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RESEARCH

Microtextural signatures in quartz grains and foraminifera from tsunami deposits of the Portuguese shelf

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Abstract

This study presents results from two sediment cores collected on the southern Portuguese shelf attempting to, partially, fill the knowledge gap of the offshore record of high-energy events. The results were obtained based on description of cores, microtextural analysis of quartz grains, and foraminiferal taphonomy. The lithostratigraphy corresponds to Late Holocene sedimentation, with interesting intercalations of medium sand rich with bioclastic fragments and erosive basal contact. In terms of microtextures, a high degree of mechanical marks on the grains associated with tsunami deposition was observed and reflects the high-energy hydrodynamic processes. In compositional terms, the higher presence of quartz grains in these units favors the increase of mechanical marks because grain-to-grain contact is more intense. Additionally, the geomorphological setting of the coring sites controlled the degree and type of mechanical microtextures observed. Furthermore, post-depositional changes and characteristics of the original sediment source contribute to explain the occurrence of dissolution in units of Geo123313-02. The foraminiferal taphonomy displayed a predominance of dissolution alteration in the test surfaces that was more evident in the silty layers. On the other hand, similar to quartz grain microtextural signature, the sandy high-energy units exhibit a slight predominance of physical processes despite the still strong presence of dissolution. The sole presence of foraminifera species from the middle to the outer shelf in some units is an indication that there was little reworking of specimens. This work aims to increase the understanding of dynamics during Holocene high-energy events and to characterize their backwash phases through the different imprints left in the sedimentary offshore record of the Portuguese Algarve shelf.

Introduction

The limitations of data collection and interpretation on the frequency and magnitude of past tsunamis constrain present-day studies aiming to define the risks of these phenomena. Therefore, geological archives are keys to reconstruct and understand past intensities and dynamics of these events. In this sense, evidence in coastal stratigraphy left by tsunamis allows correlating the parameter of waves and their characteristics with sediment transport and deposition during these events (Costa et al. 2012a).

The study on these extreme events has grown in number and in detail over the last two decades. However, evidence of backwash on the shelf is still little explored compared to onshore deposits. The study by Abrantes et al. (2008) in the Tagus delta, on the central western shallow shelf of Portugal, proved that offshore settings have the potential to preserve evidence of tsunami deposits.

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In order to contribute data on offshore tsunami deposits, surveys were conducted on the Algarve shelf (southern Portugal), which revealed not only the record of the 1755 CE tsunami but also of another event, which occurred about 3400 years BP (Reicherter et al. 2019). This event was not recorded or preserved in the onshore geological record and led to a change in the definition of recurrence periods of these phenomena for the SW sector of Iberia.

In this study, we investigate the tsunami record on the southern Algarve continental shelf by applying microtextural analysis of quartz grains (125–500-µm fraction) and taphonomic modifications of the foraminifera test as the main discriminant tools. For this purpose, two offshore sediment cores (GeoB23512-01 and GeoB23513-02—Fig. 1) were studied. With this study, we aim to increase the understanding of dynamics during Holocene high-energy events and to characterize their backwash phases through the different imprints left in the sedimentary offshore record of the Portuguese Algarve shelf.

Study area

The southern Algarve continental shelf is located on the southern Portuguese margin. Its width varies between 8 and 28 km and is characterized by a gentle slope between 0.3 and 2% (Andrade 1990). According to Lopes and Cunha (2010), three domains are identified in this sector: the inner shelf (up to 40 m deep), the middle shelf (between 40 and 90 m deep), and the outer shelf (between 90 m and the platform edge). In turn, the platform edge is well defined and lies between 110 and 150 m deep (Vanney and Mougenot 1981). On it are carved some submarine canyons (e.g., Portimão, Lagos, and Faro canyons), limited by the marginal plateaus of continental origin (Moita 1986). This morphological configuration reflects the close structural control of the geological evolution of this sector, combined with the hydrodynamic of the Mediterranean Water Vessel circulation, a high-density current that circulates through the ocean floor, eroding, transporting, and depositing sediments along the continental slope (Moita 1986; Rebus and Barton 2002; Lopes and Cunha 2010).

Fig. 1 Study area and offshore coring locations

The oceanographic conditions along the southern Algarve coast are typically low energy, with annual average significant wave height (Hs) < 1 m and with two predominant wave directions between SW and SE, being the first direction dominant (Costa et al. 2001). According to Monta (1986), the tides on the Algarve coast are *regular* semidiurnal type, with maximum amplitudes in a single cycle of up to 3.5 m. The current regime is weak on the shelf, with a predominance of drift currents (by wind action) over tidal currents.

The tectonic setting of the SW Iberian margin corresponds to a wide zone of dextral transpressive deformation, associated with the convergence of the Nubian and Eurasian plates (Rosas et al. 2009; Zitellini et al. 2009). This landscape is responsible for significant seismicity that is evidenced by earthquakes and tsunamis, such as the Lisbon earthquake and tsunami in 1755 CE, which devastated the Algarve coast (Duarte et al. 2013), the southwestern Iberian Peninsula, and the northern Atlantic coast of Morocco (Ruiz et al. 2013). The geological signatures of this event have been very well documented in the works of several authors (Hindson and Andrade 1999; Hindson et al. 1996; Kortekaas and Dawson 2007; Costa et al. 2012a,b, 2021). In addition, older tsunamis, which may have affected this region, have also been reported, such as the Tavira tsunami of 1722 CE, among other historical events, compiled in Baptista and Miranda (2009).

Methods

Sediment cores used in this work were collected by the RV METEOR expedition M152 conducted in November 2018 along the southern Algarve shelf, aiming to study sedimentological data from the 1755 CE tsunami and other possible previous events (Reicherter et al. 2019). The specific area of this study is located on the southern Algarve middle shelf. This study focuses on two obtained sediment cores GeoB22512-01 (548,084.640 m E/4089698.00 m N) and GeoB22513-02 (553,721.943 m E/4092394.269 m N) (Fig. 1). Core GeoB22512-01 and GeoB22513-02 recovered 6.42 m and 5.48 m of sediment, respectively, but only samples from the upper parts of the cores were analyzed.

