Oil & Natural Gas Technology

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Quarterly Report

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Heat Flow and Gas Hydrates on the Continental Margin of India: Building on Results from NGHP Expedition 01

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List of Tables:

SUMMARY:

In October 2008, graduate student Peter Kannberg and Professor Anne Trehu began working on the National Energy Technology Laboratory (NETL) funded project entitled *Heat flow and gas hydrates on the continental margin of India: Building on results from NGHP expedition 01.* This project is designed to complete analysis, interpretation and modeling of downhole temperature data that were acquired in spring 2006 at 21 sites drilled in gas hydrate-bearing sediments on the continental margin of India. 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 . One new insight is that buried channels and turbidite deposits are important for providing pore space in which hydrate crystals can nucleate. We hypothesize that these channels also have an influence on fluid flow and transport of methane into and through the gas hydrate stability zone (GHSZ). The objective of this project is to construct a map or regional heat flow by using the borehole data to calibrate heat flow estimates derived from observations of a bottom simulating reflection (BSR) in regional seismic data. Expedition NGHP 01 confirmed that the BSR near the boreholes reflected the base of the GHSZ on the eastern continental margin of India and in the Andaman Sea. We will then use these observations to model fluid flow and collaborate with sedimentologists working

on the cores recovered from these boreholes to test this hypothesis. The project also supports development of human resources for hydrate studies by supporting tuition for Kannberg to take courses leading to a Masters degree in oceanography and geophysics.

The fifth quarter was spent revising apparent heat flow maps of the Krishna-Godavari and Andaman basins. Poorly constrained portions of the map were removed, as were anomalies induced by seismic survey registration errors. We also constructed a heat flow profile across the Mahanadi basin. Additionally, heat flow from various continental margin environments worldwide were compiled and compared to NGHP Expedition 01 BSR-derived heat flow to see if the increase in apparent heat flow observed in all 3 study sites is a common feature of continental margins. As far as we know, this is the first such compilation, and an increase in heat flow with increasing water depth appears to be a common feature of continental margins.

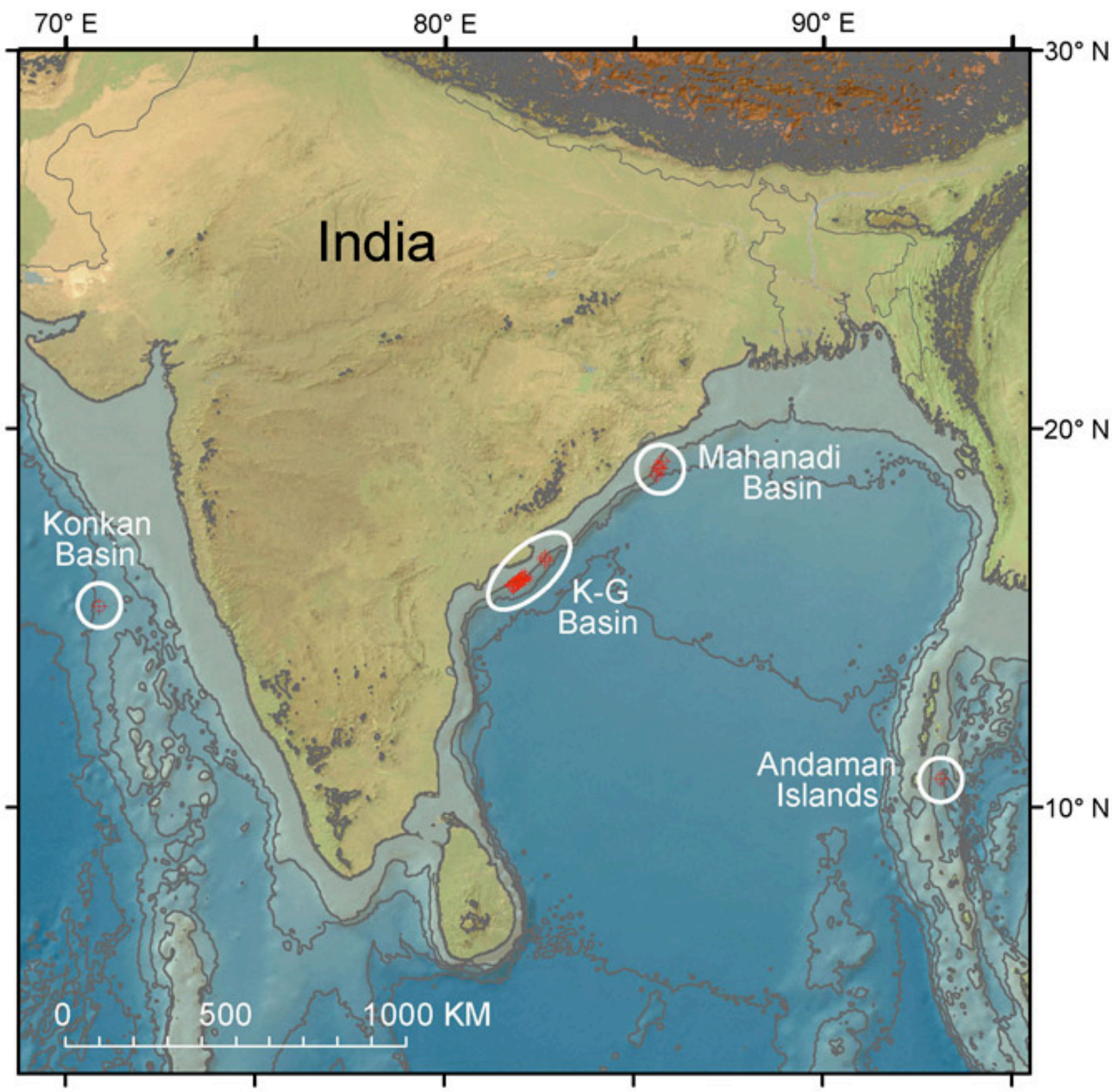

Figure 1. NGHP Expedition 01 study areas.

