NORTH-SOUTH VARIABILITY IN THE HISTORY OF DEFORMATION AND FLUID VENTING ACROSS HYDRATE RIDGE, CASCADIA MARGIN

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ABSTRACT

Hydrate Ridge is an accretionary thrust ridge located on the lower slope of the central Cascadia convergent margin. Structural mapping using 2-D and 3-D multichannel seismic reflection profiles and gridded bathymetry coupled with deep towed sidescan sonar data and ODP drilling biostratigraphy, suggest that seafloor fluid venting patterns are likely controlled by the seaward vergent structural style at the older (>1.6-1.7 Ma) crest of northern Hydrate Ridge (NHR) and by the dominantly landward vergent structural style at the younger (1.7 Ma to recent) crest of southern Hydrate Ridge (SHR). North-south structural variability across Hydrate Ridge is manifested on the seafloor as aerially extensive authigenic carbonate crusts on NHR and a minor focused occurrence of authigenic carbonate on SHR. The older stratigraphy exposed at the seafloor at NHR has likely been subjected to a longer history of sediment compaction, dewatering, and deformation than the younger slope basin strata preserved at SHR, suggesting the extent of carbonates at NHR may result from a more intense history of fluid flow through a more uplifted, lithified, and fractured NHR sequence. Furthermore, instead of abundant fault and fracture conduits as at NHR, 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. These observations suggest, stratigraphic conduits for fluid flow may be important in less uplifted, landward vergent dominated portions of Hydrate 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.

Keywords: fluid flow, gas hydrate, active margin, accretionary wedge

INTRODUCTION

On the Cascadia continental margin offshore central Oregon, Hydrate Ridge (Figs. 1 and 2) has been the focus of numerous geologic and geophysical investigations for nearly two decades. During the mid-1980's, 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 cold seep faunas [1-3]. By the early 1990's this early work was supplemented by ODP (Ocean Drilling Program) drilling (Fig. 2; Sites 891 and 892), during which gas hydrates

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were first recovered [4] and by detailed structural investigations [5]. Subsequent work, including numerous seafloor observation and sampling expeditions since the late 1990's [e.g. 6-7] and more recently a gas hydrate dedicated ODP leg in 2002 [8] (Fig. 2; Sites 1244-1252), has 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 structural mapping and core biostratigraphy, (2) the record of fluid venting, as imaged on sidescan sonar data, and (3) the surface and subsurface gas hydrate distribution, constrained by seafloor observations and ODP coring, across Hydrate Ridge in order to address how the gas hydrate-fluid venting system here may serve as an example for how the structure within accretionary wedge ridges may influence the distribution and concentration of gas hydrate along the Cascadia margin and in other accretionary wedge environments.

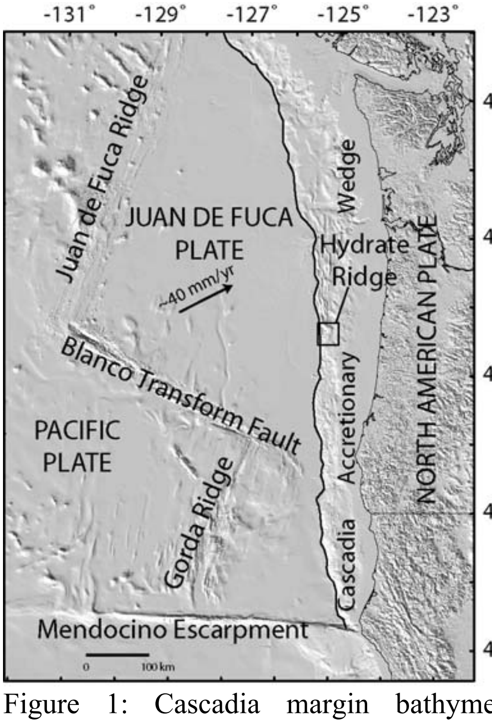

Figure 1: Cascadia margin bathymetry and topography [14] showing the Hydrate Ridge tectonic setting.

