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Shear strength characteristics of marine sediments: the influences of lithofacies and sedimentological environment

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Abstract

The undrained shear strength of marine sediment is of vital importance because of its critical role in seafloor slope stability, seafloor infrastructure, and influencing sediment dynamics that can lead to underwater landslides. Therefore, understanding the undrained shear strength of marine sediments and its influencing factors is a fundamental requirement for both offshore engineering and geoscience studies. Core data obtained from 198 sites across 46 legs of the Ocean Drilling Program/International Ocean Discovery Program (ODP/IODP) were used to analyze the undrained shear strength of marine sediments and their influencing factors. The undrained shear strength of marine sediments is significantly influenced by the depositional environment. Sediments deposited in active continental margins exhibit a higher undrained shear strength than those deposited in deep-sea and carbonate platform environments due to seismic strengthening and over-consolidation. It was found that fine-grained siliciclastic lithofacies with less than 50% carbonate content exhibited high variability and a rapid increase in the undrained shear strength with depth. In contrast, fine-grained carbonate lithofacies with more than 50% carbonate, as well as reef-facies carbonates, showed low variability and only a gradual increase in undrained shear strength with depth. Additionally, we showed a positive association between the undrained shear strength and physical characteristics including bulk density and P-wave velocity, as well as an inverse correlation with porosity. An exponential relationship was found between these physical properties and the undrained shear strength, with coefficients of determination (R^2) values of 0.71, 0.74, and 0.69, respectively.

Keywords Undrained shear strength · Lithofacies · Marine sediments · Depositional environment · Over-consolidation · Elastic properties

Introduction

One of the important characteristics of marine sediments is undrained shear strength, which plays a significant role in a variety of geological processes and marine engineering applications. Specifically, at shallow depths, undrained shear strength influences the occurrence of landslides, where submarine landslides happen when shear stress surpasses the undrained shear strength (Masson et al. 2006; Tappin et al. 2014; Zhang et al. 2023). It's important to note that the majority of submarine landslides occur within the uppermost 100 m below the seafloor (Urlaub et al. 2015; Moscardelli and Wood 2016). Therefore, understanding undrained shear strength within this "landslide" zone is paramount for assessing the resilience of seafloor slopes against submarine landsliding (Sawyer and Devore 2015; Moscardelli and Wood 2016; Pham et al. 2018; Hussein et al. 2023). At greater depths, undrained shear strength influences faulting and the propagation of earthquakes Stigall and Dugan (2010). Together, earthquakes and submarine landslides stand as persistent hazards with profound implications for coastal regions globally, often culminating in significant infrastructural damages and casualties (Kenter and Schlager 1989; Lay et al. 2005; Hornbach et al. 2010).

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Therefore, the main goal of this research is to methodically examine the undrained shear strength characteristics of marine sediments and their influencing factors using the Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP) data.

Bartetzko and Kopf (2007) found that the relationship between the undrained shear strength varied depending on sediment composition and tectonic setting. They also observed that the undrained shear strength of the sediments tended to increase with depth; however, this trend was not always present. Similarly, Kenter and Schlager (1989) examined the undrained shear strength with respect to the ocean and sediment depths. More than 2000 measurements were taken to analyze the variation in the undrained shear strength in the upper sediment layer at depths no deeper than 6 m. They found that the undrained shear strength in siliciclastic sediments increased gradually with depth and exhibited low variability, whereas in calcareous sediments, the undrained shear strength was highly variable and increased rapidly with depth. Additionally, they note that due to the granular form of the carbonate particles or interparticle cementation, the high carbonate content increases with an increase in undrained shear strength. Furthermore, Devore and Sawyer (2016) analyzed data from two locations within the IODP sites, comparing sediment properties at passive and active margins in siliciclastic sediments. Their findings indicate that sediments from active margins possess higher undrained shear strength compared to those from passive margins, attributed to differences in seismic activity.

It is worth mentioning that the undrained shear strength of marine sediments plays a crucial role in determining the stability of the submarine slopes. Given the global distribution of these sediments and increasing interest in deep-water exploration, it is essential to understand their geomechanical properties (Laberg and Camerlenghi 2008; Thomas et al. 2010). Such an understanding will enable more accurate slope stability modeling, ensuring safer marine infrastructure and operations. Although numerous studies have extensively focused on analyzing the undrained shear strength of soil, marine sediments have received comparatively less attention. To address this gap, a comprehensive investigation of the undrained shear strength of marine sediments is imperative.

Therefore, the primary contribution of this study is the systematic analysis of the undrained shear strength of marine sediments within the first 100 m below the seafloor, utilizing ODP/IODP core data. Additionally, we investigated the effects of various geological factors, such as lithofacies, depositional environment, seismic strengthening, and over-consolidation on the undrained shear strength of marine sediments. Moreover, this study examines the correlations between physical properties including porosity,

P-wave velocity, bulk density, and undrained shear strength across different depositional environments. Based on these comprehensive analyses, we have derived an empirical model that elucidates these correlations, offering valuable insights for predicting the undrained shear strength of marine sediments.

First, we introduce the datasets compiled from the ODP/IODP programs and describe the sediment types. We then investigated the various geological factors that contribute to the undrained shear strength of marine sediments, such as the depositional environment and lithofacies. Next, we present the empirical relationships between the physical properties and the undrained shear strength. Finally, we discuss the effects of over-consolidation and high sedimentation rates.

Compiled database

Site selection

The core data used in this study were collected from 198 sites across 46 legs of the (ODP/IODP) database. For all measurements, we plotted the undrained shear strength value from the seafloor to 100 m below the seafloor. We chose to analyze the 0–100 m depth zone due to the presence of a continuous sedimentary record core recovery within this interval across the sites investigated, and also because most submarine landslides occur within the uppermost 100 m below the seafloor. These data include measurements of the undrained shear strength, along with physical properties such as bulk density (BD), compressional wave velocity (Vp), shear wave velocity (Vs), and porosity. This study primarily focused on drilling sites located near continental margins, in the deep sea, and on carbonate platforms (Fig. 1). Our dataset comprises 15,532 measurements of undrained shear strength, including 5,622 from calcareous fine-grained sediments, 8,094 from siliciclastic fine-grained sediments, and 1,816 from reef-facies carbonates, with a range of 0–200 kPa.

