

Historical seismicity in oceans from sailors' testimonies

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Abstract Before seismological catalogs were routinely produced, seafarers experienced major seismic events at sea that were documented in their logs. This article analyzes some of these old records—mostly from eighteenth and nineteenth centuries—in the context of plate tectonics. Large shocks that were felt on ships are related either to earthquakes, sub-marine volcanic eruptions, or to sub-marine sliding of rocks and/or sediments. We analyze various related parameters such as the location and size of the shaking, the duration of the shock, and the associated noise. A total of 396 observations have

been retained for this study, mostly located in the Atlantic Ocean, reflecting its intense maritime traffic during the period of interest. Some of the detailed accounts allow us to clearly identify the nature of the shocks, including a possible interpretation in terms of focal mechanism. Our results, when compared to historical catalogs, reveal many previously undetected large events. Macroseismic results for a few large historical events occurring near the coasts confirm the validity of our approach, but also reveal its limitations. The good locations of most of the events allow us to relate them to plate boundaries. The Romanche transform zone has deserved particular interest due to the large number of related testimonies. This study particularly illustrates that historical seismicity may be applied to oceans. The collected testimonies also show how impressive and dangerous these large earthquakes at sea are, despite the absence of S-waves.

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1 Introduction

A major effort has been made to improve our knowledge of historical earthquakes on continents, mainly because of their importance in seismic risk assessment. Historical seismicity is also important for better understanding and modeling of the seismic cycle. In oceans, no similar effort has been made, not only because the human

impact of earthquakes is reduced, but also because it is very difficult to collect information related to past earthquakes. Events have been occasionally reported in newspapers, but damage reports are mostly documented in insurance claims, which are proprietary documents that are difficult to access. It would however be interesting to extend our knowledge of historical seismicity to oceans, where most of the plate boundaries are located. It may help to better understand the contribution of strong events at transform faults and ridges with respect to creep at the fractures zones. This would allow us to better relate the seismicity along ridges to that along transform faults. It may also provide information about faults along which tsunamis may originate.

In the past, large earthquakes that occurred close to the coasts were widely studied due to their destructive effects on the continents (e.g., Bertrand 1839; Barry 1866; Roth 1882; Sieberg 1904; Montessus de Ballore 1907, 1908, 1911). However, disregarding some cases describing the disappearance of ships in places such as the mythical Bermuda Triangle, large earthquakes occurring far from the coasts have rarely been reported (Daussy 1838; Bertrand 1839; Perrey 1847; Mallet 1858; Rudolph 1887a). This scarcity of testimonies is due to the fact that it is highly unlikely that a ship would be present in the vicinity of an epicenter at the exact time of the earthquake. Moreover, in rough sea, earthquakes may not be felt at great distance.

In this study, we have collected reports describing changes in the sea and their effects reported on board of vessels, coupled with information on their locations. This allowed us to identify historical events of tectonic origin in oceans far from the coasts. The precision in ship location may be as good as 10 km—or even better—thanks to the excellent quality of sailing instruments. When the descriptions are detailed enough (e.g., type and level of damages on the decks, time duration of the shock and the associated noise, if any) we could identify the nature of the events by distinguishing earthquakes from volcanic eruptions or other under-sea manifestations (such as submarine sliding of sediments). The information concerning the strength of the events (taking into account how strong and how long the ship had been shaken) allowed us to define a strength scale for these events. We discuss these old testimonies in the framework of the current knowledge of plate tectonics.

2 Description of the sources and the database

The present study relies on data of seafarers' testimonies collected by several scientists, ranging from the eighteenth to nineteenth centuries (see examples of testimonies in Table S1 of the Electronic Supplement). Among the earliest published studies of the nineteenth century, several notes of Daussy (1838, 1842) mentioned a high concentration of events felt in the Equatorial Atlantic. Daussy wrongly interpreted these events as being linked to a big sub-marine volcano: this zone was further called “Zone de Daussy” by Montessus de Ballore (1911). Most of the other reports were collected during the eighteenth and nineteenth centuries by various authors, mostly in North Atlantic harbors. Rudolph (1887a) consolidated all these reports and analyzed them in his thesis. The annexes of his publications (Rudolph 1887b, 1895, 1898) include mainly the data published by Daussy (11 events) and those extracted from notes published by Perrey (76 events), Mallet (22 events), Findlay (10 events), Imray (five events), and numerous other (324 events) extracted from maritime revues and regional publications, including many documents of the French *Annales Hydrographiques de la Marine* and of the *Meteorological Office of London*. This collection of data shares the same reference meridian (the Greenwich meridian). We have also added in the catalog seven data points reported in Montessus de Ballore (1908), as well as a few others coming from various reports and publications. In total, 457 testimonies have been collected.

In the initial database, we have rejected all the data that were not clearly related to earthquakes, volcanic eruptions, or sub-marine collapses. We have retained well-known historical near-coastal earthquakes, which were sometimes felt far in the ocean. Take for example the case of the 1755 Lisbon earthquake, which was felt more than 1000 km away from the epicenter. We have restricted the observations to those that contain explicitly the location of the ship (latitude and longitude) with accuracy better than one tenth of degree (thus presumably better than ~10 km for each coordinate). The date and hour are generally specified; however, we considered a few events with ambiguity on the day because their descriptions were accurate and informative, thus presumably reliable. The 396 data points remaining after this selection are listed in Table S2 of the Electronic Supplement, along with the source

of the testimonies and the main information extracted from these testimonies.

There is generally only one testimony per event, but sometimes several testimonies are reported for the same event that may describe different effects (e.g., March 11, 1855 in Equatorial Atlantic Ocean, Tables S1 and S2 of the Electronic Supplement). These testimonies may include ships that are more than 500 km apart from each other. Some testimonies also mention multiple events, or aftershocks (see for example in Table S1 the February 5, 1842 event on *The Ann Mary* ship). In most cases, as it is impossible to discriminate between the different events, we kept only the strongest one. We also questioned the independence of some testimonies, but as it is difficult to decide which ones are original, we kept all of them. For example, similar sentences may be found in two different testimonies: one from the ship *The Maries* (October 13, 1852), and the other one from the *Watch of the Wave* (March 13, 1859) (Table S1 in the Electronic Supplement).

