In addition to the spatial variability in the fluid venting across Hydrate Ridge there may also be a temporal effect. The older stratigraphy uplifted and exposed at the seafloor at NHR has been subjected to a longer history of sediment compaction, dewatering, and deformation than the younger slope basin strata preserved at SHR. ODP drilling results at Sites 892 and 1244 (beneath the slope basin cap, Fig. **F4**) confirm the stratigraphy is well lithified and fractured, much more so than in the overlying younger strata at SHR (Westbrook, Carson, Musgrave, et al., 1994; Tréhu, Bohrmann, Rack, Torres, et al., 2003). A more intense and a longer period of deformation occurred in the uppermost strata exposed at NHR compared to the younger, less deformed and less dewatered shallowest strata at SHR. This suggests the extent of authigenic carbonates at NHR may result from a longer history of fluid flow, which is supported by U/Th ages from carbonates at NHR of 68,700 and 71,700 yr and SHR of 7,300 to 11,400 yr (Teichert et al., 2003). Without an abundance of fracture conduits and with an overlying cap of relatively impermeable sediments sealing their outlet toward the seafloor, stratigraphic conduits for fluid flow likely become important at SHR. The significance of stratigraphic conduits for fluid flow was observed during Leg 204 drilling at SHR, which revealed the major authigenic carbonate occurrence there is the result of fluid flow through a high-porosity and permeable ash-rich stratigraphic horizon (Tréhu et al., 2004a).

IMPLICATIONS FOR MARGIN-WIDE GAS HYDRATE

Biogenic and thermogenic gases within the pore fluids throughout the accretionary wedge are transported into the gas hydrate stability zone (GHSZ) via faults and fractures, dipping stratigraphic horizons, or during diffuse intergranular fluid flow. Given sufficient gas saturation and sediment and/or fracture porosity and permeability, these fluids, if present within the GHSZ, will precipitate gas hydrate. Tréhu et al. (2004b) document the distribution and concentration of gas hydrate within the GHSZ across SHR and show that it is highest at the southern summit, near the location of the largest authigenic carbonate occurrence. Previous seafloor observations and sampling at SHR (e.g., Suess et al., 2001) also confirm abundant seafloor gas hydrate present at this location, which is consistent with the simple model of updip migration and anticlinal focusing of fluids near the crest of Hydrate Ridge discussed in Johnson et al. (2003) and more recently in Weinberger et al. (2005). The implications of this model and the observations at SHR would imply that most anticlinal ridges within the GHSZ across the margin would contain abundant gas hydrate near their crests. However, comparison between the history of deformation and fluid venting at SHR and NHR reveals that the duration and intensity of fluid migration, gas hydrate formation, and authigenic carbonate precipitation can vary along strike even within one accretionary ridge.

Because accretionary wedge dewatering and fluid migration are generally more intense near the deformation front and decrease with distance back into the wedge, Tréhu et al. (1999) suggested Hydrate Ridge represents an intermediate stage in the temporal evolution of gas hydrate systems within accretionary ridges across the margin. Although this is a likely model for the fluid venting and gas hydrate forming window that accretionary ridges pass into and out of with continued accretion to the margin, our recent structural work suggests that along-strike variations in structural style (primarily thrust vergence) control uplift, and thus indirectly influence the history of fluid venting and gas hydrate development within the same accretionary ridge system.