It is important to note that in the ODP/IODP, the undrained shear strength of sediments was measured using three different instruments, including the automated vane shear system (AVS), a pocket penetrometer (PEN), and a hand-held torvane (TOR)Bartetzko and Kopf (2007). Each of these tools offers unique advantages and is suitable for evaluating different types of sediments or settings. The AVS is known for its accuracy and is commonly used during ODP/IODP expeditions to measure undrained shear strength by rotating a vane within the sediment. The PEN, a handheld device, assesses the compressive strength of a sample, which can then be used to estimate its undrained shear strength. Similarly, the TOR is another handheld
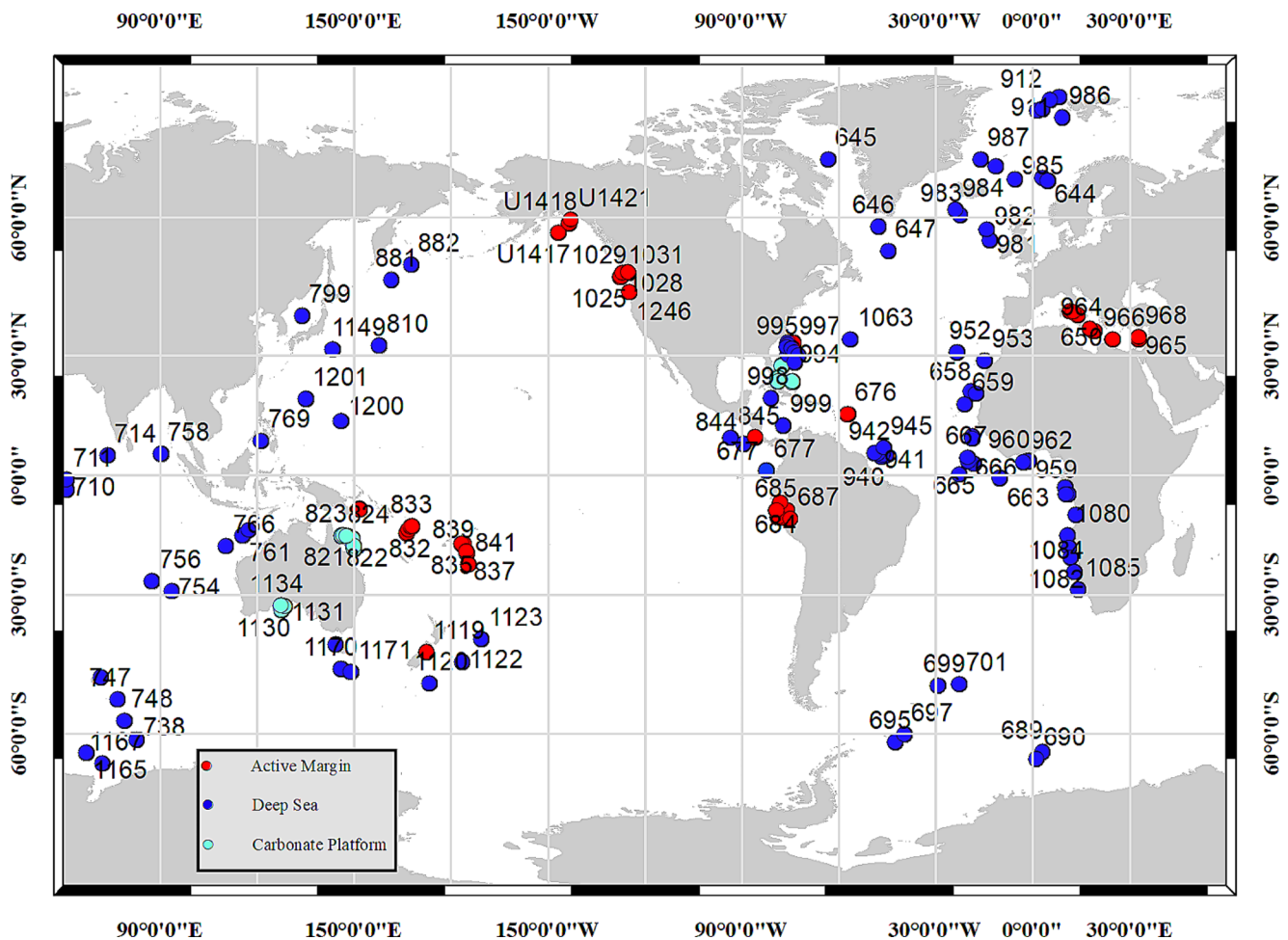
Fig. 1 A map of the world displaying the locations of ODP/IODP drilling sites utilized in this study. We have used 198 sites, including 107 from the deep sea (blue color), 64 from active margins (red color), and 27 from carbonate platforms (green color)

device that measures undrained shear strength directly by rotating a vane within the sample. However, due to differences in methodologies, this study exclusively focused on data from the AVS to ensure consistency and avoid integrating potentially variable results from different methods, such as those obtained with the torvane or penetrometer.

Sediment types and their locations

The ODP/IODP database predominantly consists of three different lithofacies: calcareous fine-grained sediments with a carbonate content of more than 50%, siliciclastic fine-grained sediments with a carbonate content of less than 50%, and reef-facies carbonates. To gather data on sediment composition, we utilized information from core descriptions published in the Proceedings of the (ODP/IODP) Initial Reports. Siliciclastic sediments were the most abundant type of sediment. Below is a brief description of these three sediment types and the data sources.

1. Siliciclastic sediments were the most abundant type of sediments collected in this study. This type of sediment includes clayey and silty compositions as well as nannofossil oozes and/or diatoms with a carbonate content of less than 50%. These sediments were collected from various depositional environments. The active continental margins studied included locations such as the Peru Margin, Blake Ridge, Costa Rica Margin, Barbados Ridge, Eastern Mediterranean, and Cascadia Margin. Deep-sea sites consisted of regions in the Caribbean Sea, Pacific, North Atlantic, Weddell Sea, African Margin, Labrador Sea, and the Gulf of Mexico. Notably, most of these sites displayed significant variations in undrained shear strength. This suggests that they are located in areas where ice rafting facilitates the transfer of silt from the slope to the continental shelf (Takahashi et al. 2011). In addition, diagenetic phases were observed at these sites.

2. Fine-grained carbonates dominated by calcareous muds and nannofossil oozes with an average carbonate

content of 87% were primarily collected from the deep-sea regions of the Indian Ocean, Caribbean Sea, Antarctic, NW Atlantic, NE Atlantic, SW Pacific, and New Zealand. The active margin samples were sourced exclusively from the Mediterranean Sea. These fine-grained carbonate sediments generally exhibited lower undrained shear strengths than their fine-grained siliciclastic counterparts. This trend may be attributed to the high abundance of nannofossil oozes within the lithofacies (Hernández-Molina et al. 2013).

3. Reef-facies carbonate samples were primarily collected from Northern Australia and the Bahamas.

Initially, we plotted the relationship between the undrained shear strength and water depth using ODP/IODP core data in the top 1 m of the sediment, as shown in Fig. 2. Generally, the undrained shear strength exhibits a weak positive correlation with water depth, indicating that the undrained shear strength is relatively insensitive to water pressure.

Result

The influences of lithofacies on undrained shear strength

Based on ODP/IODP core data analysis, the drill sites in the uppermost 100 m were classified into three types of lithofacies: (1) fine-grained siliciclastic, (2) fine-grained carbonates, and (3) reef facies carbonates. We selected 198 sites, including 104 fine-grained siliciclastic sites, 67 fine-grained carbonate sites, and 27 carbonates in the reef facies for which AVS data were available. Initial reports, carbonate content data from the Janus database, and core descriptions from the Proceedings of the ODP/IODP were used to determine the composition of the sediment. Sediments composed of fine-grained siliciclastic and fine-grained carbonates lithofacies are the most common types of sediments, respectively.

Figures 3 and 4 show how the undrained shear strength varies with depth for reef facies carbonate, fine-grained siliciclastic, and fine-grained carbonate lithofacies. Although compaction is a primary factor controlling the undrained shear strength, many other geological factors can further complicate the depth-dependent relationship in shear strength. It can be noted that the fine-grained siliciclastic sediments, which are predominantly composed of clay and silt along with nannofossil oozes and/or diatoms and contain less than 50% carbonate content, display a significant increasing trend in undrained shear strength values, reaching up to 200 kPa, as shown in Fig. 3a. This is likely due to the overburden erosion of unroofed sediments (Kitajima and Saffer 2014), and post-depositional diagenesis of coarse-grained sediment at drill sites, e.g., Legs 311 and 164. However, even within the fine-grained siliciclastic sediment lithofacies, most of the drilled sites exhibited
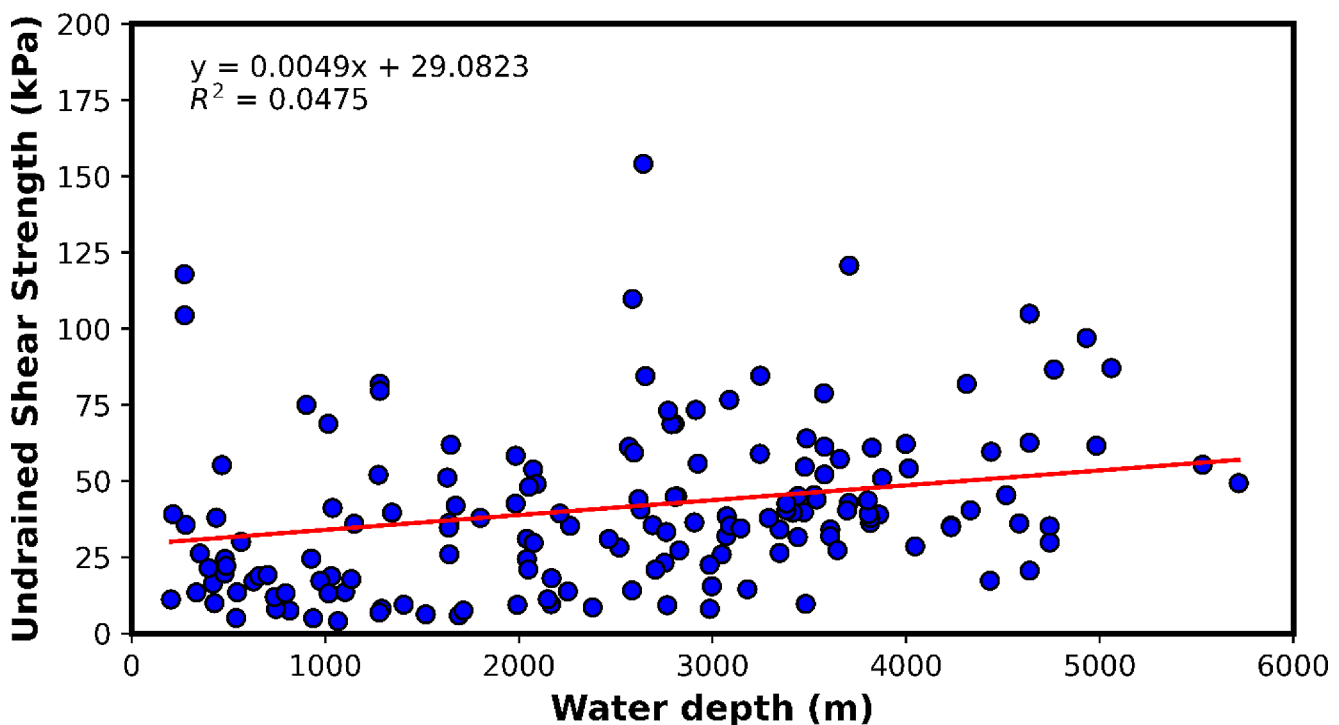

