On the consolidation state of sediments from the accretionary prism offshore Vancouver Island, North Cascadia Margin

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Received: 7 December 2021 / Accepted: 11 May 2022
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Abstract
Sediment geotechnical properties are an important component of geohazard analyses and studies on submarine slope failures on continental margins. The northern Cascadia margin is a region of repeated subduction earthquakes and related geohazards including devastating tsunamis. Despite several drilling campaigns at this margin mostly for gas hydrate studies, sediment geotechnical properties are lacking to date. We therefore investigated a set of 20 half-round samples from four drill sites of Integrated Ocean Drilling Program (IODP) Expedition 311 along a margin-perpendicular transect. Samples were analysed for Atterberg properties (liquid limit, plasticity limit, plasticity index) and consolidation state (pre-consolidation stress, over-consolidation ratio, initial void ratio and compression index). Results of these parameters are in good agreement with similar studies at the southern Cascadia margin from Ocean Drilling Program (ODP) Leg 204 and are regarded robust, despite the long time-span between sample recovery in 2005 and our analyses. Individual results are interpreted at each of the drill sites and reflect the overall tectonic state of the location within the accretionary prism. An interplay of site-specific tectonic forcing, including thrust faulting, uplift, folding, and erosion appears to govern the depth-dependent consolidation state of the sediments.

Keywords Consolidation of marine sediments · Cascadia margin · IODP Expedition 311 · Physical properties of sediments · Accretionary prism deformation · Gas hydrates

Introduction
A transect of four drill sites (U1325, U1326, U1327, and U1329) across the northern Cascadia margin was established during Integrated Ocean Drilling Program (IODP) Expedition 311 (X311) to study gas hydrate occurrences in accretionary prisms (Riedel et al. 2006a). The four transect sites were selected to stretch across the accretionary prism (Fig. 1) from the first accreted ridge (Site U1326) near the deformation front and the first inter-ridge slope-basin (Site U1325), to the second accretionary ridge and plateau (Site U1327) and the eastward limit of gas hydrate occurrence on the continental slope in water depth ~960 m (Site U1329). Sediments on the incoming plate (west of the deformation front) were drilled during Ocean Drilling Program (ODP) Leg 146 at Site 888 (Westbrook et al. 1994). Thus, the drill sites represent different stages in space and time of the evolution of the accretion process in response to subduction of the Juan de Fuca plate (e.g. Hyndman et al. 1990; Hyndman 1995; Riedel et al. 2006b; Scherwath et al. 2006), and associated gas hydrate formation (Hyndman and Davis 1992; Riedel et al. 2010).

At all drill sites investigated here, a strong seismic reflection was seen at the base of the gas hydrate stability zone (GHSZ), the so-called bottom-simulating reflector (BSR). A combination of geochemical data (gas hydrate dissociation related pore-fluid freshening upon core-recovery), core infra-red (IR) imaging, geophysical logging (P-wave velocity and electrical resistivity), in situ temperature measurements, and seismic observations of BSRs indicated that the base of the GHSZ matches the expected depth of a theoretical methane-dominated system in equilibrium with a hydrostatic pressure regime and the site-specific background pore-water salinity (Riedel et al. 2010). In situ gas hydrate concentrations (Sh, reported...
here as percent of pore-space filled with hydrate) were estimated at all sites from different techniques: logging-based electrical resistivity and P-wave velocity, pore-fluid chlorinity freshening, pressure core degassing, and IR imaging (e.g., Chen 2006; Malinverno et al. 2008; Chen et al. 2008; Torres et al. 2008; Pan et al. 2020). All techniques show overall low average concentrations of < 10% of the pore space (Fig. 2). Few exceptions of this general trend were found, e.g., at Site U1327 in a short interval between 115 and 140 m below seafloor (mbsf), where Sh is 40–60%, or within several cm-thick gas hydrate bearing sandy turbidite layers at Site U1326 at ~ 50 mbsf, with Sh values of > 60% (Torres et al. 2008). The distribution of gas hydrate is heterogenous and mostly driven by lithology (occurrence preferably in more coarse-grained sediment) and availability of methane (e.g. Malinverno et al. 2008; Malinverno 2010; Riedel et al. 2010). Against early predictions of the pore-fluid expulsion model (Hyndman and Davis 1992; Hyndman et al. 1993), the highest concentrations of gas hydrate are not generally found at greater depth above the BSR (Fig. 2), thus resulting in a more variable depth-profile of sediment strength from gas hydrate cementing.

While most of the initial work conducted during and after IODP X311 was focused on gas hydrate occurrences and formation processes, little attention has been paid to the geotechnical parameters of the sediments recovered. Standard physical properties (porosity, bulk- and grain density, thermal conductivity, shear strength) were conducted onboard on the recovered core and continuous logging data of bulk-density, porosity, electrical resistivity, P- and S-wave velocity were determined from logging-while-drilling (LWD) and wire-line logging at each site (see site-specific chapters on ‘Physical properties’ and ‘Downhole logging’ of the IODP X311 proceedings volume, Riedel et al. 2006a).

The aim of this study was to measure geotechnical parameters of sediments representing the major lithologies found along the IODP X311 drilling transect as a base for subsequent more detailed work on e.g. geohazards and sub-marine landslides. As indicated in previous work (e.g., Scholz et al. 2016), slope-failure initiation requires slope-preconditioning in addition to a trigger mechanism (e.g. earthquake shaking).
Such pre-conditioning may be related to gas hydrate dissociation and/or the presence of in situ overpressure. One possible way of overpressure estimation was described by Schneider et al. (2009) for drill sites in the Ursa Basin, Gulf of Mexico, combining downhole logging data of porosity and density with core-sample derived geotechnical properties. Yet, the critical sediment geotechnical properties (e.g. compression index or over-consolidation ratio) are missing to date for the northern Cascadia Margin.

Using the LWD- and wire-line log-data from IODP X311 and previous drilling during ODP Leg 146, Riedel et al. (2016a) defined borehole breakouts and fracture orientations to assess the horizontal stress regime along the main drilling transect. The borehole deformation observed is mainly dominated by the margin-perpendicular compression (from subduction), with an additional local overprint from faulting and gas-hydrate-related fracturing. Although the orientation of the horizontal stress is well-defined from the borehole breakout data, the magnitude of the horizontal stress compared to overburden is poorly constrained (Riedel et al. 2016a). Estimating the magnitude of the horizontal compressive stress requires laboratory-derived unconfined compressive strength values of the sediment (e.g. Zoback et al. 2003; Lin et al. 2013). This may allow determining the potential for trench-breaching tsunamiogenic rupture of a future megathrust earthquake at Cascadia, similar to the Tohoku-Oki earthquake off Japan in 2011 (see e.g. Tajima et al. 2013 for a review).

One study to define geotechnical properties was previously conducted for sediments at Hydrate Ridge on the southern Cascadia margin as part of ODP Leg 204 (Tan et al. 2006). However, values obtained at Hydrate Ridge are not necessarily applicable to the northern Cascadia margin as e.g. the background sediments are different (mineralogic composition, grain-size), as noted by Torres et al. (2008) and Riedel et al. (2010) upon comparing the abundance of gas hydrate occurrences in sand/silt within both regions.

Here, we report the results of determining geotechnical properties of sediments from the four Sites U1325, U1326, U1327, and U1329 along the margin-perpendicular transect. Samples represent the main lithologic units cored along the transect (Table 1) and represent the two main seismo-stratigraphic sediment types of (i) shallower, well-stratified slope-sediments above (ii) older, accreted sediments characterized by strong folding and faulting, often lacking coherent seismic reflectivity. Grain-size and clay-mineralogic composition was defined and compared to the available data base from onboard measurements to verify sample integrity. Consolidation parameters were defined and are put into the geologic and tectonic framework around the drill sites using the available seismic reflection images at each drill site.

With this study on sediment geotechnical properties along northern Cascadia, we are aiming to not only provide the necessary data sets for advanced analyses related to slope-failure and overpressure, but also describe first-order principles of consolidation along the margin and address the following questions:

(1) Do the accreted and slope-sediments show distinctly different geotechnical properties?
(2) Is there a depth-dependent change in consolidation behaviour of the sediments at the drill sites and is such change associated with the known gas hydrate distribution or linked to the deformation history around the sites?

These questions are rather basic, though key in defining potential trigger mechanisms for failure and investigating pre-conditioning factors. The answers can help us understand if the boundaries between the major lithological units could act as weak zones and thus promote slope failure, or...
whether the presence of gas hydrate has a significant impact on overall sediment integrity (cementation effect), strength and thus resistance to failure.

Methods

Sampling strategy and standard analyses

A total of twenty subsamples were selected (sample request 041951IODP) from recovered cores taken during IODP Expedition 311 (Riedel et al. 2006a). Sub-samples were taken at the four drill sites along the margin-perpendicular transect (Sites U1326, U1325, U1327, and U1329). The sub-samples were taken from depths ranging between 24 and 185 m below seafloor (mbsf) and represent the major lithologic units encountered, as listed in Table 1. With the exception of one sample (U1326C-8X-1, at 60.21 mbsf), the sediment did not contain any in-situ gas hydrate verified by the absence of any infra-red (IR) thermal anomaly upon core recovery and absence of pore-water freshening nearby (see detailed results in the online Expedition data base, Riedel et al. 2006a). Samples were extracted in July 2018 from the remaining working half at the IODP core repository in College Station, Texas, USA, and shipped to the laboratory of MARUM in Bremen, Germany. All samples showed significant loss of the original water content, which is no surprise given the time span of ~12 years since cores were recovered. To overcome the drying in the core repository, sediment was re-saturated with de-ionised water prior to testing. The bulk mineralogical composition of all samples was analysed using X-ray diffraction analysis (following Bahr et al. 2008). Additional analyses conducted include grain size, index properties (porosity, bulk density, grain density), and Atterberg limits (liquid limit (LL), plastic limit (PL), plasticity index (PI)). The Atterberg limits were determined using a Casagrande apparatus.

