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14. ABSTRACT

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Coordinated, High-Resolution Studies of Hydrated Sediments

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Abstract

The Naval Research Laboratory (NRL) has been conducting coordinated investigations of marine gas hydrates based on precise co-location of both direct sediment cores and data from a deep-tow multichannel seismic system. The seismic instrument (known as the Deep Towed Acoustics/Geophysics System (DTAGS)) was developed by NRL to support detailed studies of deep-ocean marine sediments by towing both the seismic source (220Hz - 1kHz, 200 dB // 1 □Pa @ 1 m) and 48 channel hydrophone array ~300 m above the seafloor in up to 6 km deep water. This instrument has proven to be ideal for studies of marine gas hydrates. Data from this system have been used to study the impact of hydrate dissociation on sediment properties on and near the Blake Ridge and on the Cascadia Margin. Investigations in the Gulf of Mexico are scheduled for Spring 2005. Using bottom mounted acoustic transponders for long baseline (LBL) navigation, we have been able to co-locate the deep-tow seismic data with sediment cores, water samples, etc. to constrain models for processes that create and dissociate marine gas hydrates in much greater detail than previously possible. We show relationships between geologic features resolved with the seismic data and geochemical evidence for variability in methane flux through the seafloor. We also present preliminary results from lattice-gas numerical simulations of gas-fluid flow through complex sediments where parameters are predicated on results obtained with DTAGS and associated geochemical samples.

Introduction

The Naval Research Laboratory (NRL) has been investigating natural marine gas hydrates for over a decade. The original work was predicated on data taken with a unique deep-tow multichannel seismic system that could resolve the detailed structure and physical properties of marine sediments within the gas hydrate stability zone, regardless of water depth. Here we discuss the evolution of NRL's investigations from seismic studies to integrated investigations of gas hydrates using a multidisciplinary approach. In the early 1980's the U. S. Navy developed sesimo-acoustic technology to support the study of marine sediment properties in the deep ocean[1]. The instrument that was developed is, essentially, an adaptation of conventional multichannel seismic technology with the source frequency band increased in order to the resolve structure and physical properties within the upper ~1 km of sediments. This requirement meant that both the source and receiver array would have to be operable at depths of at least 5 km below the surface of the ocean. We are now operating with a second generation deep-tow system that uses a digital array and improved source. The system is known the Deep Towed Acoustics/ Geophysics System (DTAGS).

Instrumentation

DTAGS is designed around a Helmholtz resonator acoustic source. This seismic source provides a source-waveform that is independent of tow depth (to ~6 km). Currently, the source produces a linear 250 ms swept-frequency waveform from 220Hz to 1kHz with a Sound Pressure Level (SPL) of 201 dB // 1 μPa @ 1 m. Because of its free-flooding design, the source can operate at any ocean depth, providing a highly repeatable source signature; in fact, a single sample of the source waveform often is used to deconvolve the data for an entire experiment with negligible degradation in resulting output waveform. Another significant advantage of the deep-tow source configuration is that the source level can be significantly lower than a surface-tow source as spreading losses are significantly reduced when operating in deep (> 1000 m) water depths.

Anther advantage of the piezoelectric source technology is that it is relatively easy to lower the SPL when operating in operational areas where interaction with marine mammals is of concern. For example, we currently have the capability to reduce the SPL by 6 dB while retaining reasonable performance by increasing the sweep length to 500 ms.

The original DTAGS system used oil-filled (analog-recording) hydrophone streamers. The pressure differentials along the array encountered during deployment and retrieval often inevitably resulted in saltwater intrusion and array failure after only two or three deployments. To overcome this problem, the new multichannel array is solid with neutrally buoyant coaxial cable connecting 48 digital hydrophone nodes (24-bit Sigma-Delta digitizing at each hydrophone). Four of these nodes have both hydrophones and depth/heading sensors. The depth/heading sensors are crucial to processing of the seismic data as the deep-tow configuration and low tow-speeds make it impractical to use "birds" to control the depth/heading of the array.