The samples were collected using a vibrocoring system, with a maximum recovery of approximately 5.5 m. GeoB22512-01 was collected at approximately 14 km from the present-day coastline and was recovered at 88 m of water depth. In turn, core GeoB22513-02 was retrieved at approximately 12 km from the present-day coast and was collected with 50 m of water depth. The horizontal distance between the two core samples is approximately equivalent to 5.3 km. After opening the cores, they were described macroscopically. The units studied in this work were sandy layers interbedded between levels of finer hemipelagic sediments located in the upper parts of both cores (coarser units within the muddy lithostratigraphic sequence). Thirty-nine samples were obtained from core GeoB22512-01 and 19 from core GeoB22513-02.

The laboratory procedures, applied to the sediment samples, were aimed at separating and treating the fraction greater than 63 µm. Initially, it was necessary to disaggregate the sediments, using a 10% diluted NaOH solution in water for 24 h. Subsequently, the samples were washed with distilled water through a 63-µm sieve. The coarser fraction (> 63 µm) was recovered and taken to the oven at 40 °C. Once dried, the samples were sieved at 0.5 ϕ intervals. These procedures were carried out in the Micropaleontology Laboratory of the Geology Faculty, Rio de Janeiro State University (UERJ).

The compositional analysis of the sediments was carried out only on the 250–500-µm fraction. With the aid of a spatula, this fraction was sub-sampled carefully, weighed, and then placed in a foraminifera sorting tray (black checkered plate), and finally analyzed under a Zeiss-Stemi 2000C binocular microscope of the Micropaleontology Laboratory of UERJ. The counted elements were grouped in biclasts (fragments of shells, mollusks, foraminifera, and other organisms), quartz, feldspar, opaques, and micas (muscovite and biotite).

For the microtextural analysis (aka. exoscopy), quartz grains of the 125–500-µm particle size fraction were analyzed. These grains were selected under the Zeiss binocular microscope Stemi 2000C and prepared for scanning electron microscopy. Mahaney (2002) and Costa et al. (2012a) investigated the statistical representativeness of this analysis and concluded that the minimum number of grains for data to be viable is between 15 and 20 per sample. The analysis of the selected quartz grains was carried out in two laboratories: at the Laboratory of the Centre of Mineral Technology (CETEM), using the SEM TM3000 Plus-HITACHI, and at the Department of Stratigraphy and Paleontology of the Geology Faculty of UERJ, using the SEM ZEISS model EVO MA 10. The methodology proposed by Costa et al. (2012a; 2014a) was applied to classify the grains. Costa et al. (2012a) suggest the analysis of, at least, five different microtextural characteristics to obtain valid results. This is because a single microfeature is not sufficient to characterize a certain sedimentary environment. Furthermore, these microtextural associations should involve the contrast between marks resulting from mechanical action (percussion marks and fresh surfaces, fractures), typically formed in a context of high energy and shock between particles and features resulting from chemical action (dissolution and adherent particles) usually associated with poor mobility, thus discriminating low-energy environments. There are also features that commonly result from long-term actions, such as grain roundness.

In the present study, each grain was described according to the microtextural characteristics revealed on its surface (Table 1). After the identification, a semi-quantitative approach was applied to each grain, based on the proportion of the microtexture present on its surface. For this, a scale of 0–5 was adopted, where: 0 (absent); 1 (up to 10% of the grain surface); 2 (10–25% of the grain surface); 3 (25–50% of the grain surface); 4 (50–75% of the grain surface); and 5 (> 75% of the grain surface). Roundness was also evaluated as a complementary attribute, according to Powers (1953), using a rating scale from 0 to 5 (0—very rounded; 1—rounded; 2—sub-rounded; 3—sub-angular; 4—angular; 5—very angular).

The focus of foraminifera analysis in this study was the external surface marks that were imprinted in the foraminifera tests. A simplified foraminifera examination was performed on the medium sized tests. Paleoecological results should be interpreted with caution due to the limited size fractions analyzed. The preparation, sorting, and scanning electron microscopy analysis of the foraminifera were conducted at the Institute of Neotectonics and Natural Hazards, RTWH Aachen University. Samples were sieved to > 63 µm and dried at 40 °C. The dried samples were homogenized and subdivided into smaller sample sizes of approx. 0.01 g. The foraminifera in each sample were counted with a Zeiss Stemi 2000C microscope with 80 × magnification. Of these, a minimum of 300 individuals was picked, identified, and stored in Krantz-cells for further investigations. Following Patterson and Tubaro (2007), 300 individuals in the samples are representative for high diversity assemblages of offshore samples. Taxonomic identification up to the rank of genera was based on several reference publications (e.g., Murray 1971, 2006; Bolivinskaya et al. 1990; Kennett and Srinivasan 1983; Loeblich and Tappan 1988; Milker and Schmiedl 2012). For further identification, images of the

Table 1 Examples for the studied microtextural features

Percussion marks		These are V-shaped or irregular depressions and are associated with the usually the result of collision between grains
Fresh surface		Characterized by the absence of dissolution, precipitation or extensive mechanical mark. In many cases, they are associated with features responsible for their preservation
Fractures		These are linear accentuated with variable incision depth, perpendicular to the exposure of fresh surfaces. They are produced by mechanical impact
Dissolution		Microtextures of chemical nature indicating the degree of dissolution on the surface of grains. The notable effects of this attribute are the destruction of fresh surfaces and angular edges and/or the formation of cavities
Adhering particles		These are characterized by the presence of exotic microparticles on the surface of the quartz grains. Interpreted as the result of chemical action

organisms found at the selected levels were taken by a HV-SEM (Zeiss Supra 55) with the secondary electron (SE) at a voltage of 3 kV and analyzed in order to assess the conservation of the surface of its tests.