Figure 1a shows the locations of the 396 testimonies. Compared to the worldwide seismicity (Fig. 1b), it is clear that this distribution mostly reflects the European origin of the testimonies and the Atlantic sea routes of the eighteenth–nineteenth centuries. Nevertheless, more than 80 % of the reported locations are close to well-identified seismic zones. We note in many cases that the location of the events are along the well-known plate boundaries, in particular along the mid-oceanic ridges and transform faults. A few other ones are related to active seismic zones distant from plate boundaries, nowadays referred to as intraplate seismicity (Sykes 1978). Some of the other locations may be related to major events occurring in continents near the coasts or slightly off shore and felt sometimes at large distances in the oceans and at harbors. For example, note the reports of the strong Charleston (North Carolina), August 31, 1886 event in several harbors of the Eastern coast of North America (Fig. 1a and Table S2 of the Electronic Supplement).

3 Determination of the type of event

From the seafarers' testimonies, it is sometimes possible to identify the nature of the related events. The 396 events have been sorted into sub-classes (Table 1) depending on the type of motion reported on board, and on whether or not an abnormal sea surface was observed. In

the first sub-class (K-type, 140 events), no change in sea level is reported: the ship vibrates, sometimes it stops for a few seconds to a few minutes, but the sea surface remains unaffected. After the shock, the ship generally keeps the same speed. These effects are frequently described as if the ship were scraping a coral reef (see for example, in Table S1, the February 9, 1823 event on the ship *Winchelsea*). It may be interpreted as due to the impact of a P-wave on the ship hull, and the detailed description of these observations may be used to infer the nature and proximity of the event. In numerous cases, sounds are heard simultaneously, indicating high frequency content ($f > 20$ Hz) in the spectrum. This is an indication of the proximity of the seismic source, as high frequencies are attenuated faster than low frequencies with distance: in sea water, absorption of sound energy and frequency are nearly proportional to each other in logarithmic scale (Fisher and Simmons 1977). In some cases, the duration of motion and sound may indicate a multiplicity of shocks (aftershocks), or suggest the complexity of the fault mechanism.

The second sub-class (O-type, 50 events) is characterized by a sudden sea-level change at the time of the shock, and the generation of roughness of the sea surface. This sea displacement is due to a tectonic rupture of the crust leading to a volumetric change at the sea floor. In some cases, the generated waves are described as mountain-high, persisting for tens of minutes (see for example in Table S1 the October 13, 1852 event felt on *The Maries*). The long duration may suggest a long-lasting source origin, such as sub-marine sliding or slope collapse. This is specified with the index “c” in the different tables. In some cases, the sea-level change is mentioned as the second stage of another type of event, in particular a K-type event.

A third sub-class corresponds to events of volcanic origin (V-type, 16 events). Such events are easily identified thanks to their external effects at the sea surface, such as the appearance of large water columns, a sudden change of color at sea surface, smoke, lightening, and loud sounds (for example the June 18, 1845 event reported on *the Victory*, Table S1). Sometimes, a sea-level change (O-type) is associated to the volcanic event (e.g., March 13, 1891 on *The Eleanor*, Table S1).

In the final sub-class (S-type event, 190 events), the events are felt, with sometimes strong motions, but the described effects on the ship and sea, if any, do not allow us to specify the nature of the event. These events are interpreted as due to the impact of a P-wave generated