The source-receiver-seafloor geometry achieved with DTAGS is critical to the high-resolution capabilities of this instrument. Of course, in relatively shallow water (say, < 200m depth) the geometric advantage over conventional systems is not significant. However, with increased interest in deep-water sites (> 500m) the advantage of the deep-tow concept becomes apparent. **Fig. 1** is a cartoon in which the advantage of the deep-tow concept is clearly demonstrated. The combination of higher-source frequency, reduced Fresnel zone and the ability to sample equivalent wavenumbers with a shorter array allow one to sample much finer structures within the seafloor. The variable spacing of the two sub-arrays used with DTAGS originally was intended to resolve low grazing-angle scattering for Navy ASW studies. However, this configuration allows us to obtain detailed imagery[2] of geologic features.

Performance of DTAGS

A demonstration of the resolution of DTAGS compared to a conventional high-resolution, surface-tow multichannel system is presented in **Fig. 2**. The data presented in this Figure were taken with a kilometer of each other on the Blake Ridge where the water depth is approximately 2800 m. The data shown in **Fig 2** clearly shows that the DTAGS seismic-section resolves important features related to the fine structure of the Bottom Simulating Reflector (BSR) that are not observable even with modern surface-tow data. Clearly, the BSR (the reflection horizon that marks the solidus-gas phase boundary that is driven by temperature and pressure) is shown to be discontinuous in the DTAGS data whereas the surface-tow data suggest that it is laterally continuous.

The resolution of geologic structure and compressional velocities within the hydrate stability zone is significantly improved with DTAGS data to the point where our data often can support the hypothesis that hydrates concentrate within highly permeable layers or fault zones where sufficient water and methane co-exist. While this is information is of critical importatance to understanding the distribution and concentration of gas hydrates, it is insufficient if one wishes to understand the processes related to the generationa nd dissociation of gas hydrates. Therefore, we expanded the NRL hydrates research program to include geochemical, geothermal, and NMR investigations where samples are carefully collocated with the geologic framework established with DTAGS observations.

Coordinated Studies

The value of the high-resolution deep-tow seismic data in studying gas hydrate is increased several fold. The seismic image shows faults (identifiable either by disjoint layering, or inferred from near vertical gas accumulation), where fluid, heat, and methane flux are most likely. Perhaps most strikingly, seismic data delineate the extent of free gas accumulations within the sediments, constraining the equilibrium hydrate stability boundary[3]. The image can also show features in the section such as basement highs or buried relict conduits that may have significant effects on the interpretation (and modeling) of the chemistry and temperatures measured at the seafloor. Further, the image can provide information on the seafloor reflectivity (within the wavelengths used) constraining the extent of such phenomena as carbonate pavements or roughness caused by chemosynthetic or hydrate mounds. In addition to the image the multichannel nature of the DTAGS data can be used to constrain sediment sound speed velocities, diagnostic indicators of gas and gas hydrate. However, in the case of the very narrow gas accumulations shown in **Fig 3**, the ray paths required for accurate velocity analysis are largely obscured, and not surprisingly, sediments well away from the gas accumulations (inferred conduits) do not exhibit anomalous sound velocities.

Seafloor Thermometry (Traditional Heat Flow)

Traditional heat flow investigations have used near surface temperature and thermal conductivity measurements to infer heat flow through the seafloor. For the study of methane hydrate in the shallow sediments we are interested in the temperature directly, as this is the quantity that impacts gas and gas hydrate distribution, not the heat flow. Knowing the temperature (geothermal) gradient at the seafloor, and extrapolating as appropriate through the hydrate stability zone provides constraints on fluid flux not available through measurement of chemical gradients alone, which only constrain flux of individual solutes.

Also thermal measurements also provide a different time scale to view changes in the flux regime. The modeling of heat transport uses essentially the same equations as the modeling of solute transport, but solute diffusion and thermal conduction occur at significantly different time scales. The thermal perturbation associated with a conduit will reach its characteristic, bell-shaped, steady state curve (**Fig 4**) much faster than solute concentration, which will eventually reach the same shape.

Numerical Modeling

Quantitative understanding of methane and hydrate dynamics in the sediments requires numerical modeling and realistic constraints provided by the coordinated field observations. Tight constraints provided by precise field measurements limit the range of models possible, resulting in a smaller uncertainty in the modeling results. Two approaches to modeling are currently being used, a more standard, finite element package, and a more developmental technique based on lattice gas.

