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INTRODUCTION

Gas in marine sediments VIII: an introduction to the Vigo conference of the shallow gas group

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Introduction

This Special Issue includes papers presented at the 8th international conference on *Gas in Marine Sediments* organised by the Shallow Gas Group and held at the University of Vigo on the Galician coast of NW Spain in September 2005. The Shallow Gas Group was joined for this conference by participants in the METROL EC-funded research programme; one of the days of the conference was dedicated to reports from this project. The conference was attended by 115 participants from 22 countries, individuals representing Australia, North and South America, and SE Asia as well as both east and west Europe. In all, 67 papers and >30 posters were presented. This programme represented a broad spectrum of current research and thinking about the many manifestations of gas in marine sediments (shallow gas, gas seeps, mud volcanoes, gas hydrates, and methane-derived authigenic carbonates) from many parts of the world. The conference concluded with a field trip; the participants sailed over the gas-laden sediments of the Ría de Vigo to visit paradise—in the form of the Cies Islands. These islands, a National Park, guard the entrance of the ría from the Atlantic Ocean. The Rías Baixas, of which this is one, are famous for their mussel farming, and many of the mussel rafts were passed on the way to the islands, allowing participants to contemplate whether the productivity of the rías is attributable to the seasonal upwelling of nutrient-rich Atlantic water, or the prolific methane beneath the seabed.

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The 19 papers presented here provide a flavour of the conference[1] but form only a small part of the continuously expanding literature on a topic which is now recognised as playing a significant role in many natural processes and offshore operations in the marine environment.

Papers from previous Shallow Gas Group conferences can be found in special issues of journals edited by Davis (1992), Jørgensen (1994), van Weering et al. (1997), Judd and Curzi (2002), Gramberg and Kontorovich (2002), and Woodside et al. (2003, 2004).

This special issue

The papers in this special double issue cover a range of topics related to gas in marine sediments. Appropriately, several opening contributions focus on different aspects of the shallow gas occurrences in the rías of Galicia, the Rías Baixas. Gassy sediments are present in the four main rías; from north to south these are Muros, Arousa, Pontevedra and Vigo. The rías are coastal indentations, drowned incised valleys, cut into granitic and metamorphic rocks and partially infilled with Tertiary to Recent sediments. Detailed investigation of the stratigraphic framework of the Ría de Pontevedra by *Durán et al.* shows that the rías experienced successive periods of erosion and deposition governed by eustatic sea-level change associated with Pleistocene glacial-interglacial cycles. It seems that gas source and reservoir sediments occur within certain facies;

[1] For logistical reasons, the paper by Evans et al. was not presented at the conference.

Durán et al. suggest that gas has been generated in estuarine organic-rich muds deposited during times of lowered sea level, and it accumulates in coarser sediments deposited during subsequent transgressive and highstand periods where they are capped by relatively impermeable Holocene muds. *Diez et al.* investigate the relationship between gas and sediment type using statistical (discriminant function) analysis applied to sediment data from the Ría de Arousa. Although a close relationship between well-sorted, fine organic-rich sediments and the presence of shallow gas accumulation has been reported subjectively by many previous authors, this is the first time that this has been confirmed statistically, showing the control sediment type has over the presence of gas. Using this correlation, Diez et al. are able to identify gassy sediments in areas too shallow for seismic surveys.

San Simón Bay, the innermost part of Ría de Vigo, is also characterised by gassy muds which, in places, extend into the intertidal zone. *Iglesias and García-Gil* suggest that gas generation here occurs both in the natural Holocene muds and also in the faecal debris accumulating beneath the mussel-farming rafts which have been present in the bay for the last 50 years. Acoustic indications of active gas escape (acoustic turbidity approaching the seabed, pockmarks and water column targets), and video evidence of gas bubbling in the intertidal zone suggest that these sediments are a source of atmospheric methane (methane was the principal component of gas samples analysed by gas chromatography).

Gassy sediments are also present further south along the Atlantic coast of Iberia in the mis-named Ría de Aveiro, a coastal barrier-lagoon in NW Portugal. This lagoon developed from an open bay as recently as the tenth century. *Duarte et al.* report evidence of sub-seabed gas on shallow seismic profiles recorded in one of the main waterways in the lagoon; the interpretation of acoustic turbidity and enhanced reflections as gas is supported by numerous instances of gas encountered in boreholes sunk into the Quaternary sediments of the surrounding area. However, they caution that care must be taken when mapping shallow gas in such shallow (<20 m) waters, as the ~10% tidal variations in water depth resulted in temporal variations in the strength and extent of the acoustic gas signature, possibly a result of bubble sizes changing in response to pressure variations.