Fig. 2 Relationship between marine sediment undrained shear strength and water depth based on ODP/IODP core data. The equation and R^2 values corresponding to the line of best fit for the plotted data are shown on the upper left
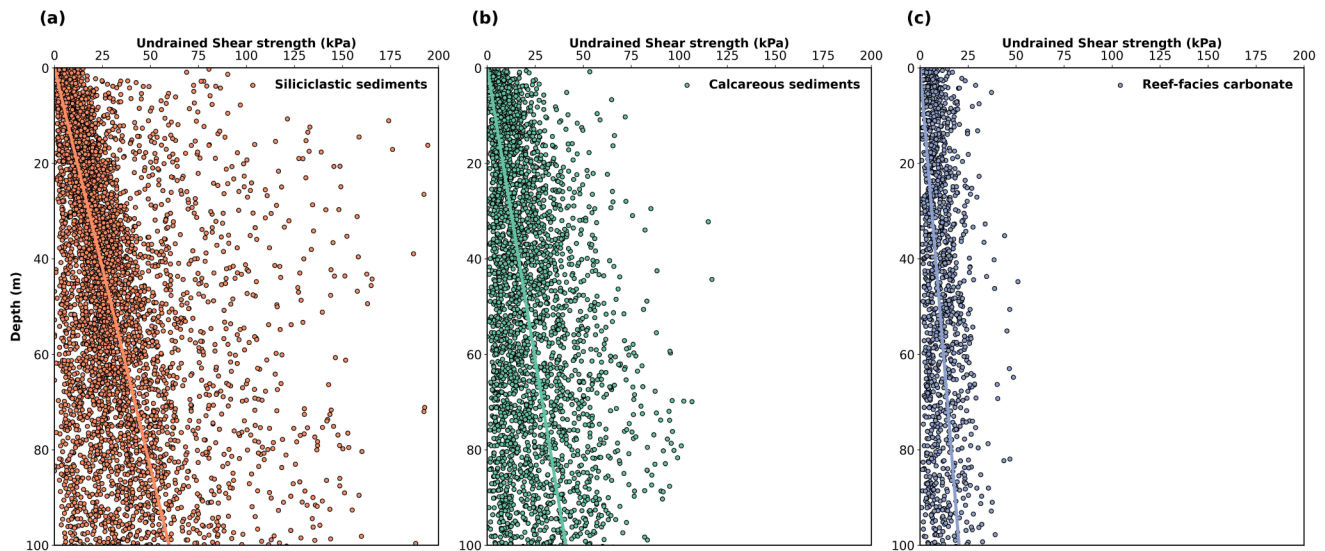
Fig. 3 Distribution of undrained shear strength (Su) relative to depth across three different lithofacies, utilizing data from 198 sites across 46 legs from the (ODP/IODP). (**a**) the undrained shear strength versus depth in siliciclastic sediment lithofacies from 104 drilling sites, (**b**) the undrained shear strength versus depth in calcareous sediment lithofacies from 67 drill sites, (**c**) the undrained shear strength versus depth in reef-facies carbonate lithofacies from 27 sites. The trend lines in the graph represent the average variation of Su with depth for each lithofacies

undrained shear strength values ranging between 0 and 70 kPa at a depth of 100 m. This is likely due to the overall fining of clastic material, which suggests deepening basin conditions coupled with high water content values.

In contrast, fine-grained carbonate lithofacies with > 50% carbonate content are exclusively developed in deep-sea environments and consist of muds and oozes with significant amounts of nannofossils and/or foraminifers. Such lithofacies displayed undrained shear strength values ranging from 0 kPa near the seafloor to 85 kPa at a depth of 100 m, as illustrated in Figs. 3b and 4. The majority of drill sites within the fine-grained carbonate lithofacies exhibited lower undrained shear strength values. This can be attributed to the dominance of nannofossil ooze in these lithofacies, which suggests an increased carbonate productivity in open ocean waters. Such observations indicate a consistent depositional environment in these regions, characterized by a minimal influx of terrigenous material and a predominant presence of biogenic matter. However, there are still data points that show increased undrained shear strength values of up to 100 kPa. These variations may be attributed to diagenetic effects, changes in carbonate content, and the impact of effective overburden stress (Oh et al. 2017).

Finally, the reef-facies carbonate lithofacies typically do not show any significant trend of undrained shear strength with depth, as one might expect given the effects of compaction. The shear strength values generally vary between 0 and 35 kPa, as illustrated in Figs. 3c and 4. This consistency might be attributed to the distinct porosity character of carbonate lithofacies that are characterized by irregular voids
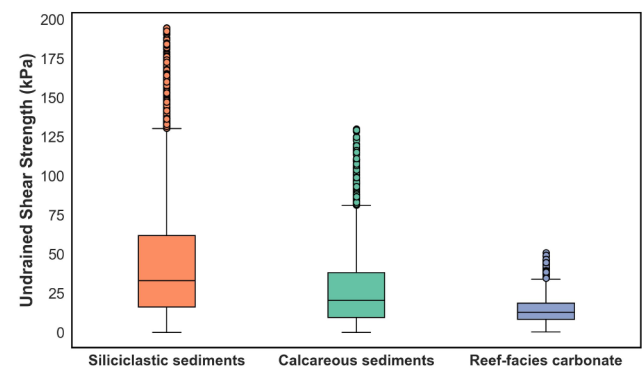

Fig. 4 Boxplot illustrating the distributions of undrained shear strength across three different lithofacies, based on data from the ODP/IODP archives

and larger bioclasts, heavily influenced by marine skeletal remains. This could make them more resistant to compaction, and as a result, the shear strength does not increase with depth, as expected.

Effect of depositional environments

Figure 5a and b illustrate the impact of the three different depositional environments on the undrained shear strength as a function of depth. Most of the data were collected from the deep-sea and active continental margins because of the higher availability of data from these environments. The data clearly show that different depositional environments exhibit significant variations in undrained shear strength with depth. For example, sediments from deep-sea and carbonate

platform environments generally have lower undrained shear strengths than those from active continental margins. Possible reasons for extremely elevated shear strength values in active continental margins suggest a strong influence of seismic strengthening on shallow sediments.

As illustrated in Fig. 5a, b and a relatively high undrained shear strength is predominantly observed in active continental margins, which are dominated by fine-grained siliciclastic sediments. This highlights the various processes contributing to the high undrained shear strength observed in this environment. The enhanced shear strength on active margins and overall paucity of submarine landslides have been suggested to be largely controlled by seismic strengthening, in which repeated exposure to low-magnitude seismicity results in progressive dewatering and densification. A key aspect of the seismic strengthening hypothesis is that strengthening is due to cumulative porosity loss (Locat and Lee 2002; Lee et al., 1990). However, the study reveals low sediment strength in some sites on the continental slope, differing from other active margins where seismic strengthening typically increases slope stability. This is likely due to the high sedimentation rates and overpressure counteracting seismic strengthening (Sawyer et al. 2017). These factors combine to make them one of the most susceptible regions to submarine landslide hazards. A notable factor potentially enhancing shear strength on active margins is over-consolidation. The analysis of Blake Ridge Site 993 within the 0–50 m interval reveals high undrained shear strength in sediments. This increase is attributable

to over-consolidation, likely due to the erosional removal of overlying material (Kimura et al. 1997; Winters 2000; Kitajima and Saffer 2014). A recent study by Molenaar et al. (2019) suggests that seismic strengthening could be a contributing cause of over-consolidation. Further discussion on these factors is provided in the DISCUSSION section.

