Velocity-Porosity Relations in Carbonate and Siliciclastic Subduction Zone Input Materials

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Abstract The mechanical, physical, and frictional properties of incoming materials play an important role in subduction zone structure and slip behavior because these properties influence the strength of the accretionary wedge and megathrust plate boundary faults. Incoming sediment sections often show an increase in compressional wave speed ($V_p$) and a decrease in porosity with depth due to consolidation. These relations allow seismic-velocity models to be used to elucidate properties and conditions at depth. However, variations in these properties are controlled by lithology and composition as well as cementation and diagenesis.

We present an analysis of shipboard measurements of $V_p$ and porosity on incoming sediment cores from International Ocean Discovery Program (IODP) expeditions at the Hikurangi Margin, Nankai Trough, Aleutian Trench, Middle America Trench, and Sunda Trench. Porosity for these samples ranges from 5% to 85% and $V_p$ ranges from 1.5 to 6 km/s. $V_p$-porosity relations developed by Erikson & Jarrad (1998), https://doi.org/10.1029/98JB02128 and Hoffman & Tobin (2004) https://10.2973/odp.proc.sr.190196.355.2004, with a critical porosity of ~30%, can represent carbonate-poor (<50 wt% CaCO$_3$), mainly hemipelagic, incoming sediment regardless of the margin. But these relations tend to underestimate porosity in incoming sediments with carbonate content greater than 50 wt%, which appear to have a critical porosity of between 45% and 50%. This discrepancy will lead to inaccuracy in estimates of fluid budget and overpressure in subduction zones. The velocity-porosity relation in carbonate sediments is non-unique due to the complexity that results from the greater susceptibility of carbonate rocks to diagenetic processes.

1. Introduction

Subduction zones host the world’s most devastating earthquakes and tsunamis. Earthquake generation, slip behavior, and seafloor/sub-seafloor deformation are tied to the physical properties and in situ stresses within the sediments and rocks that make up a subduction zone. However, these properties and conditions in situ remain poorly constrained due to limited measurements at discrete drilling locations. The porosity and pore pressure within subducting sediments directly influence the strength of subduction zones as the subduction process proceeds. Controlled-source seismic experiments are one method that can be used to estimate porosity and in situ pressure conditions, but this method requires calibration through direct measurement of porosity, seismic velocity, and consolidation in sediment and rock samples (Han et al., 2017; Plaza-Faverola et al., 2012; Tobin & Safer, 2009; von Huene & Ranero, 2003). While some models to aid in this calibration exist (Erickson & Jarrard, 1998; Hoffman & Tobin, 2004; Hyndman et al., 1993; Tudge & Tobin, 2013; Wyllie et al., 1958), they may not be applicable in all situations, including overpressure zones and carbonate-rich environments.

In this study, we utilize measurements on drill core samples acquired during ocean drilling expeditions at the Hikurangi Margin, Nankai Trough, Aleutian Trench, Middle America Trench, and Sunda Trench to examine the relation between seismic velocity and porosity for subduction zone sediments. We determine the velocity-porosity relation by modifying the existing empirical relations to better represent variations we observe in hemipelagic and pelagic sediments. We discuss the causes of deviations away from existing velocity-porosity relations.

2. Seismic Velocity-Porosity Relations

Initial efforts to define a velocity-porosity relation led to the development of the Wyllie time-average relation (Wyllie et al., 1958). This is a simple empirical relation that defines the compressional wave travel time through the bulk sample as the sum of travel time through the solid and fluid portions of the sample. This relation lacks a physical basis, so it is not applicable under a variety of conditions. Later successors of the time-average relation...
demonstrated that seismic velocity is not solely influenced by porosity, but lithology and clay content are also important factors (Castagna et al., 1985; Han et al., 1986). However, at porosities greater than 30% these relations are poorly constrained and often do not predict reasonable velocities.

Erickson & Jarrard (1998) developed a global velocity-porosity relation to estimate velocity over the full range of porosity in siliciclastic sediments. The relation is expressed as a two-part equation that uses a critical porosity ($\phi_c$) term to reflect the difference in compaction behavior when the pore-fluid is load bearing (i.e., $\phi > \phi_c$) versus when the rock matrix becomes load bearing (i.e., $\phi < \phi_c$). The form of this relation is:

$$ V_p = A + B \phi + \frac{0.305}{[(\phi - C)^2 + D]} + E(v_{sh} - F)[\tanh(G(\phi - \phi_c)) - |\tanh(G(\phi - \phi_c))|] $$

where $V_p$ is the P-wave velocity, $\phi$ is the porosity, $v_{sh}$, known as the shale volume, is a proxy for clay volume, and parameters A-G are constants. The values of these constants are provided in Table 1. It should be noted that the shale volume is not identical to clay volume although they are often used interchangeably. The shale volume is a term from well log analysis and is determined from the gamma ray log.