Laier and Jensen describe the construction of a GIS database of shallow gas occurrences, seeps, and methane-derived authigenic carbonates (MDAC) in an area stretching from the Baltic Sea, through the Kattegat to the Skagerrak. In this area, shallow gas is present in water depths ranging from 20 (in Aarhus Bay) to 360 m (in the Skagerrak). Gas accumulates in relatively thick fine-grained Holocene deposits in basins/depressions formed by glaciers, ice-streams or melt water rivers during the last ice age; gas samples have been dated at 540–2,570 years b.p. In the northern Kattegat, however, some accumulations are of Pleistocene age, and Pleistocene microbial gas has been recovered from seeps; it seems that seeps and MDAC occur only where there are shallow Pleistocene deposits covered by sand. In other areas, it is thought that all the methane is being oxidised beneath the seabed, although in coastal areas algal blooms leading to eutrophication may result in the methane-sulphate transition zone rising closer to the seabed. Whilst Laier and Jensen discuss the distribution of gassy sediments, *García García et al.* have attempted to trace the organic matter from which shallow gas has been generated in the sediments of the Rhône Delta on the French Mediterranean coast. Their study, based on analyses of the headspace gases of sediment core samples, shows that large quantities of organic matter are delivered to the Rhône prodelta during river flood events, and methanogenesis results in high concentrations of headspace methane. Organic matter transported by coastal currents is reworked and remineralised, loosing its terrestrial signature before being deposited in the methane-poor sediments of the slope and the canyons which lead to the abyssal plain.

Andreassen et al. used exploration 3D seismic data for their study of shallow gas in sediments on the Barents Sea margin, north of Norway. As they point out, high-frequency sources are more commonly used for shallow gas studies, in contrast with the <40 Hz source used in this case. Although this reduces the vertical resolution, the advantages of 3D data are more than adequate compensation, as is demonstrated in this investigation of shallow gas and associated features. By reviewing data from numerous surveys and publications, *Popescu et al.* show that gas is present beneath the seabed of the NW Black Sea in three main situations: along the coast and the shelf break (corresponding to depocentres of periods of relatively high and low sea level, respectively), and on the lower continental slope. Whereas seabed seeps are 'abundant' in the first two cases, in the third, specifically in water depths >750 m where bottom simulating reflectors (BSRs) thought to indicate gas hydrates are quite widespread, seeps are less common—it is presumed that this is because hydrates 'buffer' the upward migration of gas. *Poort et al.* investigated variations in seabed heat flow in the Dnepr palaeo-delta area of the NW Black Sea. They found that variations from the background conductive regime, most pronounced at water depths of 600–700 m, could be accounted for by the seabed topography, structurally determined fluid migration pathways, and the infiltration of cold seawater as part of a fluid flow system induced by gas ebullition. Although there is not a perfect coincidence between heat flow variations and seep sites, the data suggest that seepage involves both deep fluids and shallow gas.

The Heincke seeps described by *Hovland* are unusual in that they occur where the seabed is characterised by the coarse sediments of a palaeo-beach deposit; this is in marked contrast to the nearby, previously-described Gullfaks seeps which occur in pockmark soft silty clays of the Norwegian Trench in the Norwegian North Sea. Active bubbling was recorded at the Heincke seep, where observations of hermit crabs feeding on extensive bacterial mats suggest these seeps of thermogenic gas are contributing indirectly to the higher food chain. *Evans et al.* report that sediments flowing from mud volcanoes on land and offshore hold gas bubbles which are released slowly as, and after, they are emitted. They show that these gassy sediments can be recognised on seismic reflection data by a reverse (negative) phase reflection—seafloor phase reversals. This signature could prove valuable for recognising gassy sediments at the seabed in other situations, such as pockmarks and seeps.