GEOLOGIC SETTING

The Cascadia accretionary wedge evolved in response to the oblique subduction of the Juan de Fuca-Gorda plate system (Fig. 1) 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 [4, 8, 9]. The Quaternary portion of the accretionary wedge is widest off the Washington and northern Oregon margins, coincident with the accretion of the thick Pleistocene Astoria and Nitinat Fans [10], 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 [5, 11-13]. 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 seaward vergent 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 [5]. In addition to the SV and LV thrust faults and folds that comprise the Cascadia accretionary wedge, nine WNW-striking left-

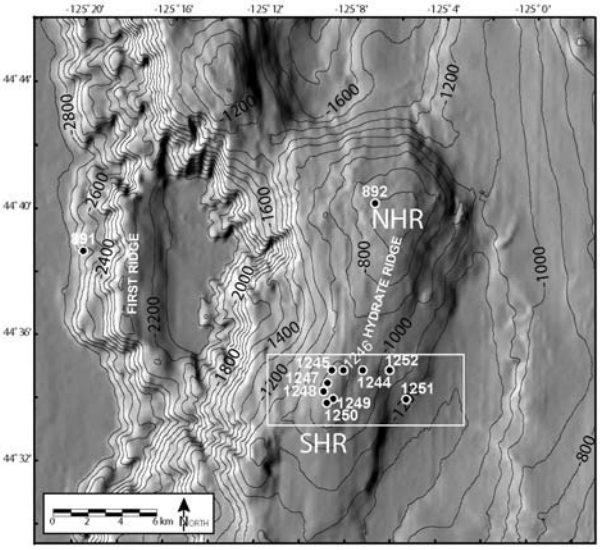

Figure 2: Hydrate Ridge bathymetry and locations of ODP drill sites. 3-D seismic survey area discussed in text is boxed.

lateral strike slip faults [15] also cut across the lower slope of the wedge. These faults form in the lower plate as a result of dextral shear of the forearc, due to the 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 [16, 17]. Above this oceanic basement terrane is a modestly deformed Eocene through Holocene forearc basin sequence [16, 18].

In the central Oregon portion of the margin discussed here (Hydrate Ridge), a transition zone exists between the northern landward vergent province and the southern seaward vergent 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 [19]. Hydrate Ridge is a composite thrust ridge, formed from both seaward and landward vergent structures. The across-strike changes in structural vergence are likely linked to high pore fluid pressure caused by the rapid deposition of the Astoria fan sediments on the abyssal plain and the upward propagation of left lateral strike slip faults into the wedge [19] These strike slip faults have also been active throughout the accretionary process, resulting in the clockwise block rotation of Hydrate Ridge through time.

STRUCTURAL HISTORY

Mapping

Recent structural mapping [19] (Fig. 3) using multichannel seismic reflection profiles from an ODP site survey conducted in 1989 (relevant portions of the lines shown in Fig. 4) and insights from mapping within the 3-D seismic survey on southern Hydrate Ridge [8, 20] reveal the variability in structural styles across the Hydrate Ridge region (Fig. 3). We have divided the regions of similar structural style and stratigraphy into three strike parallel zones (I, II, III) along three dip transects (North of Hydrate Ridge, Northern Hydrate Ridge (NHR), and Southern Hydrate Ridge (SHR)) across the wedge from Hydrate Ridge to the deformation front Fig. 3). A summary of the structural vergence variation and schematic cross sections across the dip transects are shown in Fig. 4. Assuming a model of westward wedge growth through time, Zones I, II, and III also indicate relative timing of major accretionary wedge growth (Age of major Zone I deformation > Zone II > Zone III). Because deformation on structures across the wedge has likely continued throughout the Pleistocene, position in the wedge as an indication of the relative timing of thrusting can be misleading. 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