The individuals were classified according to the degree of physical alteration when they presented fragmentation or abrasion, and dissolution marks were used to identify chemical alterations. Analytical criteria were applied in order to establish the degree of alteration. These were based on the works of Pilarczyk et al. (2011, 2012, 2020). Thus, it was considered: (0) when the shells were unaltered, being considered well-preserved; (1) slightly altered; (2) moderately altered, and (3) very altered.

Results

General description of cores

The description of cores was based on macroscopic physical aspects, such as color, type of contact, sediment composition and amount of bioclastic fragments. Based on these visual aspects, units were designated to describe the sandy intercalations present in the cores. Macroscopically, the upper part of GeoB23512-01 (Fig. 2 (I)) is composed of dark green sandy silt and silty material, with intercalations of sand layers (units B1, C1, and D1) that are rich in bioclastic granels. The basal contacts of the units are clearly erosive or sharp. The units were identified between 81–82 cm (B1), 127–158 cm (C1) and 217–218 cm (D1) below seafloor (bsf) in the referred sediment core. An intercalation of fine grayish sand was observed at the level between 23–38 cm bsf (unit A1).

In the sediment core GeoB23513-02 (Fig. 2 (II)) from the 144 cm bsf to 45 cm bsf, an extensive layer of very fine sand occurs (unit B2). It has a grayish color and features of intense bioturbation occur, which are traces of activity of living organisms such as bivalves and gastropods present in the unit. Overlying this layer, between 45 cm bsf and the top, greenish sandy silt occurs. This silt layer is interrupted by a level of sand rich in bioclastic granels between 21 and 25 cm bsf (unit A2). This level presents an erosive basal contact.

The sediment composition analysis (Fig. 2c; Appendix 1) revealed that the sandy layers of both sediment cores are predominantly composed of bioclasts and secondarily of quartz, feldspar, and few grains of opaque minerals and micas. It is important to note that units B1, C1, D1, and A2 (bioclastic sand) shows the highest percentages of lithoclastic elements when compared to those observed on units A1 and B2 (fine sand and very fine sand).

Quartz microtextures

The microtextural attributes of 315 grains from fifteen samples from GeoB23512-01 and 281 grains from twelve samples from GeoB23513-02 were identified and classified; these results are illustrated respectively in Fig. 2b and c (Appendices 2 and 3). The analysis of SEM images of the microtextures is summarized in Fig. 3.

GeoB23512-01

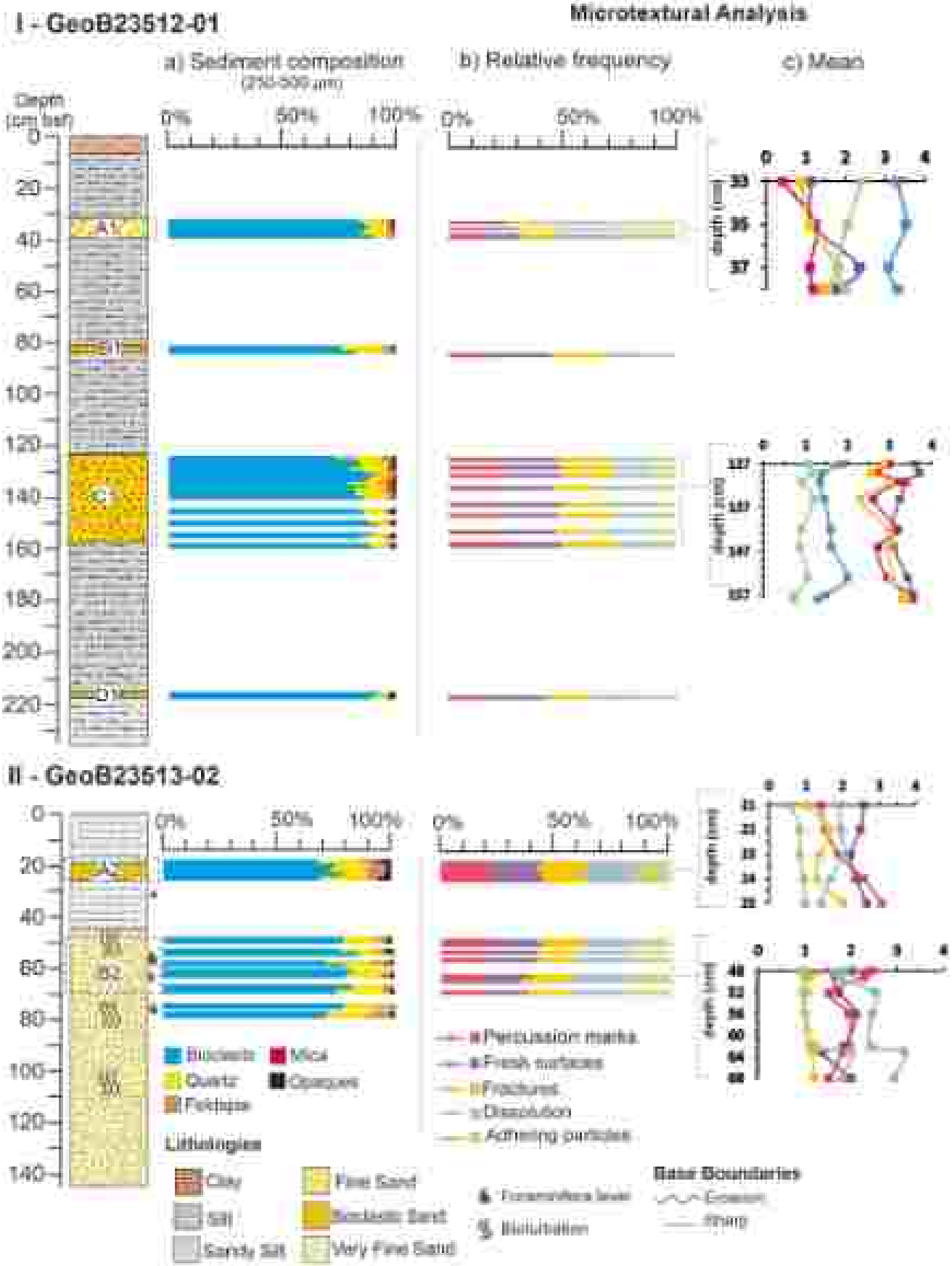
The analysis of the microtextural attributes in this sediment core disclosed distinct distributions and mean values between units A1 (very fine sand) and B1, C1, and D1 (bioclastic sand). In unit A1, there is an abundance of chemical features such as dissolution (28%) and adherent particles (25%), as opposed to percussion marks, fresh surface, and fractures, which are noticeably less frequent. In terms of mean value of the surface of grains occupied by each microtextural feature, dissolution stands out obtaining the highest value (mean $3.31 \pm$ et 0.17), followed by adherent particles (2.06 ± 0.25). The values of mechanical action marks, such as percussion marks (0.98 ± 0.26), fresh surface (1.61 ± 0.58), and fractures (1.31 ± 0.40) are relatively lower in this layer.