As Hydrate Ridge exists at the transition zone between a dominantly LV portion of the wedge to the north and a SV wedge to the south, it contains both SV and LV structures. NHR however, contains all SV structures, whereas SHR consists of two LV thrust folds juxtaposed against an older SV core (Fig. **F4,** inset C). As described above, greater uplift is expected in SV portions of the wedge because of thrust duplexing and wedge thickening from the base, as observed at NHR, and less uplift is likely in LV-dominated portions of the wedge, as observed at SHR. Thrust duplexing, wedge thickening, and uplift in SV portions of the wedge are likely to have a larger effect on fluid focusing, and thus gas hydrate formation and authigenic carbonate precipitation, compared to LV portions of the wedge. Intense focusing of fluids in SV portions of the wedge is also likely to have the effect of making thrust ridges in those regions more susceptible to slope failure. The records of slope failure in the adjoining slope basins on each flank of Hydrate Ridge provide evidence that the cap of younger slope basin sediments once preserved at NHR was eroded during Holocene and mostly late Pleistocene sediment failures (Johnson, 2004; Tréhu, Bohrmann, Rack, Torres, et al., 2003; **Watanabe,** this volume). In addition, the largest SV portion of the Cascadia accretionary wedge, from just south of Hydrate Ridge to the Rogue Canyon, catastrophically failed at least three times during the last ~1.2 m.y. (Goldfinger, 2000), whereas the LV-dominated wedge of Northern Oregon and Washington is well organized into elongate thrust ridges with only minor slope failure scars observed on their flanks.

Based on the above arguments, it is possible that SV portions of the wedge may be more susceptible to intense fluid focusing, gas hydrate formation, and slope failure than LV portions of the wedge. The interplay between all of these effects as the wedge develops through time, and the timescale at which gas hydrates remain stable within the sediment column, however, is difficult to reconstruct or predict. Additional investigations, focused on the interplay between structure in the wedge, the subsurface gas hydrate distribution, and the frequency of slope failure in the Cascadia wedge or in other gas hydrate–bearing accretionary settings, are needed to address these issues further.

CONCLUSIONS

The results of structural mapping show the style of deformation across Hydrate Ridge varies from SV at NHR to dominantly LV at SHR. This change in vergence is also coincident with more massive authigenic carbonate precipitation at NHR compared to SHR. These observations coupled with the distribution of gas hydrates in the subsurface and the records of slope failure at Hydrate Ridge, suggest variability in structural style may strongly influence the distribution and concentration of fluids and gas hydrates in the subsurface and the susceptibility of accretionary ridges to slope failure.

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REFERENCES

Carlson, P.R., and Nelson, C.H., 1987. Marine geology and resource potential of Cascadia Basin. *In* Scholl, D.W., Grantz, A., and Vedder, J.G. (Eds.), *Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins—Beaufort Sea to Baja California*. Circum.-Pac. Counc. Energy Miner. Res., Earth Sci. Ser., 6:523–535.

Carson, B., Seke, E., Paskevich, V., and Holmes, M.L., 1994. Fluid expulsion sites on the Cascadia accretionary prism: mapping diagenetic deposits with processed GLORIA imagery. *J. Geophys. Res.,* 99:11959–11970. **doi:10.1029/94JB00120**

Chevallier, J., 2004. Seismic sequence stratigraphy and tectonic evolution of southern Hydrate Ridge [M.S. thesis]. Oregon State Univ., Corvallis.

Fourtanier, E., and Caulet, J.-P., 1995. Siliceous microfossil stratigraphic synthesis of Site 892, Cascadia margin. *In* Carson, B., Westbrook, G.K., Musgrave, R.J., and Suess, E. (Eds.), *Proc. ODP, Sci. Results,* 146 (Pt 1): College Station, TX (Ocean Drilling Program), 369–374.

Goldfinger, C., 2000. Super-scale failure of the southern Oregon Cascadia margin. *Pure Appl. Geophys.,* 157:1189–1226. **doi:10.1007/s000240050023**

Goldfinger, C., Kulm, L.D., Yeats, R.S., Hummon, C., Huftile, G.J., Niem, A.R., Fox, C.G., and McNeill, L.C., 1996. Oblique strike-slip faulting of the Cascadia submarine forearc: the Daisy Bank fault zone off central Oregon. *In* Bebout, G.E., Scholl, D., Kirby, S., and Platt, J.P. (Eds.), *Subduction Top to Bottom.* Geophys. Monogr., 96:65–74.

