European Review, Vol. 14, No. 2, 181–191 (2006) © Academia Europaea, Printed in the United Kingdom

The great Lisbon earthquake and tsunami of 1755: lessons from the recent Sumatra earthquakes and possible link to Plato's Atlantis

M.-A. GUTSCHER

Universite de Bretagne Occidentale, Institut Universitaire Europeen de la Mer, UMR 6538 Domaines Oceaniques, Place Nicolas Copernic, F-29280, Plouzane, France. E-mail: gutscher@univ-brest.fr.
http://www-sdt.univ-brest.fr/ ~ gutscher

Great earthquakes and tsunami can have a tremendous societal impact. The Lisbon earthquake and tsunami of 1755 caused tens of thousands of deaths in Portugal, Spain and NW Morocco. Felt as far as Hamburg and the Azores islands, its magnitude is estimated to be 8.5–9. However, because of the complex tectonics in Southern Iberia, the fault that produced the earthquake has not yet been clearly identified. Recently acquired data from the Gulf of Cadiz area (tomography, seismic profiles, high-resolution bathymetry, sampled active mud volcanoes) provide strong evidence for an active east dipping subduction zone beneath Gibraltar. Eleven out of 12 of the strongest earthquakes ($M > 8.5$) of the past 100 years occurred along subduction zone megathrusts (including the December 2004 and March 2005 Sumatra earthquakes). Thus, it appears likely that the 1755 earthquake and tsunami were generated in a similar fashion, along the shallow east-dipping subduction fault plane. This implies that the Cadiz subduction zone is locked (like the Cascadia and Nankai/Japan subduction zones), with great earthquakes occurring over long return periods. Indeed, the regional paleoseismic record (contained in deep-water turbidites and shallow lagoon deposits) suggests great earthquakes off South West Iberia every 1500–2000 years. Tsunami deposits indicate an earlier great earthquake struck SW Iberia around 200 BC, as noted by Roman records from Cadiz. A written record of even older events may also exist. According to Plato's dialogues *The Critias* and *The Timaeus*, Atlantis was destroyed by 'strong earthquakes and floods … in a single day and night' at a date given as 11,600 BP. A 1 m thick turbidite deposit, containing coarse grained sediments from underwater

avalanches, has been dated at 12,000 BP and may correspond to the destructive earthquake and tsunami described by Plato. The effects on a paleo-island (Spartel) in the straits of Gibraltar would have been devastating, if inhabited, and may have formed the basis for the Atlantis legend.

Introduction

The Great Lisbon earthquake of 1755, with an estimated magnitude of 8.5–9.0, was felt as far away as Hamburg, the Azores and Cape Verde Islands and has the largest documented felt area of any shallow earthquake[1,2] (Figure 1). The Great Lisbon earthquake triggered a 5–15 m high tsunami and caused up to 60,000 casualties in the SW Iberia – NW Morocco region.[2,3]

Although a variety of sources for the 1755 earthquake have been proposed – Gorringe Bank[2] the Marquis de Pombal structure[6,7] and the Tagus Valley Fault[8] – the most recent work suggests a subduction fault plane in the Gulf of Cadiz[9] is the most likely candidate. Finding the fault responsible has proven difficult for two main reasons. First, the event occurred 250 years ago and therefore no instrumental recordings exist. Secondly, the plate tectonics of the region are complex, with several independent blocks/plates, moving at slow relative motions and producing numerous structures showing signs of recent deformation.