Compression tests

Sediment samples were tested using an Oedometer device at the MARUM geotechnical laboratory. Samples were prepared for all experiments by trimming from half-round core samples to form a cylinder with diameters of 26–28 mm and heights of 16–18 mm. For all experiments, two porous dishes of 6 mm height were put in place at the base and top of
samples to ensure homogenous distribution of pore fluid to sample faces. For uniaxial tests, the sample containing ring was placed inside the consolidation chamber to ensure zero lateral strain conditions. Seawater with a salinity of 35 g/L was used during experiments to submerge the samples to simulate the conditions found at the Cascadian margin. The applied vertical stress ($\sigma_v$) was incremented by factor of two every 24 h. A load of 50 kPa to 6.4 MPa was applied on specimens with surface area of approximately 5–6 cm$^2$. The loads were exerted on to the samples mechanically with the help of a weight hanger. The compression experienced by the samples were measured by a compression dial gauge. Loading sequences for all samples during the consolidation test depended on the range of compression stresses which were calculated using the depth below seafloor ($h$) attributed to the sample location and bulk density ($\rho$) used for evaluating current hydrostatic effective vertical stress ($\sigma_e$).

**Estimating consolidation parameters**

To estimate the pre-consolidation stress ($\sigma_{pc}$) the basic initial data set consists of the time-series of change in sample-height during the incremental weight increase. The data were then interpreted by using the widely-used empirical method proposed by Casagrande (1936) plotting void ratio ($e$) against the logarithm of applied vertical stress, as well as the method described by Onitsuka et al. (1995) using a plot of natural logarithm of the value ($1 + e$) against the logarithm ($\log_{10}$) of applied vertical stress. The hydrostatic effective vertical stress was calculated as difference between overburden stress (using sediment bulk density values from the drilling expedition) and hydrostatic pressure at the sample depths. These analyses also yield information on the compression index ($C_{cv}$), the initial void ratio ($e_0$), and over-consolidation ratio (OCR). The coefficient of volume compressibility ($m_v$) is defined from the changes in void ratio and pressure along the consolidation line (beyond $\sigma_{pc}$). If sufficient data points (more than 2) are available beyond the value of $\sigma_{pc}$, then a mean value of $m_v$ and a standard deviation is calculated.

Uncertainties for the geotechnical parameters OCR, $C_{cv}$, $e_0$, and $\sigma_{pc}$ defined by the Casagrande technique on the oedometer data are numerically difficult to estimate as the definition of the tangents to the compression curve is strongly user-dependent and can thus be biased. We therefore use error-propagation to define a standard deviation from linear regression analyses based on the Onitsuka-technique for $\sigma_{pc}$ and OCR (in the $\log_{10}(P)$ vs. $\ln(1 + e)$ domain) as well as for $C_{cv}$ and $e_0$ (in the $\log_{10}(P)$ vs. e-domain). Here, linear regression is implemented based on an algorithm for total least squares that allows incorporating uncertainties in each data point individually. Uncertainty for the total depth of the sample (and thus calculation of overburden) is regarded small in comparison to the magnitude in uncertainty from the oedometer data analyses described above. Core-recovery was typically high and the depth-uncertainty does not add up cumulatively throughout the cored interval as it is practically reset for each new core taken. Also, bulk density values do not vary drastically across the cored interval and impact pressure calculations insignificantly. For the purpose of error-propagation and total least squares we defined the error of the overburden pressure to be 5%.

**Tests of remoulded samples**

We analysed several samples after remoulding and complete saturation with deionized water to verify if the geotechnical properties determined on original samples are reliable. Sediment samples were chosen from Site U1327, representing the major lithologies of accreted and slope-sediments found along the northern Cascadia margin. Prior to the consolidation test in the oedometer, the samples were set to equilibrate for three days, allowing for complete swelling of clay minerals. After that, the remoulded samples were treated in the same fashion with similar weight-increments, as done for the original samples described above.

**Results**

Initially, the sub-sample locations were defined to represent all major lithologies found along the drill sites of IODP X311 using the visual core description as guidance. While the finally chosen intervals of each sample did vary from the original proposed location due to actual sediment availability (working halves had already been intensely sampled) and to ensure reliable sample quality, we ran standard index properties, grain-size, and mineralogical analyses to verify, whether the samples are matching the various lithologies (and are not mis-representative outliers).

**Index properties**

The bulk density and porosity values (Table 2, Fig. 3) agree well with the data obtained at sea (moisture-and-density, MAD) and well-log data (here we show results of the EcoScope LWD tool). If samples were too dry, the determination of porosity on our samples would tend to show lower values than those obtained at sea. Samples from Site U1327 show the largest reduction in porosity but bulk density values appear to agree with MAD and LWD data. All other samples appear to agree well with the data obtained at sea.
Grain size, sediment mineralogy, and Atterberg parameters

The grain-size analysis revealed that most samples are either clayey silt or silty clay (Table 3, Fig. 4) as no sand-rich samples remained for our analyses, consistent with the major lithologies defined from visual core descriptions (Table 1) and onboard data (Wang et al. 2007; Hashimoto and Minamizawa 2009). Sand-rich samples were mostly taken at sea as they were often gas hydrate-bearing and underwent gas hydrate-specific analyses (Torres et al. 2008). Results on the clay-mineralogy analyses reveal that our samples are representative of the general trend in sediment character at each site (Bahr et al. 2008; Bartier et al. 2008). The dominate clay-species are illite and chlorite, with minor amounts of smectite and kaolinite (Table 4, Fig. 5).

A cross plot of the Atterberg properties (Table 5) liquid limit and plasticity index reveals that our samples are mostly falling into the domain of high-plasticity clays and silts (Fig. 6), corresponding to the main lithologies sampled and grain-sizes determined. Only one sample from Site U1326 near the deformation front falls within the domain of a low-plasticity clay. The values derived show no site-specific trend along the drilling transect nor a specific depth-behaviour (Fig. 7). Overall, the values from IODP X311 compare well to those obtained at Hydrate Ridge from ODP Leg 204 on the southern Cascadia margin (Tan et al. 2006).

Consolidation parameters

Results on the pre-consolidation stress value ($\sigma_{pc}$), initial void ratio ($e_0$), and compression index ($C_c$) of the subsamples are listed in Table 6 and shown in Fig. 8. The parameters of the individual steps of the oedometer tests conducted are summarised in the Table 7. Using the depth of each sample and average bulk density of the sediment as defined from physical property analyses, the current overburden stress and thus over-consolidation ratio (OCR) was calculated. Comparing these values (Fig. 8), no specific trend along the drilling transect can be identified in any of the parameters. Theoretically, $\sigma_{pc}$ should be increasing with depth representing simple burial with no erosion, uplift, or overpressure acting on the sample's history. However, our obtained values of $\sigma_{pc}$ are more variable and do not follow this trend uniformly. The largest $\sigma_{pc}$ values are found for samples with uncommon nature: (i) the sample from Site U1327 was a stack of several thin silt layers (Fig. A1a), and (ii) the sample from Site U1326 was noted to have contained gas hydrate in situ (defined from IR imaging) and had disintegrated upon dissociation. Excluding those two samples, $\sigma_{pc}$ increases with depth at

| Core-ID | Depth within section (cm) | Depth (mbsf) | Initial water content | Final water content | Grain density (g/cm³) | Bulk density (g/cm³) | Porosity |
|---------|--------------------------|-------------|----------------------|---------------------|-----------------------|----------------------|----------|
| U1325B-4H-3 | 88–96                  | 27.74       | 0.57                 | 0.35                | n.d                   |                      |          |
| U1325B-6H-1 | 30–40                  | 43.35       | 0.46                 | 0.29                | 2.39                  | 1.57                 | 0.60     |
| U1325B-6H-1 | 114–124                | 44.19       | 0.33                 | 0.23                | 2.46                  | 1.70                 | 0.53     |
| U1325B-14X-2 | 32–42                  | 104.37      | 0.4                  | 0.28                | 2.57                  | 1.69                 | 0.57     |
| U1325B-14X-2 | 90–100                 | 104.75      | 0.37                 | 0.22                | 2.47                  | 1.67                 | 0.56     |
| U1325B-24X-5 | 63–73                  | 184.95      | 0.26                 | 0.22                | 2.34                  | 1.74                 | 0.46     |
| U1326C-8X-1a | 47–57                  | 60.21       | 0.21                 | 0.20                | 2.38                  | 1.88                 | 0.37     |
| U1326D-2X-5 | 80–90                  | 95.25       | 0.25                 | 0.17                | 2.43                  | 1.85                 | 0.412    |
| U1326D-10X-2 | 34–44                  | 167.49      | 0.15                 | 0.20                | 2.05                  | 1.75                 | 0.296    |
| U1327C-4H-3 | 120–130                | 29.35       | 0.446                | 0.29                | 2.88                  | 1.84                 | 0.562    |
| U1327C-5H-6 | 94–104                 | 43.09       | 0.274                | 0.28                | 2.87                  | 2.08                 | 0.431    |
| U1327C-8H-1b | 28–38                  | 55.93       | 0.167                | 0.19                | 2.72                  | 1.99                 | 0.431    |
| U1327C-10H-6 | 33–43                  | 81.13       | 0.282                | 0.16                | 2.34                  | 1.76                 | 0.439    |
| U1327C-12X-4 | 130–136                | 97.58       | 0.327                | 0.21                | 2.54                  | 1.80                 | 0.489    |
| U1327C-21X-1 | 63–73                  | 171.08      | 0.196                | 0.18                | 2.33                  | 1.87                 | 0.359    |
| U1329C-11H-2 | 90–100                 | 88.55       | 0.33                 | 0.25                | n.d                   |                      |          |
| U1329C-12H-3 | 64–74                  | 99.27       | 0.27                 | 0.19                | 2.73                  | 1.76                 | 0.568    |
| U1329C-12H-6 | 40–50                  | 103.53      | 0.47                 | 0.34                | 2.46                  | 1.70                 | 0.529    |
| U1329C-21X-4 | 132–142                | 175.02      | 0.228                | 0.20                | 2.87                  | 2.13                 | 0.400    |

aSample contained gas hydrate in situ, (Fig. 1a)
bSample consisted of finely stacked silt-layers (Fig. 1b)