Goldfinger, C., Kulm, L.D., Yeats, R.S., McNeill, L., and Hummon, C., 1997. Oblique strike-slip faulting of the central Cascadia submarine forearc. *J. Geophys. Res.,* 102(B4):8217–8244. **doi:10.1029/96JB02655**

Goldfinger, C., Yeats, R.S., Kulm, L.D., Applegate, B., MacKay, M.E., and Moore, G.F., 1992. Transverse structural trends along the Oregon convergent margin: implications for Cascadia earthquake potential and crustal rotations. *Geology,* 20:141–144. **doi:10.1130/0091-7613(1992)020<0141:TSTATO>2.3.CO;2**

Haugerud, R.A., 1999. Digital elevation model (DEM) of Cascadia, latitude 39N–53N, longitude 116W–133W. *Open-File Rep.—U. S. Geol. Surv.,* 99–369.

Johnson, J.E., 2004. Deformation, fluid venting, and slope failure at an active margin gas hydrate province, Hydrate Ridge Cascadia accretionary wedge [Ph.D. dissert.]. Oregon State Univ., Corvallis.

Johnson, J.E., Goldfinger, C., and Suess, E., 2003. Geophysical constraints on the surface distribution of authigenic carbonates across the Hydrate Ridge region, Cascadia margin. *Mar. Geol.,* 202(1–2):79–120. **doi:10.1016/S0025-3227(03)00268-8**

Kulm, L.D., and Fowler, G.A., 1974. Cenozoic sedimentary framework of the Gorda-Juan de Fuca plate and adjacent continental margin: a review. *In* Dott, R.H., and Shaver, R.H. (Eds.), *Modern and Ancient Geosynclinal Sedimentation.* Spec. Publ.—Soc. Econ. Paleontol. Mineral., 212–229.

Kulm, L.D., Suess, E., Moore, J.C., Carson, B., Lewis, B.T., Ritger, S.D., Kadko, D.C., Thornburg, T.M., Embley, R.W., Rugh, W.D., Massoth, G.J., Langseth, M.G., Cochrane, G.R., and Scamman, R.L., 1986. Oregon subduction zone: venting, fauna, and carbonates. *Science,* 231:561–566.

MacKay, M.E., 1995. Structural variation and landward vergence at the toe of the Oregon accretionary prism. *Tectonics,* 14:1309–1320. **doi:10.1029/95TC02320**

MacKay, M.E., Moore, G.F., Cochrane, G.R., Moore, J.C., and Kulm, L.D., 1992. Landward vergence and oblique structural trends in the Oregon margin accretionary prism: implications and effect on fluid flow. *Earth Planet. Sci. Lett.,* 109:477–491. **doi:10.1016/0012-821X(92)90108-8**

McNeill, L.C., Goldfinger, C., Kulm, L., and Yeats, R., 2000. Tectonics of the Neogene Cascadia forearc basin: investigations of a deformed late Miocene unconformity.

Geol. Soc. Am. Bull., 112(8):1209–224. **doi:10.1130/0016-7606(2000)112<1209:TOT-NCF>2.3.CO;2**

Ritger, S., Carson, B., and Suess, E., 1987. Methane-derived authigenic carbonates formed by subduction-induced pore-water expulsion along the Oregon/Washington margin. *Geol. Soc. Am. Bull.,* 98:147–156.

Seely, D.R., 1977. The significance of landward vergence and oblique structural trends on trench inner slopes. *In* Talwani, M., and Pitman, W.C.I. (Eds.), *Island Arcs, Deep Sea Trenches, and Back-Arc Basins.* Maurice Ewing Ser., 1:187–198.

Shipboard Scientific Party, 1994a. Explanatory notes. *In* Westbrook, G.K., Carson, B., Musgrave, R.J., et al., *Proc. ODP, Init. Repts.,* 146 (Pt. 1): College Station, TX (Ocean Drilling Program), 15–48.

Shipboard Scientific Party, 1994b. Site 891. *In* Westbrook, G.K., Carson, B., Musgrave, R.J., et al., *Proc. ODP, Init. Repts.,* 146 (Pt. 1): College Station, TX (Ocean Drilling Program), 241–300.