Johnson et al. [19] summarize the biostratigraphic results from ODP drilling at sites 891, 892, 1244, and 1245 (Fig. 2). The ages and thus constraints on the timing of deformation at these sites are discussed in particular because they lie within the three different structural zones; 891 in Zone III, 892 and 1244 in Zone I, and 1245 in Zone II (Fig. 2 and 3). Because the sediments at both sites 891 and 892 represent uplifted and accreted abyssal plain section [21, 22] and the core of older material of the same age at site 1244 is likely the equivalent facies cored at Site 892, the folding and thrusting at each site must have occurred after the deposition of the youngest preserved abyssal plain sediments that are present at each site (1.7-1.6 Ma). Because there could have been erosion or depositional hiatuses at each site and deposition during the accretion process, the youngest age of the uplifted abyssal plain sediments preserved at each site represents the oldest time the deformation at each site could have began. Currently, the uplift of NHR has exposed this older stratigraphic package at the seafloor surface, whereas at SHR less uplift results in the burial of the core of 1.7-1.6 Ma and older stratigraphy beneath the younger overlying slope basin sediments [8]. Because the age of the youngest sediments deformed by the frontal thrust, however, cannot be determined at ODP Site 891, Johnson et al. [19] use the range of 0.30-0.25 Ma

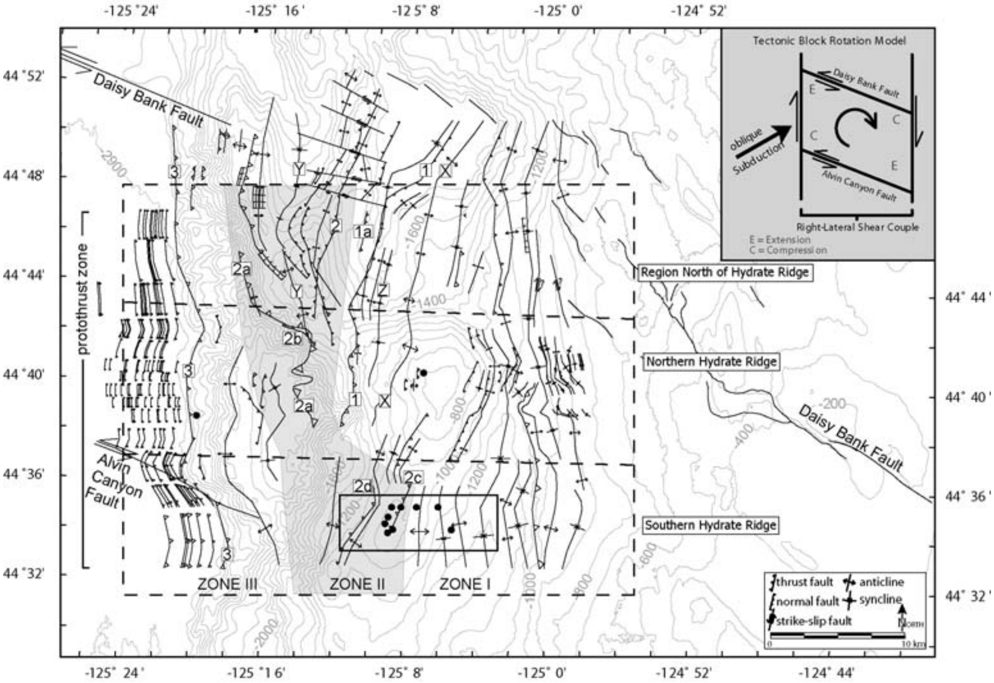

Figure 3: Structure map of the Hydrate Ridge region. ODP sites as shown in Fig. 2. 3-D seismic survey area discussed in text is boxed. Inset shows clockwise block rotation model responsible for the clockwise block rotation of Hydrate Ridge [19].