On the other hand, in samples from units B1, C1, and D1, it is observed that the microtextural attributes related to mechanical impacts are more frequent and dominant on the surfaces of the quartz grains, especially on the lower and upper limits of the expressive sand layer of unit C1 (127–128 cm bsf and 157–158 cm bsf). Percussion marks, fresh surfaces and fractures present very regular occurrence distributions, with 24% of occurrence each. Regarding grain surface dominance, fresh surfaces dominate (3.40 ± 0.21), followed by percussion marks (3.05 ± 0.36) and fractures (2.93 ± 0.33). The features of dissolution (1.56 ± 0.24) and adherent particles (0.94 ± 0.16) occur more discretely here.

Regarding roundness, in the bioclastic sand units (B1, C1, and D1), the analyzed grains exhibit an average of 2.28 ± 0.26, characterized as sub-angular. At the same time, where the very fine sand occurs (unit A1), the mean values are 3.26 ± 0.21; therefore, the grains are considered sub-angular to sub-rounded.

GeoB23513-02

In sediment core GeoB23513-02, the distribution of microtextural features did not show significant differences along the vertical analysis performed. The occurrence percentages of microtextural features differ by 1% or 2% throughout the samples analyzed. Dissolution dominates, followed by fresh surfaces, percussion marks, and fractures, while adherent particles are the least frequent. In unit A2, considering the


I - GeoB23512-01
Microtextural Analysis
a) Sediment composition
(250-500 µm)
b) Relative frequency
c) Mean
Depth (cm bsf)
0%
50%
100%
A'
B1
C
D1
depth (cm)
II - GeoB23513-02
B2
Bioclasts
Mica
Quartz
Opaques
Feldspar
Percussion marks
Fresh surfaces
Fractured
Dissolution
Adhering particles
Lithologies
Clay
Fine Sand
Silt
Bioclastic Sand
Sandy Silt
Very Fine Sand
Foraminifera level
Bioturbation
Base Boundaries
Erosion
Sharp

◂Fig. 2 Results from sediment cores Geo823512-01 and Geo823512-02. **a** Morphoscopic (compositional) variation. **b** Microtextural relative frequency. **c** Average values of the semi-quantitative microstructural classification on the microtextural feature dominance on the grain's surface

mean values of grain surface dominance, fresh surfaces (2.46 ± 0.18), percussion marks (2.10 ± 0.71), and dissolution (1.80 ± 0.25) are the most relevant microtextural features.

In unit B2, the dissolution coverage is clearly more expressive (mean 2.44 ± 0.52) in relation to the other microtextural attributes. In turn, regarding microtextural feature dominance, adhesion marks are more discrete with averages ranging between 0.94 and 2.00. Roundness presents values of 3.14 ± 0.19 in unit A2 and 2.82 ± 0.25 in B1, respectively sub-angular to sub-rounded.

Foraminifera analysis

A total of 846 SEM images of foraminifera individuals were analysed (Fig. 4) and 31 species identified (Appendix 4), of which the most frequent are *Bolivina pseudoplicata* (Heron-Allen and Earland 1930), *Cribroelphidium gerthi* (van Voorthuysen 1957), *Globigerina bulloides* (d'Orbigny 1826), *Nonion fabum* (Fichtel & Moll, 1798), *Quinqueloculina seminula* (Linnaeus 1758), *Reticulofenestra pseudoumbilicus* (Gartner 1969), and *Globigerina falconensis* (Blow 1959). The foraminifera were retrieved from 32–34 cm, 54–59 cm, 62–66 cm, and 74–78 cm bsf from Geo823513-02 (Fig. 2 (II)). Regarding abrasion, it was observed that 24% of the foraminiferal tests are unaltered, whereas the remaining 76% present some level of alteration. Individuals showing fragmentation, breakage, and abrasion marks were classified with physical alteration and those showing dissolution marks with removal of the surface were classified with chemical alteration.

The results show that the type and degree of alteration differ between the sandy and the silty layers. In the silty layer, between 32 and 34 cm bsf, it can be observed that dissolution occurs more aggressively, with a percentage of 64% (average 1.42), exhibiting small alterations to almost total destruction of the specimens. On the other hand, the effect of physical alteration in this interval occurs in only 36% of foraminifera with mean values of 1.00.

In contrast, the intervals 54–59 cm, 62–66 cm, and 74–78 cm bsf of unit B2, exhibit a slight predominance of tests worn by physical alteration, with percentages varying between 53 and 58% and with degrees of alteration between 1.11 and 1.31. The marks of alteration by dissolution are less abundant in this layer and the average values vary between 0.79 (54–59 cm bsf) and 1.10 (62–66 cm bsf).