It is also interesting to note that findings from Blake Ridge Sites 994, 995, and 997, dominated by hemipelagic accumulations of biogenic and terrigenous sediments, show a significant increasing trend in undrained shear strength with depth, as illustrated in Fig. 6a. This could be attributed to the presence of indurated diagenetic carbonates, which are concentrated in specific zones and undergo complex cementation processes, suggesting a significant role in influencing the sediment's undrained shear strength (Paull et al. 1996; Pierre et al. 2000). Conversely, Sites 679 to 687 along the Peru continental margin, characterized by organic-rich, diatomaceous sediments, exhibit higher undrained shear strength, particularly around depths of 20 m below the seafloor, as depicted in Fig. 6b. This enhancement is linked to early diagenetic processes and a distinctive diatom-rich fabric, where the rough and interlocking surfaces of diatoms improve particle connectivity, resulting in increased undrained shear strength Moreover, results from the Eastern Mediterranean sites (Leg 160), consisting of interbedded hemipelagic nannofossil ooze, clay, and sapropels, indicate that the sediment's shear strength increase is primarily due to an upsurge in organic matter content (Kopf et al. 1998), as shown in Fig. 6c.
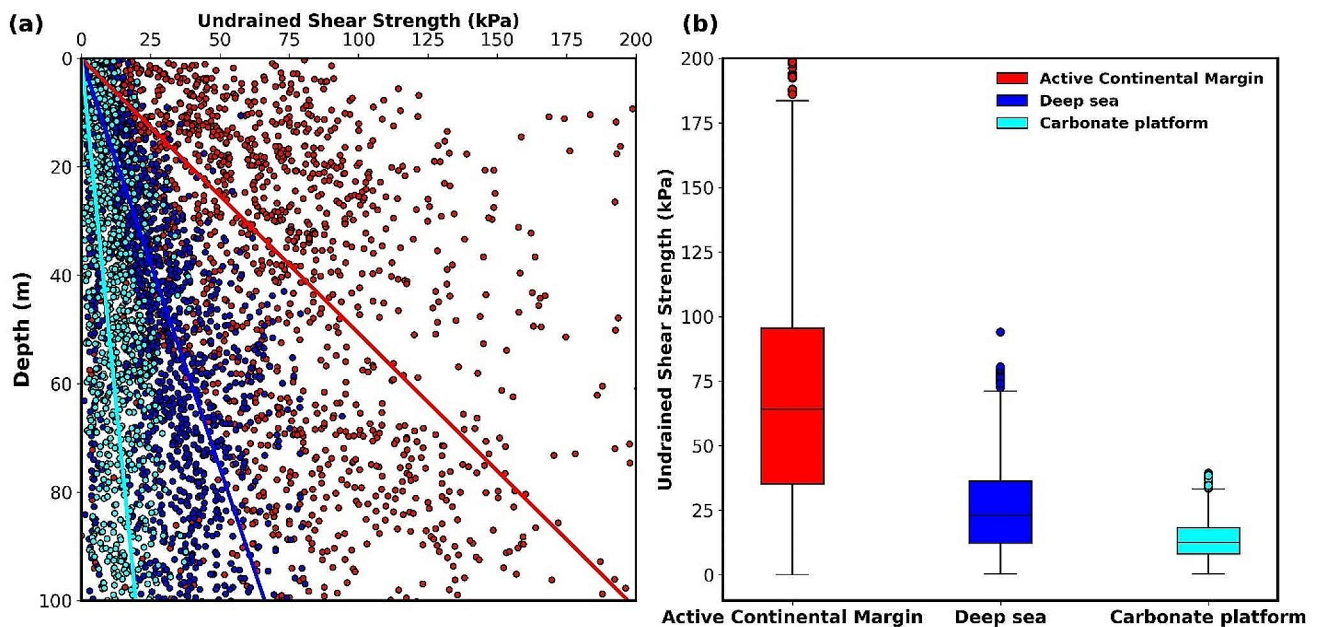

Fig. 5 (a) Undrained shear strength versus depth for three different depositional environments: active continental margin (red), deep-sea (blue), and carbonate platform (green). The trend lines represent the arithmetic mean for each lithofacies, (b) box plot showing the distributions of undrained shear strength for three different depositional environments sourced from the ODP/IODP data archives
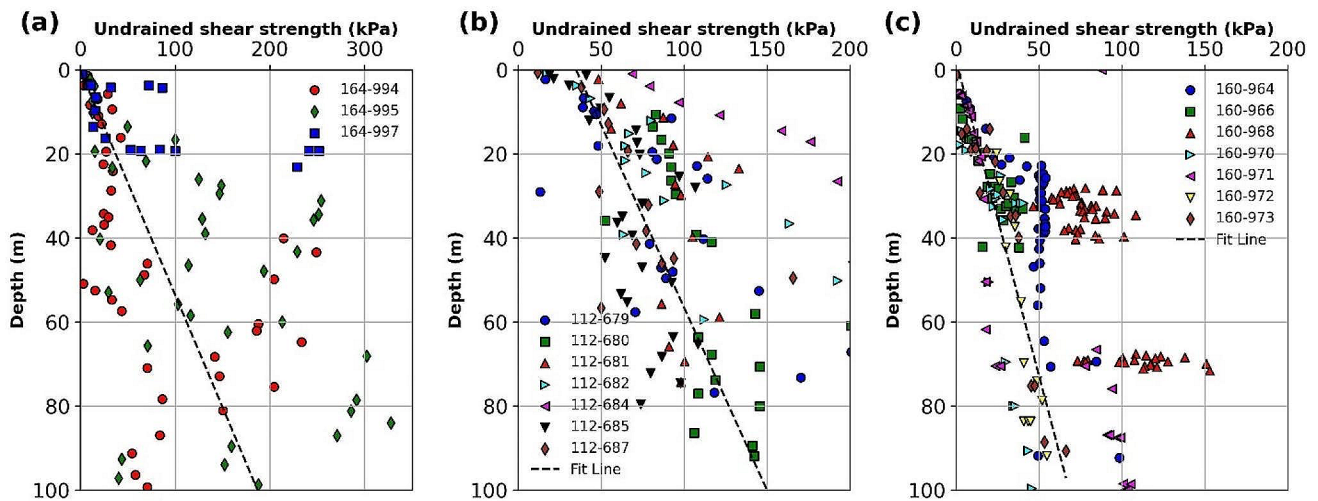
Fig. 6 (**a**) Undrained shear strength versus depth for three different sites from Blake Ridge (ODP Leg 164), (**b**) undrained shear strength versus depth for seven different sites from the Peru continental margin (ODP Leg 112), (**c**) undrained shear strength versus depth for seven different sites from Mediterranean sites (ODP Leg 160). The trend dashed lines represent the arithmetic mean

Nevertheless, lower undrained shear strength is predominantly observed in the deep-sea environments of the Pacific Ocean, NE Atlantic, Caribbean Sea, West Africa, and Indian Ocean. These regions feature fine-grained carbonates, including nannofossil oozes, calcareous muds, and clayey silt with interbedded laminae and thin silty beds. This indicates the influence of open ocean water with elevated carbonate production rates and limited terrestrial inputs. The majority of these sites exhibit undrained shear strength values ranging between 0 and 50 kPa for the upper 100 m (Fig. 5a and b), suggesting an underconsolidated appearance of the sediment, possibly resulting from a long period of non-deposition and the absence of dewatering when sedimentation began again or perhaps due to diagenetic processes acting in the smectite and ash fractions at some sites. Interestingly, the decrease in the undrained shear strength values from the NE Atlantic is associated with a sharp increase in the amount of biogenic silica. This pattern indicates that sediments rich in biogenic silica tend to have reduced undrained shear strength compared to those with more clays and carbonates Bryant et al. (1981). However, the high undrained shear strength in the upper 75 m of the sediment, reaching up to 70 kPa, may result from a mix of siliceous ooze and nannofossil ooze, forming a strong but non-rigid fabric Barker and Kennett (1988).

In the carbonate platform environments of NE Australia and the Bahamas, the shear strength typically ranges from 0 to 25 kPa within the upper 100-meter interval and does not increase with depth, as would be expected considering the compaction effect. The primary reason for this observed low shear strength in reef-carbonate sediments can be attributed to their clast-supported texture, which is characterized by a significant presence of large bioclasts. These features

result in an inconsistent particle distribution and decreased compaction, further reducing the overall shear strength. Moreover, this lower shear strength is associated with other sedimentary characteristics, such as lower bulk density and velocity, coupled with higher water content.

