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Giustiniani, Michela; Tinivella, Umberta; Sauli, Chiara; Della Vedova, Bruno
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Artículos de Investigación

Distribution of the gas hydrate stability zone in the Ross Sea, Antarctica

Michela Giustiniani
OGS, Italia
mgiustiniani@inogs.it

Umberta Tinivella
OGS, Italia
utinivella@inogs.it

Chiara Sauli
OGS, Italia
csauli@inogs.it

Bruno Della Vedova
University of Trieste, Italia
bruno.dellavedova@fondazioneinternazionale.org

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Abstract:

The theoretical gas hydrates stability zone (GHSZ) in the Ross Sea area was evaluated by mean of a steady state simple approach by using bathymetric data, sea bottom temperature, a variable geothermal gradient and assuming that the natural gas is methane. The results from our study suggest that bathymetry and distribution of the GHSZ are correlated; in fact, the GHSZ reaches a maximum (ca. 400 m) in the basins, where the water temperature is the lowest, and decreases in the banks with thickness ranging between 7 and <100 m. On the other hand, the existence and dynamics of the gas hydrate distribution is strictly related to the existence and evolution of the shallow geological and geomorphological features below the sea floor, as suggested in the past by several authors.

Keywords: Gas hydrates stability zone, Ross sea, Modeling.

1. Introduction

In the past two decades the Ross Sea Embayment area has been considered a laboratory of growing interest for the reconstruction of the past Antarctic environment, the onset of Antarctic Eocene-Paleocene glaciation, climates studies, the understanding of the tectonic deformation and global sea level changes that all have driven glacial history.

The broad over-deepened and landward sloping Ross Sea outer continental shelf occupies a 1,000 km wide embayment on the present Antarctic margin. It is delimited to the west by the Victoria Land Coast (East Antarctic Craton), to the south by the Ross Ice Shelf, to the east by the Marie Byrd Land (West Antarctica) and to the north by the continental slope and rise. Its bathymetry and sedimentary cover were formed and shaped during the continental rifting phases of Late Cretaceous and Cenozoic West Antarctic Rift System (Behrendt et al., 1991; Rocchi et al., 2002, 2005), and by the associated marine and glacio-fluvial processes.

The main Ross Sea elongated N-S sedimentary troughs, such as the Victoria Land Basin, the Drigalsky Basin, the northern continuation of the Northern Basin, the Central Basin, the Joides Basin and the Eastern Basin (Fig.1) are bounded by basement highs and morphological banks. They were formed during the late Cretaceous major rifting phase and later during the Cenozoic (Cooper et al., 1987; Davey and Brancolini, 1995; Salvini et al., 1997; Trey et al., 1999; Fielding et al., 2006; Henrys et al., 2007; Davey and De Santis, 2006; Davey et al., 2006; Cande and Stock, 2006), while a widespread igneous activity affected the West Antarctic Rift System (LeMasurier, 1990).

rey et al. (1999) observed and modeled local zones of high seismic velocities and inferred high densities in the crust unde

Trey et al. (1999) observed and modeled local zones of high seismic velocities and inferred high densities in the crust under the axes of the three major sedimentary basins: Victoria Land Basin, the Central Basin and the Eastern Basin, interpreted as mafic dikes and sills intruded in the weakened crust during the Mesozoic-Cenozoic rifting phases.

The whole Cenozoic igneous province of the western rift shoulder (Rocchi et al., 2002) includes plutons, dikes and intrusive-subvolcanic rocks in the northern Victoria Land, and the volcanic products of the McMurdo Volcanic Group and Volcanic Province (Kyle, 1990) in the southern area of the Victoria Land Basin.

In the Victoria Land Basin, the analysis of the multichannel seismic lines, reported in figure 1, exhibits Bottom Simulating Reflectors (BSR) that Geletti and Busetti (2011) assume to be caused by Gas Hydrates (GH). They calculated the theoretical depth of Gas Hydrates Stability Zone (GHSZ) by using Sloan equation (Sloan, 1990) for a portion of the seismic profile IT90AR-63S, to evaluate if the observed BSR could represent the base of the GHSZ. Assuming that the gas is composed by 100% of methane and the Geothermal Gradient (GG) is 36 °C/km, they estimated a theoretical depth of GHSZ of about 500 m below sea floor (b.s.f.) where the water column was about 880 m depth. Moreover, in the same area (Victoria Land Basin), Lawyer et al. (2007, 2012) identified on a detailed multibeam dataset an extensive field of pockmarks at 450-500 m depth and unusual flat-topped seafloor mounds. One hypothesis discussed by the authors is that these features may be carbonate banks because of their proximity to the inferred subsurface GH, although their preferred interpretation is that the features are of volcanic origin.