As we do not examine well log data in this study, our analysis we utilized clay volume in place of shale volume. Normal consolidation is used when consolidation is primarily due to mechanical compaction due to overburden stress. Cementation, previous burial, and horizontal compression can push sediment into the high consolidation realm.

As the Erickson & Jarrard (1998) relations were primarily based on Amazon Fan sediments, efforts have been made to produce relations that have been calibrated for the complex subduction zone environment. Most of these studies have used data from the Nankai Trough (e.g., Hoffman & Tobin, 2004; Hyndman et al., 1993; Tudge & Tobin, 2013) due to the wealth of data available, as the area has been the focus of multiple drilling expeditions and is well studied. Of these, a commonly used transform is the Hoffman & Tobin (2004) relation, developed for incoming and underthrust sediments from the Nankai Trough. This relation utilized the two-part equation of Erickson & Jarrard (1998) but fitted the curve to core and wireline logging data from the Shikoku Basin. The resulting relation requires $v_{sh} = 1.057$ which, if actually representing shale volume should only vary from 0 to 1; the other fitted parameters are shown in Table 1.

The Erickson & Jarrard (1998) and Hoffman & Tobin (2004) models have been used to generate estimates of porosity at subduction zones around the world (e.g., Han et al., 2017; Plaza-Faverola et al., 2012; von Huene & Ranero, 2003). However, a concerted effort to determine if these existing relations reliably represent global subduction zone velocity-porosity relations, based on the data we currently have available, has not been undertaken.

### 2.1. Velocity and Porosity inCarbonates

One factor influencing the velocity-porosity relation in subduction zone sediments that has not been well addressed in previous studies is the presence of carbonate, specifically as biogenic components. Wyllie et al. (1958) specified that the time-average equation is not applicable to carbonate rocks and Erickson & Jarrard (1998) indicate that their relation may not be accurate in materials with a high concentration of biogenic components. As most of the sediments recovered from drilling in the Nankai Trough are siliciclastic, Hoffman & Tobin (2004) did not address this issue either. However, in some regions, carbonate can be a significant component of input sediments to the subduction zone system.

In siliciclastic sediments, changes in porosity are primarily controlled by compaction, with diagenetic effects coming into play after the sediments have experienced significant burial (Maltman, 1994). In carbonate rocks, however, diagenetic processes of dissolution, cementation, and recrystallization occur at shallower depths and a faster pace than in siliciclastic rocks (Wilson, 1997). These diagenetic processes alter the rock fabric before compaction begins to have a significant influence (Anselmetti & Eberli, 1993). The diagenetic history is a primary control on the pore types in a carbonate rock and different pore types exhibit different velocity-porosity trends.

|   | Erickson & Jarrard (1998) | Hoffman & Tobin (2004) for the Nankai hemipelagic sediments at site 1173 | Modified normal consolidation |
|---|--------------------------|-----------------------------------------------------------------|-----------------------------|
| A | 0.739                    | 1.057                                                           | 0.739                       |
| B | 0.552                    | 0.305                                                           | 0.552                       |
| C | 0.13                     | 0.124                                                           | 0.13                        |
| D | 0.0725                   | 0.0513                                                          | 0.0725                      |
| E | 0.61                     | 0.61                                                            | 1.103                       |
| F | 1.123                    | 1.123                                                           | 1.07                        |
| G | 40                       | 40                                                              | 7                           |
| $\phi_c$ | 0.31                   | 0.295                                                           | 0.48                        |

| Table 1 Parameters for Velocity-Porosity Relations Discussed in This Study

|                | Normal consolidation | High consolidation | Hoffmann & Tobin (2004) for the Nankai hemipelagic sediments at site 1173 | Modified normal consolidation |
|----------------|----------------------|--------------------|-----------------------------------------------------------------|-----------------------------|
| A              | 0.739                | 1.057              | 0.739                                                          | 0.739                       |
| B              | 0.552                | 0.305              | 0.552                                                          | 0.552                       |
| C              | 0.13                 | 0.124              | 0.13                                                           | 0.13                        |
| D              | 0.0725               | 0.0513             | 0.0725                                                         | 0.0725                      |
| E              | 0.61                 | 0.61               | 1.103                                                          | 1.103                       |
| F              | 1.123                | 1.123              | 1.07                                                           | 1.07                        |
| G              | 40                   | 40                 | 7                                                              | 7                           |
| $\phi_c$      | 0.31                 | 0.295              | 0.48                                                           | 0.48                        |
Due to this complexity, a meaningful velocity-porosity transform, covering a large range of porosities, for carbonate rocks does not currently exist.