Krishna-Godavari Basin

While attempting to correlate apparent heat flow anomalies with the seismic surveys from which they were derived, it became clear that certain heat flow anomalies were the result of missing or inaccurate data. In regions where the BSR is sparse or absent, the gridding process fills in the BSR even where there are no observations. The uncertainty associated with interpolated BSR depth increases with distance from the observed BSR. However, seafloor depth is well constrained. In regions where there is an abrupt topographic change but no BSR, the gridded BSR data are smoother than the bathymetry, resulting in apparent heat flow highs and lows. Where identified, these have been removed from the dataset.

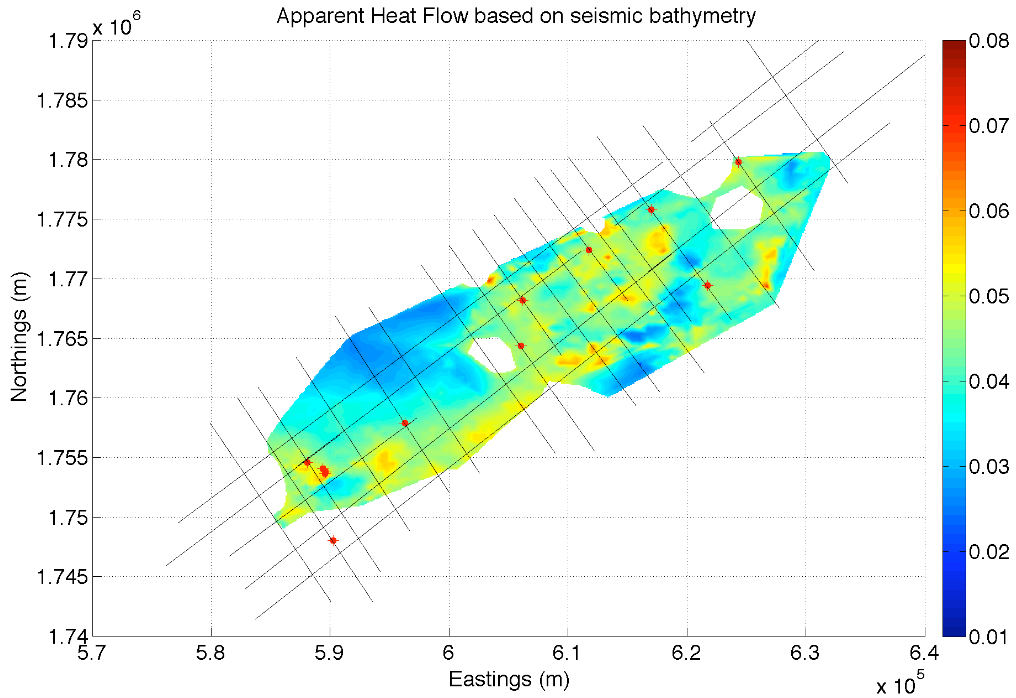

Figure 2. Updated map of K-G basin apparent heat flow. Seismic survey overlain as black lines. Solid red squares represent NGHP Expedition 01 drill sites.

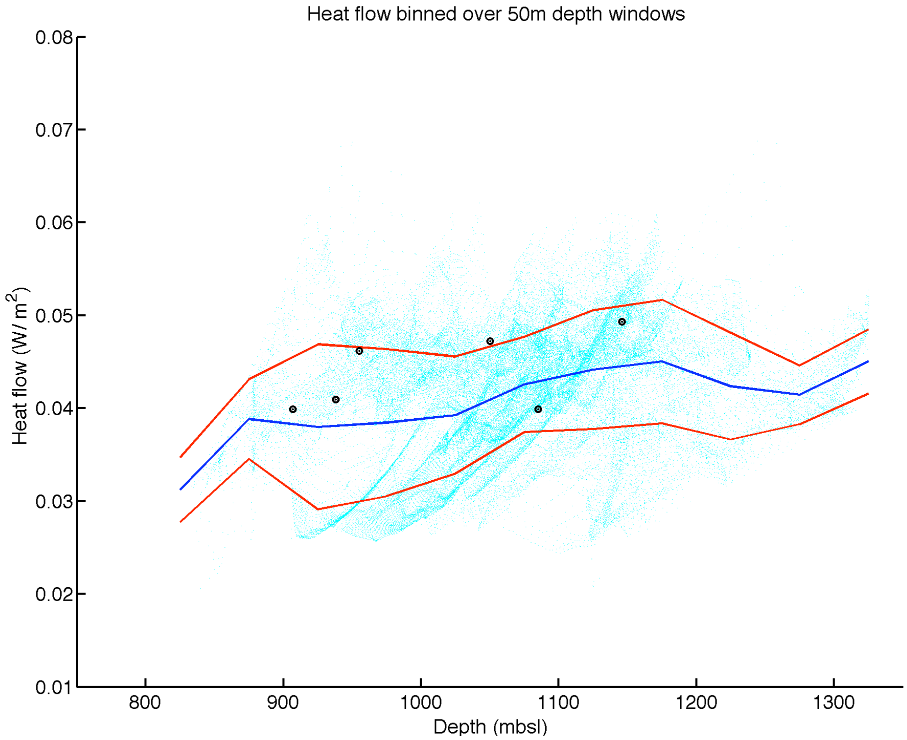

Figure 3. K-G basin apparent heat flow as a function of depth (cyan cloud plot) with binned best fit line (blue line) bracketed by red line showing one standard deviation. Black dots represent heat flow calculated from NGHP Expedition 01 drill sites.

