EPICA, c.m., 2004. Eight glacial cycles from an Antartic ice core. Nature 429.

Loutre, M.F., 2003. Clues from MIS 11 to predict the future climate a modelling point of view. Earth and Planetary Science Letters 212, 213-224.

Loutre, M.F. and Berger, A., 2003. Marine Isotope Stage 11 as an analogue for the present interglacial. Global and planetary change 762, 1-9.

Martrat, B., Grimalt, J.O., Shackleton, N.J., Abreu, L.d., Hutterli, M.A. and Stocker, T.F., 2007. Four Climate Cycls of Recurring Deep and Surface Water Destabilizations on the Iberian Margin. Science 317(1139994), 502-507.

McManus, J., Oppo, D., Cullen, J. and Healey, S., 2003. Marine Isotope Stage 11 (MIS 11): Analog for Holocene and Future Climate?

Müller, P., Kirst, G., Ruhland, G., Storch, I.v. and Rosell-Melé, A., 1998. Calibration of the alkenone index Uk'37 based on core-tops the eastern South Atlantic and global ocean (60ºN-60ºS). Geochimica et Cosmochimica Acta 62, 1757-1772.

Rodrigues, T., 2009. High-resolution Climate Study of the Past (570,000 to 300,000 years) and Present Interglacial in the Iberian Margin: a biomarkers view, Universitat Politècnica De Catalunya, Barcelona, 325 pp.

Rodrigues, T., Grimalt, J.O., Abrantes, F., Flores, J.A. and Lebreiro, S., 2009. Holocene interdependences of changes in sea surface temperature, productivity, and fluvial inputs in the Iberian continental shelf (Tagus mud patch). Geochemistry Geophysics Geosystems 10.

Rodrigues, T., Grimalt, J.O., Abrantes, F., Naughton, F. and Flores, J.-A., submitted. The last glacial-interglacial transition (LGIT) in the western mid-latitudes of the North Atlantic: abrupt sea surface temperature change and sea level implications.

Ruddiman, W.F., 2005. Cold climate during Stage 11 anlog to recent Millennia. Quaternary Science Reviews 24, 1111-1121.

Shackleton, N.J., Hall, M.A. and Vincent, E., 2000. Phase relationships between millennial-scale eventes 64,000-24.000 years ago. Palaeogeography 15(6), 565-569.

Tzedakis, P.C., 2009. The MIS 11 - MIS 1 analogy, southern European vegetation, atmospheric methane and the "early anthropogenic hypothesis". Climate of The Past Discussions 5, 1337-1365.

Villanueva, J., 1996. Estudi de les variaciones climàtiques i oceanogràfiques a l`atlantic Nord Durant els últims 300.000 anys mitjançant l`análisi de marcadores moleculars., Ramon Llull, Barcelona, 186 pp.

The Effect of Tidal Altitude on Methane Gas Bubbling from the Sediments of the Ria of Aveiro

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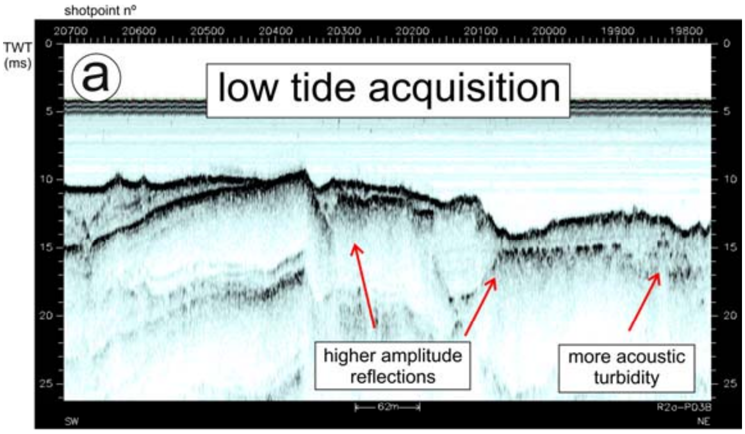
The study of gas occurrence and seepage in sedimentary basins, mainly methane, is of significant interest for its role as a greenhouse gas and potential contribution to climate changes (Hovland et al., 1993; Houghton et al., 2001; Etiope, 2004; Judd, 2004), as an important energy source and as a cause of natural hazards (Best et al., 2006). According to Best (2006), understanding these roles of methane gas requires the development of models of methane gas generation and gas fluxes, as well as the acquisition of reliable model input data, such as sediment accumulation rates, organic matter concentrations, amount of gas present, sediment shear strength, etc. Considering that the organic rich muddy sediments of estuaries and coastal lagoons are prime sources of methane gas (Kelley et al., 1995; Van der Nat and Middelburg, 2000), modern day estuaries and coastal lagoons are preferential objects for these studies on shallow methane gas generation and evaluation of gas fluxes to the atmosphere (Garcia-Gil, 2003; Duarte et al., 2007).