The presence of GH is also supported by the identification of hydrocarbons in the Ross Sea area. In fact, in the central and eastern Ross Sea, the cored Miocene muddy sediments at the Deep Sea Drilling Project (DSDP) sites (Fig. 1) showed high contents of total hydrocarbon gas (mainly methane) (McIver, 1975). In the western Ross Sea, analysis of sediments from gravity cores showed the presence of hydrocarbon gases with low concentrations of methane (Rapp et al., 1987) and in the McMurdo Sound, both CIROS-1 and MSSTS-1 wells, detected small amount of organic carbon (White, 1989; Collen et al., 1989).

In this context, we model the GHSZ by using a steady-state approach to indicate the areas where the GH may be present and to analyze their possible association with above-mentioned features. A similar study was performed in the Antarctic Peninsula with successful results (Giustiniani et al., 2009; Tinivella et al., 2011; Marín-Moreno et al., 2015). The main objective of this study is to estimate the base of the GHSZ in the Ross Sea because of its potential for the genesis and onset of seafloor geological and geomorphological features.

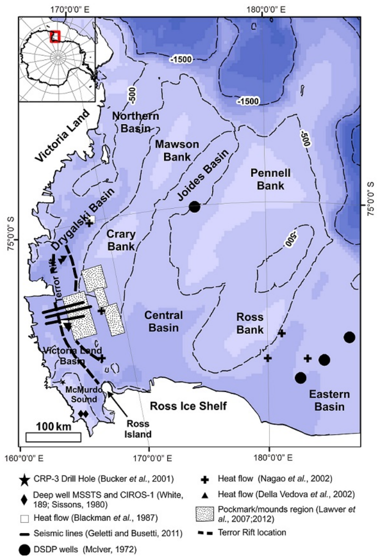

Fig. 1

Fig. 1. Map of the study area including bathymetry in meters. Position of multichannel seismic data, heat flow measurements and pockmark/mound region are showed. See details in the text.

