Oil & Natural Gas Technology

DOE Award No.: DE-NT0005669

Quarterly Report

April 2009 to June 2009

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

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Prepared for:
United States Department of Energy
National Energy Technology Laboratory

July 28, 2009

Office of Fossil Energy

Progress 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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EXECUTIVE 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 third quarter was spent refining models of apparent heat flow to remove portions of the map that contained poorly constrained extrapolation. Cross sections of the study area were then extracted from the data to investigate bathymetric effects on apparent heat flow. Simple two-dimensional models of heat flow were incorporated into applicable cross sections to determine the extent of topographic heat flow bias. The results were two-fold. Firstly, there exist strong variations in heat flow where no topographic variation exists. Secondly, where topography does affect heat flow, the theoretically modeled heat flow variations are smaller than those indicated by the apparent heat flow maps.

PROGRESS, RESULTS AND DISCUSSION:

Phase 1 – Task 4, Evaluate Effects of Bathymetry on Apparent Heat Flow:

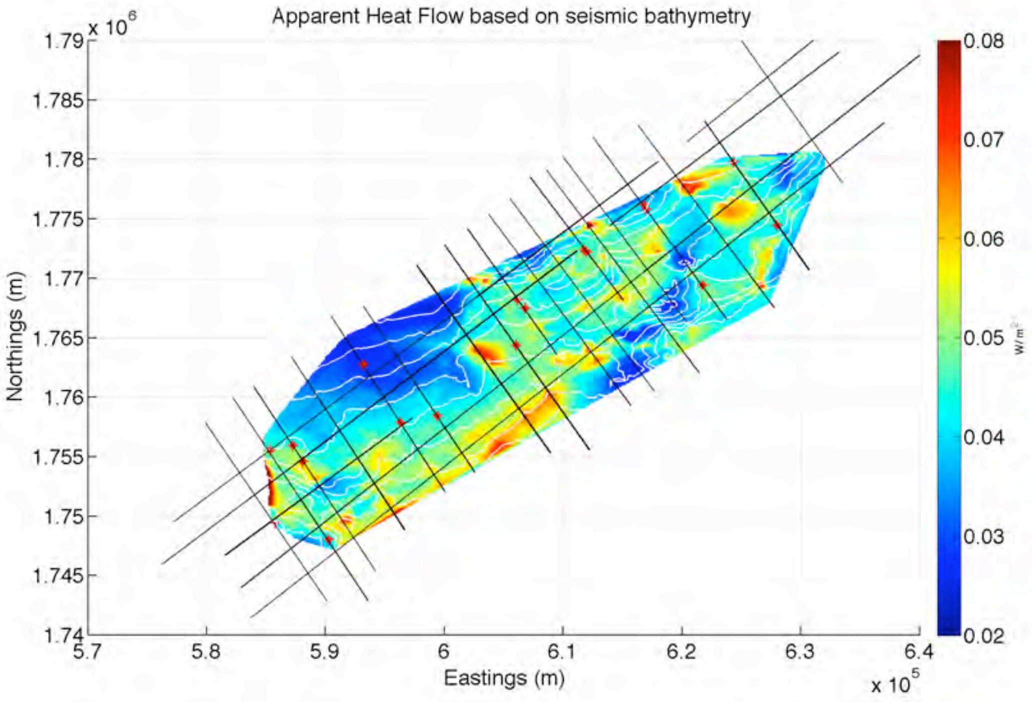

Figure 1. Updated map of apparent heat flow KG Basin. Overlain in white are isobaths derived from seismic data. Red dots indicate NGHP Expedition 01 drill sites. The previous map exhibited extrapolation errors along the periphery. These errors have been greatly reduced in the current iteration.

The map of apparent heat flow shown above was derived from topography and BSR depth as constrained by a 3D seismic survey and assumes that all heat flow is conductive and one dimensional (i.e. no lateral heat conduction is included). It also assumes that thermal conductivity and the seismic wave velocity in the sediments are constant. Work during this quarter was focused on verifying the apparent heat flow map, resulting in modification of the map around the edges to remove poorly constrained extrapolations from the data, and evaluating whether lateral variations in apparent heat flow could be explained by topography. The revised heat flow map is shown in figure 1 and 2 along with the position of drill sites. An apparent NS trough in heat flow in the western part of the study area and a basin in the northeast are better defined and show some correlation with topographic contours.