To better understand the reason for the very large scatter of apparent heat flow vs. depth data and different trends within the data, the Krishna-Godavari basin was divided into five zones as shown in figure 4. The color of these zones corresponds to the color of the cloud plot and best fit lines in figure 5.

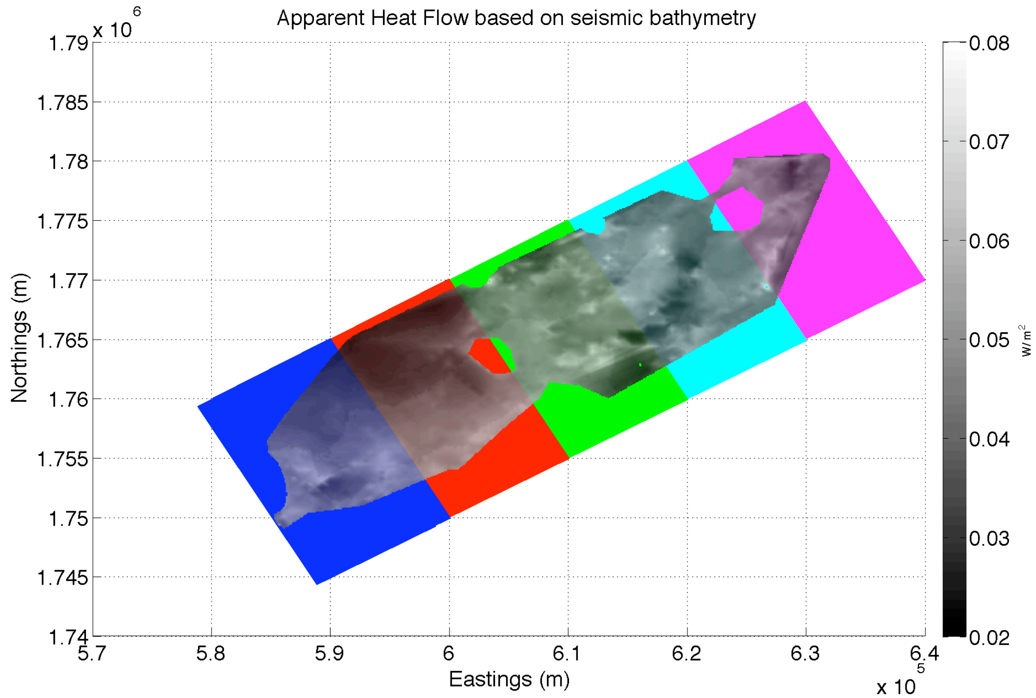

Figure 4. Apparent heat flow map of the K-G basin, with five zones shown overlain in various colors. Colors correspond to those in fig. 5.

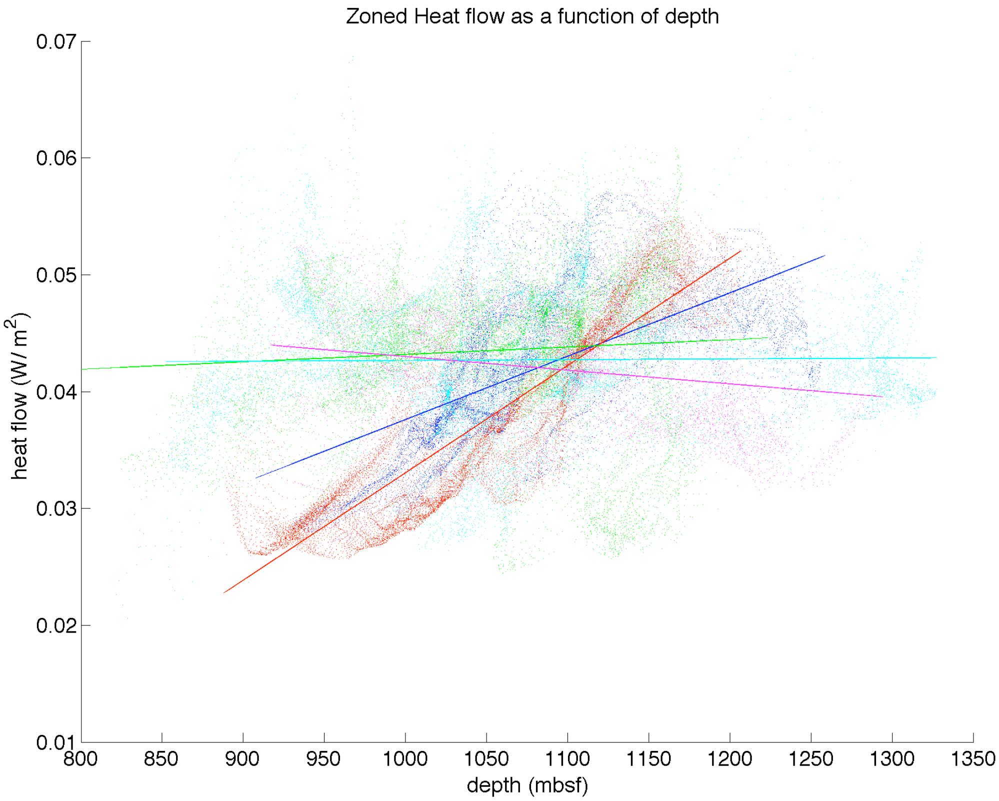

Figure 5. Cloud plot showing variation of apparent heat flow as a function of depth in zones delineated in fig. 4. Best fit line and cloud plot colors correspond to color of zone overlay in fig. 4. Note the strong increase in heat flow with increasing water depth in the southwest. This region is dominated by a low heat flow region located at relatively shallow depths. The northeast part of the study region shows little variation in heat flow with water depth.

