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Research paper

Compressional and shear-wave velocities from gas hydrate bearing sediments: Examples from the India and Cascadia margins as well as Arctic permafrost regions

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A B S T R A C T

Shear wave velocity data have been acquired at several marine gas hydrate drilling expeditions, including the India National Gas Hydrate Program Expedition 1 (NGHP-01), the Ocean Drilling Program (ODP) Leg 204, and Integrated Ocean Drilling Program (IODP) Expedition 311 (X311). In this study we use data from these marine drilling expeditions to develop an understanding of general grain-size control on the P- and S-wave properties of sediments. A clear difference in the downhole trends of P-wave (Vp) and S-wave (Vs) velocity and the Vp/Vs ratio from all three marine regions was observed: the northern Cascadia margin (IODP X311) shows the highest P-wave and S-wave velocity values overall and those from the India margin (Expedition NGHP-01) are the lowest. The southern Cascadia margin (ODP Leg 204) appears to have similar low P-wave and S-wave velocity values as seen off India. S-wave velocity values increase relative to the sites off India, but they are not as high as those seen on the northern Cascadia margin. Such regional differences can be explained by the amount of silt/sand (or lack thereof) occurring at these sites, with northern Cascadia being the region of the highest silt/sand occurrences. This grain-size control on P-wave and S-wave velocity and associated mineral composition differences is amplified when compared to the Arctic permafrost environments, where gas hydrate predominantly occurs in sand- and silt-dominated formations. Using a cross-plot of gamma ray values versus the Vp/Vs ratio, we compare the marine gas hydrate occurrences in these regions: offshore eastern India margin, offshore Cascadia margin, the Ignik-Sikumi site in Alaska, and the Mallik 5L-38 site in the Mackenzie Delta. The log-data from the Arctic permafrost regions show a strongly linear Vp–Vs relationship, similar to the previously defined empirical relationships by Greenberg and Castagna (1992). P- and S-wave velocity data from the India margin and ODP Leg 204 deviate strongly from these linear trends, whereas data from IODP X311 plot closer to the trend of the Arctic data sets and previously published relationships. Three new linear relationships for different grain size marine sediment hosts are suggested:

a) mud-dominated (Mahanadi Basin, ODP Leg 204 & NGHP-01-17): $Vs = 1.5854 \times Vp - 2.1649$
b) silty-mud (KG Basin): $Vs = 0.8105 \times Vp - 1.0223$
c) silty-sand (IODP X311): $Vs = 0.5316 \times Vp - 0.4916$

We investigate the relationship of gas hydrate saturation determined from electrical resistivity on the Vp/Vs ratio and found that the sand-dominated Arctic hosts show a clearly decreasing trend of Vp/Vs ratio with gas hydrate saturation. Though limited due to lower overall GH saturations, a similar trend is seen for sites from IODP X311 and at the ash-dominated NGHP-01-17 sediment in the Andaman Sea. Gas hydrate that occurs predominantly in fractured clay hosts show a different trend where the Vp/Vs ratio is much higher than at sand-dominated sites and remains constant or increases slightly with increasing gas hydrate saturation. This trend may be the result of anisotropy in fracture-dominated systems, where P- and S-wave velocities appear higher and Archie-based saturations of gas hydrate are overestimated. Gas hydrate concentrations were also estimated in these three marine settings and at Arctic sites using an

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effective medium model, combining P- and S-wave velocities as equally weighted constraints on the calculation. The effective medium approach generally overestimates S-wave velocity in high-porosity, clay-dominated sediments, but can be accurately used in sand-rich formations.

1. Introduction

Over the past decade, several drilling expeditions in the on- and offshore were conducted to study gas hydrate occurrences, specifically with an aim to estimate their significance as a potential future energy resource, natural geohazard, and/or potential driver in climate change. Regions studied include the Mallik drill site in the Mackenzie Delta (e.g. Dallimore and Collett, 2005), and the Alaska North Slope with the Mt. Elbert (e.g. Collett et al., 2011; Hunter et al., 2011) and Ignik-Sikumi (e.g. Schoderbek et al., 2012, 2013) drill sites. In the offshore, deep drilling was performed on the southern and northern Cascadia margin, off India, China, South Korea, the eastern US margin (Blake Ridge), and the US Gulf of Mexico. Among these drilling expeditions we have chosen three marine expeditions for which extensive wireline logging programs were conducted: (1) Ocean Drilling Program (ODP) Leg 204 (Tréhu et al., 2003) drilled on the southern Cascadia margin in 2002, (2) Integrated Ocean Drilling Program (IODP) Expedition 311 (X311) drilled on the northern Cascadia margin in 2005 (Riedel et al., 2006), and (3) India National Gas Hydrate Program (NGHP) Expedition 1 (Collett et al., 2008) drilled in 2006 in several basins on the east and west coast off India (Fig. 1).