Table 2 Index properties of sediment samples analysed
Sites U1326 and U1327. Values for Site U1325 also show a deviation from a simple increasing trend with depth in the interval between 43 and 104 mbsf, whereas values at Site U1329 decrease with depth.

Overall, many OCR-values are larger than 1 (Fig. 8b) indicating that samples are over-consolidated relative to their present burial depths. Generally, OCRs tend to slightly decrease with depth at each drill site, similar to the initial void ratio. Only at Site U1329, OCR values of all samples are above 1. The hydrostatic effective pressure (difference between overburden and hydrostatic load) increases linearly with depth for all samples and all sites (Fig. 8e).

Comparing compression index and initial void ratio, a general linear relationship may exist in the data set,
except for the two outliers noted already above (Fig. 9). The anomalous sample from Site U1327 shows the highest compression index overall (nearly 0.9) but the sample consisted of thinly layered silt-beds between muds (Fig. A1a). The anomalous sample from Site U1326 (initially gas hydrate bearing) showed a low initial void ratio but a comparably high compression index. The dissociation of the gas hydrate upon core recovery resulted in a soupy- to mousse-like sediment texture (Fig. A1b) which, given the time between sample recovery and the actual analyses, may have obscured the outcome of the oedometer test.

The Atterberg parameter of liquid-limit was proposed to show a linear relationship with the compression index for clays (e.g. Skempton 1944; Tripathy and Mishra 2011). Our data also reveal a linear relationship despite some scatter with a slightly lower gradient-value of 0.006 instead of the previously defined value of 0.007 by Skempton (1944) (Fig. 10).

### Test on remoulded samples

To test whether the analyses done are at all representative, we completed a set of oedometer tests on remoulded samples (see Fig. A3). We selected samples representing slope-sediments at burial depth of 40–50 mbsf and accreted sediments at burial depths larger than 100 mbsf from Site U1327. The oedometer test of the remoulded sample yields in both cases the same virgin compression line and compression index $C_c$ than from the original sample. The history of the samples was fully removed by the remoulding process as seen by a steady decline of void ratio values with increasing load level, compared to the clearly identifiable break in the curvature of the original sample that allowed defining a pre-consolidation pressure.

### Interpretation and discussion

#### Expected trend from accretionary prism evolution

The consolidation state (best expressed by the OCR values) of sediments is linked to the tectonic environment of each of the drilling sites across the prism. The overall subduction of the Juan de Fuca plate acts as primary force for compression and folding of the sediments along a series of thrust faults (e.g. Hyndman et al. 1990; Fig. 1). Almost all of the sediment deposited on the incoming plate is accreted to the margin (Davis et al. 1990). While the sediments are accreted, deformed and uplifted forming a series of margin-parallel ridges (Fig. 1), deposition of slope-sediments is also ongoing. These slope-sediments are a mix of hemi-pelagic

### Table 3 Grain size composition

| Core-ID          | Depth within section (cm) | Depth (mbsf) | Clay (%) | Silt (%) | Sand (%) |
|------------------|----------------------------|--------------|----------|----------|----------|
| U1325B-4H-3      | 88–96                      | 27.74        | 65       | 35       | 0        |
| U1325B-6H-1      | 30–40                      | 43.35        | 50       | 50       | 0        |
| U1325B-6H-1      | 114–124                    | 44.19        | 68       | 32       | 0        |
| U1325B-10X-2     | 60–70                      | 74.95        | 80       | 17       | 3        |
| U1325B-14X-2     | 32–42                      | 104.37       | 77       | 20       | 3        |
| U1325B-14X-2     | 90–100                     | 104.75       | 50       | 50       | 0        |
| U1325B-24X-5     | 63–73                      | 184.95       | 30       | 70       | 0        |
| U1326C-8X-1a     | 47–57                      | 60.21        | 30       | 60       | 10       |
| U1326D-2X-5      | 80–90                      | 95.25        | 80       | 20       | 0        |
| U1326D-10X-2     | 34–44                      | 167.49       | 81       | 11       | 8        |
| U1327C-4H-3      | 120–130                    | 29.35        | 82       | 18       | 0        |
| U1327C-5H-6      | 94–104                     | 43.09        | 84       | 15       | 1        |
| U1327C-8H-1b     | 28–38                      | 55.93        | 70       | 30       | 0        |
| U1327C-10H-6     | 33–43                      | 81.13        | 70       | 30       | 0        |
| U1327C-12X-4     | 130–136                    | 97.58        | 60       | 10       | 0        |
| U1327C-21X-1     | 63–73                      | 171.08       | 66       | 34       | 0        |
| U1329C-11H-2     | 90–100                     | 88.55        | 39       | 55       | 6        |
| U1329C-12H-3     | 64–74                      | 99.27        | 70       | 27       | 3        |
| U1329C-21X-4     | 132–142                    | 103.53       | 55       | 25       | 20       |

*a Sample contained gas hydrate in situ, (Fig. A1b)

*b Sample consisted of finely stacked silt-layers (Fig. A1a)
sediments and turbidites (silt- to sand-rich) and form a blanket on top of the accreted sediments. During deposition, the blanket of slope-sediments also is progressively deformed and the transition between these two types of sediment can be gradual. Seismically, the accreted sediments appear characteristically with a reflection pattern of low coherency and amplitude. This is contrasted with the high-amplitude and high-coherency slope sediments with pronounced layering.

Fig. 4 Grain size distribution of samples from this study (solid symbols) compared to samples from the onboard analyses (open symbols). Shown are clay-, silt-, and sand-fraction (in percent) for all four drill sites along the transect.
Thrust faulting (not only at the deformation front) results in uplift of the ridges and thus in a change in sedimentation style. Initial rapid, yet sporadic turbidite deposition and mix with hemipelagic sedimentation is replaced over time by the more continuous and slower hemipelagic deposition, as turbidites do not reach the top of ridges any longer. As

![Diagram of clay mineral composition](image)

**Table 4** Clay mineral composition

| Core-ID         | Depth within section (cm) | Depth (mbsf) | Smectite (%) | Illite (%) | Chlorite (%) | Kaolinite (%) |
|-----------------|---------------------------|--------------|--------------|------------|--------------|---------------|
| U1325B-4H-3     | 88–96                     | 27.74        | 10           | 50         | 25           | 10            |
| U1325B-6H-1     | 30–40                     | 43.35        | 10           | 50         | 25           | 10            |
| U1325B-6H-1     | 114–124                   | 44.19        | 10           | 50         | 25           | 10            |
| U1325B-14X-2    | 32–42                     | 104.37       | 20           | 35         | 30           | 15            |
| U1325B-14X-2    | 90–100                    | 104.75       | 20           | 35         | 30           | 15            |
| U1325B-24X-5    | 63–73                     | 184.95       | 20           | 40         | 28           | 12            |
| U1326C-8X-1     | 47–57                     | 60.21        | 24           | 22         | 30           | 14            |
| U1326D-2X-5     | 80–90                     | 95.25        | 20           | 30         | 30           | 10            |
| U1326D-10X-2    | 34–44                     | 167.49       | 15           | 35         | 32           | 10            |
| U1327C-4H-3     | 120–130                   | 29.35        | 20           | 30         | 30           | 10            |
| U1327C-5H-6     | 94–104                    | 43.09        | 10           | 30         | 40           | 10            |
| U1327C-8H-1     | 28–38                     | 55.93        | 30           | 22         | 30           | 10            |
| U1327C-10H-6    | 33–43                     | 81.13        | 15           | 30         | 30           | 15            |
| U1327C-12X-4    | 130–136                   | 97.58        | 25           | 35         | 20           | 10            |
| U1327C-21X-1    | 63–73                     | 171.08       | 10           | 40         | 30           | 10            |
| U1329C-11H-2    | 90–100                    | 88.55        | 20           | 40         | 25           | 5             |
| U1329C-12H-3    | 64–74                     | 99.27        | 5            | 60         | 20           | 5             |
| U1329C-12H-6    | 40–50                     | 103.53       | 5            | 40         | 40           | 5             |
| U1329C-21X-4    | 132–142                   | 175.02       | 30           | 30         | 20           | 10            |

*a* Sample contained gas hydrate in situ, (Fig. A1b)

*b* Sample consisted of finely stacked silt-layers (Fig. A1a)