Discussion

Lithostratigraphic interpretation

Based on the data obtained, high-energy events were detected, responsible for the deposition of units with contrasting characteristics in the stratigraphy (B1, C1, D1, and A2). Especially the C1 and A2 units, due to their largest expressions of approximately 30 cm and 5 cm, respectively, are interpreted as products of high-density flows from the coast to the sea (probably caused by the tsunami backwash) in the middle shelf of southern Portugal, generating the sudden incursion of coarse materials rich in shell gravel, interrupting the low-energy sedimentation regime. The richness in shell fragments is one of the attributes that can characterize tsunami deposits and is a good marker of the high-energy involved in sediment transport, according to Goff et al. (1999, 2000, 2010). The presence of bioclastic sand layers with intense fragments and shell gravel suggests, therefore, that they were probably deposited under conditions of higher hydrodynamic energy.

The base between the high-energy deposits (C1 and A2) with the underlying layer shows an erosional contact and indicates a high tensile force caused by (tsunami) flow incursion or backwash, reinforcing the genetic difference between both layers. Erosive surfaces were observed in deposits from the 1755 CE tsunami on the southern Portuguese coast and are commonly used to define the lower limit of these deposits (e.g., Hindson and Andrade 1999; Kortekaas and Dawson 2007; Costa et al. 2012a; 2014b).

Tsunami effects in the offshore sector were addressed by Abrantes et al. (2008) in the Tagus delta, in the SSW stratigraphic record of the shallow shelf of Portugal, referring to the events of 1969 to 1755 CE. Also, in the offshore sector of the SSW Iberian Margin, Gracia et al. (2010) recognized seven turbiditic events with erosive basis, linked to instrumental and historical earthquakes, tsunamis, and paleotsunamis. The results obtained in other zones close to the area of this study, in the expedition RV METEOR M152/1 (Reicherter et al. 2019), show high-energy deposits with erosive base and coarse-grained composition (well-sorted medium sand), at depths of 16–25 and 122 – 153 cm bsf. These deposits were radiocarbon and OSL dating, associated respectively with the 1755 Lisbon tsunami and another event that occurred at about 3400 years cal BP. These works prove that the

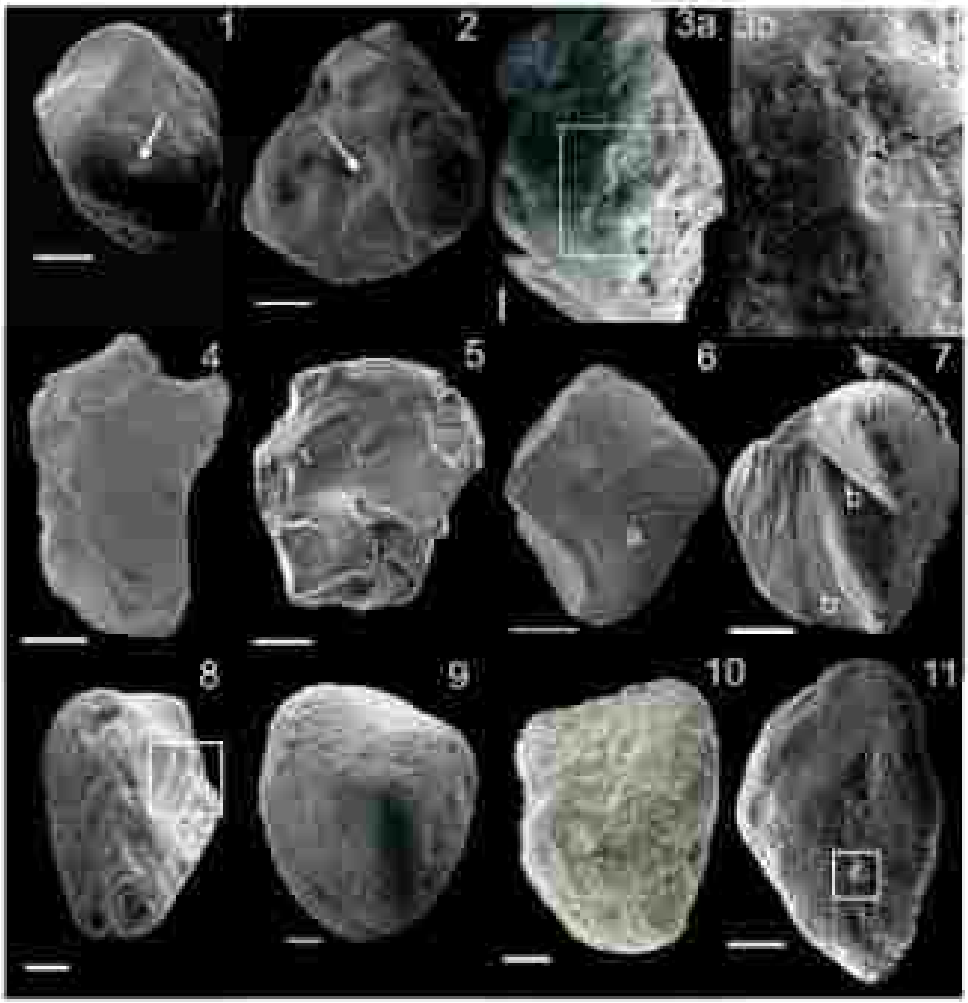


Fig. 8 SEM quartz grain imagery with Scale bar: 100 µm: 1–3a: V-shaped percussion marks; 4–5: Fresh surfaces nearly totally recrystallizing the grain; 6–7: grains with fresh surfaces: (a) conchoidal fractures; (b) linear fractures; 8: grain with strong dissolution but presenting fractures (highlighted); 9: grain with high degree of dissolution; 10–11: grains where chemical features dominate – e.g., adhering particles in the grain's surface

offshore sector has the potential to preserve evidence from high-energy events.

Microtextural analysis

High-energy deposits present intrinsic peculiarities that are sensitive to their depositional environment. This is clear when comparing the data obtained from sediment cores GeoB23512-01 and GeoB23513-02. Considering GeoB23512-01, it is notable that the quartz grains of unit A1 (33–38 cm bsf), present contrasting microtextural characteristics with units B1, C1, and D1 (81 cm, 127–158 cm, and 218 cm bsf).