Shipboard Scientific Party, 1994c. Site 892. *In* Westbrook, G.K., Carson, B., Musgrave, R.J., et al., *Proc. ODP, Init. Repts.,* 146 (Pt. 1): College Station, TX (Ocean Drilling Program), 301–378.

Shipboard Scientific Party, 2003a. Site 1244. *In* Tréhu, A.M, Bohrmann, G., Rack, F.R., Torres, M.E., et al., *Proc. ODP, Init. Repts.,* 204: College Station, TX (Ocean Drilling Program), 1–132. **doi:10.2973/odp.proc.ir.204.103.2003**

Shipboard Scientific Party, 2003b. Site 1245. *In* Tréhu, A.M, Bohrmann, G., Rack, F.R., Torres, M.E., et al., *Proc. ODP, Init. Repts.,* 204: College Station, TX (Ocean Drilling Program), 1–131. **doi:10.2973/odp.proc.ir.204.104.2003**

Snavely, P.D., Jr., 1987. Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon-Washington continental margin. *In* Scholl, D.W., Grantz, A., and Vedder, J.G. (Eds.), *Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins—Beaufort Sea to Baja California.* Circum-Pac. Counc. Energy Miner. Resour., Earth Sci. Ser., 6:305–336.

Suess, E., Carson, B., Ritger, S., Moore, J.C., Jones, M., Kulm, L.D., and Cochrane, G., 1985. Biological communities at vent sites along the subduction zones off Oregon. *In* Jones, M.L. (Ed.), *The Hydrothermal Vents of the Eastern Pacific: An Overview.* Bull. Biol. Soc. Wash., 6:475–484.

Suess, E., Torres, M.E., Bohrmann, G., Collier, R.W., Greinert, J., Linke, P., Rehder, G., Tréhu, A., Wallmann, K., Winckler, G., and Zuleger, E., 1999. Gas hydrate destabilization: enhanced dewatering, benthic material turnover and large methane plumes at the Cascadia convergent margin. *Earth Planet. Sci. Lett.,* 170:1–15. **doi:10.1016/S0012-821X(99)00092-8**

Suess, E., Torres, M.E., Bohrmann, G., Collier, R.W., Rickert, D., Goldfinger, C., Linke, P., Heuser, A., Sahling, H., Heeschen, K., Jung, C., Nakamura, K., Greinert, J., Pfannkuche, O., Tréhu, A., Klinkhammer, G., Whiticar, M.J., Eisenhauer, A., Teichert, B., and Elvert, M., 2001. Sea floor methane hydrates at Hydrate Ridge, Cascadia margin. *In* Paull, C.K., and Dillon, W.P. (Eds.), *Natural Gas Hydrates: Occurrence, Distribution, and Detection.* Geophys. Monogr., 124:87–98.

Teichert, B.M.A., Eisenhauer, A., Bohrmann, G., Haase-Schramm, A., Bock, B., and Linke, P., 2003. U/Th systematics and ages of authigenic carbonates from Hydrate Ridge, Cascadia margin: recorders of fluid flow variations. *Geochim. Cosmochim. Acta,* 67:3845–3857. **doi:10.1016/S0016-7037(03)00128-5**

Tréhu, A.M., Asudah, I., Brocher, T.M., Luetgert, J.H., Mooney, W.D., Nabelek, J.L., and Nakamura, Y., 1994. Crustal architecture of the Cascadia forearc. *Science,* 266:237–243.

Tréhu, A.M., Bohrmann, G., Rack, F.R., Torres, M.E., et al., 2003. *Proc. ODP, Init. Repts.,* 204: College Station, TX (Ocean Drilling Program). **doi:10.2973/odp.proc.ir.204.2003**

Tréhu, A.M., Flemings, P.B., Bangs, N.L., Chevallier, J., Gràcia, E., Johnson, J.E., Liu, C.-S., Liu, X., Riedel, M., and Torres, M.E., 2004a. Feeding methane vents and gas hydrate deposits at south Hydrate Ridge. *Geophys. Res. Lett.,* 31:L23310. **doi:10.1029/2004GL021286**.