**Fig. 5** Results of clay mineral composition from semi-quantitative XRD analyses using glycolated slides in addition to solid rock powders. Solid symbols are data from samples analysed in this study and open symbols are data reported by Bartier et al. (2008)
the ridges become gradually steeper over time, erosion and slope failures happen and may lead to locally derived slump-deposits (e.g., Riedel et al. 2018) that are accumulated in the basins between ridges. As the sediments get pushed into the accretionary prism over time they are exposed to different forces, not just vertical pressure from burial, but also horizontal compression and internal deformation (folding). As noted from borehole breakouts, all sites (except Site 888) show characteristic margin-perpendicular horizontal compression from subduction, locally overprinted by thrust-faulting (Riedel et al. 2016a). If the margin-normal compressional stress is greater than the vertical stress (overburden)

| Core-ID     | Depth within section (cm) | Depth (mbsf) | Liquid Limit | Plasticity limit | Plasticity index |
|-------------|---------------------------|--------------|--------------|------------------|-----------------|
| U1325B-4H-3 | 88–96                     | 27.74        | 80.94        | 39.97            | 40.97           |
| U1325B-6H-1 | 30–40                     | 43.35        | 80.7         | 34.27            | 46.44           |
| U1325B-6H-1 | 114–124                   | 44.19        | 59.58        | 30.56            | 29.02           |
| U1325B-14X-2| 32–42                     | 104.37       | 70.13        | 31.22            | 38.91           |
| U1325B-14X-2| 90–100                    | 104.75       | 66.27        | 31.37            | 34.9            |
| U1325B-24X-5| 63–73                     | 184.95       | 58.1         | 31.03            | 27.07           |
| U1326D-2X-5 | 80–90                     | 60.21        | 69.4         | 25.21            | 44.19           |
| U1326D-10X-2| 34–44                     | 95.25        | 34.66        | 20.42            | 14.24           |
| U1327C-4H-3 | 120–130                   | 167.49       | 62.42        | 27.12            | 35.3            |
| U1327C-5H-6 | 94–104                    | 29.35        | 56.28        | 21.56            | 34.74           |
| U1327C-8H-1b| 28–38                     | 43.09        | 52.62        | 25.75            | 26.87           |
| U1327C-10H-6| 33–43                     | 55.93        | 68.85        | 26               | 42.85           |
| U1327C-12X-4| 130–136                   | 81.13        | 54.89        | 27.25            | 27.64           |
| U1327C-21X-1| 63–73                     | 97.58        | 59           | 22.69            | 36.31           |
| U1329C-11H-2| 90–100                    | 171.08       | 70.757       | 40.95            | 29.8            |
| U1329C-12H-3| 64–74                     | 88.55        | 92.81        | 47.97            | 44.84           |
| U1329C-12H-6| 40–50                     | 99.27        | 70.03        | 36.82            | 33.21           |
| U1329C-21X-4| 132–142                   | 103.53       | 60.01        | 26.63            | 33.37           |

\(^b\)Sample consisted of finely stacked silt-layers (Fig. A1a)

Fig. 6 Atterberg-limits for samples from X311 and ODP Leg 204 (Tan et al. 2006). Four zones of low- and high plasticity clay or silt are defined. Most sample from the drilling campaigns are within the high-plasticity clay region, with few near the border to high-plasticity silt. Only one sample from Site U1326 falls inside the low-plasticity clay region.
**Fig. 7** Atterberg parameters (liquid limit and plasticity index) for samples from IODP X311 (solid symbols) and ODP Leg 204 (open squares)

Table 6 Compression parameters obtained from samples of IODP Expedition 311

| Core-ID       | Depth within section (cm) | Depth (mbsf) | σ_{pc} (kPa) | OCR | σ_v (kPa) | σ_h (kPa) | e_0        | Cc        | m_v (× 10^{-5}) |
|---------------|---------------------------|--------------|--------------|-----|-----------|-----------|------------|-----------|-----------------|
| U1325B-4H-3   | 88–96                     | 27.74        | 676 ± 5      | 1.36 ± 0.07 | 498.9    | 279.7     | 2.445 ± 0.032 | 0.526 ± 0.016 | 1.72 ± 0.48    |
| U1325B-6H-1   | 30–40                     | 43.35        | 790 ± 15     | 1.03 ± 0.05 | 763.4    | 437.2     | 1.539 ± 0.03  | 0.349 ± 0.02   | 1.86 ± 0.3     |
| U1325B-6H-1   | 114–124                   | 44.19        | 1175 ± 40    | 1.5 ± 0.09  | 782.8    | 445.6     | 1.197 ± 0.032 | 0.275 ± 0.018  | 1.02 ± 0.15    |
| U1325B-14X-2  | 32–42                     | 104.37       | 3960 ± 5     | 2.1 ± 0.1   | 1889.3   | 1052.5    | 1.426 ± 0.025 | 0.787 ± 0.033  | 1.94 ± 0.48    |
| U1325B-14X-2  | 90–100                    | 104.75       | 2105 ± 140   | 1.1 ± 0.09  | 1906.4   | 1056.4    | 1.438 ± 0.03  | 0.377 ± 0.037  | 1.30 ± 0.25    |
| U1325B-24X-5  | 63–73                     | 184.95       | 2070 ± 75    | 0.61 ± 0.04 | 3390.4   | 1865.2    | 0.920 ± 0.048 | 0.247 ± 0.026  | 0.73 ± 0.12    |
| U1326C-8X-1    | 47–57                     | 60.21        | 4255 ± 10    | 3.76 ± 0.19 | 1132.3   | 607.1     | 0.638 ± 0.032 | 0.626 ± 0.071  | 2.74 ± 0.1     |
| U1326D-2X-5    | 80–90                     | 95.25        | 1480 ± 10    | 0.82 ± 0.04 | 1798.8   | 960.6     | 0.716 ± 0.056 | 0.240 ± 0.026  | 0.76 ± 0.063   |
| U1326D-10X-2   | 34–44                     | 167.49       | 2090 ± 35    | 0.66 ± 0.03 | 3172.0   | 1689.1    | 0.461 ± 0.029 | 0.182 ± 0.036  | 0.68 ± 0.13    |
| U1327C-4H-3   | 120–130                   | 29.35        | 445 ± 15     | 0.9 ± 0.06  | 494.7    | 295.1     | 1.481 ± 0.081 | 0.432 ± 0.025  | 6.0 ± n.d      |
| U1327C-5H-6    | 94–104                    | 43.09        | 440 ± 180    | 0.58 ± 0.24 | 760.9    | 433.4     | 0.816 ± 0.073 | 0.241 ± 0.024  | 2.83 ± 0.89    |
| U1327C-8H-1^b  | 28–38                     | 55.93        | 4990 ± 5     | 5.06 ± 0.25 | 987.6    | 562.4     | 0.519 ± 0.03  | 0.883 ± 0.077  | 3.7 ± n.d      |
| U1327C-10H-6   | 33–43                     | 81.13        | 1590 ± 20    | 1.11 ± 0.06 | 1432.5   | 815.8     | 0.817 ± 0.05  | 0.255 ± 0.04   | 0.49 ± 0.023   |
| U1327C-12X-4   | 130–136                   | 97.58        | 2910 ± 35    | 1.69 ± 0.08 | 1724.5   | 981.2     | 1.00 ± 0.05   | 0.341 ± 0.028  | 0.56 ± 0.026   |
| U1327C-21X-1   | 63–73                     | 171.08       | 2630 ± 1065  | 0.86 ± 0.35 | 3054.0   | 1720.3    | 0.585 ± 0.06  | 0.235 ± 0.1    | 0.59 ± 0.021   |
| U1329C-11H-2   | 90–100                    | 88.55        | 2305 ± 200   | 1.56 ± 0.16 | 1484.3   | 893.6     | 0.809 ± 0.022 | 0.316 ± 0.05   | 0.91 ± 0.23    |
| U1329C-12H-3   | 64–74                     | 99.27        | 1720 ± 5     | 1.03 ± 0.05 | 1664.4   | 1001.3    | 1.427 ± 0.023 | 0.599 ± 0.03   | 2.78 ± 0.26    |
| U1329C-12H-4   | 40–50                     | 103.53       | 1600 ± 45    | 0.92 ± 0.05 | 1735.3   | 1044.4    | 0.986 ± 0.054 | 0.339 ± 0.026  | 1.39 ± 0.16    |
| U1329C-21X-4   | 132–142                   | 175.02       | 2588 ± 185   | 0.87 ± 0.07 | 2963.2   | 1765.0    | 0.733 ± 0.048 | 0.235 ± 0.026  | 0.71 ± 0.032   |

σ_{pc} pre-consolidation pressure, σ_v overburden pressure, σ_h hydrostatic pressure, OCR over-consolidation ratio, e_0 initial void ratio, Cc compression index, m_v coefficient of volume compressibility

^aSample contained gas hydrate in situ, (Fig. A1b)

^bSample consisted of finely stacked silt-layers (Fig. A1a)
the margin-normal stress direction may reflect current locking of a velocity-weakening shallow megathrust. In such a case, calculation of OCRs would yield too large values, as we have underestimated the cumulative forces acting on the sample by assuming only overburden stresses. In the absence of unconstrained compressive strength data, required for the calculation (e.g., Tajima et al. 2013), we simply assume in all following interpretations that vertical overburden stress is larger than horizontal stresses.