In unit A1, the high proportion of chemical marks is attributed to post-depositional changes, such as diagenetic processes or bioturbation. It has been described that low-energy environments are more susceptible to chemical weathering (Mahanty 2002; Vos et al. 2014). The abundance of adherent particles in these grains also justifies diagenetic traces (Mahanty 2002). Furthermore, the high mean value for its presence on the surface of grains suggests a calm and long residence time in the environment, which would be only possible in a low-energy marine depositional environment.

In contrast, units B1, C1, and D1 present higher values of mechanical marks, indicating stronger hydrodynamic processes during deposition (Mahanty 2002). The increase of percussion marks is promoted by erosion and incorporation of sediments during the initial phase of tsunami backwash. According to Costa et al. (2013a), this feature is linked to the high concentration of sediments in the water column, favoring intensive contact between grains. This justifies the maximum mean values found at 127–158 cm bsf, at the base of unit C1. Moreover, this scenario promotes the highest fracturing of the grains at this level (127–158 cm bsf) as fractures are related to strong impacts on the grain surface (Vos et al. 2014), whose incision size reflects the energy associated with their formation (Higgs 1979; Mahanty 2002).

The presence of fresh surfaces on the quartz grains of units B1, C1, and D1 in GeoB23512-01 corroborates

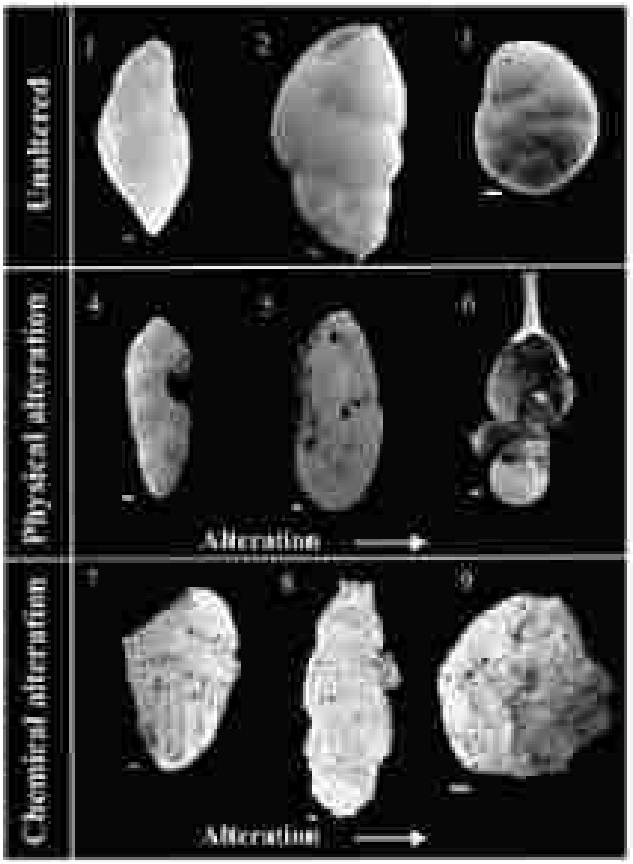


Fig. 6 SEM imagery of foraminifera tests with scale bars of 10 µm. (1, 2) *Rosalina globularis* Terquem, 1882; 3. *Elphidium advenum* Parker, 1952; (4,7) *Bolivina subaenariensis* Cushman, 1922; 5. *Quinqueloculina bicostata* d'Orbigny & Tappan 1953; (6, 9) Unrecognized; 8. *Reussoolina globosa* Le Calvez, 1959; (1–3) Well-preserved specimens. (4–6) Altered physical tests. (7–9) Images showing the degree of chemical alteration. The increase in the degree of change occurs in the direction of the arrow

strong hydrodynamic processes immediately prior or during deposition. Their occurrence results from violent collisions to the point of subtracting large percentages of the grain surface generating fractures and fresh surfaces. According to Costa et al. (2012a), the low concentration of sediments in the water column should favor the increase of these features, because the particles would have more space in the aqueous medium, and thus, the impact velocity would be higher and more energetic (higher kinetic energy). The highest mean values of fresh surfaces were detected at the top of unit C1, between 127 and 129 cm bsf. The lower sediment concentration at the top of the deposit can probably result from the last backwash phase (before settling of the fine sediments), as erosion and remobilization of sandy sediments were intensely caused by the previous waves. A slight increase of mica grains at the top of the deposit, between 127–131 cm bsf, reinforces this reasoning and might attest to the product of the final backwash phase. This is because the properties of these minerals (their density and habit) give them more buoyancy in the water column, being deposited, in lower energetic conditions.

Regarding the microtextural results obtained from Geo823513-02, it is noted that the contrasts between the mechanical and chemical attributes are not statistically significant between unit A2 (21–25 cm bsf) and B2 (48–68 cm bsf). This is due to the occurrence of dissolution marks on the grains in unit A2. It is worth noting that at the base of unit A, fresh surfaces and percussion marks exhibit an increase, whereas at the top fresh surfaces occur with higher average values than the other attributes. Similarly, the same reasoning can be applied to units B1, C1, and D1 of core Geo823512-01, and one can infer that the concentration of sediments in the water column influences the generation and intensity of mechanical microfeatures. Regarding quartz grains of unit B1, the mechanical marks occur discretely, without very contrasting mean values.

Regarding the average degree of roundness, this characteristic was not significantly different among the grains analyzed from both sediment cores. In the bioclastic sand layers (units B1, C1, D1, and A2) the grains are sub-angular, while in the fine and very fine sand layers (respectively A1 and B2), the average values correspond to grains between sub-angular and sub-rounded. It is considered that the brief duration of the event did not generate more notable changes in the grain shape.