At the present date, little of the shear-wave velocity data from IODP X311 and the India Expedition NGHP-01 have been published and we use the compilation of all the various data sets from all sites at all three margins to derive first-principle observations on the shear wave (or S-wave, Vs) and compressional (or P-wave, Vp) velocity values for the gas-hydrate-bearing and gas-hydrate-free sediments. Specifically, we derive the Vp/Vs ratio and use trends in the data to help define the base of the gas hydrate stability zone (GHSZ), which often is difficult to identify from log-measurements of electrical resistivity or P-wave velocity alone.

Typically, gas hydrate concentrations are estimated using well logs, often the electrical resistivity log following modifications to the simple Archie's relationship (e.g. Collett and Ladd, 2000; Hyndman et al., 1999; Malinverno et al., 2008) or various rock-physics models applied to P-wave velocity log measurements (e.g. Dvorkin et al., 1999; Helgerud et al., 1999; Chand et al., 2004). These results are combined with core-based approaches using pore-fluid chemical proxies, such as chlorinity (or salinity) freshening (e.g. Hesse and Harrison, 1981; Kastner et al., 1995; Ussler and Paull, 2001) to estimate gas hydrate concentrations. Using S-wave velocity as proxy to estimate gas hydrate concentrations has rarely been attempted (e.g. Carcione and Gei (2004) and Lee and Collett (2005) for logs from Mallik 2L-38 and 5L-38, Guerin et al. (2006) and Lee and Collett (2006) for drill sites from ODP Leg 204 and Guerin et al. (1999) for Sites from ODP Leg 164). In many marine environments, gas hydrate concentrations are relatively low (e.g., <5% of the pore volume, on average at the Southern Hydrate Ridge, Tréhu et al., 2004) and the effect of gas hydrate on P- and S-wave

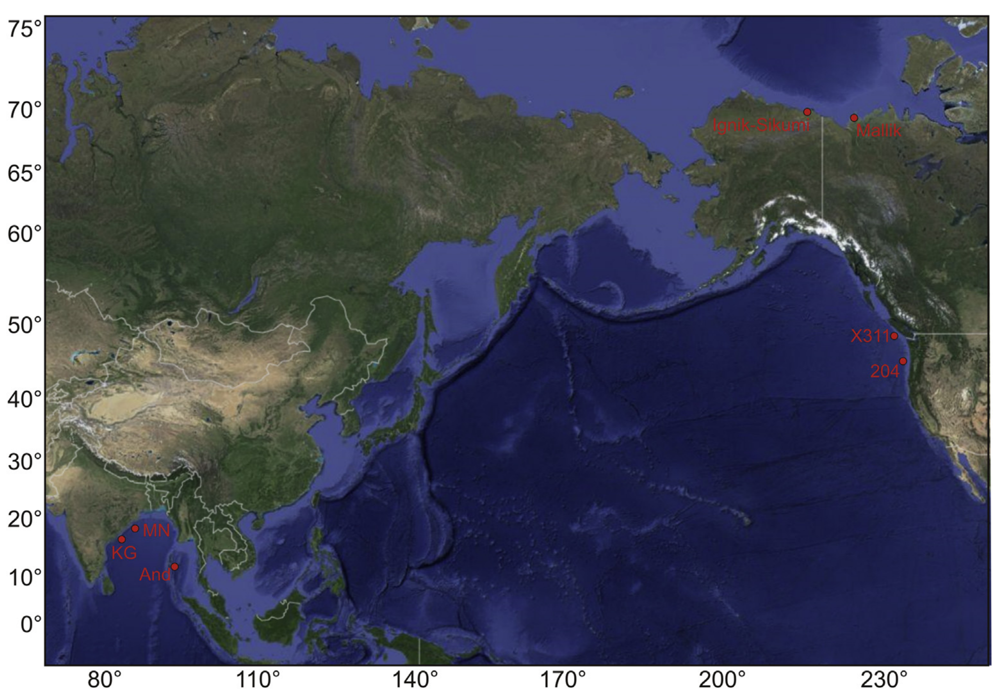

Figure 1. General locations of all drill sites used in this study: Mallik 5L-38 in the Mackenzie Delta, NWT, Canada; Ignik-Sikumi on the Alaska North Slope; IODP Expedition 311 (X311) transect off Vancouver Island on the northern Cascadia margin (Sites U1325 – U1328); ODP Leg 204 (1244–1252) on the southern Cascadia margin; India NGHP Expedition 01 sites in the Krishna-Godavari (KG) Basin (Sites NGHP-01-03, -05, -07, -14, -15, -16), and Mahanadi (MN) Basin (Site NGHP-01-19), and Site NGHP-0-17 in the Andaman Sea (And).