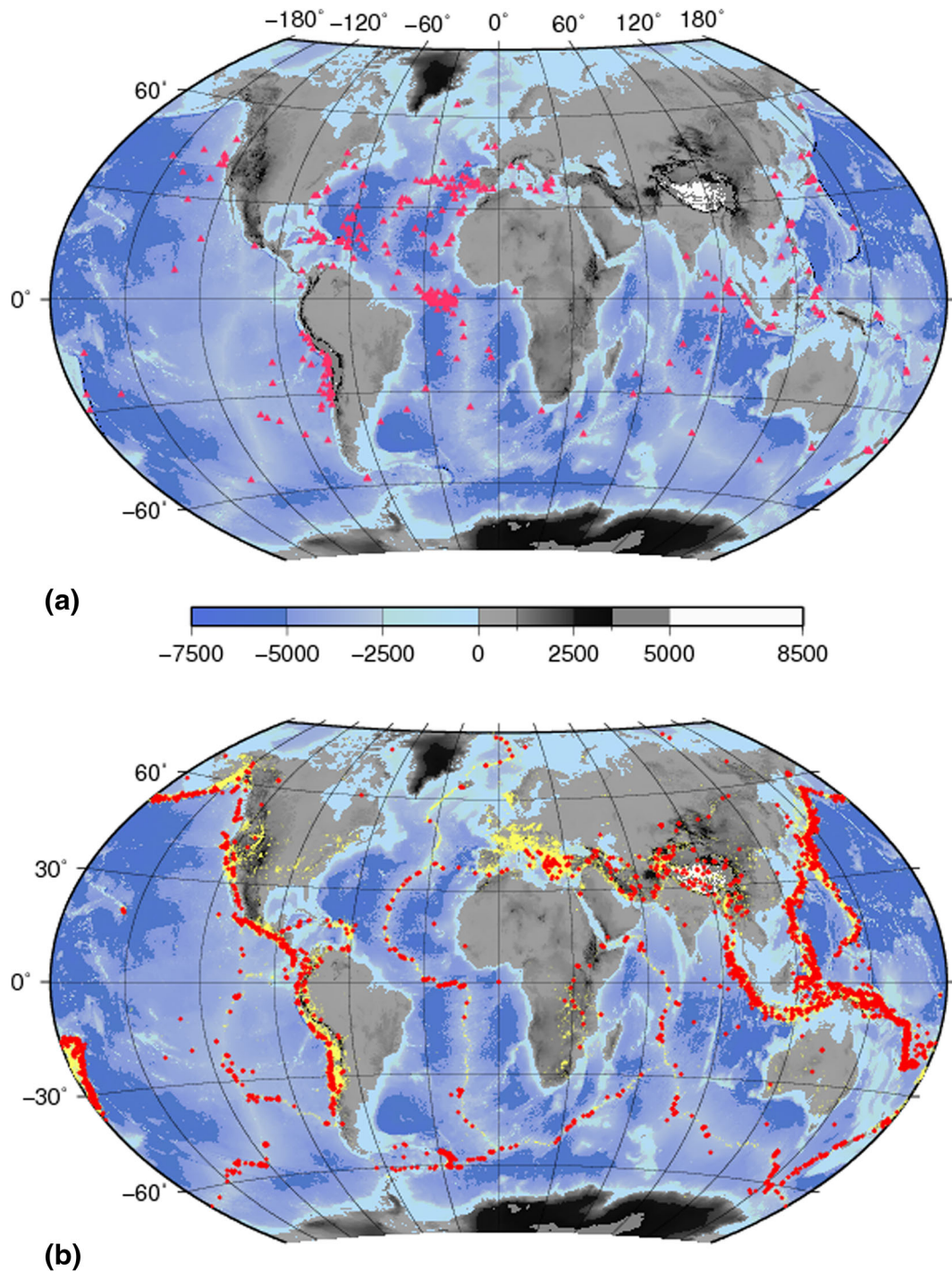


Fig. 1 Locations of the 396 events analyzed in this study **(a)**, compared to the worldwide seismicity **(b)** given by the US-National Earthquake Information Center (NEIC) for the period 1987–2010; *yellow dots*: all epicenters, *red diamonds*: magnitudes ≥ 6.0 . Bathymetric-topographic scale in meters. Note in **(a)** the

density of events higher in the Atlantic Ocean than in the Pacific Ocean, in contrast to the actual seismicity **(b)**, reflecting the high maritime traffic between Europe and America and to numerous reports by European seafarers

Table 1 The different types of tectonic events detected at sea, with their strength and the relevant number of events.

Strength type	5	4	3	2	1	Total
K	15	27	46	28	24	140
O	8	9	20	4	9	50
V	1	1	3	5	6	16
S	1	24	48	67	50	190

The levels vary from 5 (strong event with acceleration largely exceeding 1 g) to 1 (just felt without damages and fright). Type K: vibration of the ship without sea-level change; type O: oscillation of the ship with sudden sea-level change; type V: oscillation of the ship with external effects associated to volcano; type S: just felt without mention of special effect

by a local earthquake, or by a strong earthquake which occurred at great distance (large events may be felt up to a few thousands of kilometers away), or by a tidal wave.

Figure 2 shows the locations of the ships with mention of the reported type of event. Events of K-type are the most frequently observed ones, whatever the strength of the shock (sub-class S excluded). Most of K-type events are felt close to the transform faults in Central and North Atlantic oceans where strike-slip motions occur, generally without significant change in sea level. The large transform zone in the Equatorial Atlantic is however more complex than simple slip systems and will be considered in more detail later on. A strong concentration of O-type events with only a few K-type events is observed along the South American coast, where subduction earthquakes occur. Most of the V-type events are observed in well-known volcanic regions, as for example the Mid-Atlantic ridge and Central Mediterranean Sea.

4 Earthquake strength inferred from sailor's testimonies

The effects felt onboard the ships may be very impressive, and significant damages may be reported (Table S1). Some recent testimonies show that even moderate to large earthquakes may induce severe problems during navigation, even with a well-equipped ship (see for example the October 11, 1973, $M=6.3$ event on the *Jean Charcot*, Table S1). We have interpreted these observed effects in an attempt to define an intensity scale for the felt events. This approach is similar to the

one used on continents, with the difference that the main source of damages on continents is S-waves; in the case of oceans, P-waves are responsible. In his thesis (1887a), Rudolph proposed a 10-level scale based on what is felt, following studies of continental earthquakes prevalent at the time (e.g., the de Rossi-Forel scale, de Rossi 1883). Rudolph's scale is however overly detailed and very subjective; hence, we sought for a simpler and more robust one.

The strength of the events may be defined in terms of acceleration. The detailed accounts given by sailors on the effects on board (partial destructions) allow us to roughly estimate the accelerations. For example, the airborne trajectory of objects that were lying on the deck implies local accelerations greater than 1 g. Hence, we have tentatively established a new scale based on accelerations, which is limited to five levels, that we call a "strength scale" to avoid any confusion with the intensity scales on continents. Level 5 corresponds to very strong events with acceleration largely exceeding 1 g, inducing near-complete destruction of equipment on deck. Level 4 corresponds to strong events with acceleration close to 1 g. Level 3 corresponds to an event that displaces various objects on deck but with acceleration significantly less than 1 g. Level 2 is an event that causes fright without any damage. Level 1 corresponds to other shocks felt but reported without any detail about fright or damages.

A strength value is assigned to a particular event and to a particular ship. However, in contrast to what may be done on continents, a macroseismic strength and macroseismic epicenter cannot be defined due to the scarcity of the testimonies for each event. We have assumed that for the testimonies reporting a strong energy (estimated acceleration ≥ 1 g, strengths 4 and 5) the ship position is close to the ruptured area. Thus, the ship coordinates roughly gives the macroseismic epicenter of the event. We will see in the next section that the event duration is additional information to constrain the distance of the ship to the event. In Fig. 3, the ship coordinates of the strongly felt events (strengths 4 and 5) are reported. They fit well with the active seismic zones that underline the tectonic plate boundaries. In particular, those located in the Atlantic Ocean are precisely either along the middle Atlantic ridge, on the large transform faults, or along the Caribbean arc. Similarly, the events located in the Indian and Pacific oceans underline either the active mid-oceanic ridges or the subduction zones.