2. Data and modeling

We used bathymetric data from the online IBCSO (International Bathymetric Chart of the Southern Ocean) digital bathymetric model (Arndt et al., 2013) (Fig. 1), which were converted in terms of pressure considering the average water density equal to 1,046 kg/m3. We extrapolate the average water density as suggested by Giorgetti et al. (2003) for the Antarctic Peninsula because of the similarity of water temperatures and polar climate conditions. Available water column temperature profiles were obtained from the National Oceanographic Data Center website (http://www.nodc.noaa.gov/cgi-bin/OC5/WOA09/woa09.pl (last visit 01-04-2013)). We intercept the temperature profiles and the bathymetry to obtain the distribution of the seafloor temperature in the study area (Fig. 2). The comparison between bathymetry (Fig. 1) and temperature distribution (Fig. 2) shows that the seafloor morphology strongly influences the temperature distribution of water masses: colder waters occupy deeper basins, whereas in correspondence of banks the temperatures are higher than those in the basins. These findings are in accordance with the results proposed by Russo et al. (2011). In the Ross Sea area, there are a few sparse downhole temperature measurements performed in deep and shallow boreholes offshore and onshore. These measured temperature gradient values show a strong variability in the western sector of the Ross Sea. In the McMurdo Sound area, close to the Ross Island, heat flows of 160 to 250 mW/m2 have been measured (Risk and Hochstein, 1974), as well as values of up to 150 mW/m2 were detected in the Dry Valleys (Decker, 1978). In the same area, the temperature gradient in the MSSTS-1 drill hole (230 m b.s.f.) is 35-38 °C (Sissons, 1980), suggesting a heat flow of about 60 mW/m2. Bücker et al. (2001) estimated heat flow values considerably lower than other published values, with an average heat flow value of 60 mW/m2. This average estimate was calculated from an average thermal gradient of 28.5 °C/km and thermal conductivity measurements made on core samples in the northern part of the McMurdo Sound. Blackman et al. (1987) performed heat flow measurements in the Terror Rift and in the Drygalski Basin, recording values ranging between about 73 and 63 mW/m2. Della Vedova et al. (1992) collected consistent heat flow data in the deepest part of the Victoria Land Basin, with values in the Drygalski Basin (98-110 mW/m2) higher than those in the Terror Rift (79-89 mW/m2). Nagao et al. (2002) performed heat flow measurements on both the east and west sectors of the Ross Sea (Fig. 1), and their heat flow values are ranging from 110 to 143 mW/m2. Considering the published data and the regional scale of our study, we integrated the data located offshore, as reported in table 1 and in figure 1. As a first order approximation we assumed that the average measured heat flow values are conductive, in steady state condition and with no significant heat generation within the sediments. With these assumptions the conductive heat flux is constant and linearly dependent from the temperature gradient (Q=GG·K). Thus the variability range for the temperature gradient over the entire area, strongly depends on heat input from below and from the sediment thermal conductivity variability, besides the sea bottom temperature changes. Because the thermal conductivity changes in space and time depending upon nature and fabric of the rocks, water content and pressure and temperature conditions, thus if the heat flow is constant then a change in thermal conductivity (such as its increase with depth for an homogeneous sediment) implies a change in the temperature gradient. The lower assumed thermal conductivity value is equal to 1 W/m K for the few upper meters of high porosity marine sediments (Della Vedova et al., 1992; Nagao et al., 2002). The higher assumed thermal conductivity value is equal to 2.1 W/m K, from Bücker et al. (2001) that collected data ranging from 1.3 to 3 W/m K with an average value of 2.1 W/m K over the Tertiary section of CRP-3 borehole. These measurements combined with an average temperature gradient of 28.5 °C/km yield an average conductive heat flow of 60 mW/m-2.

TABLE 1. HEAT FLOW MEASUREMENTS USED.

Water Depth (m)	Heat_flow (mW/m^2)	Reference
597	121.00	Nagao *et al.* (2002)
692	117.00	Nagao *et al.* (2002)
751	117.00	Nagao *et al.* (2002)
602	110.00	Nagao *et al.* (2002)
595	135.00	Nagao *et al.* (2002)
922	143.00	Nagao *et al.* (2002)
1,060	≥51	Della Vedova *et al.* (1992)
1,020	125.00	Della Vedova *et al.* (1992)
1,032	121.00	Della Vedova *et al.* (1992)
865	100.00	Della Vedova *et al.* (1992)
870	91.00	Della Vedova *et al.* (1992)
870	98.00	Della Vedova *et al.* (1992)
885	78.00	Della Vedova *et al.* (1992)
875	103.00	Della Vedova *et al.* (1992)
875	87.00	Della Vedova *et al.* (1992)
880	100.00	Della Vedova *et al.* (1992)
885	105.00	Della Vedova *et al.* (1992)
893	118.00	Della Vedova *et al.* (1992)
912	66.00	Blackman *et al.* (1987)
909	73.00	Blackman *et al.* (1987)

Table 1

The marine conventional heat flow measurements are mostly located in the basins and were taken in the upper 5-6 m of sediments, so the measured heat flow is very sensitive to changes of the sea bottom water temperature. On the other hand, no marine heat flow measurements have been collected on the banks, besides the MSSTS and CRP deep boreholes. It is clear that all information related to GGs is very poor due to the scarcity and the uneven distribution of the data. Assuming the above two thermal conductivity end member scenarios, the resulting GGs are estimated to range between 49 and 103 °C/km, respectively. Then, adopting the discussed input data, we calculate the base of the GHSZ as the intersection between the geothermal gradient and the GH stability curve calculated using the Sloan formula (Sloan, 1998; Tinivella and Giustiniani, 2013). The results of the modeling, using two end member scenarios, are presented in figure 3.