3. Methods

3.1. Study Areas

We examine the Hikurangi, Nankai, Sunda, Middle America, and Aleutian subduction zones because the incoming sedimentary sections have been drilled in the recent IODP drilling expeditions (Figure 1) (Harris et al., 2013; Henry et al., 2012; Jaeger et al., 2014; McNeill et al., 2017; Saito et al., 2010; Wallace et al., 2019). We also utilized data from Ocean Drilling Program (ODP) sites at the Nankai and Middle America margins (Kimura et al., 1997; Moore et al., 2001; Morris et al., 2003). A list of all expeditions and sites from which data were used in this study is provided in Table 2. We use data from the relatively undeformed incoming sediment because it allows us to isolate lithologic controls on velocity and porosity from other effects. The incoming sediments have a simpler tectonic loading history (i.e., one-dimensional consolidation) compared to the more complex deformation histories of the prism sediments. Additionally, due to the thickness and structural complexity of accretionary prisms, most boreholes do not penetrate very far into the prism, recovering mostly hemipelagic sediment. On the incoming plate, where sediment packages can be much thinner, boreholes can penetrate the entire incoming sedimentary section above the basement. Thus, by examining incoming sediments, we are able to examine a greater variety of lithologies, including both hemipelagic and pelagic sediment from carbonate-rich (Middle America, Hikurangi, and Sunda) and carbonate-poor (Aleutian and Nankai) environments.
3.1. Hikurangi

At the Hikurangi margin, the Pacific plate subducts westward beneath the North Island of New Zealand at a rate of 4.5–5.5 cm/year (Wallace et al., 2004). Along the northern part of the margin, where the drill sites examined in this study are located, slow slip events occur every 18–24 months (Wallace & Beavan, 2010). The incoming sedimentary section here consists of a ~1 km thick Cenozoic to Mesozoic sedimentary sequence overlying a Cretaceous igneous province (Wallace et al., 2019). At Site U1520, the borehole was drilled down to 1054.1 meters below seafloor (mbsf). The top ~500 m section was Quaternary hemipelagic trench-wedge facies underlain by ~330 m of Late Cretaceous carbonate-rich pelagic facies, which overlaid a 170 m thick sequence of Late Cretaceous volcaniclastic facies (Barnes et al., 2019). The borehole terminated in a zone with a blend of rock types, the organization and thickness of which could not be resolved in the recovered core. Site U1526 is located above the Tūranganui Knoll seamount. The borehole was drilled down to 83.6 mbsf, penetrating a 30 m thick section of Quaternary to Late Cretaceous hemipelagic and pelagic facies above a sequence of Late Cretaceous volcaniclastic facies (Wallace et al., 2019).

3.1.2. Nankai

The Nankai Trough is located where the Philippine Sea Plate subducts beneath southwestern Japan at a rate of 4.5–5.5 cm/year (DeMets et al., 2010). This subduction zone has a 1300-year historical record including many great megathrust earthquakes ($M_w < 8.5$)—most recently, the 1944 $M_w \approx 8.0$ to 8.3 Tonankai and 1946 $M_w \approx 8.1$ to 8.4 Nankaido earthquakes (Ando, 1975; Kanamori, 1972). Sediment thickness on the incoming plate is not uniform and ranges from 600 to 2,000 m (Ike et al., 2008; Moore et al., 2001; Pickering et al., 2013). All sites examined in this study are located within the Shikoku Basin. Sites C0011 and C0012 are located near the Kashinosaki Knoll off the Kii Peninsula whereas Site 1173 is located near the trench, off Cape Muroto. Site 1177 is also located near the trench but farther to the west, off Cape Ashizuri. Recovered cores are dominantly Miocene to Quaternary siliceous hemipelagic sediments with up to ~113 m of Miocene volcaniclastic facies and less than 10 m of Miocene pelagic calcareous clay facies (Henry et al., 2012; Moore et al., 2001; Saito et al., 2010).

3.1.3. Sunda

The Sunda Trench is located off the western coast of Sumatra, where the Australian plate subducts beneath the Sunda plate at a rate of ~5 cm/year (McCaffrey, 2009). Large magnitude ($M_w 8.5$ to 9.3) megathrust earthquakes occurred on this margin in 2004, 2005, and 2007 (Lay, 2015; Lay et al., 2005). Sediment thickness on the incoming plate can be up to 5 km but was only about 1 km at Sites U1480 and U1481 (Gulick et al., 2011; McNeill et al., 2017). Sites U1480 and U1481 penetrated over 1.3 km of Miocene to Quaternary siliceous hemipelagic sediments (including gravity-flow deposits from the Bengal-Nicobar fan), ~40 m Oligocene to Miocene volcaniclastic facies, and ~60 m Paleocene to Miocene carbonate-rich pelagic sediments (McNeill et al., 2017; Pickering et al., 2020).

