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Introduction

The marine gas hydrate stability zone (GHSZ) occurs in the slope environment along many active and passive continental margins. In this environment, slope failures are common and can occur near the shelf slope break, within submarine canyons, or on the flanks of bathymetric highs, resulting in a spectrum of slope failure deposits from landslides to turbidites. On the Cascadia margin, the GHSZ occurs within the bathymetric thrust ridges and slope basins of the accretionary wedge. Here, the ridges are composed of uplifted abyssal plain deposits associated with submarine fans and/or paleo-slope basin deposits formed during the evolution of the accretionary wedge (Johnson *et al*., 2006; Torres *et al*., 2008). The adjoining slope basins contain the deposits from slope failure of the ridges. Both ridges and slope basins offshore Central Oregon and Vancouver Island were sampled by drilling during ODP Leg 204 and IODP Expedition 311, respectively (Figure 1). The recovered cores document the distribution and abundance of gas hydrate in these regions within a stratigraphy that is dominated by silt and sand turbidites, debris flows, and intervals of silty clay, separated by hemipelagic clay.

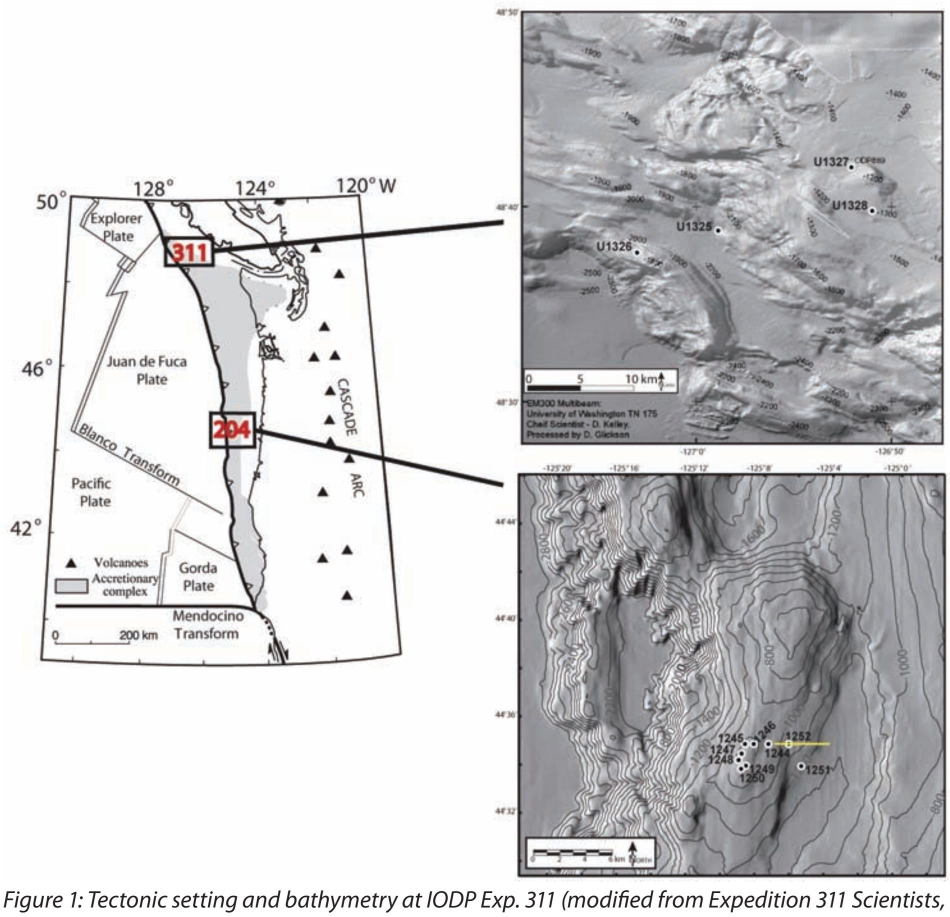

Figure 1: Tectonic setting and bathymetry at IODP Exp. 311 (modified from Expedition 311 Scientists, 2006) and ODP Leg 204 (Hydrate Ridge) core sites. Yellow line shows the location of the seismic reflection profile shown in Figure 2.