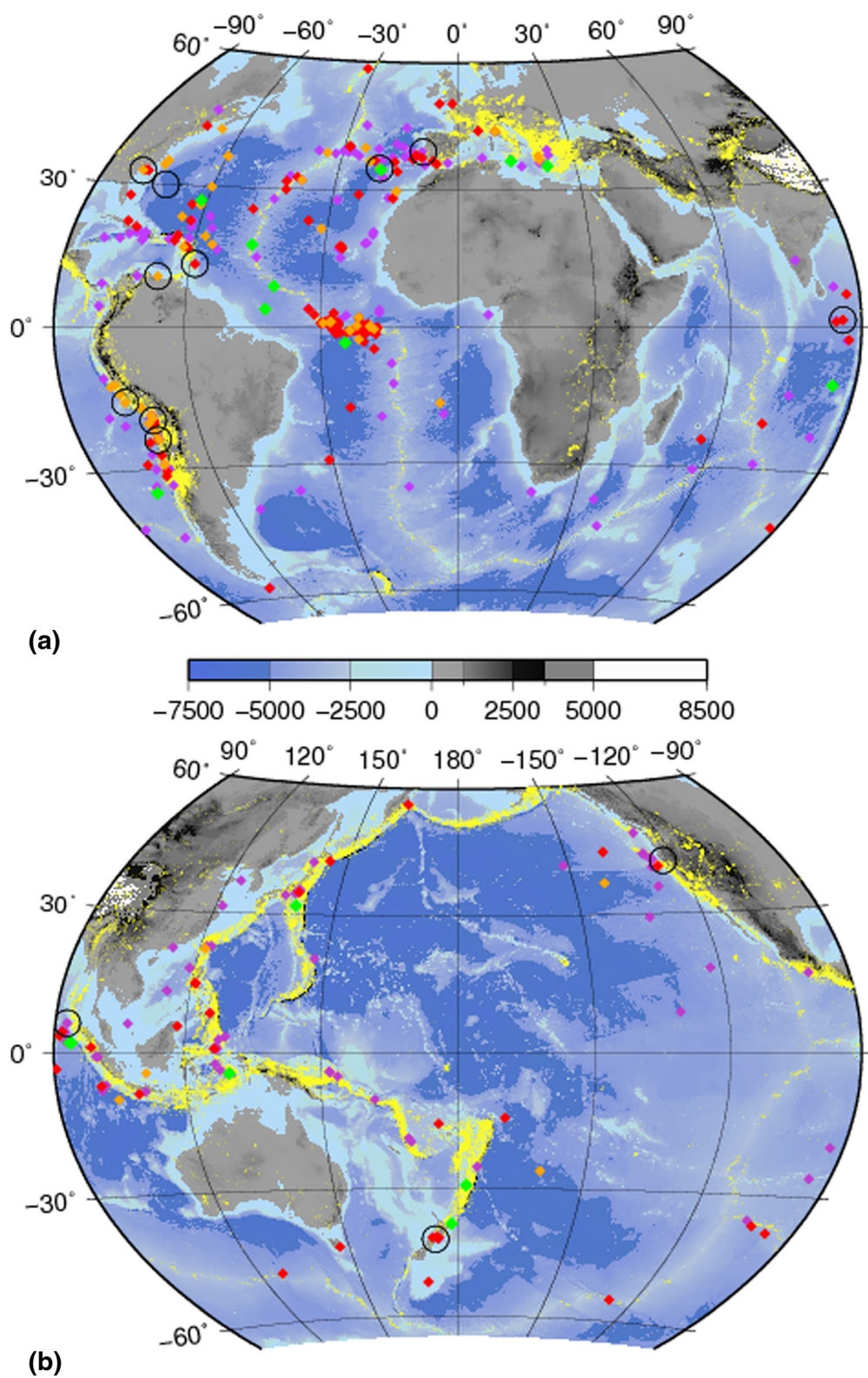


Fig. 2 Maps of the well-located events, centered on 0° (a) and 180° (b), with events sorted according to their type: *red diamonds*: type K, vibration and shock without sea-level change; *orange diamonds*: type O, sudden sea-level change; *green diamonds*: type V, volcano; *purple diamonds*: no information (type S). The *yellow points* correspond to the NEIC locations of epicenters for the period 1981–2010. Note that most of the events coincide with the plate boundaries. *Black circles* denote known large historical events mentioned in this study. Bathymetric-topographic scale in meters

5 Interpretation of the reported time durations

The time duration given in the testimonies is another interesting parameter for characterizing the energy of the events, even though it is not as easy to interpret. Among the 175 testimonies that reported time durations, 35 give time duration less than 10 s, 56 give duration between 10 and 60 s, and 84 give duration ≥ 60 s, among which 53 correspond to a very long duration ≥ 90 s. The event time duration is linked to the source process (fault rupture or land slide), to the reflection and conversion of

waves in the crust, at the sea floor and surface, and to the distance of the ship to the seismic source.

The more complex the fault rupture is, the longer the duration of the P-wave and S-wave is (S-wave then converts as P-wave at ocean floor). Recent studies based on broadband records show that large events often include several sub-events (e.g., the March 14, 1994, magnitude 7.1 event on the Romanche fault, McGuire et al. 1996). On the basis of the CMT earthquake focal solutions (Ekström et al. 2012), the P-wave half-time duration is typically of 10 s for a Mw 6.8 event, and 23 s for a Mw 8.0 event, a possibly underestimated value. Lomax and Michelini (2009) provide larger estimates, who distinguish between strike-slip, normal, and reverse oceanic faults, arriving at a half-duration of more than 100 s for some strike-slip oceanic events of large magnitude (Mw=7.8).