3.1.4. Middle America

The southern portion of the Middle America Trench is formed by the subduction of the Cocos plate under the Caribbean plate at a rate of 8–9 cm/yr (DeMets et al., 2010; Peacock et al., 2005). In this region, the incoming sediment thickness is 300–400 m (Harris et al., 2013). IODP Sites U1381 and U1414 are located off the Osa Peninsula and core samples indicate that the lithologies found there are similar to those at ODP Sites 1039 and 1253 located to the northwest. At all sites, Pliocene to Pleistocene siliceous hemipelagic sediments (up to ~152 m thick at Site 1039) were underlain by Miocene to Pliocene pelagic sediments (~270 m at Site 1039), dominantly siliceous and calcareous oozes (Harris et al., 2013; Kimura et al., 1997; Morris et al., 2003).

3.1.5. Aleutian

At the Aleutian Trench, the Pacific plate is subducted beneath the North American plate at a rate of ~5 cm/year (DeMets et al., 2010). This margin has experienced several great megathrust earthquakes, most recently in

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Table 2

| Subduction zone | Expedition/Leg | Expedition year | Drill site |
|-----------------|----------------|----------------|-----------|
| Sunda           | IODP Exp. 362  | 2016           | U1480     |
|                 |                |                | U1481     |
| Nankai          | IODP Exp. 322 & 333 | 2009 & 2010/11 | C0011     |
|                 |                |                | C0012     |
|                 | ODP Leg 190    | 2000           | 1173      |
|                 |                |                | 1177      |
| Aleutian        | IODP Exp. 341  | 2013           | U1417     |
|                 |                |                | U1418     |
| Middle America  | IODP Exp. 344  | 2012           | U1381     |
|                 |                |                | U1414     |
|                 | ODP Leg 170    | 1996           | 1039      |
|                 |                |                | 1253      |
| Hikurangi       | IODP Exp. 372B/375 | 2018          | U1520     |
|                 |                |                | U1526     |

Expeditions and Drill Sites From Which Data Used in This Study Were Acquired

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1957 and 1964 (Johnson & Satake, 1997). The incoming sedimentary section is about 800 m thick and is more terrigenous than the other sections examined in this study due to contributions of the Surveyor fan and glacimarine deposits (Jaeger et al., 2014; Reece et al., 2011). IODP Sites U1417 and U1418 are both located within the Surveyor Fan, but Site U1417 is on a distal part of the fan. The recovered cores contain Miocene to Holocene siliceous hemipelagic and biosiliceous-rich pelagic sediment (Jaeger et al., 2014). Subglacial limestones and diamict intervals are common in the cores from these sites.

3.2. Shipboard Measurements

IODP science parties acquire a variety of measurements on marine core samples while onboard the drilling vessels. The shipboard analyses are performed soon after core recovery. The IODP/ODP standard shipboard measurements include, but are not limited to, physical properties (density, porosity, water content, magnetic susceptibility, P-wave velocity, and electrical resistivity); geochemistry of pore water, gas, and mineral composition; sedimentary and structural descriptions, and age estimates from microfossils (IODP Science Support Office, 2017). The variety of datasets that are regularly collected with standardized methods during IODP expeditions allows the correlation of velocity and porosity data with information on sedimentology, structural geology, and geochemistry along with compilation and comparison of the data across the multiple subduction zones.

All the shipboard measurement data are available through the ODP (www-odp.tamu.edu/database/) and IODP databases (iodp.org/resources/access-data-and-samples). The primary shipboard measurements we use for this study are core lithologic descriptions, porosity, P-wave velocity, carbonate content determined from coulometry, and X-ray diffraction (XRD) measured on discrete core samples. The porosity is determined from wet and dry mass measurements and volume of solid measured using a gas pycnometer. The wet mass measurement is taken soon after the core liner is opened, and the dry measurement is taken after drying the sample at 105°C for 24 hr. P-wave velocity is also measured shortly after the core is opened using a caliper-type contact probe.

P-wave velocity measurements were acquired in up to three orthogonal directions when possible and we used the average of these measurements for this study. Carbonate content was calculated from total inorganic carbon concentrations as determined from coulometry. Details about the data-collection methods can be found in Blum (1997) and the expedition reports (e.g., Harris et al., 2013; Henry et al., 2012; Jaeger et al., 2014; McNeill et al., 2017; Saito et al., 2010; Wallace et al., 2019). Additional XRD data, including information on the clay minerals, were obtained from published studies (Ikari et al., 2013, 2018; Rosenberger et al., 2020; Screaton et al., 2017; Steurer & Underwood, 2003; Underwood, 2020; Underwood & Guo, 2013). As all analyses were not conducted on the same discrete samples, we identified the nearest neighbor measurements (always within 5 meters) on samples from the same lithologic unit and lithology. The resulting velocity-porosity data set is shown in Figure 2.