Lachenbruch (1968) developed an analytical solution for modeling the effects of topography on heat flow in two dimensions. Although the topography here is clearly 3D, we constructed 2D models to evaluate whether the effect of topography is of the correct order of magnitude to explain the observations. The results will guide further 2 and 3D numerical modeling. We extracted profiles of heat flow and bathymetry from the data set (figure 3, 4). In a purely conductive model, troughs focus heat flow while ridges diffuse heat flow.

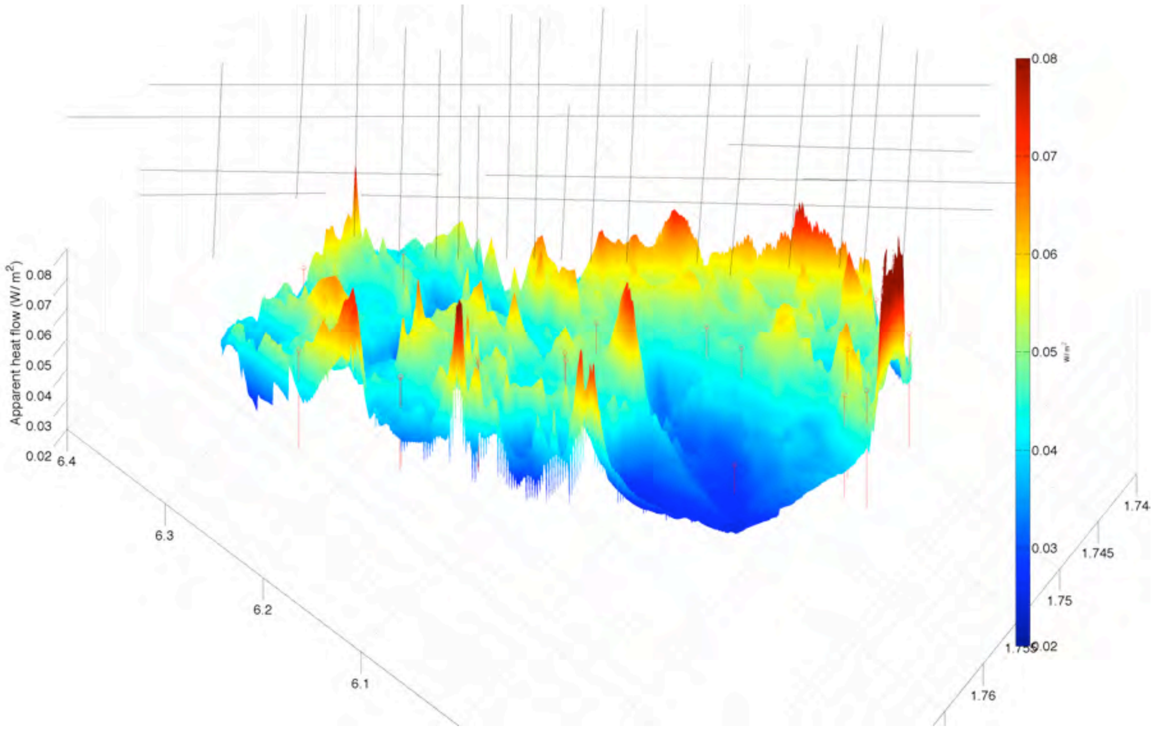

Figure 2. 3D view of apparent heat flow looking down slope from northwest to southeast above the KG basin. NGHP Exp 01 drill sites are shown as vertical red lines capped by a red circle.

Quantitatively, simplified bathymetric profiles can be used to model bathymetric effects on heat flow. Using Lachenbruch’s method for estimation of topographic disturbance of thermal gradients, we can determine where heat flow variation is the result of bathymetric changes (Lachenbruch, 1968, Ganguly, 2000). Significant departures from this estimation indicate either a thermal regime in which advection is a significant mode of heat transport and/or large variations in the thermal conductivity or seismic velocity within the sediments. Three factors affect the severity of distortion of thermal gradients by bathymetry: slope of topography, distance from slope, and vertical offset between the toe and the brink of the slope. Increased slopes and increased vertical offsets lead to higher distortion, while distortion decreases as distance from slope increases.