The finite element code SUTRA, developed by the USGS has been used in preliminary modeling of fluid conduits to determine the extent to which heat transport via fluid advection perturbs the methane hydrate stability zone. In this work the seismic image, due to its acute sensitivity to gas, is used to constrain the extent of gas below the seafloor. In some cases this gas boundary marks the interface between free gas and methane hydrate, and can be used to identify the PT boundary associated with the base of methane hydrate stability.

Pore water profiles of dissolved chemical constituents (in particular, sulfate) are useful for evaluating the biogeochemical conditions, gas flux and depositional history of a site. Under steady state conditions with high gas flux, "linear" sulfate profiles result due to diffusion and the anaerobic oxidation of methane (AOM) at the sulfate-methane interface. Such profiles were unexpectedly rare at Keathley Canyon where a "concave up" profile was far more prevalent. This type of curvature can result from changes in gas flux, downward vertical fluid advection, bioturbation or rapid sediment deposition.

Carbon isotopes can also be used to constrain the age of sediments, thereby aiding the interpretation as in the examples below in cores acquired from the Gulf of Mexico[4].

Nuclear Magnetic Resonance

Recent success in the manufacture of portable NMR devices has enabled deployment of an NMR device on a ROV[5]. This allows us to quantitatively observe formation of methane gas hydrates in porous media in a real ocean environment. Our approach is to measure liquid water signal in porous medium exposed in-situ to methane. The signal intensity (porosity) reduction yields amount of water displaced by hydrate, and the T2 relaxation times yield pore size distribution, and location of hydrate formed (large vs. small pores). Although this is a very new technique and requires more development, we expect that these remote NMR measurements will help constrain the distribution of gas hydrates within sediments on a small (several cm) scale.

Acknowledgements

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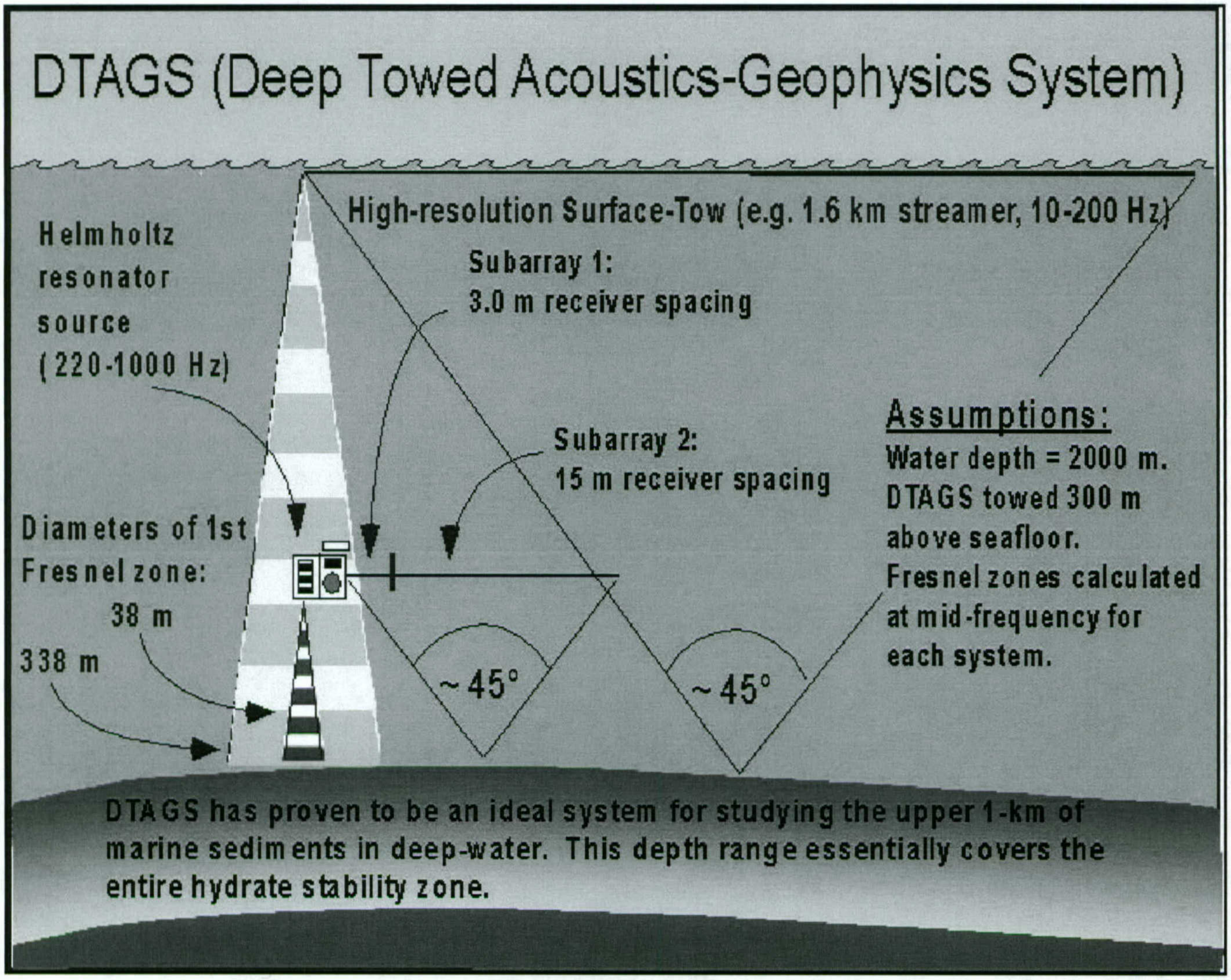