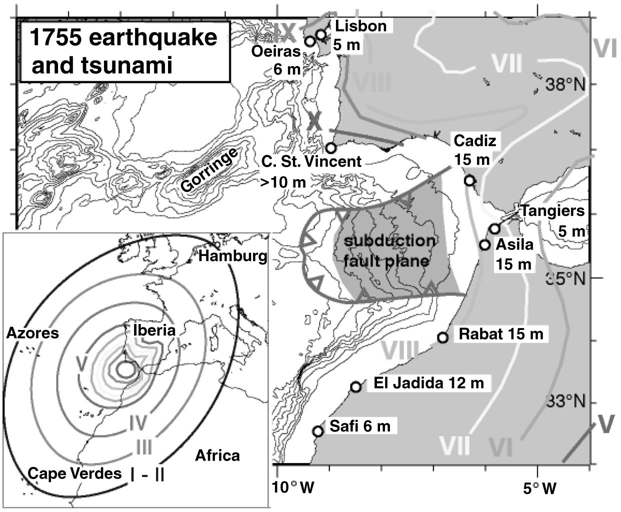

Figure 1. SW Iberia – Morocco region, with isoseismals of the 1755 earthquake (Mercalli intensity)[1,2,4] and observed tsunami heights.[3,5] Inset shows the total area where the 1755 earthquake was felt, with isoseismals.[2] The east dipping subduction fault plane (shaded) is the strongest candidate for the source of the event.

Subduction and great earthquakes

In the Iberia–Morocco region, the African plate pushes slowly (4 mm/yr) towards the NW against southern Iberia (Figure 2). But as the plate boundary here is not well defined,[10,11] it has been difficult to find a simple plate tectonic model that successfully explains all the geological observations in the region.[12,13]

However, tomographic images of the crust and upper mantle in the region, combined with recent seismic surveys, strongly support a model of subduction with slab retreat (roll-back) towards the west[14] (Figure 2). Other evidence for active subduction includes dozens of active mud volcanoes identified in the accretionary wedge, indicating active sediment compaction and fluid expulsion,[15] seismic images of thrust faults cutting to the seafloor at the base of steep morphologic scarps,[14] and new high resolution bathymetric images showing a fresh morphology at the deformation front over several hundred kilometres.

The subduction zone beneath the Gulf of Cadiz shows no evidence of recent (instrumentally recorded) earthquakes occurring along the subduction fault plane, and thus the activity of this subduction remains unclear. There are three possible explanations: (1) subduction is inactive and has ceased; (2) subduction is active, but aseismic; or (3) subduction is active and a locked seismogenic zone exists,

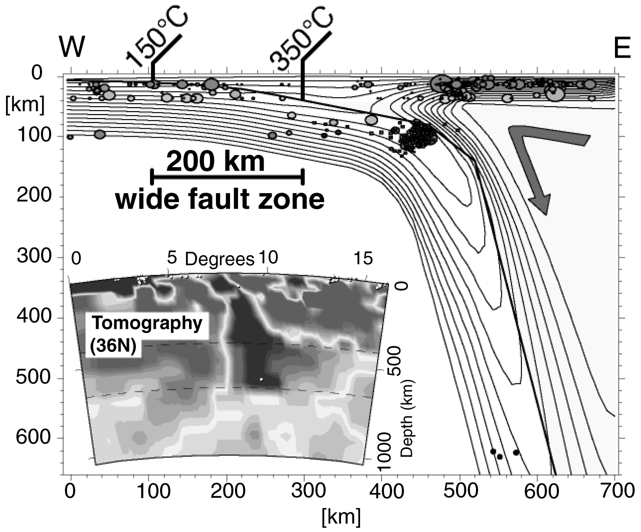

Figure 2. Cross-section of the Cadiz–Gibraltar subduction zone, with thermal model calculated using the finite-element method[18] for a subduction velocity of 1 cm/yr and a 130 Ma old slab. Geometry is based on projected seismicity and tomography (inset lower left).[14] The predicted width of the seismogenic fault zone (between the 150°C and 350°C isotherms) is 200 km.[19]