In the testimonies, it is not clear whether the long duration which is sometimes reported is related to a single shock, to the cumulative effect of several events occurring closely in time (i.e., a main shock followed by

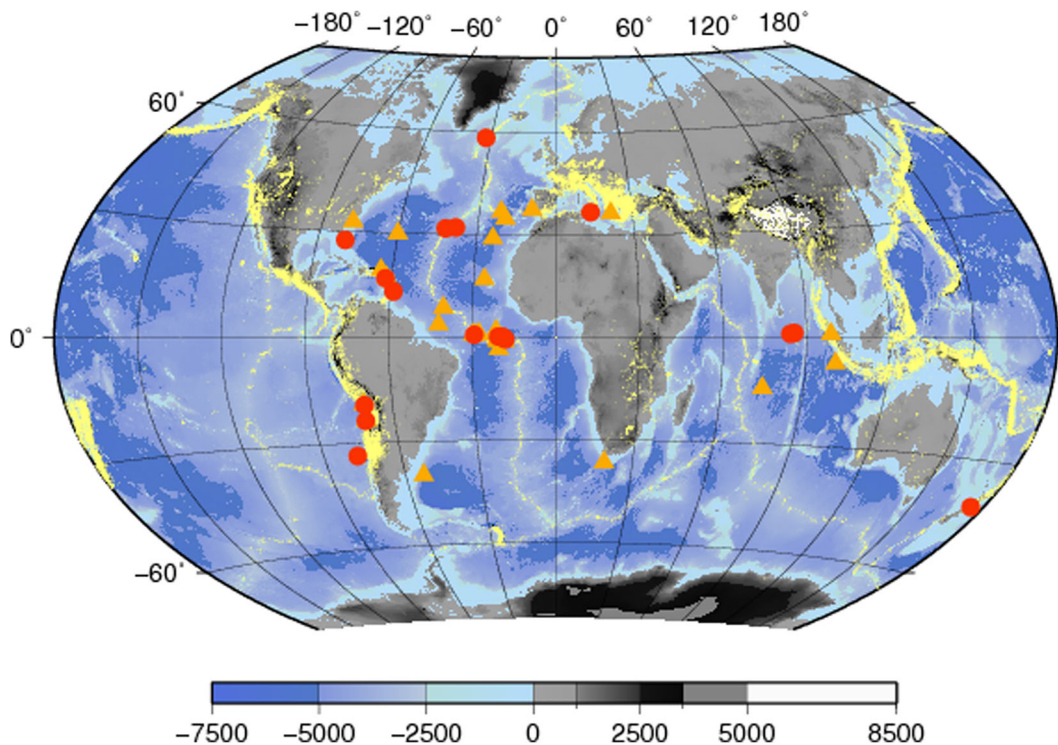


Fig. 3 Location of the strongest events with strength 5 (*red dots*) and 4 (*orange triangles*), superimposed to the instrumental seismicity 1981–2010 (*yellow dots*). Bathymetric-topographic scale is in meters. Note that most of the events are located along mid-oceanic ridges, transform faults, and subduction zones, except for a few ones which may be related to hotspots and intraplate seismicity

aftershocks), or to a complex rupture process. When the testimonies report a single shock of short duration (less than 10 s), it generally indicates a P-wave coming from a remote earthquake. In some cases, the compressive nature of the P-wave impact is easily identified owing to the description of a vertical oscillation of the ship (September 10, 1869 felt on *La Néréide*, see Table S1). The sound also gives information about the origin of the event and the complexity of the source. Loud sounds are often reported (February 9, 1823, on *Winchelsea*), but could also be simple bangs, which indicate a short distance to the source, or claps of thunder, sometimes associated with volcanic activity (March 13, 1891 on *Eleanora*, see Table S1).

The observation of events with durations larger than 2 min may not be explained with a unique fault plane on which occurred a simple smooth rupture with simple source time function. It is necessary to invoke more sophisticated sources such as a propagating source or multiple sources, related to the fractal geometry of the faults. Very long durations may better be explained by the presence of creep events or slow earthquakes occurring along ridges and transform faults. For example, Kanamori and Stewart (1976) report a rupture velocity which may be as low as a few tens of cm/s along the Gibbs fracture zone in the North Atlantic Ocean. In some cases, the whole rupture process may last more than 1 h in involving several slow sub-events (Kanamori and Stewart 1979). Landslides or slumps or bottom-floor collapses (e.g., Okal 2003) may also be at the origin of long-lasting events with a strong vertical displacement of the sea surface. A few events referring to both an acceleration greater than 1 g and a duration greater than 5 min suggest an exceptional burst of energy (October 13, 1852 on *The Maries*, or May 9, 1877 on the *John Elder*, Table S1). Such landslide events are often at the origin of tidal waves that may be felt far from the source, and which may therefore mimic intraplate events in the testimonies. They also generate a T-wave which may propagate several thousands of kilometers away (Okal 2001), but their high frequency (3–10 Hz) and generally low amplitude ensure that they are hardly felt on land (Talandier and Okal 1979) and certainly not at sea.

Whatever the origin of the event, a long duration (more than several tens of seconds) is an important criterion, in addition to a strong acceleration, to assess that the ship is close to the earthquake focus. Indeed, a remote source could give a long-lasting shake, but not

with strong accelerations. We have thus considered that events for which both the acceleration is strong (≥ 1 g) and duration is long (≥ 90 s) may be considered as strong historical events (Table 2). They are those for which the macroseismic epicenters are the most reliable. Note however that, even for these best located events, an uncertainty as large as 500 km on macroseismic epicenter is possible, as observed for the 1843 Caribbean and 1855 Central Atlantic events, for which several ship locations are reported with similar strength (Tables 2 and S2). For example, the 1843 Caribbean earthquake is reported as a very strong event by three ships (Table 2), two of them (*the Juvencelle* and *the Dee*) very close to the ruptured area East of Guadeloupe (Feuillet et al. 2011) and to the estimated epicenter (ten Brink et al. 2011), and the other one (*the Thames*) being more than 400 km away in the SSE direction from this epicenter.