Figure 1 Cartoon demonstrating advantages of deep-tow configuration.

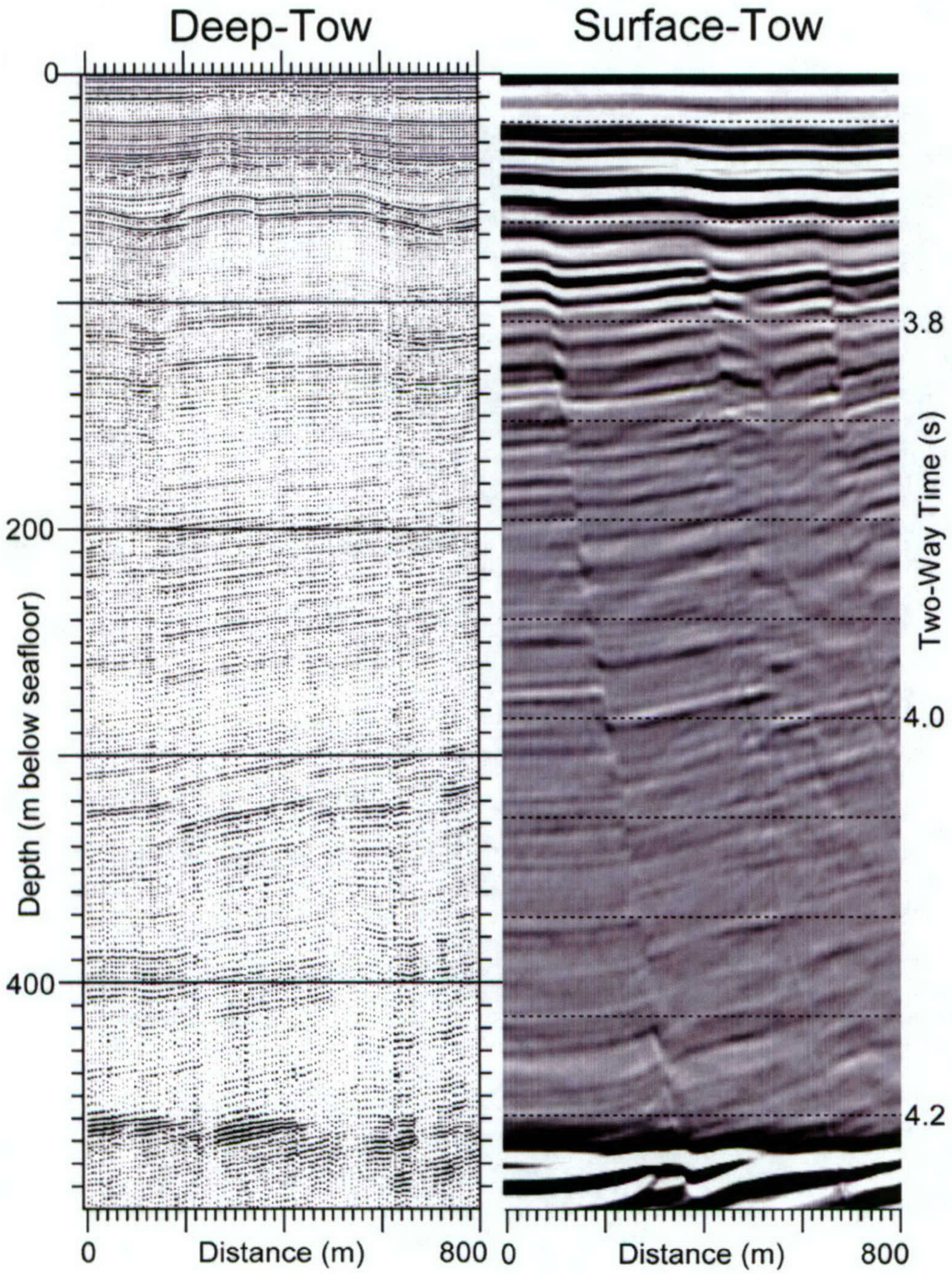

Figure 2 DTAGS data reveal details in geologic faults and structure of the BSR that is not resolved in modern surface-tow multichannel data taken on the Blake Ridge