The process of building the accretionary prism results overall in a stretch in porosity-depth relationship (Hyndman et al. 1993). At any given depth below seafloor, porosity within the prism should be higher than at the equivalent sub-seafloor depth within the sediment column deposited on the incoming plate, west of the deformation front. We therefore use the porosity data from Site 888 (Fig. 3) as a reference specifically for differentiating accreted sediments from normally deposited slope-sediments. If porosity at the drill sites along the X311 transect is close to the reference for any given depth, sediments may be normally compacted, comparable to what is expected for the abyssal plain Site 888 away from any tectonic forcing. In contrast, if porosity is below the reference trend then this may indicate that sediments have been affected by accretion-related deformation.

The process of accretion also results in dewatering of the prism with predicted upward fluid flow being largest approximately at the position of Site U1327, ~20 km landward of the deformation front (Hyndman and Davis 1992; Hyndman et al. 1993; Riedel et al. 2010). The dewatering process may also be accompanied by an upward transport of dissolved methane, which is turned into solid gas hydrate upon entering the stability zone (Hyndman and Davis 1992). However, the formation of gas hydrates is more complex and the distribution of the gas hydrate occurrence along the margin is governed by an interplay of several factors in addition to temperature and pressure (sediment type, porosity, grain size, sedimentation rate, abundance of methane and water, and microbial activity, e.g., Malinverno et al. 2008). All our samples analysed during this study were hydrate-free and thus the geotechnical properties determined are not directly affected by gas hydrate concentrations in situ (Fig. 2).

In a simplification, for our sub-samples from X311, older accreted sediments should tend to show OCR values > 1, as they likely have experienced larger burial depth in the past and were subsequently uplifted through the process of thrust faulting at ridges. As the ridges all appear to have been exposed to some local erosion and normal faulting (Riedel et al. 2018), some of the previous overburden has

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**Fig. 8** Results of determination of a pre-consolidation stress ($\sigma_{pc}$), b over-consolidation ratio (OCR), c initial void ratio ($e_0$), d compression index ($C_c$) from IODP Expedition 311 compared to results from ODP Leg 204 (Tan et al. 2006). e Effective pressure compared to hydrostatic and overburden pressure using bulk density values and an average water density of 1028 kg/m$^3$. Samples with grey filling are not representative of the main trends seen (details see text).
Table 7  Data of individual oedometer tests conducted, listing applied vertical load (pressure) and measured void ratio after each load increment.

| Sample       | Depth (mbsf) | Oedometer test |
|--------------|--------------|----------------|
|              |              | Applied pressure (kPa) | Void ratio (e) |
|              |              | 49              | 2.371           |
| U1325B-4H-3  | 27.74        | 98              | 2.342           |
|              |              | 196.1           | 2.335           |
|              |              | 390             | 2.326           |
|              |              | 490.2           | 2.28            |
|              |              | 1078            | 2.174           |
|              |              | 2358            | 2.026           |
|              |              | 4902            | 1.844           |
|              |              | 9803            | 1.674           |
| U1325B-6H-1  | 43.35        | 48.33           | 1.491           |
|              |              | 96.66           | 1.483           |
|              |              | 193.3           | 1.474           |
|              |              | 483.3           | 1.444           |
|              |              | 1063            | 1.378           |
|              |              | 2175            | 1.29            |
|              |              | 4108            | 1.19            |
|              |              | 7008            | 1.092           |
| U1325B-6H-1  | 44.19        | 48.33           | 1.118           |
|              |              | 96.66           | 1.104           |
|              |              | 193.33          | 1.088           |
|              |              | 386.7           | 1.076           |
|              |              | 870             | 1.043           |
|              |              | 1837            | 0.9899          |
|              |              | 3770            | 0.9156          |
|              |              | 7733            | 0.8245          |
|              |              | 10,630.00       | 0.7807          |
| U1325B-14X-2 | 104.37       | 98.3            | 1.311           |
|              |              | 196.6           | 1.304           |
|              |              | 491.5           | 1.276           |
|              |              | 1081            | 1.256           |
|              |              | 2163            | 1.24            |
|              |              | 4325            | 1.193           |
|              |              | 8847            | 0.9372          |
|              |              | 14,750          | 0.775           |
| U1325B-14X-2 | 104.75       | 53.35           | 1.252           |
|              |              | 160             | 1.205           |
|              |              | 320.1           | 1.177           |
|              |              | 640             | 1.135           |
|              |              | 1280            | 1.083           |
|              |              | 2667            | 1.009           |
|              |              | 5335            | 0.9209          |
|              |              | 10,670          | 0.8132          |
|              |              | 12,800          | 0.7747          |
Table 7 (continued)

| Sample              | Depth (mbsf) | Oedometer test |
|---------------------|--------------|----------------|
|                     |              | Applied pressure (kPa) | Void ratio (e) |
|                     |              | 101.1                  | 0.8367          |
| U1325B-24X-5        | 184.95       | 202.2                  | 0.8304          |
|                     |              | 505.4                  | 0.8088          |
|                     |              | 1112                   | 0.7998          |
|                     |              | 2224                   | 0.7444          |
|                     |              | 4447                   | 0.6946          |
|                     |              | 8895                   | 0.6278          |
|                     |              | 16,170                 | 0.5555          |
| U1326C-8X-1 (sampled contained gas hydrate in situ, see Fig. A1b) | 60.21 | 96.27 | 0.5831 |
|                     |              | 192.5                  | 0.58            |
|                     |              | 481.4                  | 0.569           |
|                     |              | 1059                   | 0.5561          |
|                     |              | 1155                   | 0.5521          |
|                     |              | 2407                   | 0.5316          |
|                     |              | 5295                   | 0.4764          |
|                     |              | 7702                   | 0.3817          |
|                     |              | 9000                   | 0.33            |
| U1326D-2X-5         | 95.25        | 96.7                   | 0.6951          |
|                     |              | 212.7                  | 0.6915          |
|                     |              | 367.3                  | 0.6889          |
|                     |              | 744.3                  | 0.6754          |
|                     |              | 1711                   | 0.6398          |
|                     |              | 3577                   | 0.5834          |
|                     |              | 7443                   | 0.5081          |
|                     |              | 9666                   | 0.4801          |
|                     |              | 11,600                 | 0.4606          |
| U1326D-10X-2        | 167.49       | 48.3                   | 0.4149          |
|                     |              | 145                    | 0.4032          |
|                     |              | 290                    | 0.3982          |
|                     |              | 580                    | 0.3848          |
|                     |              | 1160                   | 0.3648          |
|                     |              | 2416.5                 | 0.3382          |
|                     |              | 5315                   | 0.2947          |
|                     |              | 10,635                 | 0.239           |
|                     |              | 12,565                 | 0.2271          |
| U1327C-4H-3         | 29.35        | 48.95                  | 1.257           |
|                     |              | 97.9                   | 1.233           |
|                     |              | 293.7                  | 1.159           |
|                     |              | 587.4                  | 1.077           |
|                     |              | 1175                   | 0.9591          |
|                     |              | 2448                   | 0.8095          |
|                     |              | 4895                   | 0.7371          |
Table 7 (continued)