The studies by *Fernández-Puga et al.*, *Martín-Puertas et al.*, and *León et al.* deal with different aspects of the mud volcanoes of the Gulf of Cádiz; morphology and diapirism, mineralogy, and mud flows and carbonates, respectively. Fernández-Puga et al. explain that the local tectonic regime, the oblique convergence of the African and Eurasian Plates has resulted in faulting, gravitational extensional collapses and reactivated compressional thrusts, and the emplacement of mud and salt diapirs. These features have provided fluid migration pathways which are now indicated by seabed features: mud volcanoes, mud mounds, pockmarks and slides. These features are associated with diapirs which were emplaced during the Tortonian (Miocene) as a result of, and associated with faulting. Studies of the clay mineral content of the mud volcano breccias by Martín-Puertas et al. indicate a smectite content corresponding to the climatic and weathering conditions typical of the Miocene, but these clays are mixed with hemipelagic material typical of the current slope environment. It is argued that the clay mineral content, specifically the smectite content, might be used as an indicator of mud volcanism. Authigenic and diagenetic minerals, possibly derived from the anaerobic oxidation of methane, are also present, suggesting that fluids percolating through the sediments can alter the pristine composition of the clays, as it does at hydrothermal sites. León et al. found extensive hydrogen-derived authigenic carbonates on the seabed of the Guadalquivir Diapiric Ridge. They describe several forms of HDAC (massive crusts, "honeycombed" crusts, nodular aggregated crusts, slabs and chimneys), and suggest an evolutionary model whereby carbonate-mud mounds are built up by successive fluid venting episodes of varying rates: from active mud flow extrusions to moderate-slow seepage activity and eventually latent conditions. They argue that these episodes are modulated by tectonic and oceanographic factors responding to the convergence of the African and Eurasian plates, downslope movements of salt/shale, and the massive destabilisation of gas hydrate deposits by episodic outflows of warm Mediterranean Outflow Waters.

The methane-derived authigenic carbonates (MDAC) described by *Pierre and Fouquet* from the Congo Deep-Sea Fan are associated with a 'cold seep' biological community of bivalves and siboglinid tubeworms, and with outcropping gas hydrates. Their mineralogy (calcite, some aragonite, and occasional barite and pyrite) indicates that they formed at or beneath the sulphate-methane transition zone. Carbon and oxygen isotopes indicate that the carbon was derived from methane (mainly microbial) and water, including some from the decomposition of gas hydrates. These contrast markedly to the MDAC occurrences described by *Judd et al.* from two shallow (<100 m) sites in the Irish Sea. In one of these cases, the carbon seems to have derived from coal-bearing Carboniferous strata, in the other from Tertiary peats. The most remarkable feature about these occurrences is their extent, which is thought to total >500,000 m^2. As "seabed features formed by leaking gas" are identified by the European Commission as a special marine habitat, occurrences such as this may be deemed worthy of protection.

Two papers deal with gas hydrates at Hydrate Ridge on the Cascadia Margin. *Abegg et al.* show that there is a distinct difference between the fabric (revealed by CT scans of core samples) of gas hydrates precipitated at shallow sub-seafloor depths and those found at depths greater than 50 m beneath Hydrate Ridge. The deeper hydrates occur as vein-like bodies occupying pre-existing discontinuities (tectonically formed fractures) which may have provided migration pathways for free gas. In contrast, those formed within the shallow sediments were able to physically move sediment particles in order to crystallise, so these occur in layers parallel or sub-parallel to, or cutting, the bedding; in places, they have destroyed the original depositional fabric. Understanding the shallow sediments is further complicated if gas hydrate dissociation occurs—either naturally or during core recovery. *Piñero et al.* explain that dissociation results in the formation of soupy and mousse-like sediments in which none of the original sediment fabric is retained. They attribute similar sediment disturbance in samples from beneath the gas hydrate stability zone to gas expansion during core recovery, and advise that indicators of gas hydrate, such as chlorinity and temperature anomalies, should be used to distinguish between these causes of disturbance.

In the closing paper of this special double issue, *Muñoz-Sobrino et al.* explain how palynology can be used to shed light on the age and environment of deposition of gassy sediments, using examples from the Ría de Vigo. They distinguish several significant changes in conditions during the time period (950 A.D. to present) represented by their core samples.

This collection of papers focuses on gas in marine sediments but indicates a wide variety of relevant features and approaches to their study; it also indicates that gas is present in marine sediments over an enormous geographical area, and in numerous geological and oceanographic contexts. Clearly, an interdisciplinary approach is required because of the close interrelationships of geological, physical, chemical, microbiological, biogeochemical, biological and oceanographic processes on micro- to macro- size and time scales.

We hope that these papers, whilst providing no more than a flavour, will stimulate the interest of readers in Gas in Marine Sediments, and encourage them to delve deeper into a topic which is of fundamental importance to the workings of our planet.

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