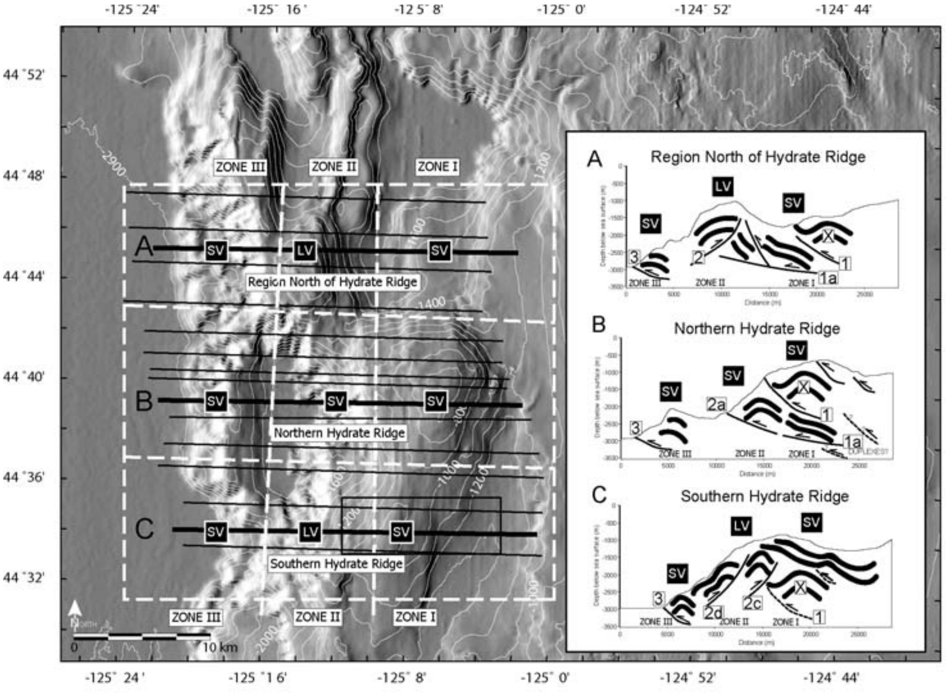

Figure 4: A summary of the structural vergence variation, seaward vergence (SV) and landward vergence (LV), and schematic cross sections across the three dip transects (A,B, C) across the region. Thin black lines represent the 2-D seismic profile line locations and the location of the 3-D seismic survey is shown boxed (black).

given by Westbrook [23] for the timing of uplift of the first accretionary ridge (Fig.2).

The above age relationships imply that because Hydrate Ridge lies farther east in the accretionary wedge and contains older deformed sediments than the first accretionary ridge, the difference in age of deformed sediments at ODP Site 892 and 1244 with the timing of uplift of ridge one at ODP Site 891 can be used as a proxy for the maximum difference in timing of accretion into the wedge. This implies NHR (Zone I deformation) was incorporated into the wedge sometime after the early Pleistocene (1.7-1.6 Ma) and the major period of uplift was likely completed by the late Pleistocene (0.30-0.25 Ma), when the earliest age of ridge one uplift (Zone III deformation), could have occurred. Because the wedge builds westward with continued accretion, the uplift of ridge one 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 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 seaward vergent 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), which is the estimated age for the initiation of ridge one uplift as described above. 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 (landward vergence in the region north of Hydrate Ridge and on SHR and seaward vergence on NHR), must have occurred sometime within this same time window (1.7-1.6 Ma to 0.3-0.25 Ma). Through sequential unfolding of biostratigraphically constrained horizons at site 1245 [24], Chevallier [20] suggests that initiation of the most eastward landward vergent fold within Zone II began 1.2 Ma and was completed by 0.3 Ma. Johnson et al. [19] suggest that this period of landward vergence at SHR was coincident with the period of landward vergence in the region north of Hydrate Ridge and seaward vergence at NHR, as all three regions appear to lie within the same location along strike within the wedge (the Zone II region). This implies that Zone II deformation throughout the region most likely occurred between 1.2 Ma and 0.3 Ma.