Profiles A, F, and D (figures 5,6 and 7 respectively) show theoretical models of heat flow derived from simplified bathymetry overlain by apparent heat flow and actual bathymetry. These three profiles were chosen because they represent three different end members of the modeling process. Profile A (figure 5) exhibits the highest slope of any of the profiles, with the heat flow being almost completely explained by topographic effects. Profile F (figure 6) exhibits topographic distortion, but is not nearly as robust as in profile A. Finally, heat flow variations occurring midslope in profile D (figure 7) cannot be explained by a conductive model. We conclude that while heat flow values across the KG basin are influenced by topographic variations, other processes are also important.

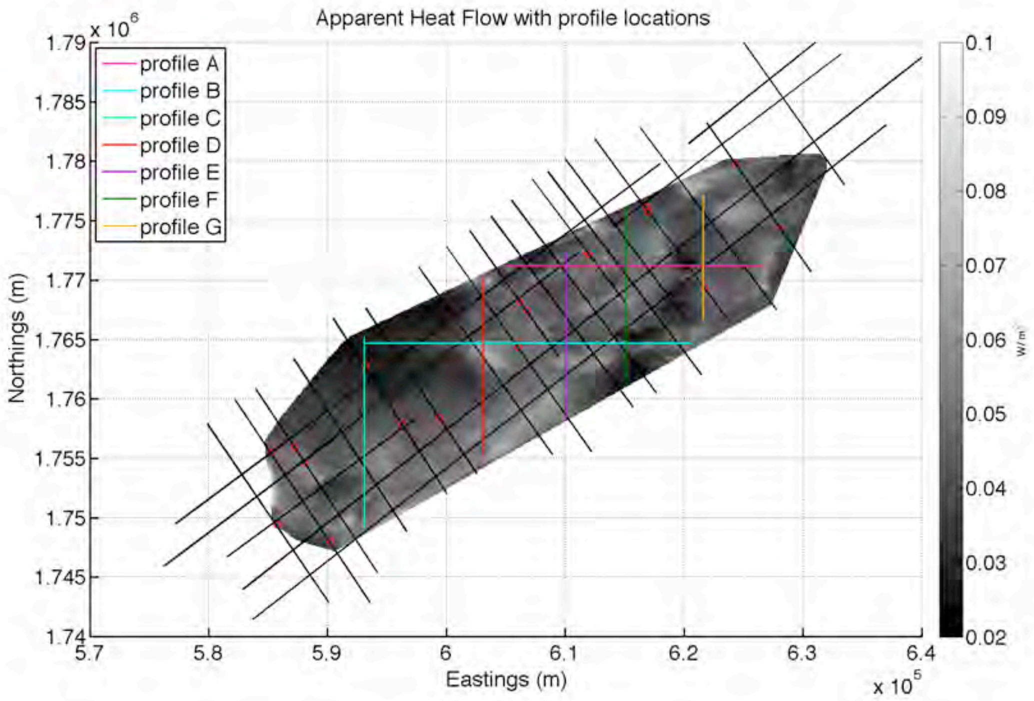

Figure 3. Graytone map of apparent heat flow in KG basin. Colored lines correspond to heat flow/bathymetry profiles in figure 4.