| Sample         | Depth (mbsf) | Oedometer test |
|----------------|-------------|----------------|
|                | Applied pressure (kPa) | Void ratio (e) |
| U1327C-5H-6   | 43.09       | 49.02          | 0.7972        |
|               |             | 49.02          | 0.7928        |
|               |             | 98.03          | 0.7912        |
|               |             | 196.1          | 0.7788        |
|               |             | 441.2          | 0.7646        |
|               |             | 1127           | 0.6784        |
|               |             | 2255           | 0.6019        |
|               |             | 4510           | 0.5335        |
| U1327C-8H-1   | 55.93       | 48.95          | 0.483         |
| (sample contained finely stacked silt beds, Fig. A1a) |             | 146.9          | 0.4646        |
|               |             | 293.7          | 0.4634        |
|               |             | 587.4          | 0.4573        |
|               |             | 1175           | 0.4521        |
|               |             | 2643           | 0.435         |
|               |             | 5581           | 0.3875        |
|               |             | 9790           | 0.1719        |
| U1327C-10H-6  | 81.13       | 49.22          | 0.7838        |
|               |             | 98.43          | 0.7805        |
|               |             | 196.9          | 0.7723        |
|               |             | 393.7          | 0.7562        |
|               |             | 984            | 0.7235        |
|               |             | 1969           | 0.6896        |
|               |             | 3937           | 0.6346        |
|               |             | 7875           | 0.5624        |
|               |             | 11,810         | 0.5159        |
|               |             | 14,770         | 0.4926        |
|               |             | 17,720         | 0.4722        |
| U1327C-12X-4  | 97.58       | 97.9           | 0.9248        |
|               |             | 244.8          | 0.9174        |
|               |             | 538.5          | 0.8964        |
|               |             | 1126           | 0.8604        |
|               |             | 2252           | 0.8122        |
|               |             | 4504           | 0.7547        |
|               |             | 7441           | 0.7052        |
|               |             | 14,880         | 0.63          |
|               |             | 29,760         | 0.5           |
| U1327C-21X-1  | 171.08      | 98.3           | 0.5543        |
|               |             | 216.3          | 0.5511        |
|               |             | 373.6          | 0.5452        |
|               |             | 756.9          | 0.5274        |
|               |             | 1740           | 0.5023        |
|               |             | 3637           | 0.473         |
|               |             | 7569           | 0.4322        |
|               |             | 9830           | 0.4138        |
|               |             | 13,760         | 0.3794        |
| Sample          | Depth (mbsf) | Oedometer test |  |
|-----------------|-------------|----------------|---|
|                 |             | **Applied pressure (kPa)** | **Void ratio (e)** |
| U1329C-11H-2    | 88.55       | 52.3           | 0.776 |
|                 |             | 104.6          | 0.7708 |
|                 |             | 235.2          | 0.7635 |
|                 |             | 548.9          | 0.7477 |
|                 |             | 1176.2         | 0.7292 |
|                 |             | 2415.7         | 0.7045 |
|                 |             | 4834.7         | 0.6427 |
|                 |             | 9700           | 0.5472 |
|                 |             | 13,900         | 0.5069 |
| U1329C-12H-3    | 99.27       | 48.14          | 1.315 |
|                 |             | 144.4          | 1.31  |
|                 |             | 288.8          | 1.299 |
|                 |             | 577.6          | 1.277 |
|                 |             | 1155           | 1.23  |
|                 |             | 2407           | 1.135 |
|                 |             | 4814           | 0.974 |
|                 |             | 7702           | 0.8304 |
| U1329C-12H-6    | 103.53      | 96.27          | 0.8903 |
|                 |             | 192.5          | 0.8754 |
|                 |             | 385.1          | 0.8613 |
|                 |             | 770.2          | 0.8336 |
|                 |             | 1540           | 0.7899 |
|                 |             | 3129           | 0.7171 |
|                 |             | 6319           | 0.6289 |
|                 |             | 11640          | 0.5233 |
| U1329C-21X-4    | 175.02      | 52.28          | 0.6572 |
|                 |             | 104.6          | 0.6475 |
|                 |             | 209.1          | 0.6311 |
|                 |             | 522.8          | 0.5972 |
|                 |             | 1150           | 0.5601 |
|                 |             | 2300           | 0.5279 |
|                 |             | 4705           | 0.4797 |
|                 |             | 9410           | 0.4186 |
|                 |             | 16700          | 0.3501 |
| U1327C-19X-2 (remoulded) | 152.59  | 48             | 1.7268 |
|                 |             | 97             | 1.6648 |
|                 |             | 194            | 1.5751 |
|                 |             | 387            | 1.4635 |
|                 |             | 774            | 1.3372 |
|                 |             | 1452           | 1.2081 |
|                 |             | 2904           | 1.0549 |
|                 |             | 5808           | 0.8899 |
|                 |             | 11616          | 0.7253 |
|                 |             | 23232          | 0.5777 |
been removed, thus OCR should be > 1. In contrast, slope-sediments should tend to show OCR values of ~ 1, as they are gradually deposited on site without tectonic overprinting (folding, uplift) or overpressure occurring. OCR values of < 1 (i.e. the sample has experienced a pre-consolidation stress smaller than expected from its burial depth) could be the result of rapid sedimentation and burial by mass-transport deposits in combination with low permeability, so that drainage is slowed down. Another explanation for apparent under-consolidation may be the presence of persistent over-pressure that prevented the sample to normally consolidate while being buried. With these generalisations in mind, we now investigate the drill sites individually.

**Site U1326—frontal ridge**

Site U1326 is situated on top of the first accreted ridge (Fig. 1). The narrow ridge and strong folding of the sediment results in poor seismic imaging across the ridge (Fig. A2). Seismic data acquired along the ridge-axis, however, show

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**Fig. 9** Relationship between initial void ratio ($e_0$) and compression index ($C_c$) for samples from IODP Expedition 311 compared to results from ODP Leg 204 (Tan et al. 2006). Uncertainties in the values from IODP Expedition 311 are shown by error bars. No uncertainty was reported for Leg 204 samples.
that the sediment-layering is still mostly intact, but that the sediment is heavily faulted (Fig. 11). The normal-faulting is a result of extension of the ridge in a NW–SE direction, perpendicular to the margin’s main compression orientation. What caused the ridge extension is unclear, but it could be linked to fast uplifting of an overall less consolidated stack of sediments that are unstable given the steep slopes (∼25°) at the centre of the ridge (Riedel et al. 2018). The prominent slope failure (dubbed Orca slide in previous publications by Hamilton et al. 2015; Scholz et al. 2016; Riedel et al. 2018) at the centre of the ridge may also be linked to extension and faulting. Porosity at Site U1326, esp. the core-derived data (Fig. 3a), show an upper section up to ∼60 mbsf of smaller values than compared to the trend of Site 888 on the abyssal plain, suggesting that the upper-most, high-porosity sediment already were removed from the ridge through erosion.

The consolidation data of samples from Site U1326 show that (with the exception of the uppermost sample potentially contaminated from initial hydrate dissociation effects) the sediment appears either normally (OCR ∼ 1) or under-consolidated (OCR < 1). Since the ridge started forming and uplift occurred, no turbidite deposition is occurring and only hemi-pelagic processes may be delivering sediment to the site. Given that the ridge has undergone extension and normal faulting linked with erosion (missing top 60 mbsf as defined from porosity), OCR values > 1 are expected. Yet, the OCR values ≤ 1 determined suggest that the ridge instead may be experiencing overpressure at depth, which is to some degree a contradiction to the extension the ridge experienced. However, extension and faulting may be episodic and linked to the earthquake cycle on this
margin (e.g. described in Hyndman 1995) that was determined from turbidite records (e.g. Adams 1990; Atwater et al. 2004; Goldfinger et al. 2012; Hamilton et al. 2015). The study by Hamilton et al. (2015) was conducted at slope-failures along thrust fault-related accretionary ridges. Here, the turbidite records were all correlated to known earthquake events from the earlier studies and no additional turbidites were seen. We interpret this as evidence that no major fault movement occurred during the a-seismic (quiet) phase of the earthquake cycle creating additional down-slope sediment transport.

This periodicity of the earthquake-cycle may thus allow a periodic build-up and release of excess pore pressure preventing the sediment from normal consolidation. Although other sites along the drilling transect are also exposed to the same earthquake cycle and potential episodic build-up and release of pore pressure, the frontal ridge at Site U1326 is laterally unconstrained and can therefore fail and collapse horizontally, which makes it unique among the sites studied.

Gas hydrates occur at Site U1326 from shallow depth (~43 mbsf) down to the base of the GHSZ, usually only within the silt and sandy turbidite layers (Riedel et al. 2006a; Torres et al. 2008). The highest concentration of gas hydrate bearing turbidites was seen in an interval of 50–100 mbsf (Fig. 2). With only two samples with reliable OCR values, no correlation between the consolidation trend and hydrate distribution can be made.

**Site U1325—inter-ridge slope basin**

Data from Site U1325 located within the first intra-ridge basin show considerable complexity in the determined OCR values. The basin that developed east of the first accreted ridge is filled with slope-sediments that were derived through a turbidite-tributary channel, which now has been cut off from modern sediment supply. The turbidite-rich slope sediments are covered by a thin veneer of Holocene sediments (see Fig. A3 in the IODP X311 Site U1325 Proceedings volume). Porosity data at Site U1325 show an upper high-porosity layer up to ~4 mbsf, similar in porosity-values as identified on the abyssal plain Site 888 (Fig. 3b). This presumably Holocene sediment cover is followed by a 15 m thick interval of sediment showing porosity ranging from 40 to 60%, lower than what would be expected from Site 888 and a normal compaction trend. This interval is dominated by sand and silty-sand layers. Beneath the sand-rich section, porosity falls back to a normal trend up to a depth of 70 mbsf, gradually decreasing from ~68 to ~48%, nearly identical to Site 888.

Underneath the basin and layered slope-sediment cover, a strongly folded anticline developed with its apex located ~500 m west of Site U1325 (Fig. 12). The drilling intersected two lithological units above the boundary to sediments belonging into the anticlinal fold. Sediment samples derived from depths belonging to Units Ib and II are considered to be slope sediments, with accreted sediments underneath (Units III and IV). OCR values of the samples in the interval up to 104.4 mbsf are all >1 indicating an apparent over-consolidation. As seen from the seismic image (Fig. 12), the upper erosional unconformity indicates that some material has been removed prior to the deposition of sediments of Unit Ia. The sediments comprising Units Ib and II experienced uplift and tilting due to movement from the underlying anticlinal fold. Using average density values for these sediments, the derived pre-consolidation pressure values indicate that these sediments have experienced a much higher pressure in the past. We re-interpret the boundary between lithologic Units II and III to be at 104.5 mbsf, at the noted change in lithology within Core U1325B-14X-2, which is ~2 m deeper than determined onboard. This change in major lithology correlates with the difference in the OCR and pre-consolidation stress values. Samples from inside the anticlinal fold (Unit III) are in contrast apparently under-consolidated (OCR < or very close to 1). Sediment layers from this depth interval are much more folded and seismic reflectivity is reduced (Fig. 12), typical for the accreted type sediments. The under-consolidation may be a result of over-pressure build-up within the anticlinal fold, potentially linked to the earthquake cycle that could episodically enhance fluid flow from depth. The overlying sediment package of over-consolidated slope-sediments could be an effective seal preventing the over-pressure from being dissipated quickly.

Gas hydrate concentrations at Site U1325 are on average lower than at Site U1326 and tend to increase with depth (Fig. 2). The first noted gas hydrate (by IR imaging and pore-fluid freshening) occurred at 73 mbsf. The highest hydrate concentration again is identified at individual thin silt/sand turbidite layers (Malinverno et al. 2008; Torres et al. 2008) but the LWD-resistivity data also suggest an average concentration of 10–15%, especially in the 50 m above the base of the GHSZ (Fig. 2). Thus, the noted change in OCR values is not correlated to the gas hydrate occurrence or changes in concentration with depth.

