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Technology Status Assessment

Heat flow and gas hydrates on the continental margin of India: Building on results from NGHP expedition 01

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Heat flow and gas hydrates on the continental margin of India:
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CURRENT STATE OF INFORMATION OR TECHNOLOGY

Background

Summary:

Gas hydrate distribution in sediments depends on methane supply, which in turn depends on fluid flow. When drill data are available to calibrate seismic observations of the base of the gas hydrate stability zone (GHSZ), the seismic observations can be used to map variations in apparent heat flow, and anomalies in apparent heat flow that cannot be attributed to other factors, like variations in thermal conductivity or topography, can be interpreted to results from subsurface fluid flow. We propose to use a distinctive seismic event known as the Bottom Simulating Reflection (BSR) to map heat flow on the continental margin of India and to relate the apparent heat flow to fluid flow, gas hydrate distribution and slope stability. Prior modeling indicates that the depth to the BSR is sensitive to fluid flow rates in the range of ~0.1-10.0 cm/yr (e.g. Trehu et al., 2003a, Torres et al., 2004). The results will have implications both for evaluating the resource potential of gas hydrates and their impact on climate.

In spring 2006, the Directorate General of Hydrocarbons (DGH) sponsored an expedition that drilled 21 sites on the Indian continental margin to prospect for gas hydrates (referred to NGHP Exp. 01). In addition to finding several rich gas hydrate deposits, this expedition provided a number of important new insights into the geologic conditions leading to such deposits (Rose et al., 2008), and thus builds on knowledge obtained during previous drilling expeditions on the Blake Ridge (ODP Leg 164; Paull et al., 1996) and in Cascadia (ODP Leg 204 and IODP Exp 311; Trehu et al., 2003; Riedel et al., 2006). One new insight is that buried channels and turbidite deposits are important for providing pore space in which hydrate crystals can nucleate. It is likely that they also have an influence on fluid flow and transport of methane into and through the GHSZ. When integrated with sedimentolgical studies of the cores recovered during NGHP Exp. 01 (Joel Johnson, personal communication, 2008), the proposed study will test this hypothesis.

Current state of the technology or research:

Temperature is a critical parameter for gas hydrate studies (e.g. Ruppel, 2000; Trehu, 2006) for at least 2 reasons: 1) because it determines (along with pressure and the chemical composition of porewater and free gas) whether gas hydrate is stable, and 2) because temperature variations can drive fluid flow, which controls the migration of gas into and through the gas hydrate stability zone. Heat flow measurements, however, are difficult to make on continental margins where large diurnal, seasonal and longer term variations in water bottom temperature are present (Villinger et al., in press), requiring deep drill holes to obtain measurements representative of temperature at depth. In areas with seafloor seeps, moreover, shallow deposits of gas hydrate and/or carbonate inhibit penetration of heat flow probes into the seafloor.

Observations of a distinctive seismic reflection, known as the bottom simulating reflection or BSR, that is common in gas hydrate-bearing regions provide an opportunity to map regional variations in apparent heat flow. The BSR has been shown to result, in many cases, from the contrast between sediment that contains gas hydrate and sediments that contain free gas. Although it can be difficult (and non-unique) to determine the amount of gas hydrate and free gas from the BSR observations, this reflection can be used to determine regional variations in heat flow (e.g. Zwart et al., 1996) if a number of parameters are known about the system (Grevemeyer and Villinger, 2003) Questions that must be answered include:

1) Is the system in thermal equilibrium?

2) Is the velocity of seismic waves in the hydrate-bearing sediments known (for conversion of observations of the two-way travel time of seismic waves to the BSR to estimates of subseafloor depth)?
3) Are pore water salinity and gas composition adequately well known?

If drilling data, including downhole temperature measurements, geophysical logging results, and chemical analysis of recovered core samples, are available, then the first question can be answered and results can be extrapolated from the core sites by calculating the temperature in the subsurface by assuming that the depth of the BSR indicates the gas hydrate stability boundary. Variations in the temperature gradient can then be combined with information on the average seafloor temperature and on sediment thermal conductivity to construct a regional map of apparent heat flow.