Table 1. Earthquakes of $M \geq 8.5$

	Date	Magnitude	Latitude/Longitude	
1. Chile	1960 05 22	9.5	− 38.24	− 73.05
2. Alaska	1964 03 28	9.2	61.02	− 147.65
3. NW Sumatra	2004 12 26	9.0	3.30	95.78
4. Kamchatka	1952 11 04	9.0	52.76	160.06
5. Ecuador	1906 01 31	8.8	1.0	− 81.5
6. Sumatra	2005 03 28	8.7	2.08	97.01
7. Rat Isl. Alask.	1965 02 04	8.7	51.21	178.50
8. Andr.Isl. Alask	1957 03 09	8.6	51.56	− 175.39
9. Assam – Tibet	1950 08 15	8.6	28.5	96.5
10. Kuril Islands	1963 10 13	8.5	44.9	149.6
11. Banda Sea	1938 02 01	8.5	− 5.05	131.62
12. Chile-Argent.	1922 11 11	8.5	− 28.55	− 70.50

gradually accumulating stress until it is released in the next great earthquake. Recently acquired data from the seafloor in the Gulf of Cadiz region as well as GPS data[16,17] suggest the third hypothesis is correct. In this case the Cadiz subduction zone would exhibit the same type of behaviour as the Nankai (SW Japan), Cascadia (NW USA), and Northern Sumatra (Indonesia) subduction zones.

Indeed, such subduction zones are marked by long periods of quiescence, during which the relative motion between the two plates is stored as elastic deformation (like cocking a spring of the cord of a cross-bow). This interseismic stage can last tens, hundreds or even thousands of years. For Nankai, great earthquakes $M \geq 8$ occur on average every 90–200 years[20,21]. For Cascadia the repeat time is several hundred to one thousand years[22] and for Northern Sumatra the interval between great earthquakes is estimated to be several hundred years.[23]

It is worth noting that 11 out of 12 of the greatest earthquakes ($M \geq 8.5$) of the past 100 years occurred along subduction fault planes. Table 1 shows the list as provided by the USGS National Earthquake Information Center.

In most cases, only subduction earthquakes have the great dimensions (length and downdip width) necessary to generate the tremendous seismic moment of a magnitude 8.5 earthquake.

Paleoseismology and recurrence interval

Sediment cores from the Horseshoe Abyssal Plain have sampled a series of turbidite deposits covering the entire abyssal plain with thicknesses ranging from

20 cm to over 2 m.[24] The volume of several of these turbidite flows exceeds 1 km.[3] A maximum of 21 individual turbidites were cored spanning roughly the period since 35 ka.[24] The upper-most turbidite in both the Horseshoe and Tagus abyssal plains has been dated as being contemporaneous with the 1755 earthquake.[25] The older turbidties are likely to have been triggered by great earthquakes in the past. The chronology of these turbidite flows suggests a periodicity of 1500–2000 years.

Coarse-grained deposits in the lagoon behind a sand-bar near the port of Cadiz were identified as overwash deposits generated by a tsunami, because the 6 m high sand barrier is well above the maximum storm surge height. Dating allowed this tsunami deposit to be correlated to the 1755 earthquake. An older tsunami deposit beneath the first was dated at 2200 BP (200 BC) and corresponds to descriptions of a tsunami in Roman records from the city of Cadiz.[26] If the source of these two tsunamis is the same, then a recurrence time on the order of 2000 years is indicated.

Thus, these two different types of sedimentological data both suggest a recurrence time on the order of 1500–2000 years.[9,27] This recurrence time is generally consistent with the convergence rates indicated by GPS measurements in the Morocco–Iberia region, suggesting westward motion of stations in the Gibraltar block at velocities of 5–10 mm/a.[16,17] For such velocities, 10–20 m of slip could accumulate during the inter-seismic phase of the seismic cycle along a locked fault zone.

Link to Plato's Atlantis

Records of an even older earthquake and tsunami in the Gulf of Cadiz region may be contained in the dialogues of Plato, *The Timaeus* and *The Critias* (Plato, 360 BC), better known as the Atlantis legend.[27] In these dialogues, Plato describes a culture, living in the Atlantic, with a capital on a small island located beyond the 'pillars of Heracles' (the straits of Gibraltar).