**Site U1327**

Site U1327 is situated at the foot of a small accreted ridge belonging to an uplifted plateau (Fig. 1). This plateau is uplifted along a mid-margin back-thrust (Westbrook et al. 1994). The seismic character around this drill site is dominated by the difference in slope-sediment layers of high reflection amplitude (0–80 mbsf) deposited above low-reflectivity and incoherent accreted sediments (Fig. 13). The geometry of the plateau and thrust-faults, including breakout-analyses (Riedel et al. 2018) suggest that the accreted
sediments are deformed and folded in an SW-NE orientation (margin-perpendicular) although the seismic data no longer can image any coherent layering at these depths.

Gas hydrates at Site U1327 occur in overall low concentrations of < 10% from ~ 110 mbsf to the base of the GHSZ at ~ 230 mbsf. An interval of very high concentrations (Sh is 40–60%), especially noted in Hole U1327A (where LWD data were acquired, Fig. 2) was not intersected at the same depth interval (and not at the same high concentration level) in adjacent drill holes (U1327B–U1327E), suggesting a lens-like occurrence of this high-concentration interval, dipping towards the NE perpendicular to the seismic line shown in Fig. 13 (compare to Figure F66, IOPP X311 proceedings volume, available online at http://publications.iodp.org/proceedings/311/105/105_f66.htm).

Results of the consolidation tests show that the slope-sediments have OCRs of less than 1 and are thus apparently under-consolidated. Most of the slope-sediments drilled at Site U1327 must have been deposited prior to the uplift of the plateau, as this region no longer receives sediment from the nearby turbidite tributary channel (Fig. 1). Some minor locally-derived sediments may be re-deposited from erosion of the accreted ridge. The OCR values < 1 are most likely a result of rapid deposition and burial of these slope-sediments. Underneath the boundary
to the accreted sediments (at ~ 80 mbsf), samples show OCR values larger than 1. Thus, the accreted sediments (that are also older than the cover of slope-sediments, Akiba et al. 2009) have seen previously a vertical stress larger than current burial depth, which may be a result of the thrust faulting and uplift of the ridge and entire plateau. The lowest sample has again an OCR values < 1 and could be associated with overpressure build-up at greater depth, similar to what was observed at Site U1325.

No correlation of the OCR trend with either porosity or gas hydrate occurrence is evident; but at this Site, OCR appears as expected from an accretion and uplift-related depth-trend with general distinction into accreted (over-consolidated) and slope-sediment (under-consolidated). The accreted sediments also do not show signs of over-pressure build-up.

Site U1329

Site U1329 is located the farthest east along the drilling transect and at the eastern limit of the regional gas hydrate occurrence. Here, the seafloor shows abundant canyons and channels indicating mass wasting and down-slope sediment transport (Fig. 1). Seismically, the site is characterized by an overall low reflectivity with little to no sediment layering discernible (Fig. 14). At a depth of 175 mbsf, a major unconformity was drilled with a sediment hiatus of missing ~ 4.5 Ma (Akiba et al. 2009). At a depth just above the unconformity (~ 175 mbsf) sediment age at Site U1329 is > 6 Ma, more than twice as at all other sites for the same depth interval. This unconformity is not imaged well seismically. However, a weakly developed reflection seen in the seismic record corresponds to the boundary between lithologic Units II and III at this site (Fig. 14a).

Porosity at Site U1329 (Fig. 3d) is nearly constant with depth at ~ 60% down to ~ 175 mbsf, the depth of the noted
Fig. 14 Over-consolidation ratio (OCR) at U1329 and comparison to seismic data: a Portion of the margin-perpendicular multi-channel seismic (MCS) line PGC9902-07 and b single-channel seismic (SCS) line PGC0408-03 acquired parallel to the margin. The MCS data image the boundary between lithologic Units II and III (white dashed line), whereas the SCS data show a weakly developed bottom-simulating reflector (BSR) marking the base of gas hydrate stability zone (BGHSZ).
unconformity. Porosity drops to values below 40% below 175 mbsf. No gas hydrate was sampled at this site and pore-fluid freshening may be only very weakly developed. A BSR is seen on seismic data acquired in a margin-parallel direction but is not well developed in any of the seismic records (Fig. 14b). The hydrate occurrence zone is thus very thin and no top of hydrate occurrence could be defined with confidence (noted by question mark in Figs. 2 and 3d).

Samples from Site U1329 show a general decreasing trend of OCR values with depth. With the exception of the shallowest sample at ~88 mbsf, all values are near an OCR value of 1 indicating that they currently reside at a depth close to the maximum overburden ever seen. We interpret this as a result of the continued erosion and re-deposition at this slope-situated site combined with the overall larger age of sediments and tectonic history they experienced.

In Summary, the selected samples from the drilling transect yield geotechnical properties that are generally in good agreement with processes expected from building an accretionary prism and to govern the individual compaction and consolidation trend. However, several uncertainties exist and assumptions were applied that do result in a probably significant error in the actual values reported; yet, the main distinction in OCR values being above or below 1 are regarded robust. One of the most significant sources of error is the age of the samples and artificial drying experienced during storage in the repository. Although we attempted to counter-balance this by re-saturating the samples with de-ionised water prior to testing, this may not have been fully successful. Estimating the pre-consolidation stress using the Onitsuka-method from the oedometer test data has an inherent uncertainty related to the sparseness of data points available per test. This sparseness results in an uncertainty in the analysis to obtain the compression index $C_c$ from plots of $\log_{10}(\sigma)$ vs. void ratio and the definition of pre-consolidation pressure and initial void ratio. All uncertainties related to the mathematical derivation of the parameters are included in Table 6 but we cannot define a numerical uncertainty based on the effect of artificial drying.

Additional sub-sampling from the IODP Expedition 311 cores and analyses of geotechnical properties are envisioned for the future to allow more detailed site-by-site comparisons, including adding samples from the vent-site U1328 to investigate the nature of focused fluid flow and fracturing (Zühlsdorff and Spiess 2004) on geotechnical properties. Especially Site U1326 would benefit from additional sub-sampling and consolidation tests. Ideally, new samples should be collected at the location of the Orca slope-failure scar allowing sampling of sediment that was previously covered by a sediment pile up to 80 m thick (Riedel et al. 2016b) with gravity coring and no need for deep drilling.

Conclusions

Our analyses present a first set of geotechnical data from samples of IODP Expedition 311 on the northern Cascadia margin. Analyses were not performed initially after the cruise but with considerable time lag (~12 years after recovery). However, results obtained are regarded overall meaningful as values obtained compare overall well to those from Hydrate Ridge on the southern Cascadia margin. Grain size and mineral composition are determined for verification of sediment composition and agree to results obtained at sea during drilling. Geotechnical parameters of the Atterberg limits reveal an overall character typical for silty clay and clayey silt and show similar inter-parameter relationships as previous studies had suggested for these types of sediment. Results from oedometer tests (compression index, initial void ratio, over-consolidation ratio) are interpreted at each drill site and reflect the tectonic history of each site in the overall realm of an accretionary prism, dominated by thrust-faulting, folding and uplift, accompanied by local erosion and deposition of slope-derived turbidites and hemipelagic sediments. Over-pressure within an antiformal fold at Site U1325 may be present, as suggested by OCR values < 1 within the depth-range of the antiformal fold. Similarly, the frontal ridge at Site U1326 may be experiencing some overpressure at greater depth, but this is possibly contradicted by the lateral extension (and associated normal faulting) occurring at this ridge. We conclude that the values obtained for all sub-samples are basically robust and can be used in subsequent geohazard studies to assess slope-failures, modelling of potential over-pressure regimes, and subduction-related tectonic analyses of horizontal compressive stresses and borehole breakouts. However, we also aim to further sub-sample the cores from Expedition 311, densifying the sample-number, especially at Site U1326, and augment our analyses to include triaxial testing of samples to obtain unconfined compressive strength values. Upcoming expeditions to the margin may also allow new gravity coring, with a focus on the Orca slide-scar.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11001-022-09487-9.

Acknowledgements Samples and data were provided by the Integrated Ocean Drilling Program (IODP), which is funded by the U.S. National Science Foundation and participating countries under management of IODP Management International, Inc. We thank the captain and crew of the R/V JOIDES Resolution and the technical staff for their support at sea. We further express our gratitude to the curator-team at the IODP repository in College Station, Texas, USA: Calie Payne, Phil Rumford, Cathie Smith, and Chad Broyles.
Funding Open Access funding enabled and organized by Projekt DEAL. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. No funding was received to assist with the preparation of this manuscript.

Declarations

Conflict of interest The authors have no conflict of interest and no competing interests to declare that are relevant to the content of this article.