This zoned breakout allows scatter in the cloud plot field to be correlated to specific regions. There are two distinct trends when viewing the cloud plot. The first is a shallow heat flow gradient as a function of depth, as shown by the green, blue, and magenta lines in fig. 5. The steep heat flow gradient (blue and red lines) are from the southwest zones. These zones are dominated by a low heat flow area as seen in the northernmost (landward) portions of the red and blue zones (fig. 4). This low heat flow region is at relatively shallow depths (fig. 6), giving the zones a steep heat flow gradient. It is hypothesized that the bathymetric ridge positioned to the south (seaward) of this low heat flow zone is trapping sediment, which is affecting heat flow in the region. Seismic lines show a basin associated with the low heat flow region. Focusing on a transect across the red sub-zone, we will construct a 2D model that includes the effects of sedimentation and lateral flow driven by topography during the 6th quarter of this project.

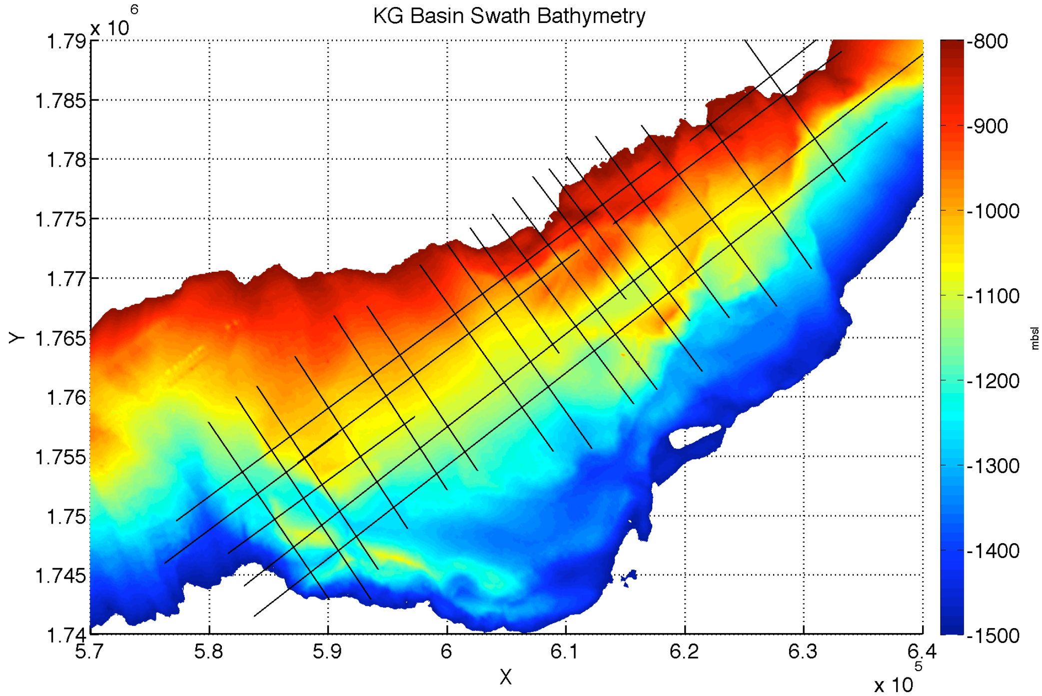

Figure 6. K-G basin bathymetry, from 800-1500 meters water depth. Seismic survey lines are overlain in black.

Heat flow is a product of conductive and convective processes. Convective fluid flow can be focused by faults. Figure 7 shows thrust faults, as identified by Yu et al. (in review), overlain on the apparent heat flow map of the K-G basin. While these faults can be associated with increased heat flow, some of the heat flow anomalies are not correlated with known faults. The faults found through analysis of the 3d seismic survey are shown as black lines in the inset of figure 8. The BSR could not be resolved in the 3d survey due to the higher frequencies used, so a direct comparison of increased apparent heat flow as a result of fault-focused fluid flow was not attempted by Yu et al.