These results reveal that the wedge in this region advanced westward in a series of three structural phases since the late Pliocene-early Pleistocene (1.7-1.6 Ma): a seaward vergent phase (1.7-1.2 Ma), a dominantly landward vergent phase (1.2-0.3 Ma), and a seaward vergent phase (0.3 Ma to recent). Superimposed on this structural vergence variation with time is the influence of left-lateral strike-slip faulting, which appears to have resulted in the clockwise rotation of structures during their accretion (Johnson et al., in review).

SEAFLOOR VENTING DISTRIBUTION

The manifestations of fluid venting on the crest of NHR are very extensive, as imaged on deep-towed sidescan sonar data [25], compared to those on southern Hydrate Ridge (Fig. 5). 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 at NHR has resulted in the exposure of older stratigraphy (>1.7-1.6 Ma) at the seafloor. The existence of duplexed seaward vergent thrust faults beneath northern Hydrate Ridge 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 seaward vergent wedge building events (Fig. 4). Duplexing is more prevalent in seaward vergent portions of the wedge in the Hydrate Ridge region because the detachment for such thrusts typically lies several hundred meters above the basement/cover contact [13], leaving a portion of the incoming abyssal plain section to be incorporated into the wedge through duplexing from below (resulting in substantial thickening of the accretionary wedge above the basal décollement). In contrast, landward vergent detachments in this region usually lie closer to the basement/cover contact [13], virtually offscraping all of the incoming section and incorporating it into the wedge through accretion. On SHR, this type of duplexing is less pervasive, as shortening there during zone I and II deformation was accommodated on both seaward and the landward vergent thrust faults and folds west of the crest (Fig. 4). This mixing of structural styles presumably results in less net uplift at SHR. Less uplift at SHR has also help to preserve the cap of younger slope basin sediments that is preserved there and absent from NHR. This cap of younger stratigraphy likely acts as an impermeable seal that inhibits fluid escape to the surface. Perhaps these two reasons explain the lack of massive authigenic carbonates on SHR.