Tréhu, A.M., Long, P.E., Torres, M.E., Bohrmann, G., Rack, F.R., Collett, T.S., Goldberg, D.S., Milkov, A.V., Riedel, M., Schultheiss, P., Bangs, N.L., Barr, S.R., Borowski, W.S., Claypool, G.E., Delwiche, M.E., Dickens, G.R., Gracia, E., Guerin, G., Holland, M., Johnson, J.E., Lee, Y.-J., Liu, C.-S., Su, X., Teichert, B., Tomaru, H., Vanneste, M., Watanabe, M., and Weinberger, J.L., 2004b. Three-dimensional distribution of gas hydrate beneath southern Hydrate Ridge: constraints from ODP Leg 204. *Earth Planet. Sci. Lett.,* 222:845–862. **doi:10.1016/j.epsl.2004.03.035**

Tréhu, A.M., Torres, M.E., Moore, G.F., Suess, E., and Bohrmann, G., 1999. Temporal and spatial evolution of a gas-hydrate-bearing accretionary ridge on the Oregon continental margin. *Geology,* 27(10):939–942. **doi:10.1130/0091-7613(1999)027 <0939:TASEOA>2.3.CO;2**

Weinberger, J.L., Brown, K.M., and Long, P.E., 2005. Painting a picture of gas hydrate distribution with thermal images. *Geophys. Res. Lett.,* 32(4):L04609. **doi:10.1029/ 2004GL021437**

Westbrook, G.K., 1994. Growth of accretionary wedges off Vancouver Island and Oregon. *In* Westbrook, G.K., Carson, B., Musgrave, R.J., et al., *Proc. ODP, Init. Repts.,* 146 (Pt. 1): College Station, TX (Ocean Drilling Program), 381–388.

Westbrook, G.K., Carson, B., Musgrave, R.J., et al., 1994. *Proc. ODP, Init. Repts.,* 146 (Pt. 1): College Station, TX (Ocean Drilling Program).

Zellers, S.D., 1995. Foraminiferal biofacies, paleoenvironments, and biostratigraphy of Neogene–Quaternary sediments, Cascadia margin. *In* Carson, B., Westbrook, G.K., Musgrave, R.J., and Suess, E. (Eds.), *Proc. ODP, Sci. Results,* 146 (Pt 1): College Station, TX (Ocean Drilling Program), 79–113.

Figure F1. Cascadia margin bathymetry and topography (Haugerud, 1999) showing the Hydrate Ridge tectonic setting in the Cascadia accretionary wedge.

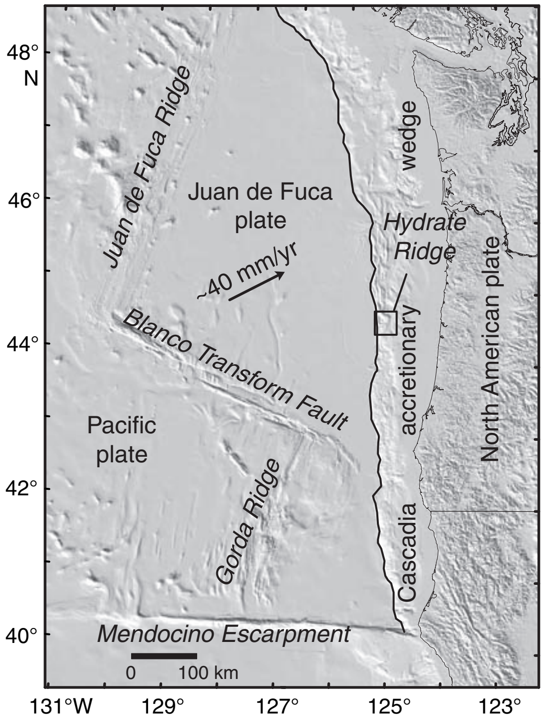

Figure F2. Hydrate Ridge bathymetry and locations of ODP drill sites. 3-D seismic survey area is boxed (solid line). NHR = northern Hydrate Ridge. SHR = southern Hydrate Ridge.