The Ria of Aveiro is a recent barrier-lagoon system composed of a complex network of tidal channels, tidal flats, salt marshes and supra-tidal sand isles, located along the northwest Portuguese coast. The semi-diurnal tidal cycle is the strongest forcing mechanism in the dynamics of the Ria of Aveiro. The small water volume at low spring tides is $65x10^2$ m^3, and barely covers the main tidal channels. The tidal prism at spring tides is about $80x10^2$ m^3, and more than doubles the water mass in the lagoon, covering the extensive tidal flats and salt marshes that constitute the majority of the lagoon area (Teixeira, 1994).

Early descriptions of possibly methane gas related phenomena in the lagoon area date back to the 1755 great Lisbon earthquake. The answers from local parishes to the Marquês de Pombal enquiries on the 1755 earthquake report that the Vouga river waters “boiled as if they were on fire” and that the waters from the Mira lagoon (at the south end of the Ria) “appeared to boil so hard that they would break at the lagoon shore as if they were sea waves” (Coelho, 2005; Oliveira, 2005); these tales may be explained by gas releases from seismically destabilized sediments.

The first unequivocal direct observations of escape of biogenic methane from several drill holes in Quaternary sediments from the area surrounding the Ria of Aveiro were reported by the Portuguese Geological Survey in 1967 (Faria et al., 1967). Since then, similar evidence has been observed in other land wells for water exploration. More recent investigations with chirp and boomer high resolution seismic data in tidal channels of the Ria de Aveiro (Pinheiro and Duarte, 2003a; Pinheiro and Duarte, 2003b; Pinheiro *et al.*, 2003; Duarte *et al.*, 2007; Duarte, 2009) have shown extensive acoustic evidence of gas accumulation and seepage, including acoustic turbidity, enhanced reflections, acoustic blanking, domes and acoustic plumes in the water column (flares).

The abundance of seismic data in the Ria of Aveiro, both in time and space allowed the quantitative investigation of the hypothesis that the tidal cycle affects the extent and distribution of seismic evidence of gas (Duarte *et al.*, 2007; Duarte, 2009). Local changes in gas related seismic features as well as the data on amplitudes of the channel bottom reflections from the seismic profiles in the tidal channels of the Ria of Aveiro, provide very strong evidence that tides have an effect on the acoustic response of gas rich sediments (Figures 1 and 2; Duarte, 2009). In September of 2006, gas samples were collected from extensive bubble trains observed during falling tide in a docking pier (“Doca Pesca”) in the Ria of Aveiro. The analysis of the gas samples composition by chromatography revealed that the gas was mostly methane (J. Coutinho, personal communication). The gas bubbling in the “Doca Pesca” pier showed a similar pattern with tidal altitude to the one between amplitude strengths and tidal altitude. The gas bubbling started with falling tide and petered down as the tide turned and rose. This independent observation supported the hypothesis that bubbling and gas escape in the Ria de Aveiro can be triggered by falling tide and that its effect is detected pervasively by the chirp system.