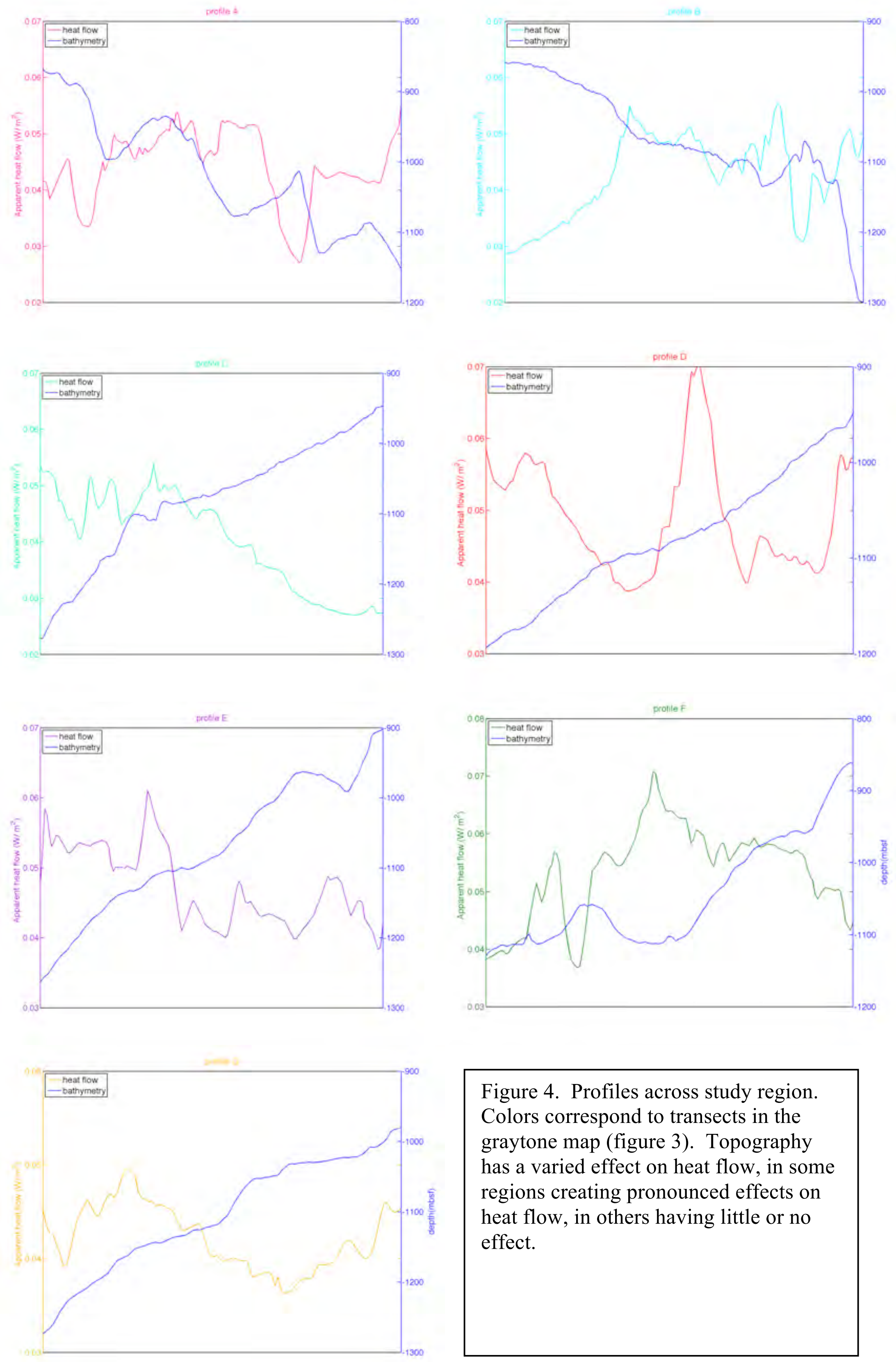

Figure 4. Profiles across study region. Colors correspond to transects in the graytone map (figure 3). Topography has a varied effect on heat flow, in some regions creating pronounced effects on heat flow, in others having little or no effect.

Drilling data taken during NGHP Expedition 01 showed an increase in heat flow with increasing depth (Trehu et al., 2008). In this study, heat flow values derived from BSR depths support this finding. When derived heat flow values from KG basin are plotted against depth, there is a clear trend of heat flow values increasing with depth (figure 8). In figure 9, these values are binned over a 50 m depth interval and plotted with the associated standard deviation. Heat flow values obtained via down hole temperature tools are plotted on this same plot. All of these values but one fall within a standard deviation of the BSR-derived heat flow. Average heat flow increases by 15 mW/m^2 over a 400 m depth increase. The average slope of study area is 1.5 degrees. In a simplified model of average bathymetry over the entire basin, using Lachenbruch's equations again, we find that average heat flow near the base of the slope should increase relative to the background heat flow by 3-4%. Using BSR-depth derived heat flow we see increases in background heat flow on the order of 15%. This would further indicate that a solely conductive model of heat flow cannot explain heat flow values as high as those derived from either BSR depth or borehole temperatures.

Additionally, it is worth noting that all but one of the borehole heat flow values lies above the average (binned) BSR heat flow trend. This is significant in that those sites were chosen for their strong BSR (among other factors), which is indicative of increased methane flux, the resultant of fluid flow.