The chronology given by Plato indicates destruction of Atlantis at 11.6 ka (9000 years before Egyptian priests in Sais recounted the tale to Solon. Solon lived around 600 BC. Plato lived from 420–340 BC). In *The Timaeus*, the sudden destruction is described: 'there occurred violent earthquakes and floods; and in a single day and night of misfortune all your warlike men in a body sank into the earth, and the island of Atlantis in like manner disappeared in the depths of the sea. For which reason the sea in those parts is impassable and impenetrable, because there is a shoal of mud in the way; and this was caused by the subsidence of the island'.

Today there are no major islands in the straits of Gibraltar, but thousands of years ago, during the Last Glacial Maximum (from 20 ka to 15 ka), the global eustatic sea level was 130–100 m lower than present, and rose to −50 m by 11 ka[28,29] (Figure 4). Sea-level remained fairly stationary from about 12.5 ka

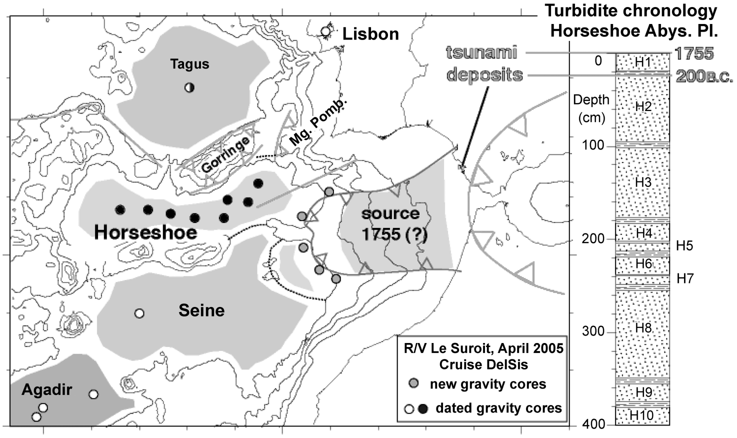

Figure 3. Paleoseismology in the Gulf of Cadiz region. A sedimentological record of great earthquakes exists in the form of tsunami deposits[26] and deep-sea turbidites. 21 turbidites dated across the Horseshoe Abyssal Plain over the past 35 ka indicate a turbidite periodicity of 1500–2000 yrs.[24] The uppermost turbidite has been dated as being contemporaneous with the 1755 event.[25] Turbidite H8 has been dated at 12 ka, which corresponds roughly to the date provided by Plato for the inundation of Atlantis.

until 11.5 ka at around -60 m.[29] These eustatic sea-level changes were due to melting of the ice-sheets at the onset of the most recent interglacial period.

In the western straits of Gibraltar, several shoals rise to within 50 m of sea-level and were islands prior to 11 ka.[30] The largest of these paleo-islands was about 5–6 km in size, and may be a candidate for a formerly inhabited, sunken island. Both the effect of lower sea-levels on the paleo-coastline and the presence of islands in the western straits of Gibraltar were previously discussed as being the possible origin of the Atlantis legend.[30] The Spartel Bank hypothesis as outlined in this earlier study emphasized gradual destruction by inundation lasting several centuries (due to a sea level rise of 4 m per century). However, the sudden destruction described by Plato (in a single day and night) requires a catastrophic event.

As indicated above, the Gulf of Cadiz – Straits of Gibraltar region, is struck regularly by great earthquakes and tsunami. A 1 m thick turbidite deposit, containing coarse-grained sediments from underwater avalanches, may correspond to the destructive event described by Plato. This layer, identified as turbidite H8, has a mean thickness of 50–120 cm and a total estimated volume of 5.8 km^3 (Figure 3).[24] It is the thickest of the postglacial series and has been dated at 12.05 ka.[24] For comparison, the turbidite associated with the great Lisbon earthquake of 1755 has an estimated volume of about 1 km^3.