Current approaches and limitations:

During NGHP Exp. 01, 58 high-quality in situ temperature measurements were made at 12 sites (Collett et al., 2008). Data quality is excellent both because of high-precision calibration of the temperature tools prior to the experiment (Heesemann et al., 2006) and because of generally good weather conditions during the expedition. Figure 1 shows the derived temperature/depth profiles at 3 of the sites along with the predicted gas hydrate stability boundary, determined using CSMHYD (Sloan, 1998) for pure methane in seawater. The observed depth to the BSR is also shown (Collett et al., 2008). For Site 17, the effects of varying pore water chemistry are given to illustrate the effect of those parameters. Analysis of pore waters recovered from samples during NGHP Exp. 01 did not show large departure from a seawater salinity (Collett et al., 2008). In all three cases, the predicted BSR depth (the intersection of the red and blue lines) corresponds closely to the observed BSR depth. Figure 2 shows the relationship between the predicted and observed BSR depth for all sites drilled during NGHP Exp. 01. The only outlier is a site on the eastern margin of India (KK Basin), where the seismic reflection originally interpreted to be a BSR is more likely an unconformity that is unrelated to gas hydrates. It is important to note that BSR depths were determined completely independantly from the temperature data by M. Riedel (personal communication, 2006). These observations confirm that the base of gas hydrates stability here is in thermal equilibrium and thus validate our approach to calculating the apparent heat flow from regional observations of the BSR.

In our analysis of the results from the downhole temperature data, we plotted the slope and intercept of the best-fit thermal gradient at each site as a function of water depth. Those results are plotted in Figure 3. The observed decrease in the seafloor intercept with increasing water depth was expected and can be compared to physical oceanographic data on bottom water temperatures to confirm the absence of major local perturbations to seafloor temperatures. The increase in the thermal gradient with increasing water depth, however, is surprising. There is no a prior reason why thermal gradient would increase downslope from 35 to 55 ^{o}C/km over a distance of only ~8 km (see map on Fig 5a for the distribution of drill sites in the KG basin). Because the thermal conductivity, as measured from core samples and inferred from lithology, does not change significantly downslope (Collett et al., 2008), this downslope increase in thermal gradient indicates that some other process (e.g. fluid flow or erosion) is affecting the thermal gradient.

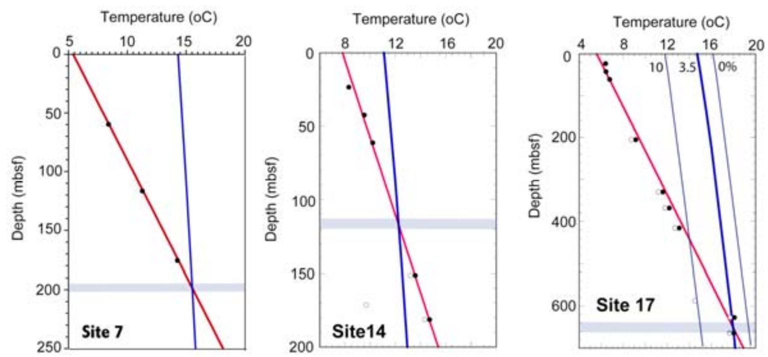

Figure 1. In situ temperatures determined from data acquired during NGHP Exp. 01. Open circle are the derived temperature prior to application of instrument calibration corrections; filled circles are corrected data.