Undrained shear strength and physical properties relationship

Figure 7a, b, and c illustrate the relationships between the undrained shear strength and bulk density, P-wave velocity, and porosity across three different depositional environments: the active continental margin, deep sea, and carbonate platform. The data suggest that porosity is inversely related to the undrained shear strength, whereas both the density and P-wave velocity showed a positive correlation with the undrained shear strength. In general, sediments from an active continental margin environment exhibit lower porosity and higher P-wave velocity, bulk density, and undrained shear strength than those from a deep-sea environment.

Selecting sites from the deep-sea environment were collected from various oceans, including the Pacific Ocean, Antarctic, West Africa, Caribbean Sea, and Indian Ocean. These sites are characterized by clayey silt, nannofossil ooze, and/or diatoms, with rare laminae of fine silty sands. As illustrated in Fig. 7a, b, and c the results from the deep-sea sites indicate lower P-wave velocities, bulk densities, and undrained shear strengths. In contrast, the porosity exhibited significant variation. This variation can be attributed to the enhanced presence of biogenic materials, such as diatomaceous oozes or muds, which are known to retain higher moisture content and thereby contribute to a lower undrained shear strength. However, the highest values for
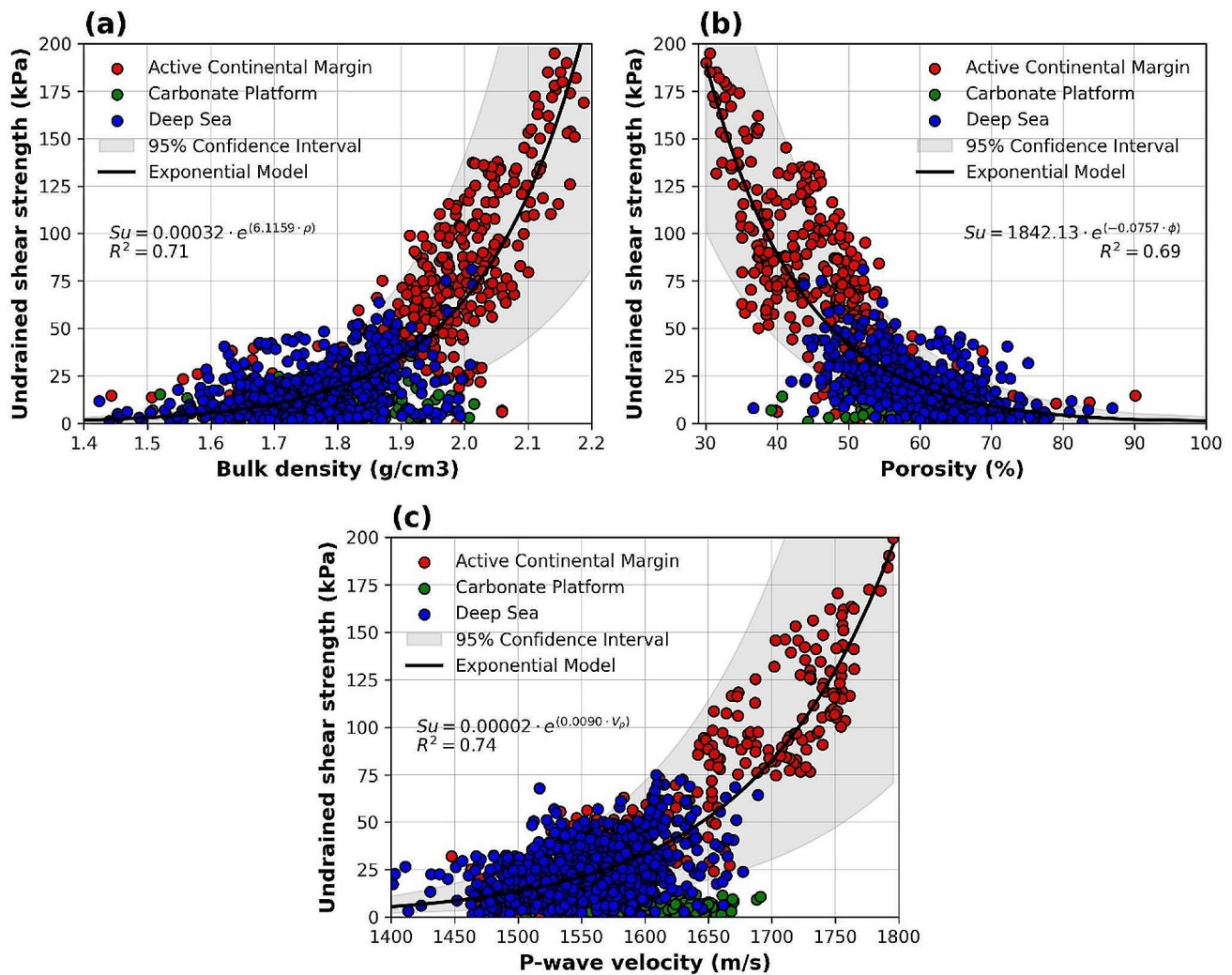
Fig. 7 The relationship between undrained shear strength (Su) and physical properties for three different depositional environments based on the ODP/IODP data. (**a**) Su and bulk density, (**b**) Su and poros-ity, (**c**) Su and P-wave velocity. The exponential model is represented by the solid line. The grey-shaded regions depict the 95% confidence intervals

bulk density, P-wave velocity, and undrained shear strength are recorded in regions of Antarctica, the Subantarctic, and the North Pacific deep-sea environment. Concurrently, the porosity in these regions decreases to approximately 40%. This is largely attributed to the presence of ice-loaded sediments, remnants of past geologic ice episodes, and coarse-grained (sandy) debris flows (Bartetzko and Kopf 2007; Graw et al. 2021).

Conversely, the active continental margin environment overall shows low porosity and high P-wave velocity, bulk density, and undrained shear strength signatures. This suggests that the rocks in these areas are strongly affected by diagenetic phases. For example, drill sites from the Cascadia Margin and Barbados Ridge contain coarse-grained sediments, indicating a terrigenous origin. The extensive diagenetic alteration in these sediments causes them to

exhibit higher undrained shear strength, P-wave velocity, bulk density. In contrast, porosity displays lower values. However, at some sites in Blake Ridge and Costa Rica, an increase in undrained shear strength, bulk density, and P-wave velocity is observed, along with a decrease in porosity, even in the absence of diagenesis. These changes may be attributed to the removal of overlying sediments by erosion or mass wasting (Winters 2000). It is noteworthy that some data points from the Eastern Mediterranean sites still show a decrease in undrained shear strength alongside an increase in P-wave velocity, bulk density. Conversely, the porosity could be as low as 40% (Fig. 7a, b, and c). This may be attributed to the loss of organic matter in the sediments, likely due to shallow-water conditions (Kopf et al. 1998; Wang et al. 2022).

Finally, the carbonate platform regions in the Great Australian Bight, NE Australia, and the Bahamas primarily consist of reef-carbonate sediments, which include mudstone, wackestone, packstone, and grainstone, interspersed with floatstone layers. Additionally, the sedimentary sequence is marked by the presence of turbidites and periplatform ooze (Bernet et al. 2000; Eberli et al. 2002). The presence of turbidite layers with high interstitial water content, which reduces the friction between sediment particles(Jo et al. 2015), may explain the observed low undrained shear strengths, bulk density, and P-wave velocity in these sediments. Concurrently, their porosity can reach levels as high as 75%, as illustrated in Fig. 7a, b, and c.

We characterized the relationship between physical properties and the undrained shear strength using an exponential fitting of $Y = a \cdot \exp(b \cdot X)$. This also suggests that there might exist a monotonic relationship between the physical characteristics including bulk density (g/cm3), P-wave velocity (m/s), and porosity (%) with the undrained shear strength. Specifically, the exponential fitting results are given as:

$$Su = 0.00032 \cdot e^{(6.1159 \cdot \rho)} \tag{1}$$

$$Su = 0.00002 \cdot e^{(0.0090 \cdot Vp)} \tag{2}$$

$$Su = 1842.13 \cdot e^{(-0.0757 \cdot \varphi)} \tag{3}$$

Here, ρ represents bulk density, Vp is the P-wave velocity, and ϕ is porosity.

Discussion

Impact of seismic strengthening at active margins

Figure 8 presents a conceptual model that explains how seismic strengthening (a process in which sediment compaction is intensified by seismic activity) impacts sediment in two different marine environments within the upper 100 m below the seafloor. In deep-sea settings, sediment compaction is solely governed by gravitational forces, leading to a consistent reduction in porosity and a gradual increase in undrained shear strength starting at the seafloor. This compaction is directly related to vertical effective stress, highlighting the connection between sedimentation, burial, and strength Lambe and Whitman (1969).