The processes responsible for producing chemical features and mechanical impact marks do not share similarities (Mahanty 2002; Costa et al. 2012a; Vos et al. 2014). Therefore, it is considered that the dissolution features on the grains in units A2 and B2 of Geo823513-02 are related to post-depositional changes or poor resurfacing (predominance of source sediment features). These are eolian paleodunes submerged at around -80 m of water depth, according to the continental shelf surface sediment chart (Hydrographic Institute 2009). Dunes have been commonly described with strong dissolution features (Mahanty 2002; Costa et al. 2012a; Vos et al. 2014). Thus, it is possible that the quartz grains analyzed already hold chemical imprints which supports the lack of microtextural heterogeneity in core Geo823513-02. Difficulties in recognizing microtextural signatures related to tsunami events were reported in Klümmerer et al. (2020), who investigated sediments from the 1755 CE tsunami on the southern Portuguese continental shelf in the vicinity of Faro. The authors detected only a small increase in percussion marks, and that a possible change in general sedimentation after the 1755 CE event may have influenced the signature in the outer shelf sedimentary record.

The compositional analysis of only particles of the 250–300-µm fraction somewhat limits reaching more

conclusive interpretations. However, it indicates the compositional elements that can be related to higher hydrodynamics. Although the biogenic elements dominate in more than 70% of the samples from both cores, it is noteworthy that there are levels in the bioclastic sand layers (units B1, C1, D1, and A2) where there is an increase in the percentage of quartz grains. This may indicate changes in hydrodynamics that are reflected in the composition of the sediments. The incorporation of quartz grains in the water column, therefore, induces higher mechanical stress during collisions, since these materials have a higher density than the biogenic elements, which is translated by the formation of a higher number of mechanical microstructures.

Another important factor that argues for the microstructural differentiation exhibited in the is the configuration of the local bathymetry. Turbulent backwash flows return to the sea causing erosion and re-deposition of sediments with velocities influenced by the submarine topography (Dawson and Stewart 2007; Sugawara et al. 2008). In this study, Geo1B23512-01 is located in the vicinity of the Portimão canyon, which causes an 8-km-long incision in the shelf (Dias 1987). This pronounced structure may act as an "outlet" through which flow transports and deposits sediments with higher velocities. From a hydrodynamic point of view, the flow velocity is directly related to the depth of the water column, calculated using the formula $c = \sqrt{gh}$, in which g is the acceleration of gravity and h is the depth (Barman 2019). Thus, the wave travels faster in deeper areas than in a shallower area once the work of the bottom friction begin to act on the continental shelf. For this reason, the energy of the backwash flow on the Portimão canyon and its vicinity played a determining role in the higher degree of sediment reworking, having a direct effect on the final configuration of the deposit and justifying the microstructural and compositional lateral variation observed between the two sediment cores studied. This reasoning supports the presence of more mechanical marks in Geo1B23512-01 than in Geo1B23513-02.

Recognizing microstructural signatures in tsunami deposits in the offshore context is not a simple task, as it is a dynamic environment open to processes that impair the preservation of these features. However, we proved that through the application of this technique, we were able to distinguish signatures that allow identifying high hydrodynamic processes, such as tsunami backwash, mainly in the Geo1B23512-01 core. Despite the challenges in establishing a vertical trend along the tsunami deposit of Geo1B23513-02 (due to the strong presence of dissolution), it is possible to detect at the base and top of the A2 deposit (21–25 cm bsf) an increase in mechanical marks, especially fresh surfaces. Many local factors can influence the formation of such features, such as the energy of the event, the source and sediment concentration, and also post-depositional processes, as already reported here. Furthermore, it is observed that the sedimentary composition plays an important role in the formation of microstructural signatures.

Foraminifera taphonomy

Preservation and taphonomic features in foraminiferal tests can reveal information of tsunami flow velocity, sediment concentration, abrasion, and post-depositional environmental processes (Mamo et al. 2009). In this study, the occurrence and degree of dissolution (Fig. 4 (7–9)) observed in tests from the silty layer (32–34 cm bsf) of Geo1B23513-02 may be a result of the low-energy environment. According to Keller et al. (1992) these environments promote a high deposition of organic matter in the sediment which can favor boring fauna to rework the organic matter, producing acid-saturated microenvironments that lower the pH of the water, triggering chemically altered shells (Corliss and Hallock 1988; Murray 1989; Walker and Burton 1990).

In unit B2 (54–59 cm, 62–66 cm, and 74–78 cm bsf), a combination of physical and chemical processes occurs with a slight predominance of physical alteration marks, some of them often of difficult recognition (Fig. 4 (4–6)). The occurrence of physical alteration marks can be attributed to an increase in the energy of the environment, therefore providing deposition of particles in the very fine sand fraction, in contrast to the overlying low-energy silty layer. However, the resulting transport energy was not sufficient to generate more intense abrasion and fragmentation, possibly because in these very fine sand layers, there is a dominance of bioclastic components in about 80% of the sedimentary composition. The experiments by Martin and Liddel (1991) prove that even in high-energy environments, the foraminifera tests are not totally altered by abrasion caused by friction with carbonate sediments, as occurs in mixed and siliciclastic environments.

Moreover, the species identified in this study are from the middle to the outer shelf. It is interpreted that these individuals did not undergo relevant reworking triggered by the phase tsunami inundation and backwash flows. Briguglio and Hohenegger (2011) attest that the poor preservation of foraminifera shells by abrasion is a consequence of transport processes. In turn, Quinchia et al. (2016) verified the presence of broken/altered marine species, however, in onshore deposits as a product of the highly energetic transport of the initial tsunami inundation phase.

In this work, it is emphasized that the dissolution characteristics of the quartz grains of unit B2 of Geo1B23513-02 are interpreted as a characteristic inherited from the sedimentary source, or even a result of

post-depositional changes. In fact, bioturbation imprints are present in this unit and have the capability to trigger the occurrence of dissolution in the foraminifera test (Walker and Burton 1990; Parsons and Brett 1991; Kaufer et al. 1992).