The benefit of using the shipboard data for this study is that there is a large quantity of data available. However, there is also inherent uncertainty associated with the data. The physical properties measurements used in this study were acquired over a 21-year period. While the measurement procedures have been standardized and consistent over that period, there will be uncertainty in the measurements due to differences in the apparatuses and users.

We reexamined original waveforms acquired using the shipboard P-wave caliper during the expeditions to assess uncertainty in the P-wave velocity data that may come from differences in wave arrival picking methods. We randomly selected at least 10 waveforms from each expedition and re-picked the wave arrivals. Our picks matched the arrivals identified during the expeditions, indicating that the picking procedure was consistent across multiple expeditions and users. Although we cannot double-check the porosity and compositional measurements, we did exclude samples with grain densities less than 2.0 g/cm³ and greater than 2.9 g/cm³ as densities outside of this range are unlikely for marine sediment so resulting porosity is likely incorrect. This range includes the grain densities of common minerals in the recovered sediment including quartz (2.65 g/cm³), feldspar (2.56 g/cm³), smectite (2.0–2.6 g/cm³), illite (2.6–2.9 g/cm³), and calcite (2.71 g/cm³) (Deer et al., 2013).

We exclusively used the shipboard measurements on the retrieved cores and did not use well log data because not all the sites had logging operations or obtained both the sonic and porosity logs. Using an electrical resistivity-derived porosity log would lead to increased uncertainty in the porosity measurement as we do not have the data to calibrate the resistivity-porosity relationship at each site. Furthermore, using the shipboard data allows...
for a more direct linkage between the velocity-porosity relation and other factors such as lithology and composition. As velocity and porosity are both influenced by confining pressure, there may be some concern that the unconfined shipboard measurements will not reflect the velocity-porosity relation at depth. However, Kitajima & Saffer (2012) showed that the velocity-porosity relation is independent of the stress path in normally consolidated sediments.

4. Results

Many of the velocity-porosity data follows the Hoffman & Tobin (2004) curve and the normal consolidation curve defined by Erickson & Jarrard (1998) (Figure 2). Samples from the Nankai Trough tend to be overconsolidated (Kitajima & Saffer, 2014) and fall along Erickson & Jarrard’s high consolidation curve. There are, however, two main clusters of outliers that are not well described by any of these curves. The first cluster falls below the curves with velocities that are significantly lower than is predicted based on their porosities. The data in this cluster come from the Sunda and Aleutian subduction zones. The second cluster falls above the curves; the measured velocity is faster than the velocity expected for the measured porosities. This cluster is dominated by samples from the Hikurangi margin.

4.1. Low Velocity Cluster

Samples in the low velocity cluster (yellow shaded region in Figure 2) are hemipelagic sands and mud with low clay and carbonate content. Comparing these samples to samples taken from depths above and below revealed that the recorded porosities were much lower for these samples than for neighboring samples although the velocities were fairly consistent, and the core descriptions indicate no major change occurred. Due to the
inherent uncertainty associated with the shipboard measurements, it is likely that these porosity measurements are erroneous although the grain densities are consistent with our expected range, falling between 2.59 and 2.87 g/cm³. As we cannot double-check the porosity measurements without obtaining the original sample, which will have dried out and therefore will be altered, we exclude these samples from the rest of the analysis.

4.2. High Velocity Cluster

The lithologies of the samples that dominate the high velocity cluster (red shaded region in Figure 2) are volcaniclastic and carbonate materials (Figures 3 and 4). The volcaniclastic materials, particularly those from Hikurangi, tend to have a much higher clay content than other lithologies (Figure 3). This is not unexpected; ash in contact with seawater reacts to form hydrous clay minerals. In the case of samples from Hikurangi and Sunda, smectite is the dominant clay mineral (Rosenberger et al., 2020; Underwood, 2020). Smectite clays contain abundant interlayer water, accounting for up to 25% of the bulk mass (Brown & Ransom, 1996). This interlayer water is easily removed by oven drying at elevated temperature (i.e., 105°C), resulting in an overestimate of porosity. Therefore, it is likely that the velocity measured for the volcaniclastic sediments is correct, but the porosity may be overestimated and does not reflect the actual sample porosity. The velocity and porosity may also be influenced by the presence of zeolite and calcite cement (Wallace et al., 2019).