Conversely, active margins are subjected to both gravitational compaction and seismic activity, resulting in enhanced compaction due to seismic shaking. This dual influence significantly reduces both the void ratio and porosity, leading to a more pronounced increase in undrained shear strength at shallower depths compared to deep-sea conditions. Sedimentary sequences along active margins exhibit higher normalized undrained shear strength values compared to deep-sea environments. This indicates that seismic strengthening plays a crucial role in sediment consolidation. The resulting increase in Su may contribute to the improved slope stability observed in these regions, which could explain the relatively low occurrence of landslides along subduction zones (Strozyk et al. 2010; Sawyer and DeVore 2015; Molenaar et al., 2019).

Influence of sedimentation rate on undrained shear strength

To investigate the impact of sedimentation rates on undrained shear strength and submarine slope stability, we utilized data from the Gulf of Alaska as a distinct active margin and compared these findings with results from other active margins to clarify the broader implications of sedimentation rates on undrained shear strength. We focused on the depth range of 0–50 m below the seafloor due to the continuous sedimentary record in this interval throughout this margin. Furthermore, there was significant scatter in the shear strength data below this depth, indicating core disturbance.

Fig. 8 Conceptual model of seismic strengthening within the upper 100 m below the seafloor, illustrating the contrasting sediment compaction mechanisms between deep-sea and active margin environments
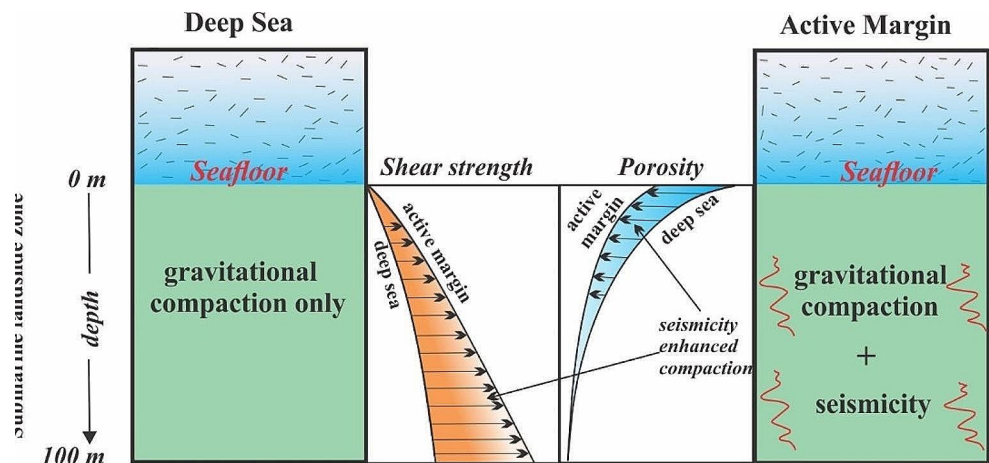
Figure 9a reveals that the Gulf of Alaska margin (IODP Leg 341) exhibits a lower undrained shear strength than is typically expected for an active margin, largely due to substantial sediment influx from the Bering Glacier, estimated at around 925 km³ over the past ∼130 kyr, one of the highest rates globally (Montelli et al. 2017). In contrast, areas outside this region, such as the Patton-Murray Sea mount (ODP Leg 145), demonstrate typical pelagic sedimentation rates and follow expected active margin shear strength trends. This suggests seismic strengthening across offshore Alaska, with exceptions in glacially influenced areas like the Surveyor Fan (IODP Leg 341), where high sedimentation rates are prevalent. Exceptionally high sedimentation rates are often observed in areas close to glacially eroded regions (Elverhøi et al. 2002; Nygard et al. 2007). Therefore, the high sedimentation rates in the Gulf of Alaska emerge as the primary factor in its low undrained shear strength.

The lower sedimentation rates at Patton-Murray Sea Mount (ODP Leg 145) indicate that the sediments are much older than those at (IODP Leg 341), and aging can also result in enhanced shear strength (Schmertmann 1991). However, in the Gulf of Alaska, the high sedimentation rates and overpressure seem to counteract both seismic strengthening and aging effects, leading to weaker sediments that diverge from typical active margin characteristics (Sawyer and Devore 2015). Furthermore, the high sedimentation rates in the Gulf of Cadiz and the Ross Sea (Demaster et al. 1996; Lobo et al. 2004; Mulder et al. 2009), similar to those in southern Alaska but with lower seismic activity, support our findings (Fig. 9b). Therefore, we conclude that while seismic strengthening slightly increases shear strength in regions like southern Alaska, the overriding effect of high sedimentation rates leads to increased slope instability, a pattern also observed in the Gulf of Cadiz, the Ross Sea, and Alaska, regardless of tectonic setting.

The influence of over-consolidation on undrained shear strength

The over-consolidation ratio (OCR) is defined as the ratio of the past maximum effective vertical stress ($\sigma'_{v\,max}$) to the current effective vertical stress (σ'_v) as presented in Eq. 5 (Narongsirikul et al., 2020).

$$OCR = \frac{\sigma'_{v\,max}}{\sigma'_v} \tag{4}$$

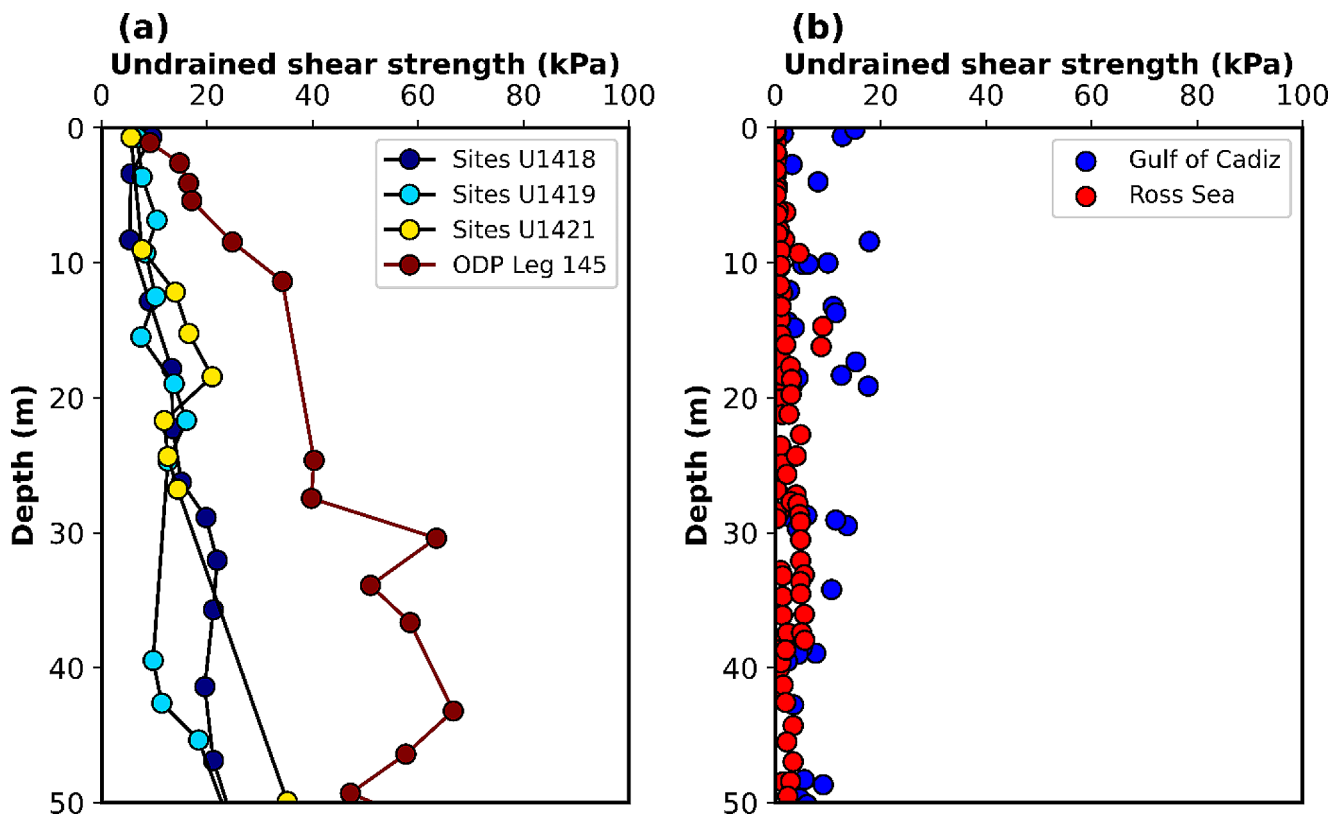**Fig. 9** (**a**) Undrained shear strength versus depth for the uppermost 50 m below the seafloor, utilizing data from active continental margin sites, including the Gulf of Alaska margin and the Patton-Murray Seamount in the Southern Alaska margin, (**b**) undrained shear strength versus depth for the uppermost 50 m below the seafloor utilizes data from active continental margin sites, including the Gulf of Cadiz and Ross Sea margin
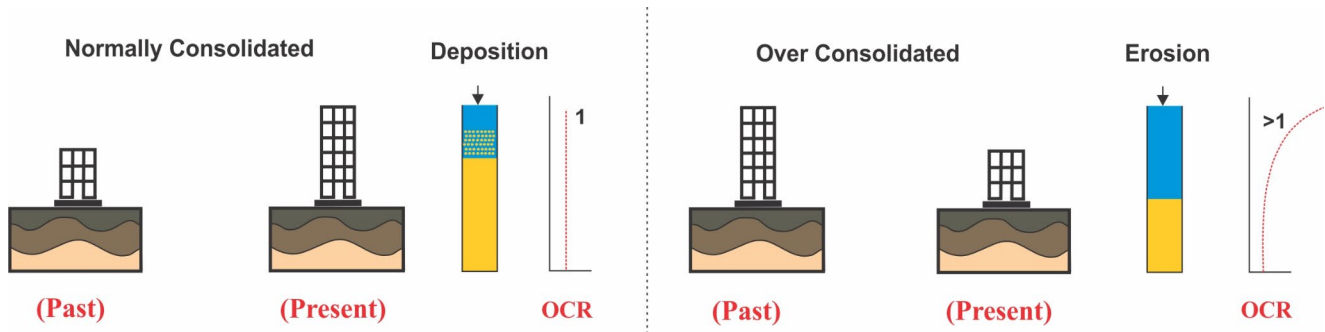
Fig. 10 A conceptual illustration of the over-consolidation ratio (OCR) in marine sediment layers that are affected by depositional and erosional processes. (**a**) in the normally consolidated sediment layer, the effective stress in the present condition is greater than in the past, resulting in an OCR of 1. This reflects the continuous additional depo-sition and unconsolidated sediments that increase the present effective stress without altering the OCR, (**b**) in the over-consolidated sediment layer, the present effective vertical stress is less than the effective stress in the past, resulting in an OCR greater than one due to erosion and, therefore, a higher shear strength. Modified after Dorvinen (2016)