The identification of slope failure deposits is most often determined through visual core descriptions coupled with particle size analyses. Discreet measurements of particle size, however, are labor intensive and are often not collected at a sampling interval high enough to capture the range in bed thickness and occurrence observed in slope environments. As an alternative down core magnetic susceptibility (MS) measurements, which are routinely collected at 2.5 cm intervals during ODP and IODP expeditions, can be used to identify slope failure deposits and thus help characterize the host stratigraphy and depositional processes in marine gas hydrate-bearing regions.

Magnetic Susceptibility: A Mixed Signal

MS can be used to identify slope failure deposits by tracking the abundance and composition of detrital magnetic minerals that are transported during slope failure events with other sand and silt sized particles. These deposits are often density sorted, with the magnetic minerals concentrated near the base of each deposit, and are marked by positive excursions in MS from a low baseline MS characteristic of hemipelagic clay. In addition to a MS signal driven by detrital magnetic mineral abundance, Housen and Musgrave (1996) and more recently, Musgrave *et al*. (2006) and Larrasoaña *et al*. (2006 and 2007), have documented the presence of the diagenetic magnetic iron sulfide minerals greigite (Fe_3S_4) and pyrrhotite (Fe_7S_8) in gas hydrate bearing sediments through rock magnetic measurements (e.g. isothermal remnant magnetization, IRM). Precipitates of greigite and pyrrhotite are thought to form within the gas hydrate stability zone by microbially mediated anaerobic methane oxidation (AMO) (Larrasoaña *et al*., 2007 and refs. therein). These precipitates, once formed, may remain in the sediments as a wake of mineralization long after the sulfate methane transition (SMT) migrates up section and may even be left behind as the bottom of the GHSZ migrates upward through time (e.g. Musgrave *et al*., 2006). If large (>0.5 cm), these precipitates can be visually identified in cores as magnetic iron nodules and have been documented in gas hydrate bearing cores from the Indian Ocean (Collett *et al*., 2008) and along the Cascadia margin (Tréhu *et al*., 2003). Given the potential presence of magnetic iron sulfides in gas hydrate bearing sediments, positive excursions in MS could be interpreted as either changes in the detrital or diagenetic magnetic mineralogy or a mixture of both.

Using MS to Identify Slope Failure Deposits on the Cascadia Margin

In this article we focus on the slope failure record at ODP Site 1252, which is located on the eastern flank of Hydrate Ridge, just upslope from an anticline that has served to trap sediments derived from the crest of Hydrate Ridge (Figure 2). Eastward of this fold is a deeper adjoining slope basin, which was cored at ODP Site 1251 and ultimately receives most of the slope failures originating on the crest and eastern flank of Hydrate Ridge (Figure 2). Examination of the 3-D seismic and core data at Site 1252, shows a thick wedge of sediments near the base of the slope basin sequence that is acoustically chaotic and truncated against an uplifted anticline (Figure 2). Sediment from this interval contains some clay clast debris flow deposits within a generally silty clay stratigraphy (Tréhu *et al*., 2003). The MS in this same interval is generally high, compared to the background, baseline MS, and marks the beginning of an apparent cycle of four high MS zones (Figure 3, A-D). Correlation of the uppermost high MS zone (A) with the uppermost seismically defined and cored debris flow and turbidite deposits father down slope at Site 1251 (Johnson *et* *al*., 2010), suggests this and the lowermost MS high (D) or at least 2 of the 4 high magnetic susceptibility zones at Site 1252 are related to slope failures. Absent from all 4 of the high MS zones, are visible sand or silt beds comparable to those observed at IODP Site U1325B offshore Vancouver Island, where visual core descriptions of sand and silt beds of various thickness are well correlated with the positive MS values that deviate from a low baseline MS of hemipelagic clay (Figure 4). This suggests that the origin of the MS highs at ODP Site 1252 may be related in part to the presence of diagenetic magnetic iron sulfides. However, rock magnetic measurements at Site 1252 (Larrasoaña *et al*., 2006) reveal that in the interval that contains the four highs in MS, the magnetic mineralogy is consistent with the presence of magnetite (Figure 3). The increases in MS are thus most likely tracking concentrated zones of detrital magnetite associated with slope failure deposits, rather than concentrations of diagenetic iron sulfides. To investigate this further, we examined the pattern of total organic carbon (TOC) and Sulfur (S) abundance down core at Site 1252 (Figure 3). These data show that the highest concentrations of TOC and S occur in the intervening low MS intervals. The association of high TOC with fine grained clay is consistent with slow settling of particulate organic carbon during fine grained suspension dominated sedimentation. The increases in bulk sulfur concentration are likely tracking