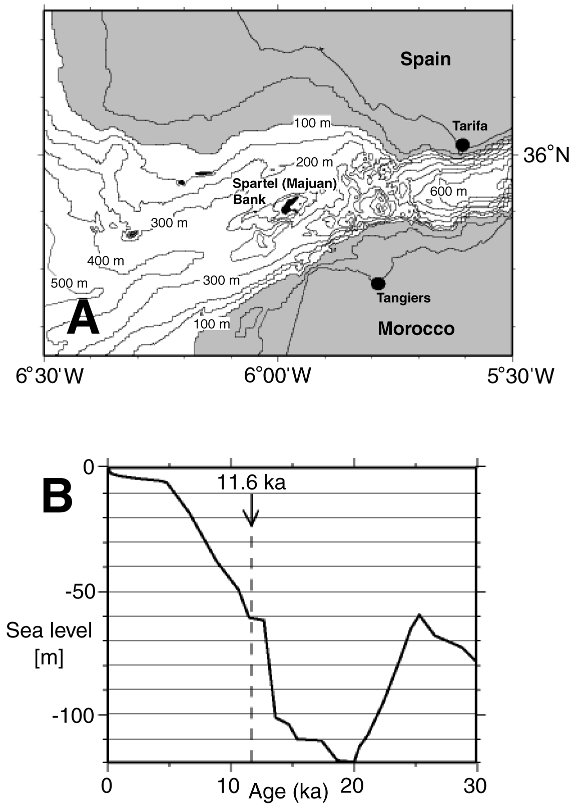

Figure 4. (a) Bathymetry of the straits of Gibraltar, with coastline at about 14 ka shaded grey (the current 100 m depth contour). Spartel paleo-island was slightly above sea-level, but exposed to the effects of great earthquakes and tsunami. (b) Eustatic sea-level curve.[28,29] 11.6 ka is the date given by Plato for the destruction of Atlantis.

One of the most remarkable coincidences is that the type of destruction described by Plato (in a single day and night, by violent earthquakes and floods) is a very accurate description of the sudden (catastrophic) destruction associated with a great ($M > 8$) earthquake. Indeed, in 1755, tsunami waves persisted for less than 24 hours,[3] and this was also the case following the 26 December 2004 tsunami in the Indian Ocean. The occurrence of this type of earthquake and tsunami, in the geographic region chosen by Plato for his narrative, appears to be more than just fortuitous.

The Gulf of Cadiz – Straits of Gibraltar region is situated above an east dipping subduction zone,[14] characterized by a wide locked seismogenic zone and a long repeat interval (up to 2000 years) between great earthquakes.[9] Tsunami modelling of the subduction fault plane can reproduce most of the historical observations with regard to travel time and amplitudes in the Gulf of Cadiz – Madeira region.[31] Subduction zones are environments of locally strong uplift and strong subsidence. Co-seismic subsidence caused by great earthquakes in the Cascadia forearc are reported to be 0.5–2 m,[32] and for the Great Alaska earthquake of 1964, co-seismic subsidence of 1–2 m was observed.[33] During the Great Sumatra earthquake of December 2004, coastlines were significantly changed through the combined effects of the tsunami-induced erosion and local earthquake-induced subsidence. Some low-lying islands were partially submerged.

If inhabited, Spartel Island would have been devastated by the combined effects of ground shaking, earthquake induced subsidence (of several metres) and a 10 m high tsunami wave. These catastrophic natural phenomena offer a scientifically plausible mechanism, which could account for the type of destruction described by Plato regarding the island of Atlantis.[27] They occur regularly (at long time intervals) in the geographic region chosen by Plato for his narrative. This does not, however, demonstrate that Atlantis ever existed. Only the discovery of artefacts and/or signs of construction can provide definitive proof.

Conclusions

Great subduction earthquakes and the associated tsunami have a tremendous societal impact and can destroy or heavily damage vast regions, as demonstrated in SW Iberia in 1755 and SE Asia in December 2004. Eleven out of 12 of the greatest earthquakes ($M \geq 8.5$) of the last 100 years occurred along subduction fault planes. All of these great events that produced tsunami, are in subduction zones. The dimensions of the Gibraltar subduction fault plane (roughly 200×200 km) are sufficient to generate an earthquake of moment magnitude $M = 8.64$ for a co-seismic slip of 10 m. This amount of movement can accumulate over a period of 1000–2000 years (given the 5–10 mm/yr estimated subduction velocity). This period is consistent with available paleoseismological data on the recurrence interval of great earthquakes in the region (1500–2000 years).