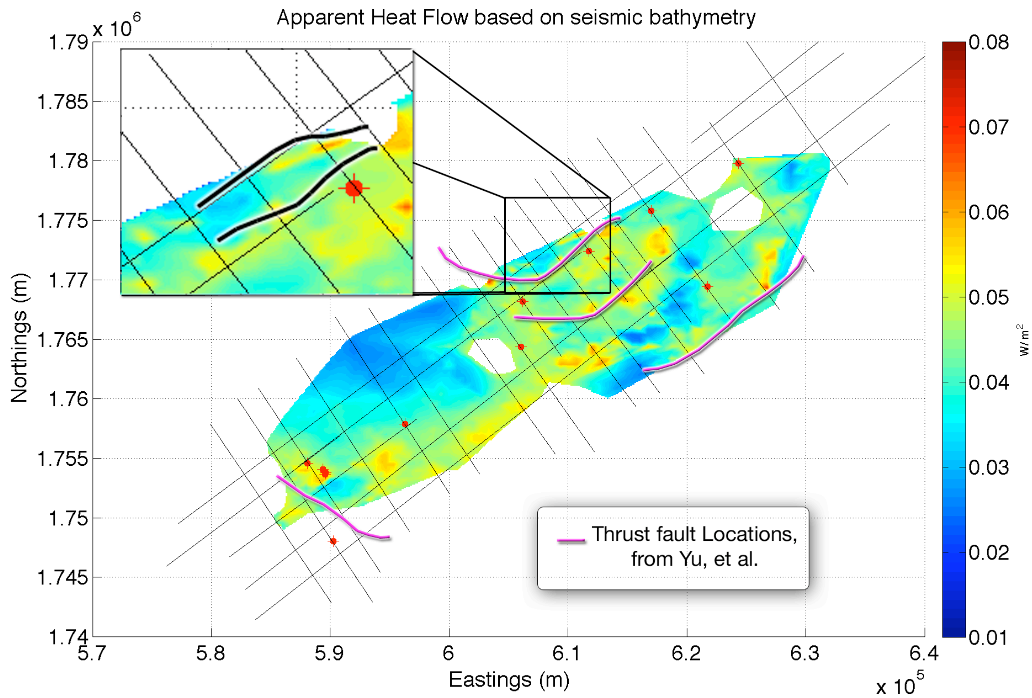

Figure 7. Apparent heat flow map of the Krishna-Godavari basin overlain by faults (magenta lines)as found by Yu, et al (in review). Inset shows faults (black lines) as found in 3d seismic section.

<u>Andaman Basin</u>

Our previous Andaman basin apparent heat flow map systematically overestimated the heat flow in the region. This was due to our using a seafloor temperature that was ~3 degrees Celsius than the temperature measured during drilling operations. Upon further investigation, we found a programming error that was resulting in incorrect determinations of seafloor depth in the code that was calculating seafloor temperature on a grid based on a temperature vs. depth profiles from the World Ocean Atlas and the bathymetric grid. This error was corrected to produce the maps in this report. The mismatch between the thermal gradient measured at NGHP Site 17 and the BSR-derived thermal gradient in the previous map has now disappeared.

Updated Andaman plots:

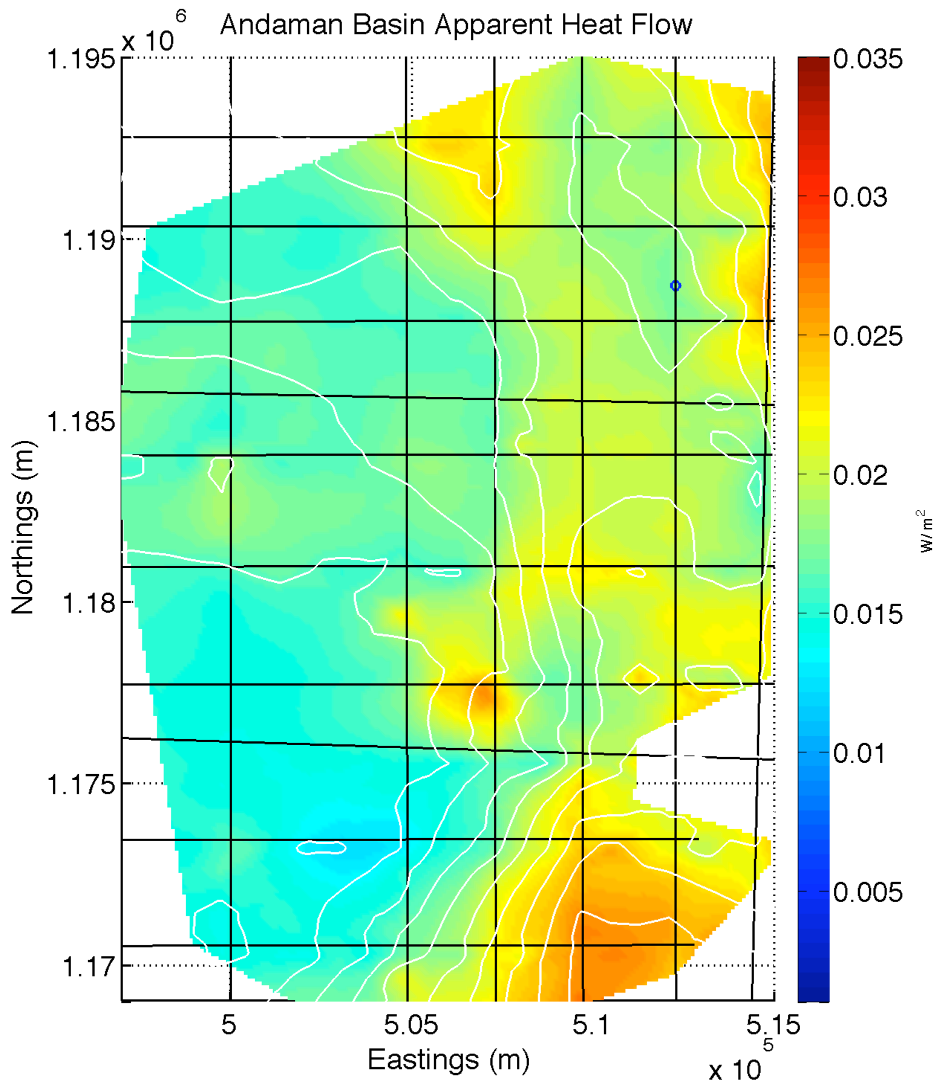

Figure 7. Apparent heat flow in the Andaman Basin. The blue circle is site 17 from NHGP Expedition 01. Black lines represent seismic survey lines. White lines indicate seafloor bathymetry.