While many carbonate-rich samples reside in the high velocity cluster many others of the same lithology and similar carbonate content fall along the curves. Note, we use carbonate content from coulometry instead of the calcite content determined from XRD analysis because more coulometry data are available. In general, the measured carbonate and calcite contents show similar trends. If the carbonate weight percent is combined with the XRD clay data, however, the weight percent may sum to be greater than 100%.

At the Middle America margin, high porosity calcareous oozes with carbonate contents of ∼80 wt.% follow the Erickson & Jarrard (1998) normal consolidation curve (Figure 4b). However, from visual inspection of the velocity-porosity data, these carbonate-rich materials appear to have a critical porosity of ∼45% to 50%, which is higher than the critical porosities of 30%–39% defined by Erickson & Jarrard (1998) and Hoffman & Tobin (2004). At Hikurangi, marl samples with carbonate contents of ∼30–60 wt.% fall in a zone with porosities between 55% and 30% and velocities between 1.5 km/s and 2.5 km/s (Figure 4a). Additionally, Hikurangi chalks have porosities ranging from 50% to 30% and velocities ranging from 2.0 km/s to 2.5 km/s. Within these broad ranges, some of the chalks and marls lie along the Erickson & Jarrard curve while others reside in the high velocity cluster. It is clear that neither carbonate content nor lithology is the sole parameter influencing whether or not carbonate-rich materials follow the standard velocity-porosity curve.

Figure 5 shows the velocity and porosity data from Hikurangi plotted with depth. This reveals that some of the variations observed in the velocity-porosity cross plot are associated with specific depths and can be divided into five zones within the carbonate-rich pelagic facies based on their characteristics with respect to velocity and porosity. At 510 mbsf, above which the formation is composed of hemipelagic sediments, the carbonate content jumps from less than 30 wt.% to more than 40 wt. %. Carbonate-poor, hemipelagic sediments above 510 mbsf and first carbonate-rich zone, dominantly composed of marls, between 510 and 645 mbsf show a gradual increase in velocity as porosity decreases with depth, as is expected for compaction of sediment due to overburden pressure.
In the second carbonate-rich zone, from 645 to 690 mbsf, carbonate content remains the same but there is a rapid 0.44 km/s increase in velocity with only a slight decrease in porosity. In the third zone, 690–770 mbsf, there is a 10% drop in the porosity, but velocity remains the same. At 770 mbsf, there is an increase in the carbonate content to 80 wt.% and the dominant lithology switches to chalk. Velocity in the fourth zone (770–795 mbsf) ranges from 2.2 to 3.1 km/s and porosities are consistent with the marls in the preceding zone. In the fifth zone located from 795 to 848 mbsf, the carbonate content increases to greater than 90 wt.% and porosity increases by 10% while velocity decreases to 2.1–2.5 km/s. Below 848 mbsf the recovered core samples are dominantly volcaniclastic conglomerate with variable textures. The greater variability in porosity and velocity observed in this section of the hole is likely due to differences in clast size and organization and zeolite cementation observed in the samples (Wallace et al., 2019).

5. Discussion

We have so far shown that deviations from existing velocity-porosity relations in incoming sediment occur for samples with high clay or carbonate content. These deviations may be caused by problems in the methods of data collection used or by differences in the way velocity and porosity evolve in siliciclastic and carbonate sediments in response to stress, temperature, and time. In the first case, a new velocity-porosity relation may be unnecessary. In the second case, caution should be exercised when using existing velocity-porosity relations to estimate stress and fluid content in subduction zones. In this case, additional work would be required to characterize the velocity-porosity variations and underlying causes.

5.1. Clay Bound Water Correction

Given the high clay content present in the volcaniclastic sediments and associated overestimate of porosity, it is likely that correcting the porosity for the loss of interlay water will shift the data so the samples will follow the Erickson & Jarrard (1998) curve. This would require a 10%–25% decrease in the measured shipboard porosity (total porosity + interlayer water). This correction can be done using cation exchange capacitance (CEC) (Henry, 1997). Figure 6 shows the results of the porosity correction based on the CEC analysis performed on a subset of samples from both the Sunda and Hikurangi margins (Dutilleul, Bourlange, Conin, & Géraud, 2020; Dutilleul, Bourlange, Géraud, & Stemmelen, 2020). For the Hikurangi samples, the difference between the shipboard and CEC-corrected porosities for carbonate and siliciclastic sediments is small, however, the difference for the volcaniclastic sediments is significant. When the corrected porosity is used in the velocity–porosity plot, the volcaniclastic sediments fall along the Erickson & Jarrard (1998) curve for normally consolidated sediment with a high shale volume, as is expected for clay-rich sediment. For a volcaniclastic sample from the Sunda Trench, the CEC correction reduced the porosity estimate from 46.6% to 27.4%. The correction in the siliciclastic and carbonate sediments is greater for Sunda sediments than for Hikurangi sediments due to the higher clay content at Sunda (Figure 3b).