Older events struck the South Iberia region during Roman times and earlier. One such event, 12,000 years ago, may have been at the origin of the Atlantis legend. The type of destruction, as well as its timing, is consistent with a catastrophic destruction by shaking and inundation following a great earthquake and tsunami.

References

1. J. M. Martinez-Solares, A. Lopez and J. Mezcua (1979) Isoseismal map of the 1755 Lisbon earthquake obtained from Spanish data. *Tectonophysics*, **53**, 301–313.

2. A. Johnston (1996) Seismic moment assessment of earthquakes in stable continental regions – III. New Madrid, 1811–1812, Charleston 1886 and Lisbon 1755. *Geophys. J. Int.*, **126**, 314–344.
3. M. A. Baptista, S. Heitor, J. M. Miranda, P. M. A. Miranda and L. Mendes Victor (1998) The 1755 Lisbon; evaluation of the tsunami parameters. *J. Geodynamics*, **25**, 143–157.
4. A. Levret (1991) The effects of the November 1, 1755 'Lisbon' earthquake in Morocco. *Tectonophysics*, **193**, 83–94.
5. T. El-Mrabet (1991) Tarikh azalazil bi Al Maghrib (Historical seismicity in Morocco, in Arab). Thesis 3rd cycle, University of Rabat, 370 pp. E. Bard, B. Hamelin, M. Arnold, L. Montaggioni, G. Cabioch, G., Faure and F. Rougerie (1996) Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature*, **382**, 241–244.
6. N. Zitellini, L. A. Mendes *et al*. (2001) Source of 1755 Lisbon earthquake and tsunami investigated. *Eos (Transactions, American Geophysical Union)*, **82**, 285–291.
7. E. Gracia, J. J. Danobeitia, J. Verges, J. and PARSIFAL Team (2003) Mapping active faults offshore Portugal (36°N–38°N): Implications for seismic hazard assessment along the southwest Iberian margin. *Geology*, **31**, 83–86.
8. S. P. Vilanova, C. F. Nunes and J. F. B. D. Foncesca (2003) Lisbon 1755: a case of triggered onshore rupture? *Bull. Seism. Soc. Am.*, **93**, 2056–2068.
9. M.-A. Gutscher (2004) What caused the Great Lisbon Earthquake? *Science*, **305**, 1247–1248.
10. R. Sartori, L. Torelli, N. Zitellini, D. Peis, and E. Lodolo (1994) Eastern segment of the Azores-Gibraltar line (central-eastern Atlantic): an oceanic plate boundary with diffuse compressional deformation. *Geology*, **22**, 555–558.
11. I. Jimenez-Munt, M. Fernandez, M. Torne and P. Bird (2001) The transition from linear to diffuse plate boundary in the Azores-Gibraltar region. *Earth and Planet. Sci. Lett.*, **192**, 175–189.
12. J. P. Platt and R. L. M. Vissers (1989) Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar arc. *Geology*, **17**, 540–543.
13. L. Lonergan and N. White (1997) Origin of the Betic-Rif mountain belt. *Tectonics*, **16**, 504–522.
14. M.-A. Gutscher, J. Malod, J.-P. Rehault, I. Contrucci, F. Klingelhoefer, L. Mendes-Victor and W. Spakman (2002) Evidence for active subduction beneath Gibraltar. *Geology*, 30, 1071–1074.
15. L. M. Pinheiro, M. K. Ivanov, A. Sautkin, G. Akhmanov, V. H. Magalhaes, A. Volkonskaya, J. H. Monteiro, L. Somoza, J. Gardner, N. Hamouni and M. R. Cunha, (2003) Mud volcanism in the Gulf of Cadiz: results from the TTR-10 cruise. *Marine Geology*, **3269**, 1–21.
16. J. M. Miranda, R. M. S. Fernandes and L. Matias (2005) Geodetic constraints to the evaluation of the Tagus Valley seismic risk, Proceedings EGU Conference, Vienna, 2005. *Geophysical Research Abstracts*, **7**, CD-ROM.