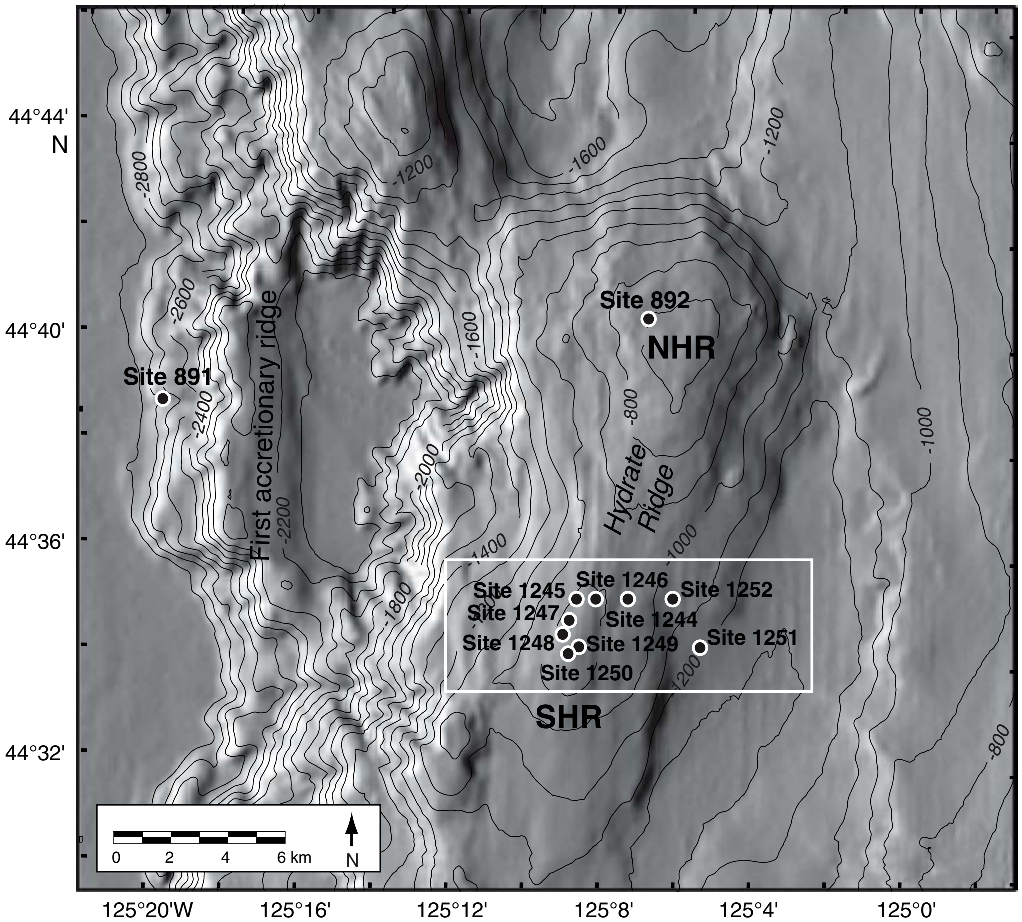

Figure F3. Structure map of the Hydrate Ridge region. ODP sites as shown in Figure F2, p. 13. 3-D seismic survey area is boxed (solid line). Black dashed lines delineate the geographic regions discussed in text. Zone II is shaded to differentiate it from Zones I and III. Labels on structures coincide with those shown in Figure F4, p. 15.