Fig. 11 (**a**) Typical stress-strain curves indicating the peak shear strength for the over-consolidated ratio (OCR) and normally consolidated (NC) sediments. Modified after Sorensen and Okkels (2013), (**b**) over-consolidation ratio (OCR) as a function of depth from ODP Leg 104(Sites 642 through 644), ODP Leg 105 (Sites 646 and 647), ODP Leg 138(Sites 844 through 847), and ODP Leg 113(Sites 689, 690, 693, 695, 696, and 697). According to Richards and Hamilton (1974), the vertical dashed line represents the bottom limit of "normal consolidation"
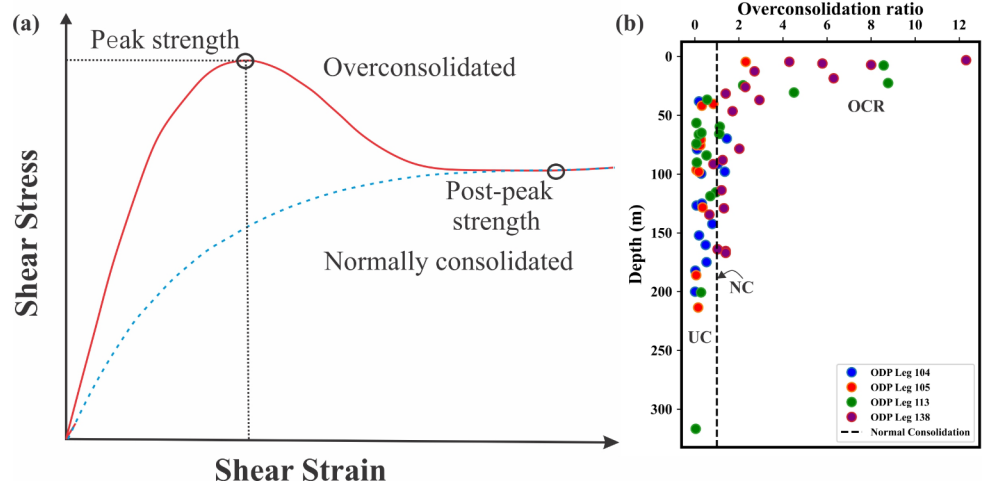
Generally, sediments are labeled as OCR when their current stress levels are below what they have endured in the past. This can be due to factors such as uplift and erosional unloading (Pender 1978; Bjørlykke and Jahren 2015). The OCR also serves as an indicator of the sediment consolidation state. When the OCR is equal to 1, the sediments are normally consolidated (NC), indicating that the current effective stress is the maximum stress the sediment has ever experienced. Sediments with an OCR less than 1.0 are considered under-consolidated (UC), suggesting that they are still in the process of consolidation and have not yet reached their maximum historical effective stress (Terzaghi et al. 1996; Narongsirikul 2020), as shown in Figs. 10 and 11b. In contrast, an OCR greater than 1 indicates that the sediment has been historically buried at much deeper depths compared to its current position, classifying it as an OCR.

Figure 11a schematically shows the stress-strain behavior of the same sediments in both their NC and OCR states. OCR sediments have a higher peak strength, which occurs just before failure, followed by a subsequent reduction in the stress ratio. Afterwards, the shear strength levels out to a constant value due to particle realignment along the failure plane (Sorensen and Okkels 2013). Notably, this constant strength value remains the same whether the sediment started as NC or OCR (Schädlich and Schweiger 2014). Figure 11b demonstrates the variation of OCR with depth, using data from several ODP legs. The results show a transition from high OCR values within the top 50 m below the seafloor to NC or UC states. The uniform OCR values across all sites from ODP Leg 138 are attributed to porosity reduction due to factors such as overburden erosion, dissolution, or diagenetic processes like cementation (Lee 1982). In contrast, data from ODP legs 104, 105, and 113 reveal sediment states ranging from UC to OCR, with a predominant trend towards NC. In all cases, the calcareous sediments are NC to OCR, whereas the diatomaceous sediments consistently exhibit OCR due to the strong microfabric formed by the diatom sediments (Wiemer and Kopf 2017).
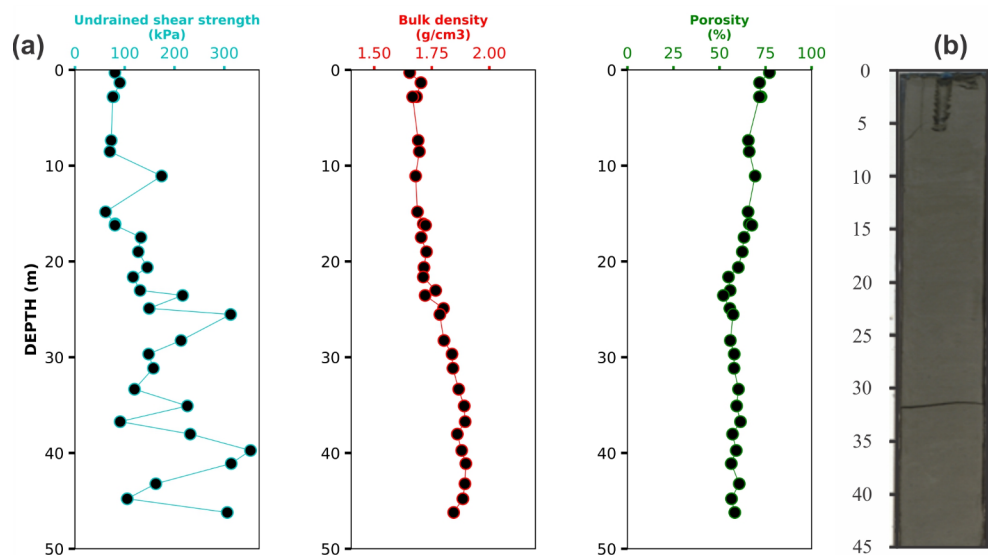
To enhance our understanding, we analyzed data from ODP Leg 164 (Site 993), focusing exclusively on the first 50 m due to the extent of available data. The site mainly features nannofossil-rich clays, punctuated by layers of