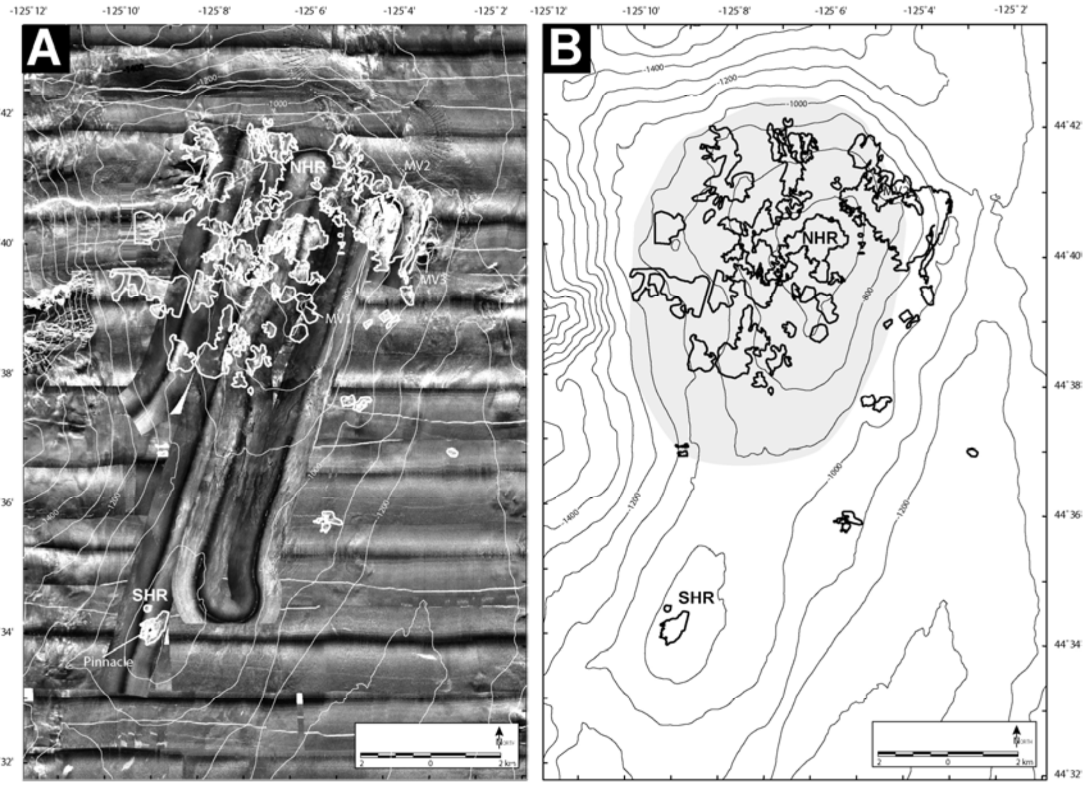

Figure 5: A. Deep-towed sidescan sonar imagery across Hydrate Ridge. High backscatter sites (light tones (outlined in white), which were groundtruthed by seafloor observations and sampling, represent sites of seafloor or shallow subseafloor authigenic carbonate locations [25]. B. The same region with sidescan data removed to emphasize the greater abundance of authigenic carbonates (high backscatter sites outlined in black) on NHR compared to SHR. The approximate extent of the older (>1.7-1.6 Ma) stratigraphy exposed at or near the seafloor at NHR is shown as grey overlay and is coincident with the region of most intense authigenic carbonate precipitation. This is in contrast to SHR, which has limited authigenic carbonate occurances and is capped by younger (<1.7.1.6 Ma- recent) slope basin stratigraphy.

HISTORY OF FLUID VENTING

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) confirm the stratigraphy is well lithified and fractured, much more so than in the overlying younger strata on SHR [4, 8]. A more intense and a longer period of deformation of the uppermost strata exposed at NHR compared to the younger, less deformed and less dewatered strata at SHR, suggests the extent of authigenic carbonates at NHR may result from a longer history of fluid flow. 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 on SHR. The significance of stratigraphic conduits for fluid flow was observed during ODP Leg 204 drilling on SHR, which revealed the major authigenic carbonate occurrence there was a result of fluid flow through a high porosity and permeable ash rich stratigraphic horizon [26].

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 via faults and fractures, dipping stratigraphic horizons, or during diffuse intergranular fluid flow. Given sufficient gas saturation and sediment porosity and fracture permeability, these fluids, if present within the gas hydrate stability zone, will precipitate gas hydrate. Tréhu et al. [27] document the distribution and concentration of gas hydrate within the gas hydrate stability zone across southern Hydrate Ridge and show that it is highest at the southern summit, near the location of the largest authigenic carbonate occurrence. Previous seafloor observations and sampling on southern Hydrate Ridge (e.g. [7]) also confirm abundant seafloor gas hydrate present at this location. This is consistent with the simple model of up dip migration and anticlinal focusing of fluids near the crest of Hydrate Ridge discussed in Johnson et al. [25] and more recently by Weinberger et al. [28]. The implications of this model and the observations at southern Hydrate Ridge would imply that all anticlinal ridges within the gas hydrate stability zone 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 is more intense near the deformation front and decreases with distance back into the wedge, Tréhu et al. [29] 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 and thus uplift, can significantly 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 landward vergent portion of the wedge to the north and a seaward vergent wedge to the south, and between two left-lateral strike-slip faults, it contains both seaward vergent and landward vergent structures. NHR however, contains all seaward vergent structures whereas SHR consists of two landward vergent thrust folds juxtaposed against an older seaward vergent core (Fig. 4; inset C). As described above, greater uplift is expected in seaward vergent portions of the wedge due to thrust duplexing and wedge thickening from the base, as observed at NHR, and less uplift is likely in landward vergence 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 [30; Johnson et al., in prep]. In addition, the largest seaward vergent 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 Ma [31], 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, we hypothesize that SV portions of the wedge may be more susceptible to intense fluid focusing, gas hydrate formation, and slope failure than LV potions of the wedge. 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 may serve as future tests to this hypothesis.