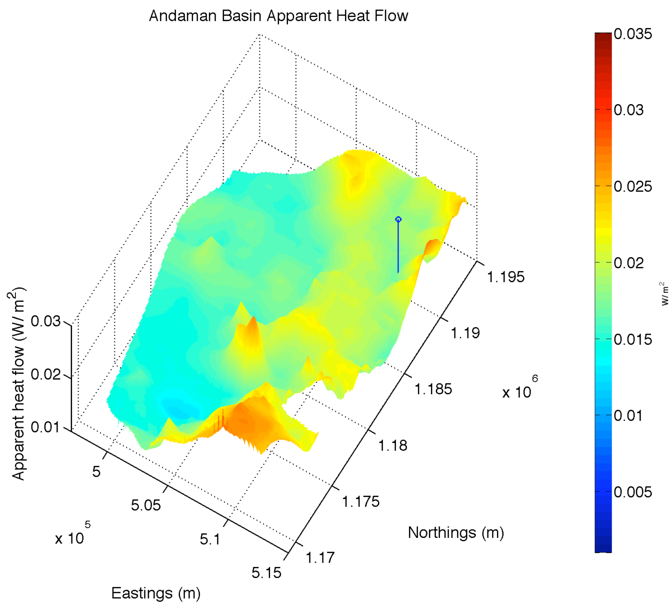

Figure 8. Andaman Basin as viewed from the southeast looking northwest. The blue vertical line is NGHP drill site 17.

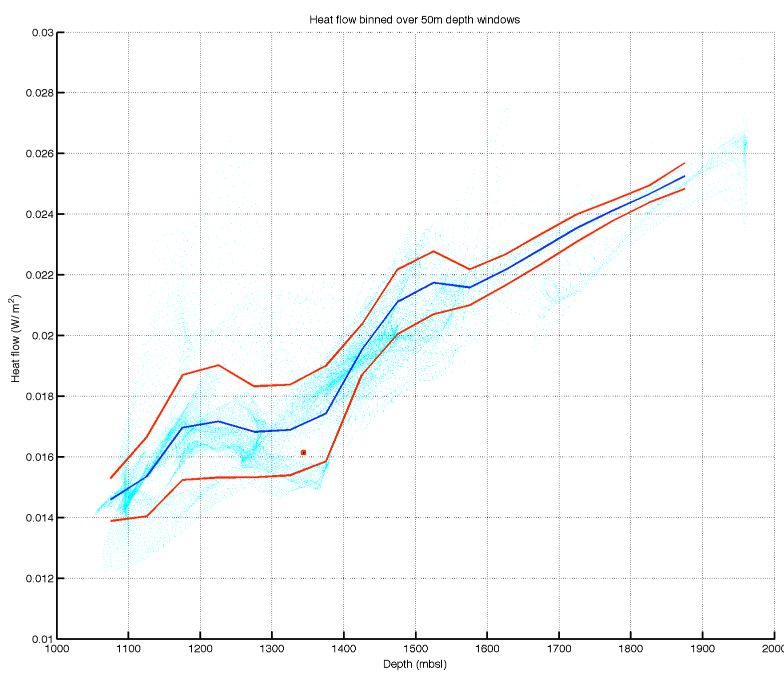

Figure 9. Heat flow as a function of depth for the Andaman Basin (cyan cloud points). Also plotted is average heat flow values binned over 50m depth windows (blue line) showing one standard deviation (red lines). Shipboard measurement derived heat flow at site 17 shown as red open square.

Mahanadi Basin

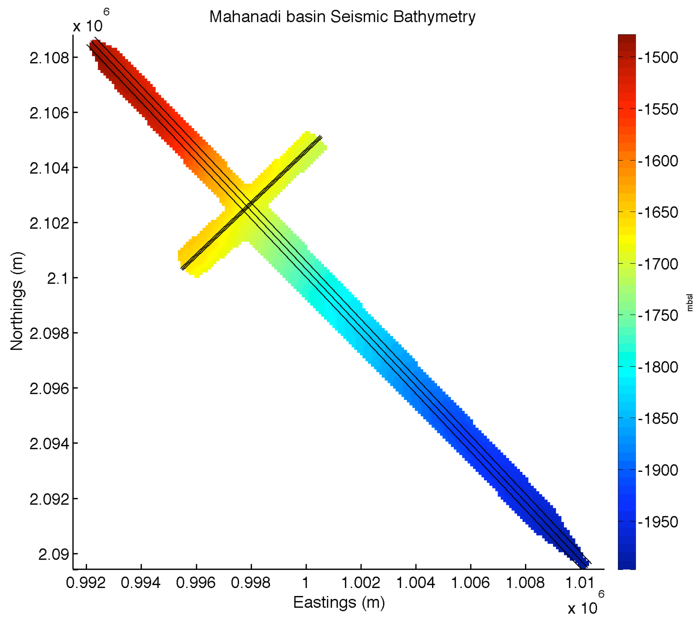

Figure 10: Mahanadi Basin bathymetry based in seismic surveys (shown as black lines).