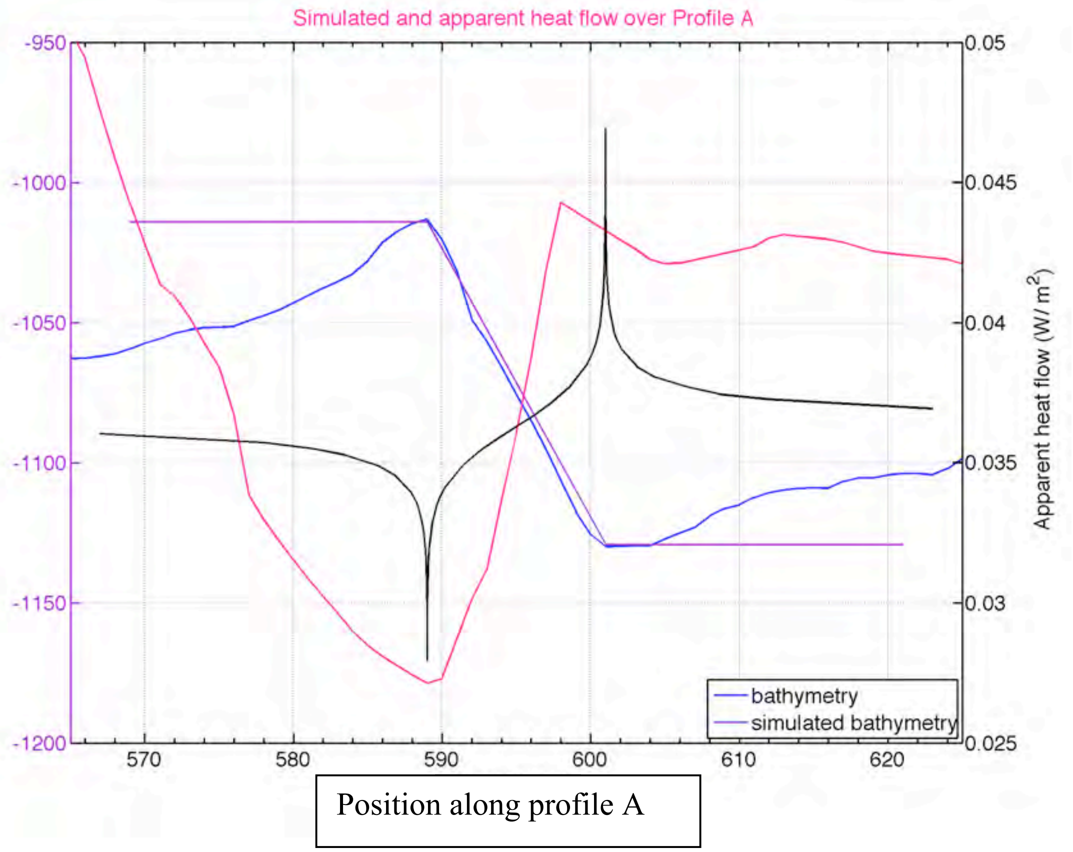

Figure 5. Bathymetric profile (blue) with corresponding apparent heat flow (magenta) overlain by expected heat flow (black) derived from simulated bathymetry (purple). Simulation derived from equations from

Lachenbruch (1968). The lateral extent of this figure represents only a portion of profile A, and was chosen to highlight the high-angle feature shown above.