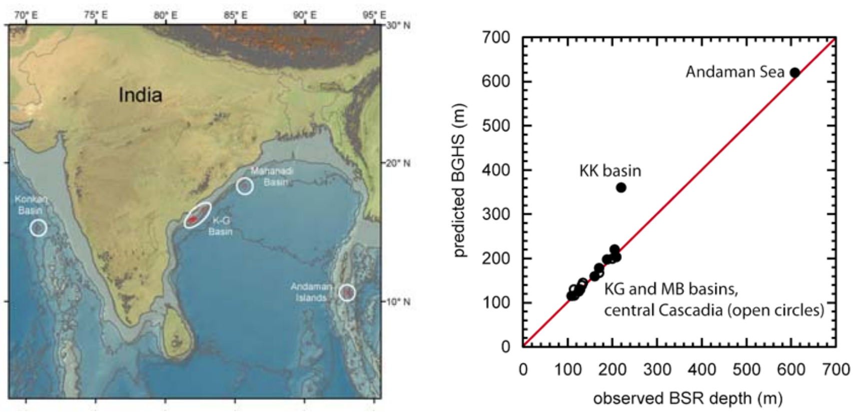

Figure 2. (left) Location map showing the 4 regions sampled during NGHP Exp. 01. Sites 4 and 7 were in the K-G basin. Site 17 was in the Andaman Sea. (right) Predicted vs. observed BSR depth. The agreement between the predicted and observed depths indicates that gas hydrates are in thermal equilibrium.

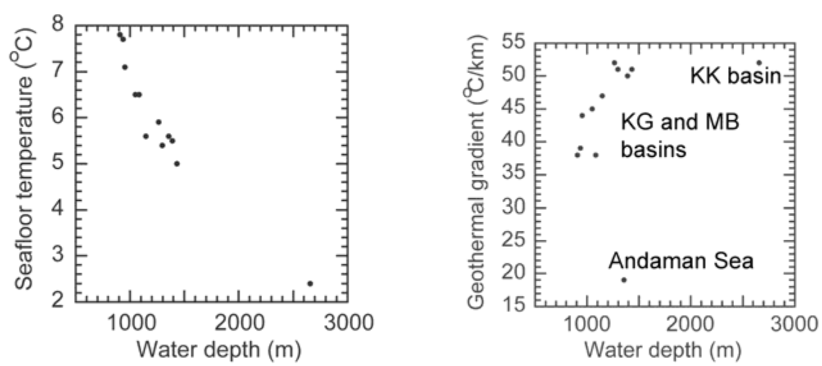

Figure 3. (left) Intercept (predicted seafloor temperature) of the best-fit line relating temperature to subseafloor depth plotted against water depth. (right) Slope (thermal gradient) of best-fit line relating temperature to subsurface depth plotted against water depth.

Inadequacies of the current state of analysis:

The NGHP project only provided funding for data acquisition and in initial processing. No funding was provided for interpretation and modeling of the results. Now that has been confirmed that the quality of the data is excellent and that the results merit further analysis, we plan to pursue this analysis following the produre outlined below.

DEVELOPMENT STRATEGY

Problem being addressed relative to inadequacies identified above:

One possible explanation for the apparent increase in heat flow with increasing water depth in the KG and Mahandi basins is topographically and stratigraphically driven fluid flow, as modeled for the passive margin on the east coast of North America (Dugan and Flemings, 2000). In their study, drill data from ODP Site 1073 were available to test some aspects of the model, but no BSR is observed in the region, so BSR-derived heat flow could not be used as a constraint. Note that the magnitude of flow in the model (Fig. 4) – 1-10 mm/yr – is in the range in which BSR depth is most sensitive to fluid flow. If the pattern indicated in Figure 3 is determined to be a regional feature in the proposed BSR-derived heat flow map, and if other explantions (slope instability; disruption of conductive heat flow by topography), we will construct models of this type to attempt to match the data during a continuation of this project that will be proposed for year 2.

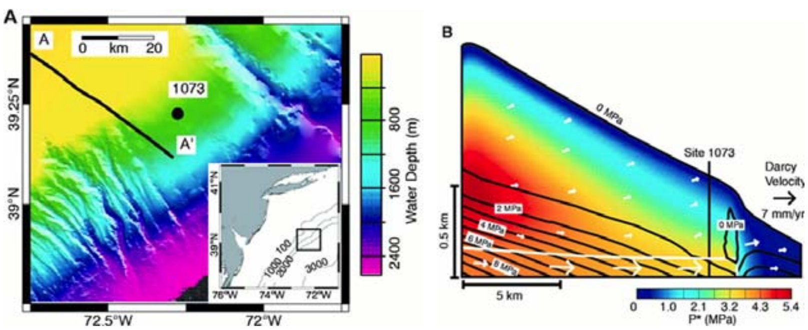

Figure 4. A. Topographic map of the central U.S. passive margin. B. Results of 2D pore fluid flow model that incorporates the effects of topographic pressure gradients and variations in permeability.