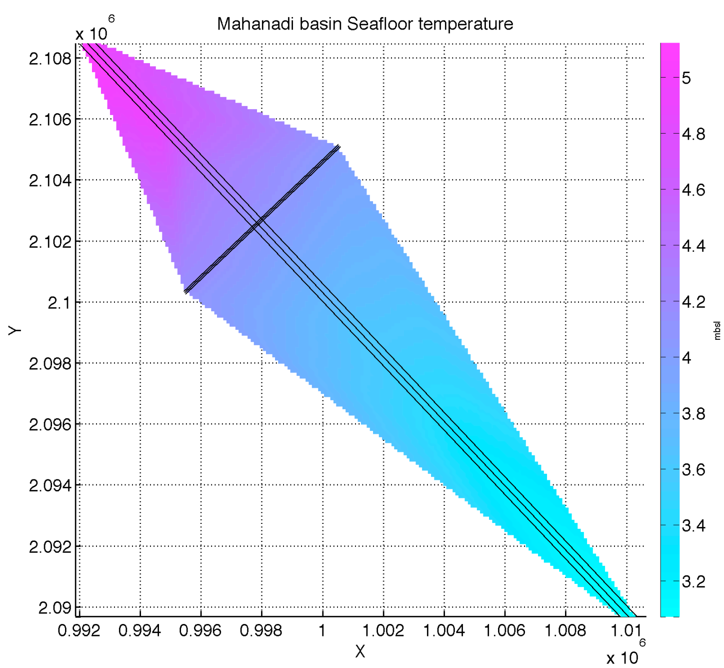

Figure 11: Mahanadi basin temperature at seafloor based on World Ocean Atlas 2005.

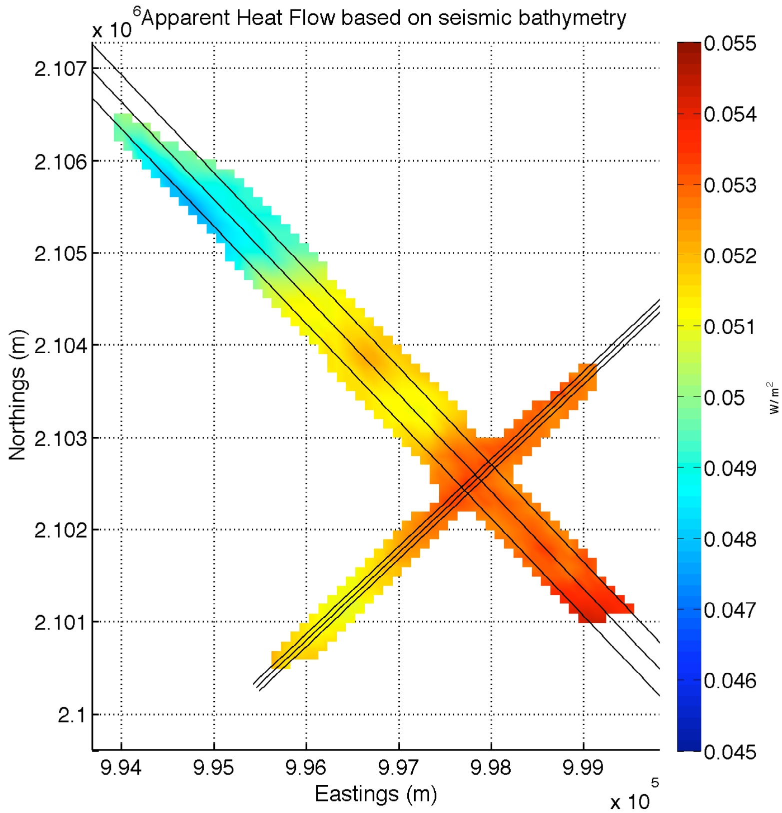

Figure 12. Mahandi apparent heat flow map. This map is a subset of the bathymetry and temperature map shown above, due to BSR being absent in the rest of the seismic lines.

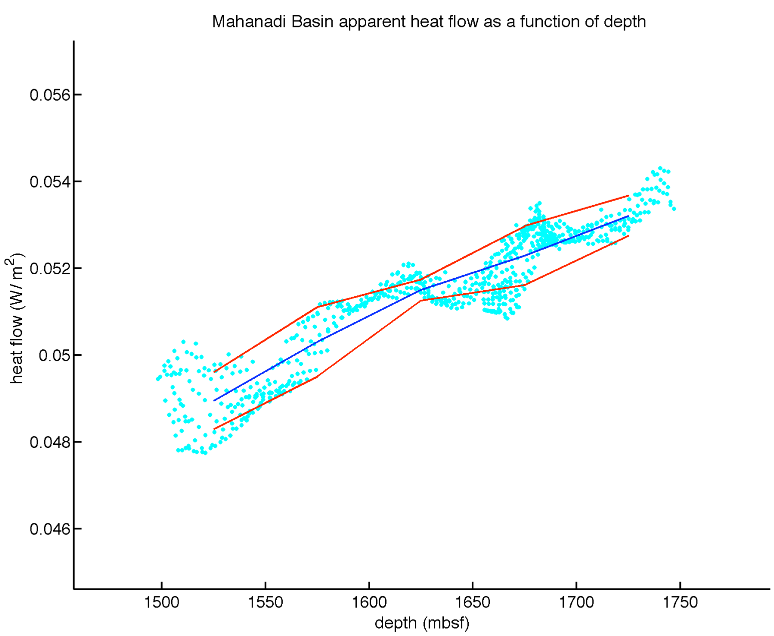

Figure 13. Mahanadi basin cloud plot (cyan points) with best fit line (blue line) binned over 50 meter depth windows, bracketed by the standard deviation of bins (red line).