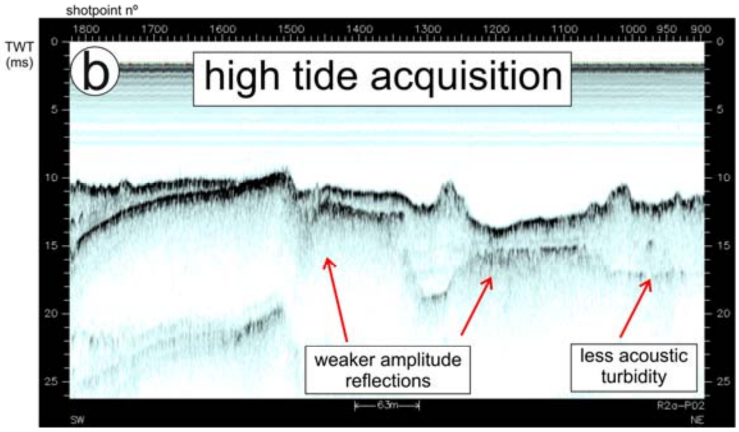


Figure 1. Comparison of approximately coincident chirp profiles P02 (a) and P03B (b) acquired in the Terminal Sul during cruise RIAV02A (Pinheiro and Duarte, 2003b), during high tide and low tide, respectively. Evidence for gas is stronger in the profile acquired during low tide, when compared with the profile acquired during high tide: amplitude of the reflections is stronger and acoustic turbidity is more abundant during low tide (adapted from Duarte, 2009).

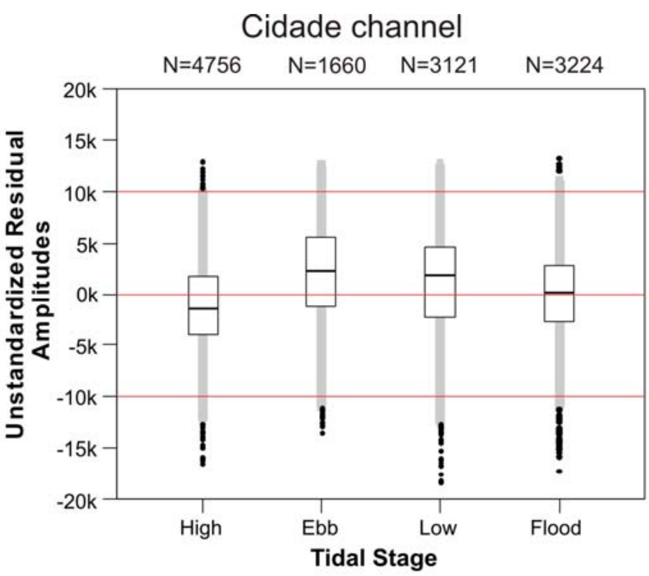


Figure 2. Box plots of unstandardized residual first break amplitudes at each tidal stage of the Chirp profiles acquired during cruises RIAV02 and RIAV02A, in the Cidade channel (Pinheiro and Duarte, 2003a; Pinheiro and Duarte, 2003b; figure adapted from Duarte, 2009). The residual data is expected to reflect changes in amplitude not related to energy reduction and attenuation processes linked to the distance of the signal source to the reflector (e.g. spherical divergence of the signal; for a detailed discussion see Duarte, 2009). Residual amplitudes for the Cidade channel have different biases according to the tidal stage, with greater than predicted amplitudes during low tide with maxima during ebb; residual amplitudes during flood are evenly distributed around 0; the lowest residual amplitudes occur mostly during high tide.

The described effect of tides on gas bubbling and on the acoustic signal of gas will impact the mapped distribution and extent of gas evidence and its use to quantify gas volumes. The relative increase in reflections amplitude during tidal fall probably reflects changes of methane solubility due to decreasing pressure; either ebullition as observed in other parts of the lagoon or as observed in tidal marshes by other authors (e.g. Jackson *et al.*, 1998), or changes towards resonant bubble sizes (Best *et al.*, 2004) cause an increase in gas reflectors detected by the seismic systems and influence the interpretation of gas evidence. Either way, 4D surveying will be required to determine the impact of this semi-diurnal control on the extent and distribution of gas and, in particular, on the assessments of methane fluxes from lagoon sediments to the water column and to the atmosphere.