deformed beds and clay clasts conglomerates (Paull et al. 1996). Structural observations and undrained shear strength measurements from the sediments of Leg 164 indicate a positive correlation between the abundance of over-consolidation and sediment undrained shear strength. As illustrated in Fig. 12a, the results indicate high undrained shear strength values of up to 350 kPa. Unlike what might be expected, this site doesn't display a significant trend of increasing porosity and bulk density with depth. Moreover, the recovered cores, as shown in Fig. 12b, did not provide evidence of pervasive cementation, diagenesis, or other processes that might have increased the undrained shear strength of the sediments. This indicates that the high undrained shear strength observed may be primarily due to over-consolidation from past overburden removal. The over-consolidation of sediments has been observed across various ODP/IODP legs. For instance, in Cascadia Margin legs leg 204 and 311 show over-consolidation due to erosion (Riedel et al. 2006). In the Yermak Plateau ODP leg 151, the increases in undrained shear strength indicating over-consolidation from ice sheet pressure. This is believed to be due to the effects of grounded ice sheets originating from Svalbard and possibly from the Barents Sea (Flower 1997; Oregan et al. 2010; Gebhardt et al. 2011). Similarly, Labrador Sea ODP leg 105 exhibits increased undrained shear strength near the surface, suggesting over-consolidation due to shallow overburden stress (Richards 1967; Dadey and Silva 1989).

Evaluating shear strength prediction accuracy using physical properties

To demonstrate the effectiveness of our proposed models that link physical properties and undrained shear strength (Su), we utilized existing equations to forecast shear strength based on physical properties. These equations were then applied to new data to evaluate their predictive accuracy. We employed Eq. (1) to estimate shear strength using density (ρ), Eq. (2) to estimate shear strength using compressional wave velocity (Vp), and Eq. (3) to estimate shear strength using porosity (φ). Our analysis indicated that all three equations provided satisfactory outcomes, with density being the most dependable predictor, followed by Vp and porosity, as illustrated in Fig. 13a, b, and c, respectively. Notably, the models showcased their efficacy by enhancing the coefficient of determination (R^2) for undrained shear strength predictions.

Moreover, we utilized multi-parameter linear regression to establish an empirical correlation between undrained shear strength and physical properties such as bulk density (BD), P-wave velocity (Vp), and porosity (POR) based on the core data. The correlation defined by the multi-parameter linear regression is presented as:

$$Su = 100.849 * BD + 0.011 * Vp - 1.758 * POR - 65.525 \qquad (5)$$

As illustrated in Fig. 10, the results indicated that the multi-parameter regression leads to higher R^2 values and enhances the accuracy of predicting shear strength compared to predictions compared to predictions made by individual predictions as shown in Fig. 13d. The effectiveness of multi-parameter regression can be attributed to its ability to incorporate abundant physical information about the targeted formation.

Conclusions

We analyzed the undrained shear strength of marine sediments, focusing on the uppermost 100 m of sediment. The analysis is based on data from 198 sites collected during
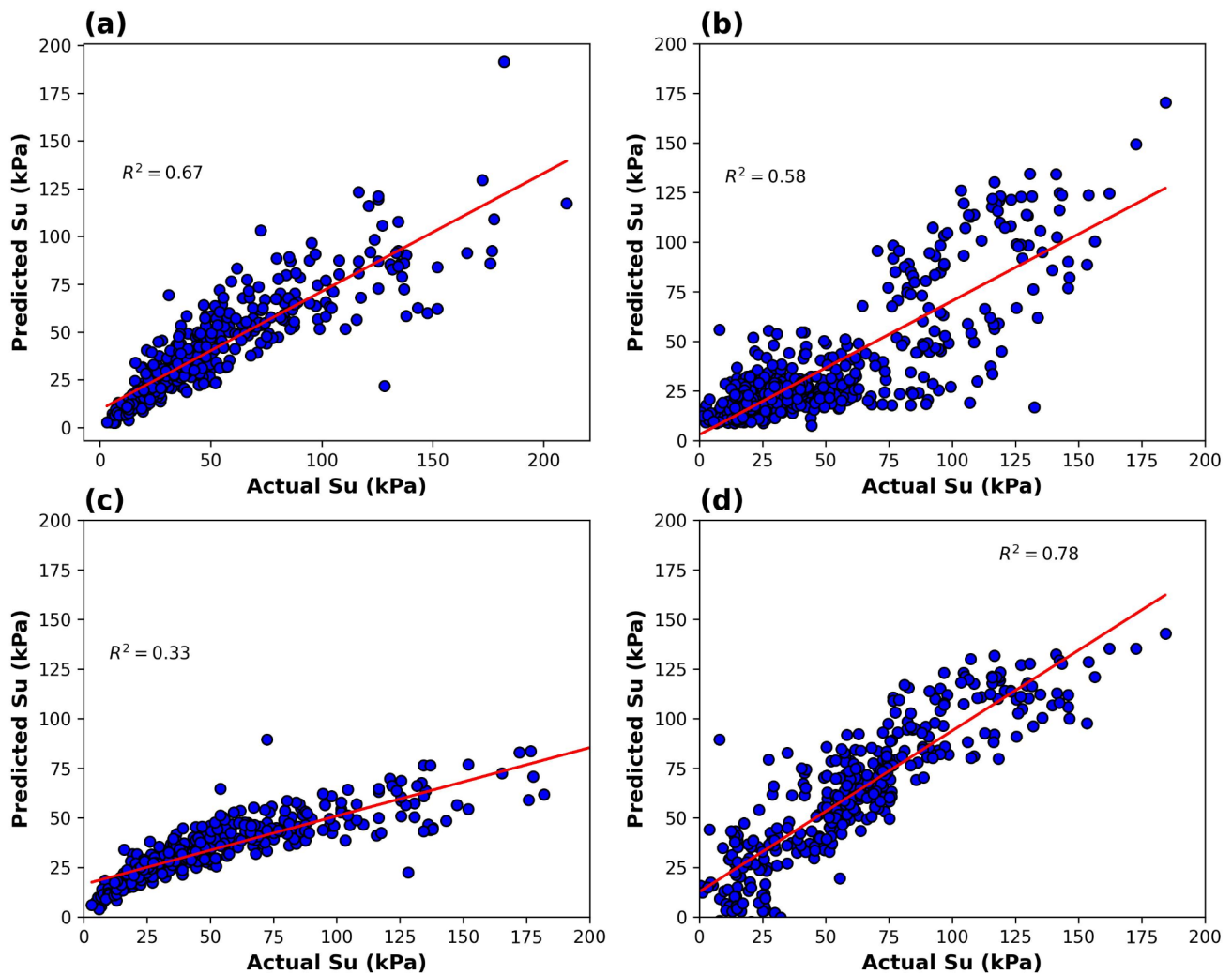
Fig. 12 (a) Examples of undrained shear strength, bulk density, and porosity versus depth using data from ODP site 993, (b) core photo from ODP Leg (interval 164–993 A-1 H, 0–45 cm) showing no evidence of pervasive cementation, diagenesis, or other processes that might increase the undrained shear strength of the sediments

Fig. 13 Crossplots of actual versus predicted undrained shear strength (Su) of marine sediments. (**a**) using bulk density, (**b**) using P-wave velocity, (**c**) using porosity, (**d**) using a multi-parameter regression includes bulk density, P-wave velocity (Vp), and porosity

46 ODP/IODP legs covering a wide range of settings. The results shows that the undrained shear strength of fine-grained siliciclastic sediments generally increases with depth, reaching values up to 200 kPa. Conversely, the undrained shear strength of fine-grained carbonate sediments also exhibits an increasing trend as depth increases, but the values are comparatively lower, averaging around 100 kPa. Unlike the other sediment types, reef-facies carbonates do not display a consistent trend in undrained shear strength with respect to depth. The active continental margins generally exhibit higher undrained shear strength compared to deep-sea and carbonate platform environments. This is largely attributed to seismic strengthening, pronounced diagenetic effects, particle interlocking in diatomaceous sediments, and over-consolidation of shallow sediments, which result from the removal of overburden pressure due to erosion. We also identified exponential relationships between various physical properties and undrained shear strength which can be used to predict the undrained shear strength of marine sediments in a fast and straightforward manner.

Data availability Data and core photos associated with this research are available and can be accessed via the following URL: https://www.iodp.org/resources/access-data-andsamples.

Declarations

Ethical approval Not applicable.

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