Brief discussion of the methodology:

Most of the elements needed to undertake this study are in place. Grids of seismic data have already been acquired and processed by DGH and were used to locate the drill sites (Fig. 5), and the SEGY data files will be made available to us (T. Collett, personal communication, 2008). Many of these lines show a strong BSR (Fig. 6).

The software needed to effectively and efficiently display the data and digitize the BSR traveltime are available via a donation to Oregon State University from Seismic Micro-Technology, Inc. In addition, we have developed software to convert the observations to estimates of heat flow, including examination of various source of uncertainty as part of our analysis of data from Leg 204 and Exp 311 (Trehu, 2006, Trehu et al., 2007).

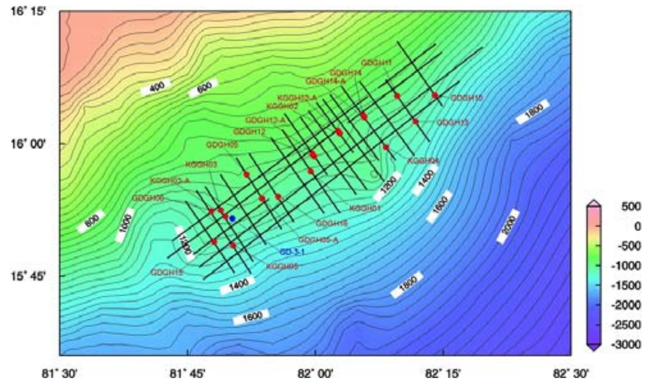

Figure 5. Topographic map and track lines of seismic data in the KG basin. Locations of proposed drill sites are also shown.

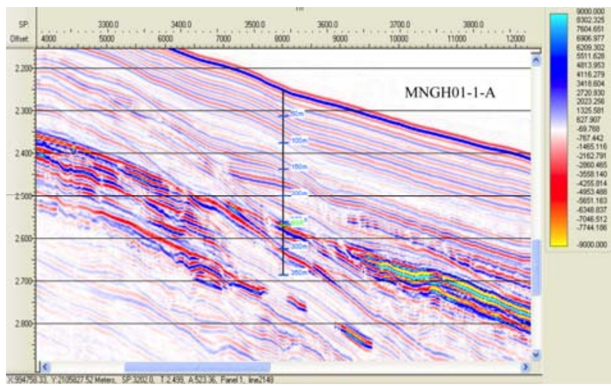

Figure 6. Example of seismic data from the eastern continental margin of India. A clear BSR is observed.

POTENTIAL IMPACT OF THIS PROJECT

Benefits and potential impact on the exploration or ultimate production of hydrates, or the understanding of hydrate's role in the natural environment:

This study will provide information on the regional extent of the gas hydrate stability zone and the thermal processes that control it, information that is critical for "appraising hydrate distribution in the natural environment." This effort also includes "direct calibration of geophysical interpretations through reference to data collected in situ" because in situ data are needed to: 1) confirm that the BSR represents the base of the gas hydrate stability zone; 2) constrain the parameters needed to convert the regional seismic travel time observations to heat flow estimates; and 3) tie the interpretation of apparent heat flow to lithology and geologic structure. This project will thus increase our understanding of the impact of topography and stratigraphy on heat, and by proxy fluid flow, in continental margin sediments and the impact of this flow on gas hydrate distribution. It will also contribute to training the next generation of gas hydrate researchers.

REFERENCES (relevant and used in this assessment report)

Collett, T, M. Riedel, J. Cochran, R. Boswel, J. Presley, P. Kumar, A. Sathe, A. Sethi, M. Lall, V. Sibal, and the NGHP Expedition 01 Scientists, Expedition 01 of the Indian National Gas Hydrates Program from Mumbai, India to Chennai, India, Directorate General of Hydrocarbons (India), Initial Report, 2008.

Dugan, B., and P.B. Flemings, Overpressure and Fluid Flow in the New Jersey Continental Slope: Implications for Slope Failure and Cold Seeps. *Science* 289:288–291, 2000.