6 Evaluation of our results with known large historical earthquakes

It is interesting at this stage to compare our results with those obtained on land for known historical earthquakes appearing in our database. Earthquakes noted in Table S2 with * are the known historical earthquakes reported in the United State Geological Survey (USGS) world catalog of historical seismicity, with in addition a few other events reported in articles (Fig. 2). This list of historical events is not exhaustive, in particular concerning aftershocks. On the other hand, our study may have missed historical events for which reports probably exist, in particular events in the South hemisphere, and even in North Atlantic (e.g., the 1817, magnitude 7 Carolina event, Hough et al. 2013). We consider hereafter some earthquakes that occurred close to the coast or near islands, so that macroseismic and tsunami details connected with their magnitude and sometimes their location and fault rupture are available. We briefly compare this information to that deduced from the testimonies at sea.

The 1755 Lisbon Earthquake This large event induced liquefaction, landslides, and a large tsunami which led to an estimated magnitude of 8.7 ± 0.4 , with a rupture length of 180–280 km, and an average displacement of 10–14 m (Johnston 1996). Its location is debated, as is its tectonic context. By comparison with the February 28, 1969 event, a thrust fault with strike $\sim 45^\circ$ N is often

Table 2 List of the main events (strength 4 and 5, duration ≥ 90 s)

Year	Month	Day	Hour	Minutes	Lat (°N)	Lon (°E)	Region	Ships' name	Duration (s)	Type	Strength
1823	2	9	13	10	1.35	85.58	Indian O.	The Winchelsea	120	K	5
1836	1	28	21	00	-0.67	-20.17	Central Atlantic O.	Le Philantrope	180	K	4
1843	2	8	10	40	13.30	-58.91	West Atlantic O.	The Thames	90	KO	5
1843	2	8	-	-	16.91	-62.30	West Atlantic O.	The Juvencelle	90	OK	5
1843	2	8	10	37	17.01	-61.76	West Atlantic O.	The Dee	90	K	4
1845	6	18	21	30	36.68	13.74	Mediterranean S.	The Victory	600	V	5
1852	10	13	-	-	0.16	-19.00	Central Atlantic O.	The Maries	900	Oc	5
1853	11	10	11	00	-7.00	100.63	Indian O.	The Albrecht Beyling	120	KO	4
1855	1	23	21	11	-41.26	174.83	SW Pacific O.	Pandora	90	KO	5
1855	3	11	18	30	-0.95	-18.33	Central Atlantic O.	The Alma	120	K	4
1855	3	11	18	16	2.00	-21.50	Central Atlantic O.	The Copernicus	180	K	4
1856	12	30	04	15	-0.17	-19.25	Central Atlantic O.	The Regina Coeli	120	K	4
1858	4	17	20	45	27.47	-79.47	West Atlantic O.	The Pacific	720	K	5
1859	3	13	-	-	0.03	-19.00	Central Atlantic O.	The Watch of the Wave	900	Oc	5
1861	3	20	19	15	0.33	-20.58	Central Atlantic O.	The Melbourne	300	K	5
1866	1	30	10	15	31.95	-38.40	North Atlantic O.	The Komet	180	OK	5
1875	6	19	19	00	-3.33	-20.42	Central Atlantic O.	The Deutschland	180	K	4-3
1877	5	9	20	20	-23.72	-70.78	SE Pacific O.	The John Elder	270	KO	5
1884	12	22	02	35	36.73	-21.28	Azores Isl.	The Elisabeth Rickmers	200	K	4-3
1885	9	1	10	15	58.28	-32.42	North Atlantic	The Tjalfe	90	K	5
1890	11	20	-	-	8.75	-40.47	Central Atlantic O.	The P.J. Carleton	120	V	4
1891	3	13	19	30	3.78	-42.05	Central Atlantic O.	The Eleanora	600	V-O	4-3
1893	10	31	13	20	16.20	-26.10	Cape Verde Isl.	The Othello	180	K	4-3

List of the main events (strength 4 and 5, duration ≥ 90 s), with indication of occurrence time, approximate coordinates of the ship, geographic location, ship name, type of event (K: vibration and shock without sea-level change; O: sudden sea-level change (index c indicates probable sea floor collapse); V: volcanic activity), and strength of the event, defined after the level of damages and fright. The 1843 Caribbean and 1855 Central Atlantic events appear three and two times, respectively, with significantly different locations (see text)

assumed, but a tsunami analysis (Baptista et al. 1998) rather favors a rupture elongated along the shelf. It was felt all along the European Atlantic coast, and in some Atlantic islands (Cape Verde, Azores, Canary and Madeira). It is reported by several testimonies at sea as a strength 5 event of K-type. This is compatible with the suggested focal solution; however, the large tsunami suggests an O-type event.

The 1812 Caracas earthquake This event includes three sub-events of magnitudes 7.1, 7.4, and 6.0 along a ENE-WSW fault system, with rupture lengths of 70 km and 90–100 km for the two first events, respectively (Choy et al. 2010). The tectonic context at the boundary between Caribbean and South American plates is well characterized. Only one testimony is

available for this event. Curiously, in spite of the proximity of the ship to the fault, the estimated strength is only 3, with a duration of only 11 s. No straightforward explanation is proposed for this apparent contradiction.

The 1843 Leeward Island earthquake This large megathrust event ruptured the deeper part of a ~300-km long fault segment along the North America-Caribbean plate boundary (Feuillet et al. 2011). It induced numerous hydrological perturbations, landslides, cliff collapses, and vertical land displacements. Its magnitude, estimated from intensity values, is at least 8.5 (Feuillet et al. 2011; Hough 2013). Most of the testimonies report a long duration (more than 1 min) consistent with this large magnitude. The type of event, KO, is

consistent with the reported vertical displacements and with the tectonic context of oblique convergence.