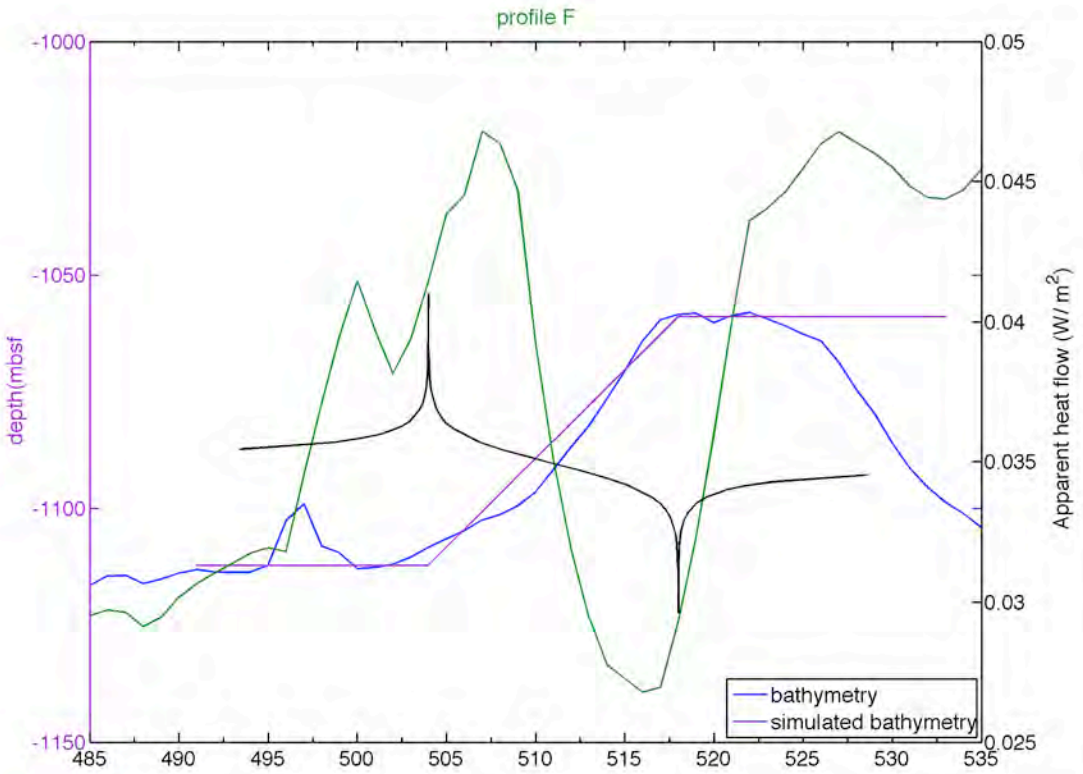

Figure 6. Bathymetric profile (blue) with corresponding apparent heat flow (green) overlain by theoretical heat flow (black) derived from simulated bathymetry (purple). Simulation derived from equations from Lachenbruch (1968). The lateral extent of this figure represents only a portion of profile F.

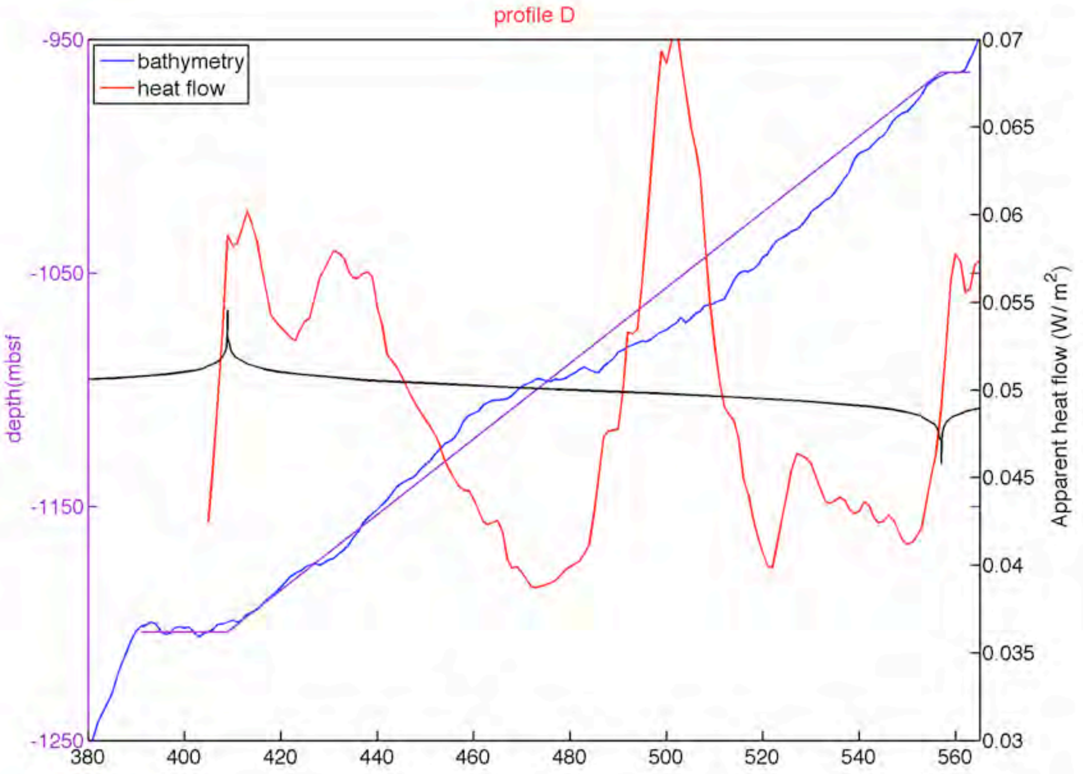

Figure 7. Bathymetric profile (blue) with corresponding apparent heat flow (red) overlain by theoretical heat flow (black) derived from simulated bathymetry (purple). Simulation derived from equations from Lachenbruch (1968). This profile shows no correlation between expected and actual heat flow values. Apparent heat flow varies considerably along the slope, which cannot be explained though topography in a conductive model. The lateral extent of this figure represents only a portion of profile D.