17. R. Reilinger, S. McClusky, D. Ben Sari, T. Mourabit, F. Gomez and M. Barazangi (2001) Active deformation in Morocco from repeat GPS observations. *EOS Trans. AGU*, Fall Meeting 2001 supplement (abstract).
18. M.-A. Gutscher and S. M. Peacock (2003) Thermal models of flat subduction and the rupture zone of great subduction earthquakes. *Journal of Geophysical Research*, **108**, B1, 2009, doi:10.1029/2001JB000787.
19. E. Thiebot and M.-A. Gutscher (in press) The Gibraltar Arc seismogenic zone (part1): constraints on a shallow east dipping fault plane source for the 1755 Lisbon earthquake provided by seismic data, gravity and thermal modeling. *Tectonophysics* (in press).
20. H. Kanamori (1972) Tectonic implications of the 1944 Tonankai and the 1946 Nankaido earthquakes. *Phys. Earth. Planet. Inter*. **5**, 129–139.
21. M. Ando (1975) Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan. *Tectonophysics*, **27**, 119–140.
22. C. Goldfinger, C. H. Nelson, J. E. Johnson and Shipboard Scientific Party (2003) Holocene earthquake records from the Cascadia subduction zone and northern San Andreas Fault based on precise dating of offshore turbidites. *Ann. Rev. Earth Planet. Sci*., **31**, 555–577.
23. T. Lay, H. Kanamori *et al*. (2005) The Great Sumatra-Andaman earthquake of 26 December 2004. *Science*, **308**, 1127–1133.
24. S. M. Lebreiro, I. N. McCave and P. Weaver (1997) Late Quaternary turbidite emplacement on the Horseshoe abyssal plain (Iberian margin). *J. Sedimentary Res*., **67**, 856–870.
25. J. Thomson and P. Weaver (1994) An AMS radiocarbon method to determine the emplacement time of recent deep-sea turbidites. *Sedimentary Geology*, **89**, 1–7.
26. L. Luque, J. Lario, C. Zazo, J. L. Goy, C. J. Dabrio and P. G. Silva (2001) Tsunami deposits as paleoseismic indicators: examples from the Spanish coast. *Acta Geologica Hispanica*, **36**, 197–211.
27. M.-A. Gutscher (2005) Destruction of Atlantis by a great earthquake and tsunami? A geological analysis of the Spartel Bank hypothesis. *Geology*, **33**, 685–688.
28. L. D. Labeyrie, J. C. Duplessey and P. L. Blanc (1987) Variations in the mode of formation and temperature of oceanic deep waters over the past 125,000 years. *Nature*, **327**, 477–482.
29. E. Bard, B. Hamelin, M. Arnold, L. Montaggioni, G. Cabioch, G., Faure and F. Rougerie (1996) Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature*, **382**, 241–244.
30. J. Collina-Girard (2001) Atlantis off the Gibraltar Strait? Myth and geology. *Comptes Rendus de l'Académie des Sciences de Paris*, **333**, 233–240.
31. M.-A. Gutscher, M. A. Baptista and J. M. Miranda (in press) The Gibraltar Arc seismogenic zone (part 2): constraints on a shallow east dipping fault plane source for the 1755 Lisbon earthquake provided by tsunami modeling and seismic intensity. *Tectonophysics Sp*. (in press).

32. J. J. Clague (1997) Evidence for large earthquakes at the Cascadia subduction zone. *Reviews in Geophysics*, **35**, 439–460.
33. S. R. Holdahl and J. Sauber (1994) Co-seismic slip in the 1964 Prince William Sound earthquake: a new geodetic inversion. *Pure and Applied Geophysics*, **142**, 55–81.

About the Author

Marc-Andre Gutscher is a member of the research staff at the Institut Universitaire Europeen de la Mer at the University of Brest and specializes in tectonics, marine geology and earthquake generation in subduction zones.