References

Best, A. I., M. D. Richardson, et al. (2006). "Shallow seabed methane gas could pose a coastal hazard." EOS **87**(22): 213, 217.

Best, A. I., M. D. J. Tuffin, et al. (2004). "Tidal height and frequency dependence of acoustic velocity and attenuation in shallow gassy marine sediments." Journal of Geophysical Research-Solid Earth **109**(B8): -.

Coelho, A. G. (2005). Do "Inquérito do Marquês de Pombal" ao estudo de Pereira de Sousa sobre o Terramoto de 1 de Novembro de 1755. O grande terramoto de Lisboa. Lisbon, FLAD e Público. **1:** 143-188.

Duarte, H. (2009). High-resolution seismic reflection investigation of gas accumulation and seepage in the tidal channels of the Ria of Aveiro barrier lagoon (Portugal). Geociências, University of Aveiro. **Ph.D.:** 172.

Duarte, H., L. M. Pinheiro, et al. (2007). "High-resolution seismic imaging of gas accumulations and seepage in the sediments of the Ria de Aveiro barrier lagoon (Portugal)." Geo-Marine Letters **27**(2-4): 115-126.

Etiope, G. (2004). "GEM - Geological Emissions of Methane, the missing source in the atmospheric methane budget." Atmospheric Environm. **38**(19): 3099-3100.

Faria, J. B., G. Zbyszewski, et al. (1967). "O aparecimento de gás na Gafanha da Boa Hora (Vagos)." Bol. Minas. Lisboa **4**(2): 125-130.

Garcia-Gil, S. (2003). "A natural laboratory for shallow gas: the Rias Baixas (NW Spain)." Geo-Marine Letters **23**(3-4): 215-229.

Houghton, J. T., Y. Ding, et al. (2001). Climate change 2001: the scientific basis. Cambridge, U.K., Cambridge University Press.

Hovland, M., A. G. Judd, et al. (1993). "The Global Flux of Methane from Shallow Submarine Sediments." Chemosphere **26**(1-4): 559-578.

Jackson, D. R., K. L. Williams, et al. (1998). "Sonar evidence for methane ebullition in Eckernforde Bay." Continental Shelf Research **18**(14/15): 1893-1915.

Judd, A. G. (2004). "Natural seabed gas seeps as sources of atmospheric methane." Environmental Geology **46**(8): 988-996.

Kelley, C. A., C. S. Martens, et al. (1995). "Methane dynamics accross a tidally flooded riverbank margin." Limnology and Oceanography **40**(6): 1112-1129.

Oliveira, C. S. (2005). Descrição do Terramoto de 1755, a sua extensão, causas e efeitos. O sismo. O tsunami. O incêndio. O grande terramoto de Lisboa. Lisboa, FLAD e PUBLICO. **1:** 23-86.

Pinheiro, L. M. and H. Duarte (2003a). Campanha RIAV02, Technical Report (unpublished), Dep. Geol. Mar., Inst. Geol. Min.

Pinheiro, L. M. and H. Duarte (2003b). Campanha RIAV02A, Technical Report (unpublished), Dep. Geol. Mar. Inst. Geol. Min.

Pinheiro, L. M., H. Duarte, et al. (2003). Campanha RIAV03, Technical Report (unpublished), Dep. Geol. Mar., Inst. Geol. Min.

Teixeira, S. B. (1994). Dinâmica Morfosedimentar da Ria de Aveiro (Portugal). Departamento de Geologia. Lisboa, Universidade de Lisboa. **Ph.D.:** 396.

Van der Nat, F. J. and J. J. Middelburg (2000). "Methane emission from tidal freshwater marshes." Biogeochemistry **49(2)**: 103-121.