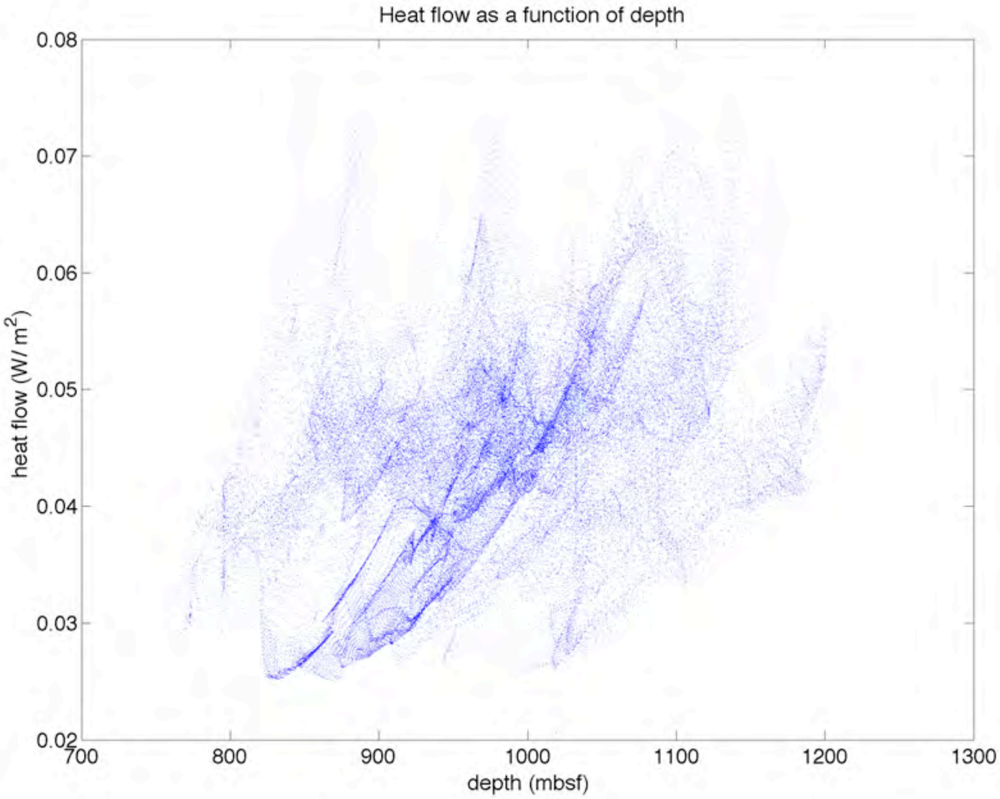

Figure 8. Cloud plot of heat flow as a function of depth for the entire study area.