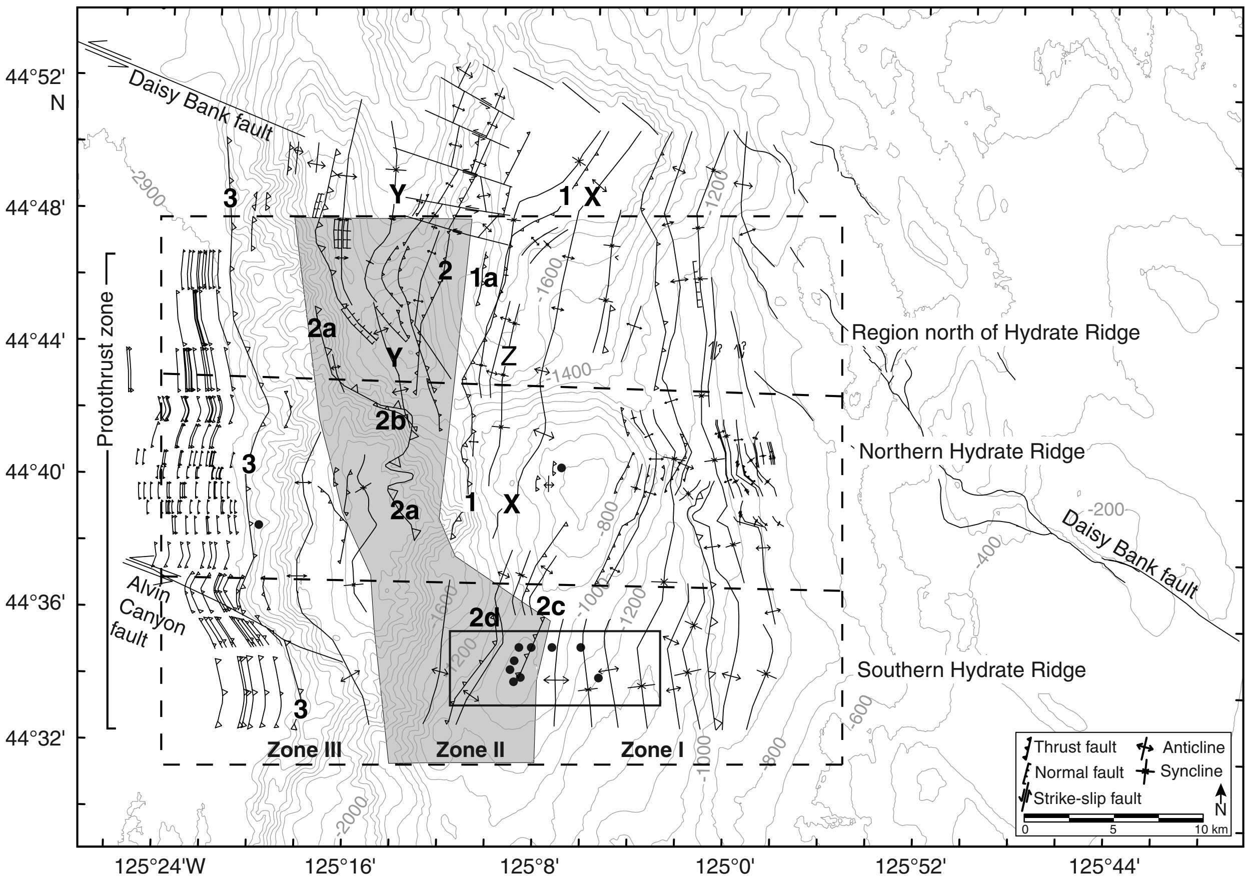

Figure F4. Summary of the structural vergence variation (seaward vergence [SV] and landward vergence [LV]) and schematic cross sections across three dip transects (A, B, C) in the Hydrate Ridge region. Thin dotted lines (black) represent the two-dimensional seismic profile line locations and the location of the three-dimensional seismic survey is shown as a solid box (black). White dashed lines delineate the geographic regions discussed in text. Labeled faults (1, 1a) as also shown in Figure F3, p. 14, depict relative order of westward accretion (1 oldest, 3 youngest). Solid lines on the profiles indicate observed faults, dashed lines are inferred.