CONCLUSIONS

The results of structural mapping and the distribution of fluid venting and gas hydrate concentrations across Hydrate Ridge show the structural style across the 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

[1] Suess E., Carson B., Ritger S., Moore J.C., Jones M.L., Kulm L.D., Cochrane G.R. *Biological communities at vent sites along the subduction zone off Oregon*. Biological Society of Washington Bulletin, The hydrothermal vents of the eastern Pacific: An overview. 1985; 6: 474-484.

[2] 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., Scamman R.L.,1986. *Oregon subduction zone: Venting, fauna, and carbonates*. Science 1986; 231: 561-566.

[3] Ritger S.D., Carson B., Suess E., *Methane-derived authigenic carbonates formed by subduction-induced-pore-water expulsion along the Oregon/Washington margin*. Geological Society of America Bulletin 1987; 98: 147-156.

[4] Westbrook G.K., Carson B., Musgrave R.J., et al. *Proceedings of the Ocean Drilling Program, Initial Reports* 146: College Station, Texas, Ocean Drilling Program, 1994.

[5] MacKay M.E., Moore G.F., Cochrane G.R., Moore J. Casey, Kulm L.D. La*ndward vergence and oblique structural trends in the Oregon margin accretionary prism: Implications and effect on fluid flow*. Earth and Planetary Science Letters 1992; 109: 477-491.

[6] Suess E., Torres M.E., Bohrmann G., Collier R.W., Greinert J., Linke P., Rehder G., Tréhu A., Wallmann K., Winckler G., Zuleger E. *Gas hydrate destabilization: enhanced dewatering, benthic material turnover and large methane plumes at the Cascadia convergent margin*. Earth Planet Science Letters 1999; 170: 1-15.

[7] 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 P., Tréhu A., Klinkhammer G., Whiticar M.J., Eisenhauer A., Teichert B., Elvert M. *Sea floor methane hydrates at Hydrate Ridge, Cascadia Margin*. In Paull C.K., Dillon W.P. (Eds.), Natural Gas Hydrates Occurrence, Distribution, and Detection. American Geophysical Union. Geophysical Monograph 2001; 124: 87-98.

[8] Tréhu A.M., Bohrmann G., Rack F.R., Torres M.E., et al. *Proceedings of the Ocean Drilling Program, Initial Reports [CD-ROM]*, 204: College Station, Texas, Ocean Drilling Program, 2003.

[9] Kulm L.D., Fowler G.A., *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, Special Publication, Society of Economic Paleontologists and Mineralogists 1974: 212-229.

[10] Carlson P.R., Nelson C.H., *Marine geology and resource potential of Cascadia Basin*. In Scholl D.W., Grantz A., Vedder J.G. (Eds.), Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins. Houston Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Sciences Series 1987: 523-535.

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

[12] Goldfinger C., Kulm L.D., Yeats R.S., Appelgate B., MacKay M.E., Moore G.F. *Transverse structural trends along the Oregon convergent margin: Implications for Cascadia earthquake potential and crustal rotations*: Geology 1992; 20: 41-144.

[13] MacKay M.E. *Structural variation and landward vergence at the toe of the Oregon accretionary prism*. Tectonics 1995; 14: 1309-1320.

[14] Haugerud R.A. *Digital elevation model (DEM) of Cascadia, latitude 39N-53N, longitude 116W-133W.* U.S. Geological Survey Open-File Report 99-369, 1999.

[15] Goldfinger C., Kulm L.D., Yeats R.S., McNeill L., Hummon C. *Oblique strike-slip faulting of the central Cascadia submarine forearc*. Journal of Geophysical Research 1997; 102: 8217-8243.