Conclusion

The sedimentary characteristics observed in the studied cores allowed the detection of high-energy events in the sand units B1, C1, D1, and A2, mainly regarding the units C1 and A2 due to their significant expressions in the stratigraphy. The set of contrasting features in the lithostratigraphy, such as erosive basal contact, compositional characteristics with abundant bioclastic gravels, as well as ecozoic and taphonomic data, allow interpreting them as a result of a high-density flow from the coast towards the sea, caused by the tsunami backwash.

From the microstructural analysis, it was detected that the GeoB22512-01 core registered a higher frequency and degree of mechanical marks in the bioclastic units B1, C1, and D1. This abundance indicates that these units were sculpted in a high-energy hydrodynamic environment. On the other hand, in the GeoB22513-02 core, despite high values of mechanical action at the base of the unit considered tsunamigenic (unit A2), there was little microstructural contrast with the lower unit B2, due to the stronger presence of dissolution in the grains of quartz in A2. It is very likely that in addition to the concentration of sediments in the water column, the local bathymetry and the geomorphic framing play an important role in the impression of the microtextures, since the backwash was channelled more intensely through the Portimão canyon, thus promoting the generation of mechanical impressions mainly in the GeoB22512-01 sounding (Fig. 3 A and B).

Sediment composition also played a role in the generation of microtextures. This is due to the slight increase of quartz

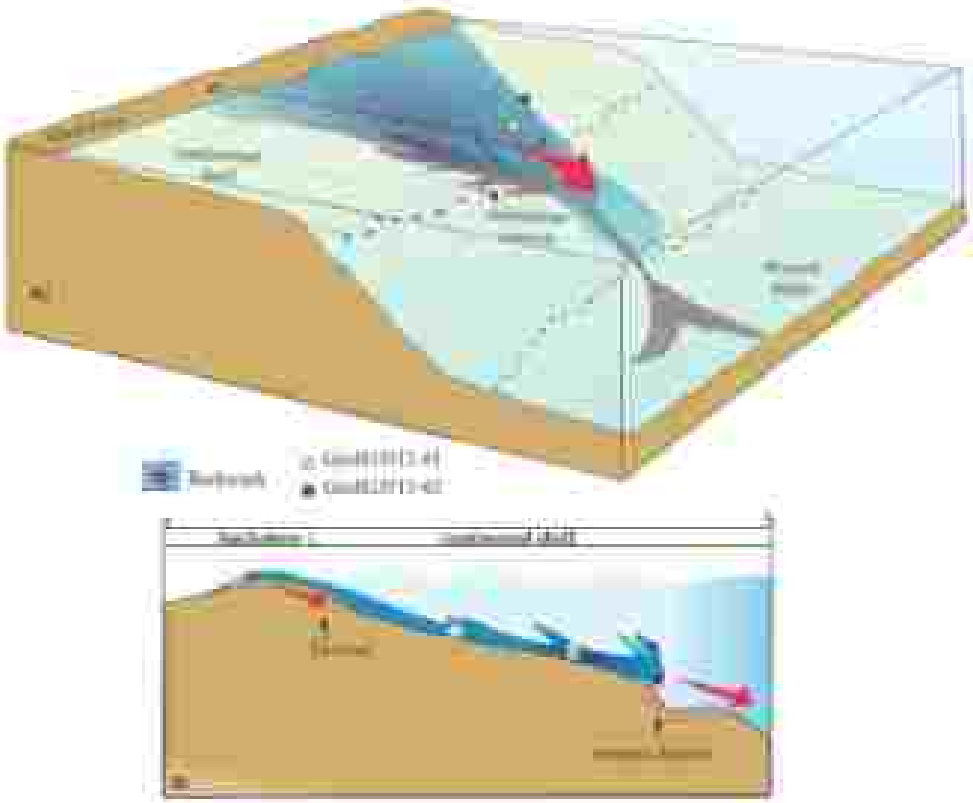


Fig. 9 Conceptual model of the backwash dynamics. A Diagram illustrating approximately the position of the cores in relation to the Portimão canyon. The backwash flow concentrated in the canyon reaches higher velocity as the depth increases. As energy is proportional to velocity, the flow channeled through the Portimão canyon promotes more generation of mechanical marks (percussion marks, fractures, and fresh surfaces) on the quartz grains of the GeoB22512-01 core, which is more influenced by this energy than the core GeoB22513-02. B The schematic profile a-b illustrates the generation of mechanical microtextures, controlled by the concentration of sediments in the water column during the different stages of the flow. The backwash causes erosion and redeposition of sediments in the sea, in I, the high concentration of sediments carried by the initial erosion favors the formation of fractures and percussion marks. Since most of the sediments were remobilized by previous flows), the low concentration of sediments in the water column, in II, generates more mechanical collisions, favoring the predominance of fresh surfaces

grains inserted into the water column by erosion triggered by the backwash flow. This is enough to intensify the mechanical shock between the quartz grains in the bioclastic units. Furthermore, post-depositional changes and original features of the sedimentary source may help to explain the lack of microstructural homogeneity in Geo[8233 13-02].

From the results of taphonomy, it was evident that in the silty layer, the foraminifera were essentially altered by dissolution. On the other hand, in the sandy unit, there is a slight increase in the test abrasion, despite that, the occurrence of dissolution is still noted. The exclusive presence of marine foraminifera (medium to outer platform) in the sandy units attests that there was only reworking of sediments close to the source. The taphonomic analysis needs a more vertical approach in the cores; a deep paleoecological study of these specimens is suggested.

It is not possible to detect the deposition of tsunamis with a single isolated proxy, but the combination of evidence obtained in this study, added to the local sedimentological context and the results obtained in the literature, allowed us to presume that the C1 and A2 units are related to the backwash dynamics of tsunamis. Finally, the continuation of investigations of the offshore sedimentary record of the SW sector of Portugal is fundamental to extend the understanding of tsunami events in the past, as well as to understand their risks in the future.

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Declarations

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