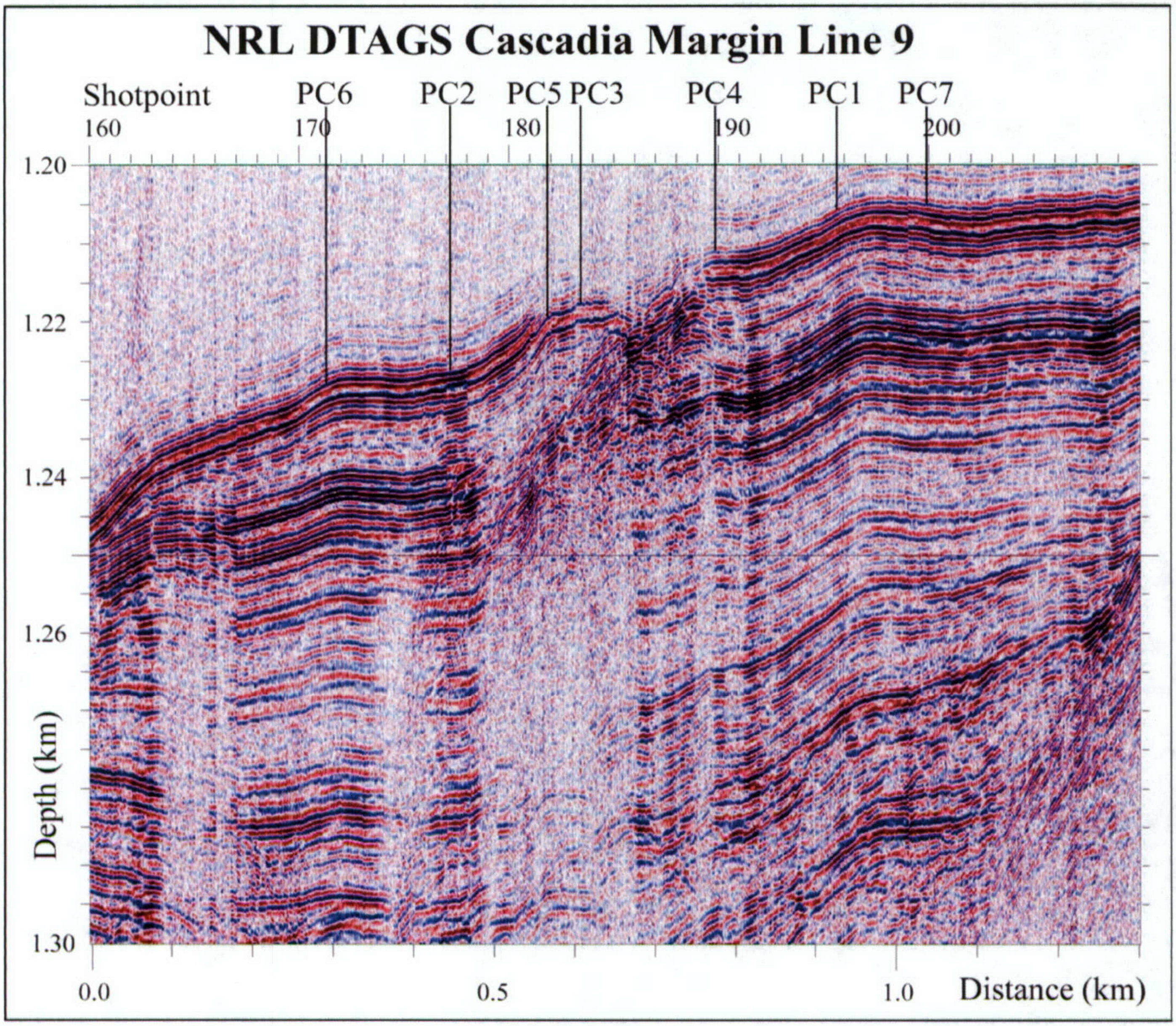

Figure 3 Some wipeouts or blank zones in seismic data from the Cascadia Margin hydrate stability zone are extremely narrow, requiring precise navigation to correlate coring and thermometry with geo-hydrology.

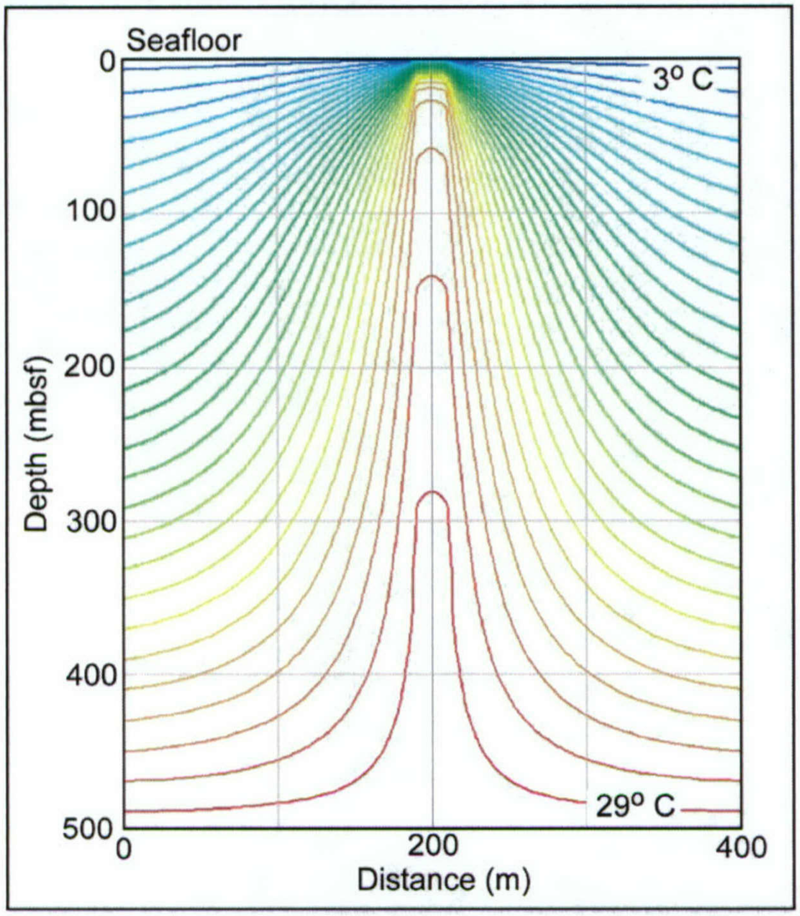

Figure 4 . The thermal regime surrounding a fluid conduit exhibits bell-shaped isotherms and results in anomalously high gradients near the conduit. For most marine sediments the steady state requires thousands to tens of thousands of years. In the case of pore water solutes, lines of equal concentration will attain the same shape but require over an order of magnitude more time.