[16] Snavely P.D., Jr. *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 -Beaufort Sea to Baja California, Volume 6: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series 1987: 305-335.

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

[18] McNeill L.C., Goldfinger C., Kulm L.D., Yeats R.S. *Tectonics of the Neogene Cascadia forearc basin: Investigations of a deformed late Miocene unconformity*. Geological Society of America Bulletin 2000; 112: 1209-1224.

[19] Johnson J. E., Goldfinger C., Bangs N.L.B., Tréhu A. M., Chevallier J. *Structural vergence variation and clockwise block rotation in the Cascadia accretionary wedge, offshore Oregon*. Tectonics 2005 (in review).

[20] Chevallier J. *Seismic sequence stratigraphy and tectonic evolution of Southern Hydrate Ridge* [M.S. thesis]: Corvallis, Oregon, Oregon State University 2004: 1-117.

[21] Shipboard Scientific Party. *Site 891*, In Westbrook G.K., Carson B., Musgrave R.J. et al. Proceedings of the Ocean Drilling

Program, Initial Reports 146: College Station, Texas, Ocean Drilling Program, 1994: 241-300.

[22] Shipboard Scientific Party. *Site 892*, In Westbrook G.K., Carson B., Musgrave R.J. et al. Proceedings of the Ocean Drilling Program, Initial Reports 146: College Station, Texas, Ocean Drilling Program, 1994: 301-378.

[23] Westbrook G.K. *Growth of Accretionary Wedges off Vancouver Island and Oregon*. In Westbrook G.K., Carson B., Musgrave R.J. et al. Proceedings of the Ocean Drilling Program, Initial Reports 146: College Station, Texas, Ocean Drilling Program, 1994: 381-388.

[24] Shipboard Scientific Party. *Site 1245*, In Tréhu A.M., Bohrmann G., Rack F.R., Torres M.E., et al. Proceedings of the Ocean Drilling Program, Initial Reports [CD-ROM], 204: College Station, Texas, Ocean Drilling Program, 2003.

[25] Johnson J.E., Goldfinger C., and Suess E. *Geophysical constraints on the surface distribution of authigenic carbonates across the Hydrate Ridge region, Cascadia margin*. Marine Geology 2003; 202: 79-110.

[26] Tréhu A.M., Flemings P.B., Bangs N., Chevallier J., Gracia E., Johnson J.E., Liu C.-S., Liu X., Riedel M., and Torres M.E. *Feeding methane vents and gas hydrate deposits at south Hydrate Ridge*: Geophysical Research Letters 2004; 31: doi:10.1029/2004GL021286.

[27] Tréhu A. M., G. Bohrmann Rack, F., Collett T., Goldberg D., Long P.E., Milkov A.V., Riedel M., Schultheiss P., Torres M.E., 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., Weinberger J.L. *Three-dimensional distribution of gas hydrate beneath southern Hydrate Ridge: Constraints from ODP Leg 204*. Earth and Planetary Science Letters 2004; 222: 845-862.

[28] Weinberger J.L., Brown K.M., Long P.E., *Painting a picture of gas hydrate distribution with thermal images*. Geophysical Research Letters 2005 (in press).

[29] Tréhu A.M., Torres M.E., Moore G.F., Suess E., and Bohrmann G. *Temporal and spatial evolution of a gas hydrate-bearing accretionary ridge on the Oregon continental margin*: Geology, 1999; 27: 939-942.

[30] Johnson J. E. *Deformation, Fluid Venting, and Slope Failure at an Active Margin Gas Hydrate Province, Hydrate Ridge Cascadia Accretionary Wedge*. [Ph.D. Dissertation] Corvallis, Oregon, Oregon State University 2004: 1-145.

[31] Goldfinger C., Kulm L.D., McNeill L.C., Watts P. *Super-scale failure of the southern Oregon Cascadia margin*. Pure and Applied Geophysics 2000; 157: 1189-1226.