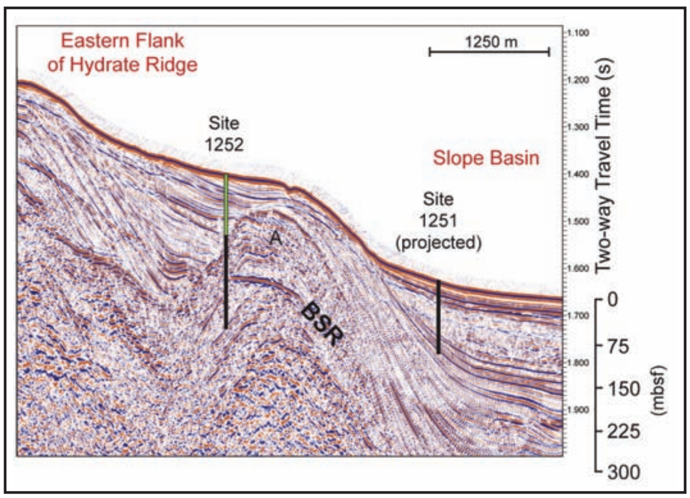

Figure 2: Multichannel seismic reflection data at ODP Site 1252 (with Site 1251 projected). Notice the slope basin sediments at Site 1252 (shown in green) that have accumulated against the uplifted anticline (A) on the eastern flank of Hydrate Ridge.

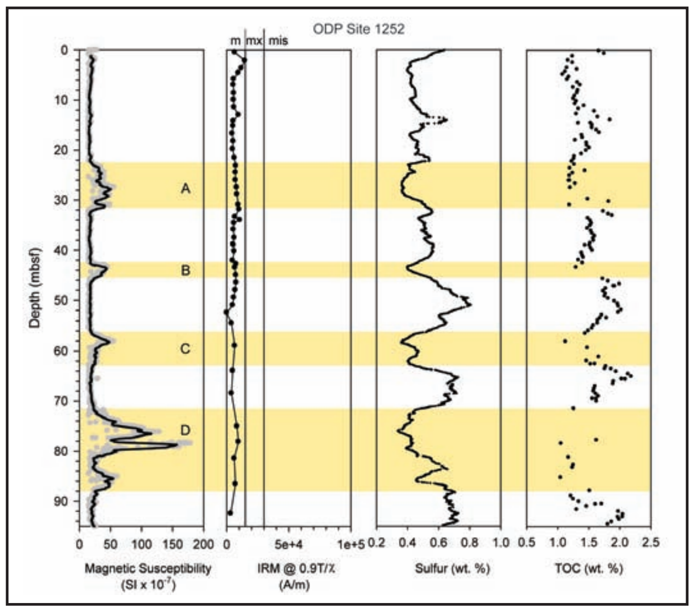

Figure 3: Down core measurements of MS, IRM (isothermal remnant magnetization), bulk Sulfur from XRF (calibrated from unpublished S data courtesy of Ji-Hoon Kim, Oregon State University), and TOC (total organic carbon) for Site 1252 Hole A at Hydrate Ridge, offshore central Oregon. IRM data and interpreted magnetic mineralogy (M = magnetite, MX= mixed magnetite and magnetic iron sulfides, and MIS = magnetic iron sulfides) from Larrasoaña et al. (2006). Notice the lack of MIS or MX mineralogy within the four high MS zones (A-D, marked in yellow) and the corresponding low sulfur and TOC contents. MS zone D is observed on the seismic data (Figure 2) as the chaotic wedge of sediments near the base of the slope basin sequence and contains both debris flow and silty clay deposits. MS zone A is equivalent to the thick, chaotic, seismic wedge cored at Site 1251 (Figure 2), where debris flows and sand and silt turbidites were recovered. MS zones B and C contain non-distinct cores of silty clay and clay, however, the MS, TOC, Sulfur, and magnetic mineralogy characteristics suggest these two zones are slope failure dominated as well.

pyrite abundance, which is greater in the presence of abundant, labile TOC (Berner, 1984). Framboidal pyrite was observed in smear slides examined throughout the record at Site 1252 and black iron sulfide precipitates were visible on the split core surfaces within the fine grained portions of the core (Tréhu *et al*., 2003).