The 1855 Wellington, New Zealand earthquake This event occurred on the southern offshore extension of the Wairarapa fault, which stretches NE-SW through North Island in New Zealand. The westward motion of the Pacific plate with respect to the Australo-Indian plate is accommodated by subduction along the Hikurangi trench and by strike-slip along the Wairarapa fault. The 1855 event induced an important uplift of the southwest termination of North Island (Darby and Beanland 1992). Its magnitude is estimated to 8.0. Not surprisingly, the only available testimony from a ship anchored in Wellington harbor describes it as a KO-type event with strength 5.

The 1868 Arica and 1877 Taracapa South American earthquakes These two large events are each estimated of magnitude $M_w \sim 8.8$ from macroseismic information and from the great tsunami they generated (Comte and Pardo 1991). They filled a seismic gap of more than 900 km along the Chilean subduction zone on both sides of the Arica bend. First, the 1868 event broke the northern part of the gap with a rupture length of about 500 km. A 7.4-magnitude event occurred in 1869 at the southern end of the rupture zone, followed by other large events from 1870 to 1876. The large 1877 event broke the southern part of the gap, with a rupture length estimated to be 420 km. The sailors' testimonies reported these events as O-type, as expected for subduction zones, but curiously there is only one report with strength 4 for the large 1868 event, whereas the smaller 1869 event reaches strength 5. Only two reports concern the 1877 event, with a maximum strength of 5, but many aftershocks were also reported with high strengths.

The 1886 Charleston, South Carolina event This event was felt in a large part of the Southeastern USA, its magnitude is estimated from macroseismic intensities to 7.3–7.4 (Johnston 1996) or possibly slightly less (6.9–7.1, according to Bakun and Hopper 2004). The tectonic context is poorly known, and there is debate about earthquake location, either offshore or onshore (Bakun and Hopper 2004). Four testimonies are concerned with this event and favor type O, although no tsunami had been reported. The strength (2 to 3) does not reflect the high magnitude of the event.

The 1823 and 1881 North Indian Ocean earthquakes These two events are located far from the coasts, their macroseismic epicenters and magnitudes rely on a small number of observations. The 1823 event is 50 to 200 km west of Sri Lanka, with estimated magnitudes of 6.7 or 7.9, depending on the method used (Martin and Szeliga 2010; Szeliga et al. 2010). The two available testimonies depict an event of strength 5 of K-type, although focal solutions in this region generally include a thrust component (e.g., Bergman and Solomon 1985) which could also favor O-type. The very large 1881 Car Nicobar Island earthquake, with a magnitude of 8.9 to 9.3, was barely felt by a single ship. This may have been due not only to the distance of the ship to the rupture (400 to 700 km), but also to the predominance in this region of strike-slip mechanisms with a NW-SE strike which does not favor P-radiation in the ship direction (to the SE of the macroseismic epicenter).

These various examples illustrate the limitations of our method based on sailors' testimonies for recovering historical seismicity, but they also show the relatively good performance of this method. We may have missed large events, as for example the 1886 Hayward California earthquake (Johnston 1996), for which many testimonies are available but lack accurate coordinates, or the 1817 offshore Carolina earthquake (Hough et al. 2013). By contrast, some events such as the 1884 Azores earthquake give rise to numerous testimonies where scientific analyses are scarce. In the open sea, our approach appears to be the only way to identify previously undetected large events. This is the case for example along the Mid-Atlantic transform zone that we consider hereafter.

7 Close-up on the St-Paul, Romanche, and Chain transform zone

The Saint Paul, Romanche, and Chain fracture zones in the Central Atlantic (Fig. 4) deserve particular attention because a large number of testimonies are available in this region and because their structure and seismicity are well documented. These three faults constitute one of the largest transform zones in the oceans. They offset the mid-Atlantic ridge left laterally by about 2000 km, among which 950 km are associated to the Romanche transform fault. Short ridge segments link the three transform faults. The slip along the Romanche fault is