5.2. Carbonate Complexity

The relation between velocity and porosity is much more complex in carbonate material than in siliciclastic sediments. In siliciclastic sediments, the velocity-porosity relation is primarily controlled by composition and...
compaction (Erickson & Jarrard, 1998). In carbonate-rich sediments, on the other hand, the velocity-porosity relation is less influenced by the carbonate mineralogy and compaction but largely controlled by the depositional lithology and the diagenetic processes that occur in the sediment (Anselmetti & Eberli, 1993). Diagenetic processes that occur much earlier and more rapidly in carbonate sediments than in siliciclastic sediments probably control the depth variations of both velocity and porosity observed in the Hikurangi data. Concentrations of strontium, which is released during carbonate diagenesis (Kastner et al., 2014), measured in the pore fluids recovered from Site U1520 start to increase around 509 mbsf, where the marls are first observed (Ayres et al., 2020). The concentration reaches a maximum at 647.3 mbsf, consistent with the top of Zone 2 where we observe a marked increase in the P-wave velocity (Figure 5) and remain high above 800 mbsf after which they begin to decrease. This suggests that diagenesis is prevalent at Site U1520, especially within Zones 2–4.

Assuming carbonate-rich sediments that have not experienced diagenetic alteration would follow a velocity-porosity curve based on siliciclastic sediments, a synthetic velocity log—based on the measured porosities—can be used to infer the pore type in rocks that have experienced alteration (Anselmetti & Eberli, 1999). If the synthetic velocity log is equivalent to the measured velocity the pore type is predicted to be interparticle (pore space between individual grains or crystals). A synthetic log that is slower than the measured velocity indicates the pores are integrated into a rigid frame-like rock fabric, such as intrafossil or moldic porosity. The presence of moldic
porosity indicates significant diagenetic alteration. A synthetic log that is faster than the measured velocity indicates intense fracturing, which we do not expect to see as we are working with laboratory measurements on intact samples instead of borehole logs.

We calculated the synthetic velocity log using the Hoffman & Tobin (2004) velocity-porosity relation. The resulting synthetic curve is shown as a black line in Figure 5. In the first carbonate zone, the synthetic and measured velocities are very similar indicating interparticle porosity. This suggests that compaction due to overburden stress is likely the controlling mechanism behind the changes in velocity and porosity in this zone and cementation-dissolution processes have probably not begun. In Zones 2 through 5, the synthetic velocity is slower than the measured velocity, suggesting an increase in velocity is caused by diagenetic alteration consistent with high strontium concentrations observed by Ayres et al. (2020). In Zone 2, increased cementation at grain contacts may cause a sudden increase in velocity without a corresponding change in porosity as grains are bound together and creating a rigid framework while not yet significantly affecting the interparticle pore space. The decreased porosity observed in Zone 3, may reflect a longer period of cementation so that the pore space begins to be infilled but, as the rigid framework is also present in Zone 2, we observe only a decrease in porosity without an associated increase in velocity as the bulk modulus remains the same. The greater range in velocity in Zone 4 may be caused by an increase in carbonate content. In Zone 5, dissolution of grains, creating moldic pores, could result in a higher porosity but would not affect the cement framework so velocity remains higher than expected for the
measured porosity. There is a higher concentration of pressure solution and stylolitic seams in Zone 5 indicating a high degree of diagenesis (Barnes et al., 2019). The microstructural analysis needed to support this interpretation of the velocity-porosity variations with depth has not yet been done and is beyond the scope of this study.

5.3. Updated Velocity–Porosity Relations

The Erickson & Jarrard (1998) and Hoffman & Tobin (2004) relations can reasonably predict seismic velocity in siliciclastic marine sediment from the subduction zones examined but they tend to underestimate the velocity in many carbonate-rich rocks. Due to the complex dependence porosity and velocity have on diagenetic processes in carbonate rocks, a velocity-porosity relation would have to account not only for variations in carbonate content but also for the diagenetic history of the material, which would be site-specific. The samples and analysis required to constrain the diagenetic history in an area would probably eliminate the need for a predictive velocity-porosity relation. However, the existing relations can be modified to better represent the range of velocities and porosities observed in pelagic sediments.

In Equation 1, parameters A-D describe the behavior of the curve at porosities above the critical porosity \( \phi_c \), whereas parameters E-G influence the behavior of the curve at porosities below the critical porosity. Because there is little variation in the velocity at high porosity (Figure 2), we use the same values for parameters A-D that were used in the normal consolidation curve of Erickson & Jarrard (1998) and focus on modifying these parameters to develop a model that reflects the velocities and porosities measured for pelagic and hemipelagic sediments at lower porosities. A modification of the high consolidation curve is provided in the Figures, S1, S2, and Table S2 in Supporting Information S1.