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References

Adams J (1990) Paleoseismicity of the Cascadia subduction zone: evidence from turbidites off the Oregon-Washington margin. Tectonics. 9:569–583. https://doi.org/10.1029/TC009i004p00569
Akiba F, Iinoue Y, Saito-Kato M, Pohlman J (2009) Data report: diatom and foraminiferal assemblages in Pleistocene turbidite sediments from the Cascadia margin (IODP Expedition 311), northeast Pacific. In Riedel M, Collett TS, Malone MJ, and the Expedition 311 Scientists (eds) Proceedings of the IODP, 311: Integrated Ocean Drilling Program Management International, Inc., Washington, DC. https://doi.org/10.2204/iodp.proc.311.211.2009
Atwater BF, Tuttle MP, Schweig ES, Rubin CM, Yamaguchi DK, Hemphill-Haley E (2004) Earthquake recurrence inferred from paleoseismology. In A.R. Gillespie, S.C. Porter, and B.F. Atwater The Quaternary period in the United States, Volume 1, Developments in Quaternary Sciences, Elsevier Ltd., Amsterdam. pp. 331–350. https://doi.org/10.1016/S1571-0866(03)01015-7
Bahr A, Bohrmann G, Teichert BMA (2008) Data report: bulk mineralogical composition of Cascadia Margin sediments, IODP Expedition 311. In: Riedel M, Collett TS, Malone MJ, and the Expedition 311 Scientists (eds) Proceedings of the IODP, 311. Integrated Ocean Drilling Program Management International, Inc., Washington, DC. https://doi.org/10.2204/iodp.proc.311.201.2008
Barter D, Blanc-Valleron M-M, Rouchy JM, Pierre C (2008) Data report: clay mineralogical composition of northern Cascadia margin sediments, IODP Expedition 311. In: Riedel M, Collett TS, Malone MJ, and the Expedition 311 Scientists (eds) Proceedings of the IODP, 311. Integrated Ocean Drilling Program Management International, Inc., Washington, DC. https://doi.org/10.2204/iodp.proc.311.208.2008
Casagrande A (1936) The determination of pre-consolidation load and its practical significance. In: Proceedings of the 1st International Conference on Soil mechanics and Foundation Engineering, Cambridge, MA, vol 3, pp 60–64
Chen M-AP (2006) Northern Cascadia marine gas hydrate: constraints from resistivity, velocity, and AVO [M.S. thesis]. University of Victoria, British Columbia. https://dspace.library.uvic.ca/handle/1828/2293
Chen M-AP, Riedel M, Spence GD, Hyndman RD (2008) A down-hole electrical resistivity study of northern Cascadia marine gas hydrate. In Riedel M, Collett TS, Malone MJ, and the Expedition 311 Scientists (eds) Proceedings of the IODP, 311. Integrated Ocean Drilling Program Management International, Inc., Washington, DC. https://doi.org/10.2204/iodp.proc.311.203.2008
Davis EE, Hyndman RD, Villinger H (1990) Rates of fluid expulsion across the n. Cascadia accretionary prism: constraints from new heat flow and multichannel seismic reflection data. J Geophys Res 95:8869–8889. https://doi.org/10.1029/JB095iB06p08869
Goldfinger C, Nelson CH, Morey AE, Johnson JR, Patton J, Karabanov E (2012) Turbidite event history-methods and implications for Holocene paleoseismicity of the Cascadia Subduction Zone. United States Geological Survey, Professional Paper 1661-F, 170 p. https://doi.org/10.3133/pp1661F
Hamilton TS, Enkin RJ, Riedel M, Rogers GC, Pohlman JW, Benway HM (2015) Slipstream: an early Holocene slump and turbidite record from the fronton of the Cascadia accretionary wedge off western Canada and paleo seismic implications. Can J Earth Sci 52:405–430. https://doi.org/10.1139/cjes-2014-0131
Hashimoto Y, Minamizawa S (2009) Data report: quantitative analysis of grain size distribution for coarse sediments in an accretionary prism: an example from the Cascadia accretionary prism. In Riedel M, Collett TS, Malone MJ, and the Expedition 311 Scientists (eds) Proceedings of the IODP, 311. Integrated Ocean Drilling Program Management International, Inc., Washington, DC. https://doi.org/10.2204/iodp.proc.311.205.2009
Hyndman RD (1995) The Lithoprobe corridor across the Vancouver Island continental margin: the structural and tectonic consequences of subduction. Can J Earth Sci 32:1777–1802. https://doi.org/10.1139/e95-138
Hyndman RD, Davis EE (1992) A mechanism for the formation of methane hydrate and seafloor-bottom-simulating reflectors by vertical fluid expulsion. J Geophys Res 97(B5):7025–7041. https://doi.org/10.1029/90JB03061
Hyndman RD, Yorath CJ, Clowes RM, Davis EE (1990) The northern Cascadia subduction zone at Vancouver Island: Seismic structure and tectonic history. Can J Earth Sci 27(3):313–329. https://doi.org/10.1139/e90-030
Hyndman RD, Wang K, Yuan T, Spence GD (1993) Tectonic sediment thickening, fluid expulsion and the thermal regime of subduction zone accretionary prisms: the Cascadia margin off Vancouver Island. J Geophys Res 98(B12):21865–21876. https://doi.org/10.1029/93JB02391
Hyndman RD, Spence GD, Chapman R, Riedel M, Edwards RN (2001) Geophysical studies of marine gas hydrate in northern Cascadia. In: Paull CK, Dillon WP (eds) Natural gas hydrates: occurrence, distribution, and detection, vol 124. American Geophysical Union Geophysical Monograph Series, Washington, DC, pp 273–295
Lin W, Conin M, Moore JC, Chester FM, Nakamura Y, Mori JJ, Andersen L, Brodsky EE, Eguchi H, Expedition 343 Scientists (2013) Stress state in the largest displacement area of the 2011 Tohoku-Oki earthquake. Science 339(6120):687–690. https://doi.org/10.1126/science.1229379
Malinverno A (2010) Marine gas hydrates in thin sands that soak up microbial methane, Earth Planet. Sci Lett 292:399–408. https://doi.org/10.1016/j.epsl.2010.02.008
Malinverno A, Kastner M, Torres ME, Wortmann UG (2008) Gas hydrate occurrence from pore water chlorinity and downhole logs in a transect across the northern Cascadia margin (Integrated Ocean Drilling Program Expedition 311). J Geophys Res 113:B08103. https://doi.org/10.1029/2008JB005702
Onitsuka K, Hong Z, Haray Y, Yoshitake S (1995) Interpretation of oedometer test data for natural clays. Soils Found 35(3):61–70. https://doi.org/10.3208/sandf.35.61

Pan H, Li H, Chen J, Riedel M, Holland M, Zhang Y, Cai S (2020) Quantification of gas hydrate saturation and morphology based on a generalized effective medium model. Mar Pet Geol 113:104166. https://doi.org/10.1016/j.marpetgeo.2019.104166

Riedel M, Collett TS, Malone MJ, and the Expedition 311 Scientists (2006a) Proceedings of the IODP, 311. Integrated Ocean Drilling Program Management International, Inc., Washington, DC. https://doi.org/10.2204/iodp.proc.311.2006a

Riedel M, Willoughby EC, Chen M-AP, He T, Novosel I, Schwalenberg K, Hyndman RD, Spence GD, Chapman NR, Edwards RN (2006b). Gas hydrate on the northern Cascadia margin inferred from borehole breakouts. Geochem Geophys Geosyst 17:3529–3545. https://doi.org/10.1002/2016GC006433

Scholz NA, Riedel M, Urlaub M, Spence GD, Hyndman RD (2016) Submarine landslides along the northern Cascadia margin, offshore Vancouver Island, British Columbia: why preconditioning is likely required to trigger slope failure. Geo-Mar Lett. https://doi.org/10.1007/s00367-016-0452-8

Skempton AW (1944) Notes on the compressibility of clays. Q J Geol Soc London 100(1–4):119–135

Tajima F, Mori J, Kennett BLN (2013) A review of the 2011 Tohoku-oki earthquake (Mw 9.0): large-scale rupture across heterogeneous plate coupling. Tectonophysics 586:15–34. https://doi.org/10.1016/j.tecto.2012.09.014

Tan B, Germaine JT, Flemings PB (2006) Data report: consolidation and strength characteristics of sediments from ODP Site 1244. Hydrate Ridge, Cascadia continental margin. In: Tréhu AM, Bohrmann G, Torres ME, Colwell FS (eds). Proceedings of the Ocean Drilling Program, Scientific Results, 204, 1–148. http://www.odp.tamu.edu/publications/204_SR/VOLUME/CHAPTERS/102.PDF. Accessed 02 July 2021

Torres ME, Tréhu AM, Cespedes N, Kastner M, Wortman UG, Kim J-H, Long P, Malinverno A, Pohlman JW, Riedel M, Collett TS (2008) Methane hydrate formation in turbidite sediments of northern Cascadia IODP Expedition 311. Earth Planet Sci Lett 271:170–180. https://doi.org/10.1016/j.epsl.2008.03.061

Tripathy S, Mishra AK (2011) On the use of skempton’s compression index equation. Geotech Geol Eng 29:129–135. https://doi.org/10.1007/s10706-010-9359-8

Wang J, Gao Y, Li Q, Yang C, Chen Q, Wei Q, Wang X, Hu G (2007) Grain size constraint on gas hydrate occurrence: evidence from sediment size during IODP 311. Adv Earth Sci 22(7):659–665. https://doi.org/10.11867/j.issn.1001-8166.2015.09.1028

Westbrook GK, Carson B, Musgrave RJ (1994) Proceedings of the Ocean Drilling Program Initial Reports, 146 (Pt. 1). Ocean Drilling Program, College Station, TX. https://doi.org/10.2973/odp.proc.ir.146-1.1994

Zoback MD, Barton CA, Brudy M, Castillo DA, Finkbeiner T, Grolimund BR, Moos DS, Peska P, Ward CD, Wiprut DJ (2003) Determination of stress orientation and magnitude in deep wells. Int J Rock Mech Min Sci 40:1049–1076. https://doi.org/10.1016/j.ijrmms.2003.07.001

Zühlendorf L, Spiess V (2004) Three-dimensional seismic characterization of a venting site reveals compelling indications of natural hydraulic fracturing. Geology 32(2):101–104. https://doi.org/10.1130/G19993.1

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