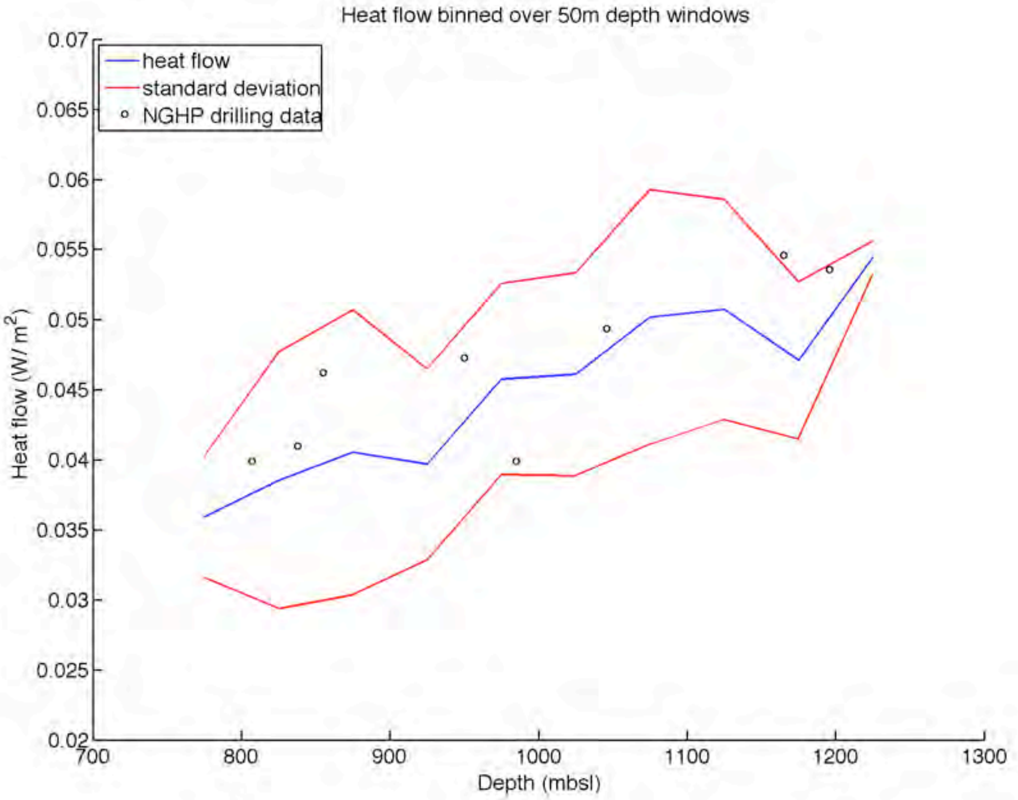

Figure 9. Heat flow as a function of depth binned over 50 meter depth windows, overlain by NGHP Exp 01 temperature tool data. All drilling derived heat flow values fall within a standard deviation of the binned data, save one. Uncertainty of the drilling-derived heat flow is estimated to be ± 0.05 W/m^2.

Phase 1 –Task 4, Evaluate Effects of Bathymetry (and sedimentation rate) on apparent heat flow:

During the 4th quarter we will evaluate heat flow in the other two study sites. Seismic data from the Mahadi Basin and Andaman Sea are limited. In the Andaman Sea, we will focus on modeling the effect of rapid sedimentation, including changes in the sedimentation rate with time, on the apparent heat flow. The anomalously low thermal gradient here results in an anomalously thick gas hydrate stability zone.

Phase 2 – Task 5, Develop Numerical Model:

All datasets have been translated into 3D to facilitate transition into phase 2.

This task is scheduled for the second year of the project provided the project goes forward after a go/no go decision based on preliminary results from Task 4. Results of the third quarter of year 1 indicate that 3D modeling is needed to explain the data. During the 3rd quarter, Kannberg took a special topic course on heat flow in the Earth to obtain the theoretical background for proceeding to this modeling phase of the project.

Phase 2 – Task 6, Interpret Modeling Results:

This task is scheduled for the second year of the project provided the project goes forward after a go/no go decision based on preliminary results from Task 4.

COST STATUS:

Table 1. Project costing profile for Budget Period 3.

	April (planned)	April (actual)	May (planned)	May (actual)	June (planned)	June (actual)
PI salary & fringe benefits	1,627	571	1,627	569	1,627	569
GRA salary & fringe benefits	2,271	2,418	2,271	2,435	2,271	2,108
Computer subscription	250	500	250	250	250	250
Travel	0	0	0	0	0	0
Postage	0	0	0	12	0	0
Tuition	0	3,132	0	0	0	0
Indirect Costs	2,160	1,612	2,160	1,519	2,160	1,352
TOTAL	9,206	8,234	6,308	4,776	6,308	4,279

PUBLICATIONS, CONFERENCE PRESENTATIONS AND OTHER PRODUCTS:

- BSR depth, and apparent heat flow maps have been updated.
- 2-d models along transects of the KG basin have been generated.

References:

Ganguly, N., G.D. Spence, N.R. Chapman, R.D. Hyndman. 2000. Heat flow variations from bottom simulating reflectors on the Cascadia Margin. Marine Geology 164, 53-68, 2000.

Lachenbruch, A. 1968. Rapid estimation of the topographic disturbance to superficial thermal gradients. Reviews of Geophysics Vol. 6, No. 3, August, 1968.

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.

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