One of the limitations of the Erickson & Jarrard (1998) model is that it constrains the matrix velocity (velocity at zero porosity) to fall between 5.49 km/s \((v_{sh}=0)\) and 4.3 km/s \((v_{sh}=1)\), for sandstone and shales, respectively. The sandstone matrix velocity comes from Raymer et al. (1980) who estimate that it ranges from 5.49 to 5.94 km/s. Velocities for many of the low porosity, high carbonate pelagic samples approach a velocity of 6.0 km/s or greater. The matrix velocity for limestone is estimated to range between 6.40 and 7.01 km/s (Raymer et al., 1980). In this study, we assumed a matrix velocity of 6.5 km/s when \( v_{sh} = 0 \), which is consistent with the velocity of calcite (Wang, 1966), and 4.3 km/s when \( v_{sh} = 1 \), as was assumed by Erickson & Jarrard (1998). These assumptions constrain parameter F to be 1.07 and require:

\[
E = \frac{1.1}{\tanh(G\phi_c)} \geq 1.1
\]

As the velocities of the carbonate-rich sediments start to increase rapidly between 45% to 50% porosity, the critical porosity likely falls within this range. We assume it to be 48%. Choosing a different critical porosity between 45% and 50% does not have a significant impact as this choice only shifts where the rapid velocity increase begins.

The parameter G influences the rate of velocity increases at the critical porosity. As our data indicate this rate is relatively small, we find that \( G = 7 \) represents the data well (Figure 7). If a different critical porosity had been chosen, slight variations in G would result in a very similar fit to the one shown in Figure 7. All parameters used in the modified relation are provided in Table 1. Figure 8 shows the residuals between the measured and predicted velocities, where the total clay content was used as the shale fraction, for both the Erickson & Jarrard (1998) normal consolidation curve and our modified velocity-porosity model. The residuals are the same for porosities greater than 48%, this is expected since the models are the same at porosities greater than the critical porosity.
For high carbonate samples (>85 wt. %), the Erickson & Jarrard (1998) model tends to underestimate the measured velocity (Figure 8a). The modified model does not improve the residuals, as it tends to overestimate the velocity of both the high and low carbonate sediments. However, the modified model better represents the range of velocities and porosities observed in carbonate-rich marine environments although it does not currently provide reliable predictions. The model could be improved by calibrating it for clay content, but we currently lack the data needed to do this. The addition of a carbonate fraction parameter could be useful; however, it requires more carbonate-rich samples over a range of porosities and velocities. Even with the inclusion of a parameter reflecting carbonate content, the relation would still be incomplete due to the impact of pore type. Therefore, it is important to remember that this modified velocity-porosity relation is not a predictive relation for all carbonate-rich rock but is instead a representation of the full range of velocities and porosities we observed in the siliciclastic and carbonate marine sediments.

In the future, the evolution of velocity-porosity relations can be further investigated by also conducting deformation tests at elevated pressure and temperature. Once the sediments are subducted or accreted, the stress states change so it is crucial to investigate the effects of loading paths on the velocity-porosity relation. Kitajima and Saffer (2012) reported that the velocity-porosity relation in the low-carbonate rocks from the Nankai Trough is independent of stress paths. By conducting similar experiments on carbonate-rich rocks at elevated pressure and temperature, we ought to be able to assess whether the Erickson & Jarrard (1998) relation or our proposed relation is appropriate to characterize all the marine sediments.

6. Conclusions

A robust understanding of velocity-porosity relations in subduction zone sediments is important for constraining both the stress state and fluid budget of the subduction zone. While siliciclastic subduction zone sediments can be reasonably well described by existing models, relations in carbonate-dominated subduction zones remain problematic. This is due to the variety of pore types that can result from diagenetic processes in carbonates and
the complex effects this can have on the measured seismic velocity. While a global relation describing velocity-porosity variations in carbonate-rich sediment cannot be defined with the available data and may never be attainable, our work provides a model that reflects the full range of velocities and porosities observed in both siliciclastic and carbonate incoming sediment from multiple subduction margins.

Subduction zones are heterogeneous and ignoring that heterogeneity can impact the way we interpret data. Therefore, based on our analysis of the data, the estimation of porosity-and subsequently pore pressure and fluid content-from seismic-velocity data would benefit from the utilization of multiple velocity-porosity relations to examine the sensitivity of the results. In regions with high carbonate content, the modified relation presented in this study may be a good starting point for such an analysis.

Data Availability Statement

All the data used in this study are available through the IODP data repositories (iodp.org/resources/access-data-and-samples).

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