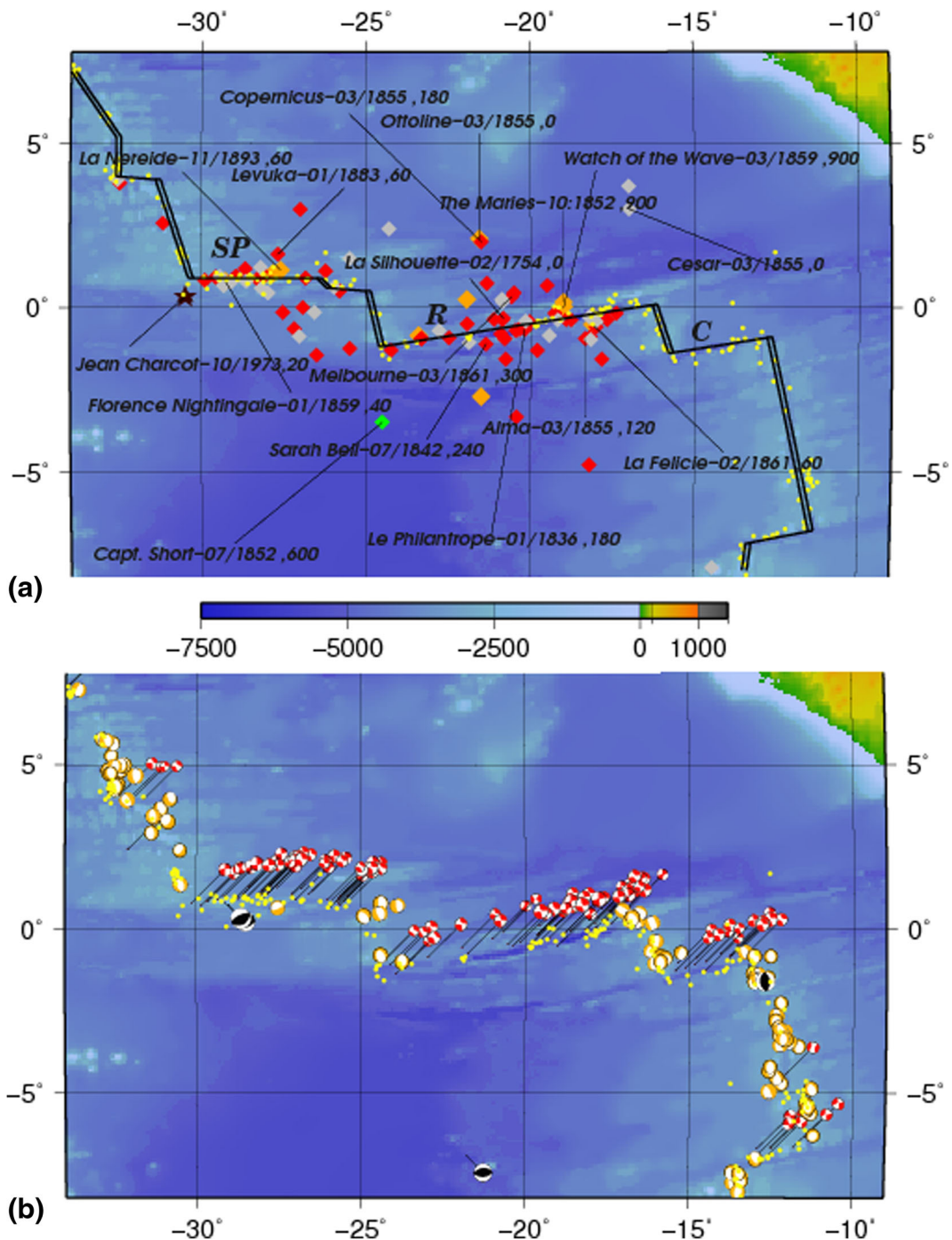


Fig. 4 **a** Locations of the events felt in the Equatorial Atlantic Ocean, along the Saint Paul (SP), Romanche (R), and Chain (C) transform faults, with indication of the type of event: red diamonds: K-type, ascribed to strike-slip faulting; orange diamonds: O-type, ascribed to normal or thrust faulting; green diamonds: V-type (volcanic event); light gray diamonds: S-type (no information). Ship name, date (month/year), and duration are reported for the

main events. The black star corresponds to a recent testimony for which the epicenter is known (Table S1). Double lines indicate ridge axis, simple lines transform faults. **b** Instrumental seismicity (NEIC, 1987 to 2010), with centroid moment tensor solutions (CMT, 1977 to 1997) in red for strike-slip faulting, in orange for normal faulting, in black for thrusts. Bathymetric scale in meters

slow (~ 1.75 cm/year, Cande et al. 1988). The structure of this transform zone has been widely studied from seismic surveys including multi-beam and high-resolution multichannel seismic reflection experiments (Honnorez et al. 1991; Bonatti et al. 1994, 1996). The central part of the Romanche transform zone is a 100-km wide trough, peaking at more than 6000 m. A ridge stretches along part of this trough to the North, with a few peaks of more than 2000 m (Bonatti et al. 1994). The Romanche transform zone also includes several inactive hanging valleys with very abrupt flanks, in particular between longitudes 18.3°W and 19.3°W . The analysis of the seismicity (Fig. 4b) reveals that the fault planes are nearly vertical with a horizontal strike-slip motion, the mean foci being slightly deeper on the Romanche fault than on the Chain fault (Abercrombie and Ekström 2001). The relative contribution of a seismic slip in the global displacement remains controversial (McGuire et al. 1996; Abercrombie and Ekström 2001).

Most of the reported testimonies concern events that are very close to the transform fault segments (only few of them are along the ridge segments) in contrast to what is observed in the instrumental seismicity (Fig. 4b). The absence of observations near the Chain fault reflects the low maritime traffic in this region. Even though a majority of the observations are identified as K-type—as expected for strike-slip faults—we observe numerous O-type events, associated with normal faults and collapses (see Table S2). This may be a consequence of the highly variable topography of this region, with strong slopes favorable to land sliding (Honnorez et al. 1991). Some reports relating strong changes in sea level to giant waves destroying or shaking the ships violently for tens of minutes may be linked to large-scale collapses along the slopes of ridges and suspended valleys (October 13, 1852 on *The Maries*; March 13, 1859 on *The Watch of the Wave*, Table S1). The only V-type event, south of the western termination of the Romanche transform zone (July 17, 1852 on *The Capt. Short*), may not be related to any nearby volcanic relief.

8 Conclusions

The seafarers' accounts of the eighteenth and nineteenth centuries, describing the effects of large earthquakes on ships, allowed us to identify historical seismic events in oceans and to locate them

with good accuracy. Well-detailed descriptions (including how the ship is shaken, the shock duration, the level of damage on the decks, the associated sounds—see Tables S1 and S2) allowed us to identify the nature of the events in distinguishing earthquakes, volcanic eruptions, and other under-sea manifestations. In some cases, it has also been possible to identify the nature of the seismic source (strike-slip or vertical displacement) from the description of the waves the ship faced. Table 2 displays a catalog of historical events we have identified on the basis of strong acceleration (≥ 1 g) and long duration (≥ 90 s). These two criteria denote the proximity of the ship to the macroseismic epicenter of a very strong event.

A comparison, for a few large historical earthquakes, of the information extracted from testimonies at sea with that given by macroseismic intensities and tsunami observations on land demonstrates the relatively good performances of our method, but also shows its limitations. It is however encouraging to see that new large earthquakes have been identified and that their locations follow the major seismic zones now identified from instrumental seismicity.

A rough image of the plate boundaries (in particular of the Mid-Atlantic ridge) was thus available at the end of the nineteenth century, from the compilation of Rudolph (1887a) in his thesis. Unfortunately, this data was neglected for a long time and did not achieve the full impact it deserved. For example, the data could have been used by Wegener (1915) to strongly support his theory of continental drift.

In spite of difficulties associated with the reliability and scarcity of testimonies and the biases related to maritime routes, these new data open the door for historical seismicity in the oceans in modern-day theory of plate tectonics. The interpretation of testimonies relating the observed effects to a source type as well as the definition of an intensity scale are other challenges to overcome.

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