The concentrations of magnetite that result in the four MS highs observed at ODP Site 1252 most likely formed from density sorting associated with an increase in slope failures in these intervals. These episodes of slope failure are separated by lower MS, TOC-rich, and S-rich hemipelagic clays, which formed from the slow vertical accumulation of suspended particles. Bioturbation may have disrupted any original, coarser beds associated with the slope failure episodes or the deposits in these intervals may represent the fine grained, proximal remnant of slope failures that continued to travel down slope, a model consistent with additional seismic data that show all four events may have correlative, deeper, and thicker, seismic equivalents near ODP Site 1251 (Johnson *et al*., 2010).

Conclusions

Characterizing primary and secondary sedimentary processes and products in gas hydrate-bearing stratigraphy is important to accurately reconstruct depositional environments and diagenetic processes associated with carbon cycling and gas hydrate dynamics. Given the potential mixed signal of MS in gas hydrate-bearing stratigraphy, we caution the use of MS as a way to track detrital mineral concentrations associated with slope failure unless independent rock magnetic measurements can rule out the presence of diagenetic magnetic iron sulfides. In our case, without the IRM data at ODP Site 1252, the lack of visible core evidence of slope failure may have led us to speculate that the two middle MS anomalies were diagenetic in origin. In addition, proper tracking of detrital and diagenetic mineral phases in gas hydrate bearing regions may also allow us to examine possible relationships between slope failure and paleo-methane flux in gas hydrate-bearing regions (e.g. Hong *et al*., 2010).

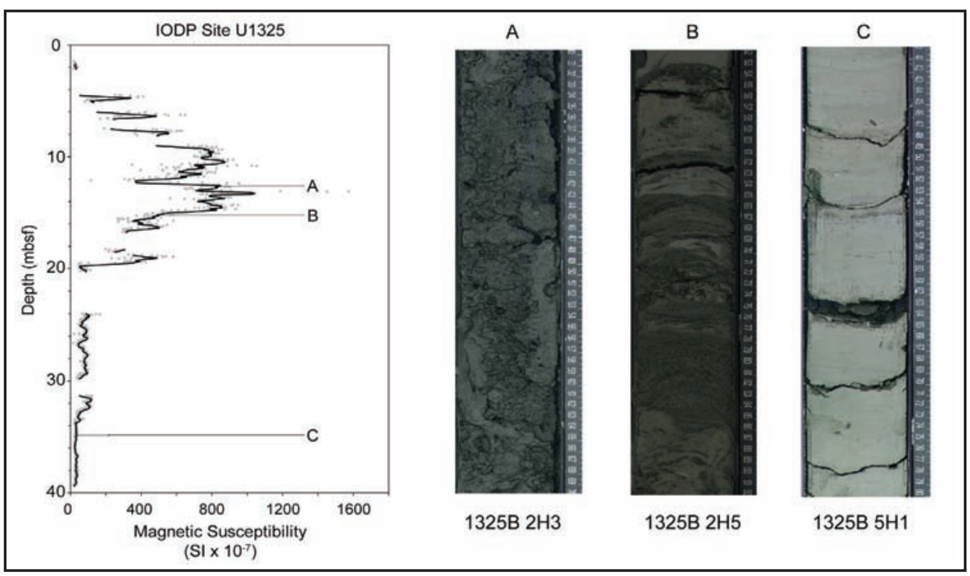

Figure 4: MS record at Site U1325 Hole B, offshore Vancouver Island and selected core photos. (A) Thick, massive sand turbidite and (B) thin turbidite sand beds correlate with high MS values. (C) Hemipelagic clay dominated interval that corresponds with low MS.

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