Margin heat flow compilation

Figure 14 shows where the three study regions lie in relation to other worldwide margins, both passive and active. Heat flow from other regions was determined through various means, from traditional bowstring seafloor heat flow measurements (which are sensitive to seasonal water temperature fluctuations) as well as BSR derived heat flow. This compilation provides a first glimpse at where the K-G and Andaman basin fell within a global compilation. As noted above, average K-G basin heat flow is skewed by the shallow, low heat flow zone. When those two steep gradient zones are removed and the best fit line is recalculated, the slope becomes 0.72*10^-5, which is a better fit to the other margins. This is an initial compilation, with additional data from other regions being incorporated as available.

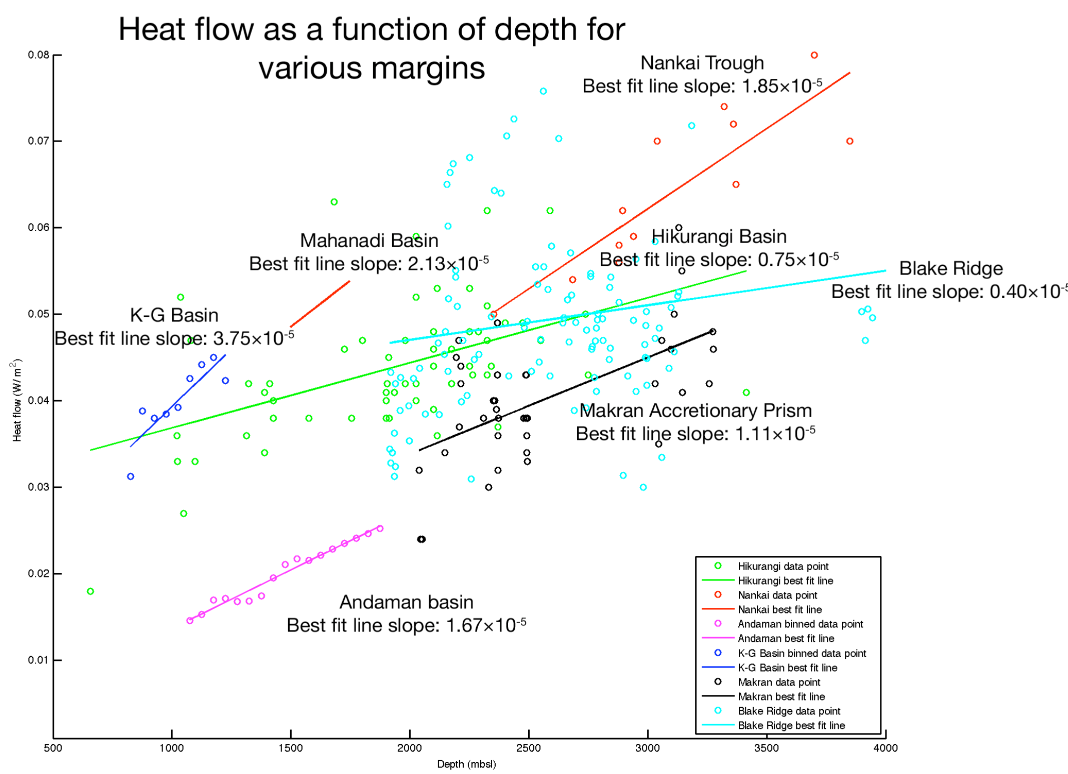

Figure 15. Compilation of heat flow at various margins, both active and passive.

References for Figure 15:

Blake Ridge:
Ruppel. C., Von Herzen, R. P., Bonneville, A., 1995. Heat flux through an old (~175 Ma) passive margein: Offshore southerstern United States. Journal of Geophysocal Research, v. 100, B10, 20037-20057.

Makran:
Kaul, N., Rosenberger, A., Villinger, H. 2000. Comparison of measured and BSR-derived heat flow values. Makran accretionary prism, Pakistan. Marine Geology, 164, 37-51.

Hikurangi:
Townend, J., 1997. Estimate of conductive heat flow through bottom-simulating reflectors on the Hikurangi and southwest Fiordland continental margins, New Zealand. Marine Geology, 141, 209-220

Nankai:
Yamano, M., Uyeda, S., Aoki, Y., Shipley, T. H., 1982. Estimates of heat flow derived from gas hydrates. Geology, v. 10, 339-343.

Table 1. Project costing profile for Budget Period 5.

	October (planned)	October (actual)	Nov. (planned)	Nov. (actual)	Dec. (planned)	Dec. (actual)
PI salary & fringe benefits	1,627	522	1,627	523	1,627	523
GRA salary & fringe benefits	2,271	2,201	2,271	2301	2,271	2,201
Computer subscription	250	250	250	250	250	250
Travel						
Tuition		0		3,590	3,148	0
Indirect Costs	2,160	1,374	2,160	1,513	2,160	1,374
	9,206	4,347	6,308	8,177	6,308	4,348

note: Travel expenses associate with travel to the AGU meeting will appear in the budget for January, 2010.

PUBLICATIONS, CONFERENCE PRESENTATIONS AND OTHER PRODUCTS:

- This research was presented at the American Geophysics Union Annual Meeting, December 14-18 in the "Gas Hydrates: Results of Recent Field Investigations III Posters" session under the title "Heat flow and gas hydrates on the continental margin of India: Building on results from NGHP expedition 01."

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