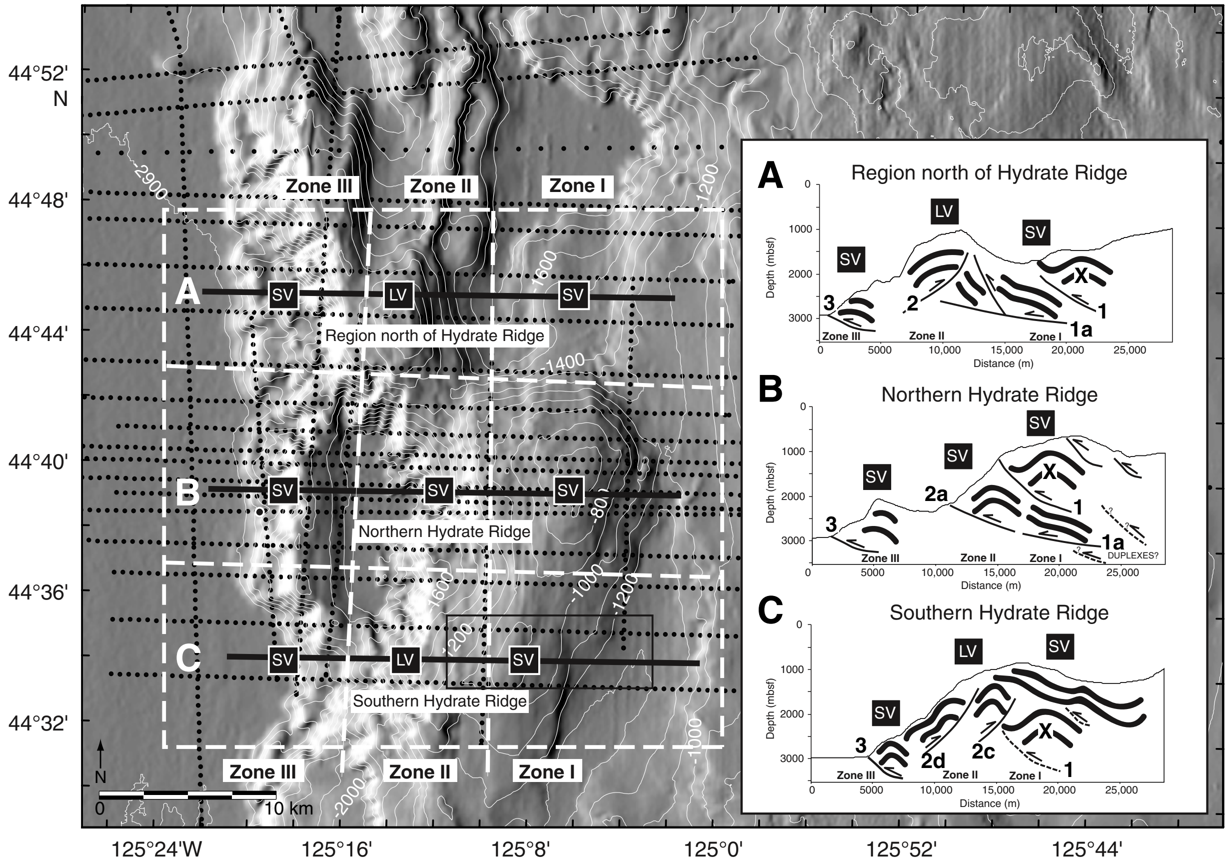

Figure F5. A. Deep-towed sidescan sonar imagery across Hydrate Ridge. High backscatter sites (light tones), which were groundtruthed by seafloor observations and sampling, represent sites of seafloor or shallow subseafloor authigenic carbonate locations (Johnson et al., 2003). **B.** The same region with sidescan data removed to emphasize the greater abundance of authigenic carbonates (high backscatter sites outlined in black) on northern Hydrate Ridge (NHR) compared to southern Hydrate Ridge (SHR). The approximate extent of the older (>1.7–1.6 Ma) stratigraphy exposed at or near the seafloor at NHR is shown as gray overlay and is coincident with the region of most intense authigenic carbonate precipitation. This is in contrast to SHR, which has limited authigenic carbonate occurrences and is capped by younger (from <1.7–1.6 Ma to recent) slope basin stratigraphy.