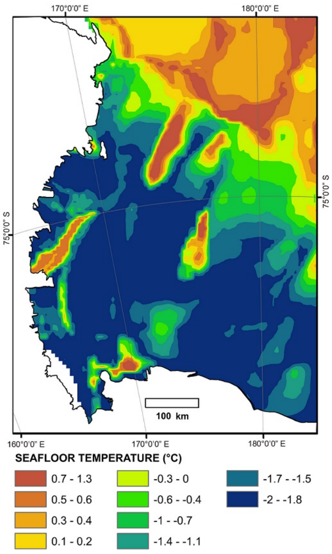

Fig. 2.

Fig. 2. Seafloor temperature distribution (in degrees celsius), water column temperature data from National Oceanographic Data Center website.

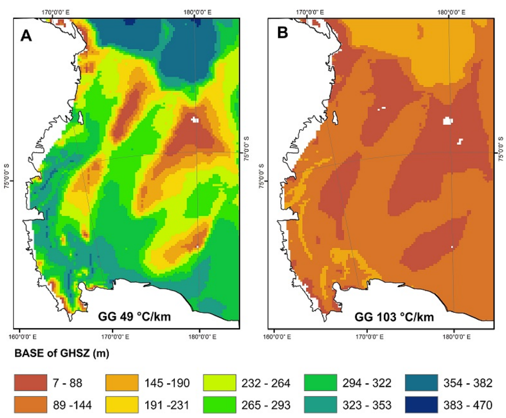

Fig. 3

Fig. 3. Distribution of the base of the GHSZ from the seafloor (in meters). A. GG equal to 49 °C/km; B. GG equal to 103 °C/km.

3. Discussion

In this study, we propose a reconstruction of the distribution of the GHSZ in the Ross Sea in order to infer whether the shallow seafloor geological and geomorphological features identified by different authors could be related, at regional scale, to the GH presence. The results of this study, summarized in figure 3, display the distribution of the GHSZ as a function of the two geothermal gradient scenarios. In particular, the distribution of the GHSZ from the seafloor, obtained by using a GG of 49 and 103 °C/km, respectively, assumes that the entire Ross Sea could be interested either by an average low heat flow of the order of 60 mW/m2, or that the basin is geologically active with a much higher heat flow. The distribution of the GHSZ is strongly influenced by the bathymetry. In fact, in proximity of the banks, where the water depth is shallower, the GHSZ results strongly influenced with thickness that ranges between 7 and less than 100 m. On the other hand, the GHSZ thickness increases in proximity of the basins to values exceeding 400 m related to bathymetry and seafloor temperatures. Moreover, some geological and geomorphological features are the expression of gas hydrates presence, dissociation or dissolution, causing sediment collapse and pockmark formation under the condition of fluid expulsion cessation or environmental changes (i.e., Sultan et al., 2010). For example, in the area where Lawver et al. (2007, 2012) identified a field of pockmarks and unusual flat-topped seafloor mounds, the distribution of these features seems to be associated to the GHSZ. In fact, the depth to the base of the GH thickness could range between 85 and 345 m b.s.f. for a GG equal to 49 °C/km and between 20 and 145 m b.s.f. for a GG equal to 103 °C/km, thus confirming that these features could be related to GH for a wide range of possible heat flow conditions. In the same area, Geletti and Busetti (2011) hypothesized the presence of gas hydrates based on the analysis of seismic data. Our study supports the indirect detection of GH suggested by these authors. However, we estimate a shallower depth of GHSZ because of the different assumed GG. Our modeling suggests a depth of about 310 m b.s.f. for the lower average GG and of about 130 m b.s.f. considering the higher average GG.

4. Conclusions

The theoretical GHSZ in the Ross Sea area was evaluated assuming a steady state simple modeling on the base of bathymetric data, sea bottom tempera-ture, heat flow and a variable geothermal gradient, and assuming that the natural gas is methane. The results from our study suggest that bathymetry and distribution of the base of the GHSZ are correlated in the Ross Sea, In fact, in proximity of the banks, the GHSZ results display thickness that ranges between 7 and less than 100 m. On the other hand, the GHSZ thickness increases in proximity of the basins to values exceeding 400 m related to bathymetry and seafloor temperatures. Moreover, the existence and dynamics of the gas hydrate distribution is strictly related to the existence and evolution of the shallow geological and geomorphological features below the sea floor, as suggested in the past by several authors. In conclusion, the presence of some geological and geomorphological features can confirm the GH presence in the Ross Sea

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