Grevemeyer, I., H. Villinger, Gas hydrate stability and the assessment of heat flow through continental margins, Geophys. Jour. v. 145, p. 447-460, 2001.

Flores, J.-A., A.E. Molina, C. Alvarez, F.-J. Sierro, L. Giosan, J.E. Johnson, Calcareous nannofossil biostratigraphy from sediment cores recovered in the Arabian Sea, Bay of Bengal and Andaman Sea during NGHP Exp. 01 (abst.), International Conference on Gas Hydrates, Feb. 6-8, 2008.

Heeseman, M., H. Villinger, A.T. Fisher, A.M. Trehu, S. Witte, Data report: testing and deployment of the new APCT-3 tool to determine in situ temrpatures while piston coring, in Riedel, M., T.S. Collett, M.J. Malone, and the Expedition 311 Scientists, Proc. Integrated Ocean Drilling Program, vol. 311, 2006.

Lyle, M., Koizumi, I., Richter, C., and Leg 167 Scientists, Proc. ODP, Init. Repts. 167, Ocean Drilling Program, Texas A&M University,College Station TX TX 77845-9547, USA, 1997.

Paull, C.K., R. Matsumoto, P.J. Wallace, et al.. *Proceedings of the Ocean Drilling Program, Initial Reports* 164, Ocean Drilling Program, College Station, Texas, 1996.

Riedel, M, T. Collett, M. Malone, and Expedition 311 Scientists, Proceedings of the Integrated Ocean Drilling Program, Volume 311 Expedition Report.

Rose, K, J.E. Johnson, L. Giosan, and NGHP-01 Shipboard Party, Lithologic and geologic controls on gas hydrate occurrances: examples from the Mahanadi, Krishna-Godavari and Andaman Basins (abst.) International Conference on Gas Hydrates, Feb. 6-8, 2008

Ruppel, C. . Thermal state of the gas hydrate reservoir. Pp. 29–42 in *Natural Gas Hydrate in Oceanic and Permafrost Environments*, M. D. Max, ed., Kluwer Academic Publishers, Dordrecht, The Netherlands, 2000.

Sloan, E.D., *Clathrate Hydrates of Natural Gases*, 2nd edition, Marcel Dekker Inc. Publishers, New York, 705 pp. 1998.

Torres, M.E., K. Wallmann, A.M. Tréhu, G. Bohrmann, W.S. Borowski, and H. Tomaru. Gas hydrate dynamics at the Hydrate Ridge southern summit based on dissolved chloride data. *Earth and Planetary Science Letters* 226:225–241, 2004

Trehu, A.M., D.S. Stakes, C.D. Bartlett, J. Chevallier, R.A. Duncan, S.K. Goffredi, S.M. Potter, K.A. Salamy, Seismic and seafloor evidence for free gas, gas hydrates, and fluid seeps on the transform margin offshore Cape Mendocino, J. Geophys. Res., 108, 2263 (19 pp.), doi:10.1029/2001JB001679, 2003a.

Trehu, A.M., G. Bohrmann, F.R. Rack, M.E. Torres, Proc. ODP, Init. Repts. 204, [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M Un., College Station TX 77845-9547, USA, 2003b

Trehu, A.M., Subsurface temperatures beneath southern Hydrate Ridge, in Trehu, A.M., Bohrmann, G. Torres, M.E., and Colwell, F.S. (eds.), Proc. Ocean Drilling Prog., Scientific Results, v. 204, College Station, TX (Ocean Drilling Program). 1-26, doi:10.2973/odp.proc.sr.204.114.2006. 2006

Trehu, A.M., H. Villinger, A. Fisher, In situ temperatures in the NGHP Exp. 01 drill sites: implications for gas hydrate stability (abst.), International Conference on Gas Hydrates, Feb. 6-8, 2008.

Villinger, H., A. M. Trehu, I. Grevemeyer, Seafloor marine heat flux measurements and estimation of heat flux from seismic observations of bottom simulating reflectors, SEG special volume of gas hydrates, in press.

Wang, K., Hyndman, R.D., Davis, E.E., Thermal effects of sediment thickening and fluid expulsion in accretionary prisms: Model and parameter analysis, J. Geophys. Res., v. 98, p. 99, 1993.

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