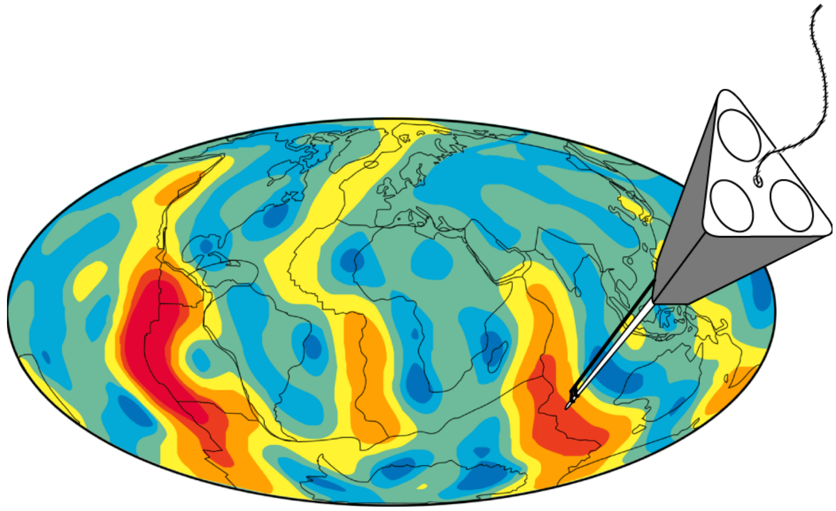

Workshop on

The Future of Marine Heat Flow:

Defining Scientific Goals and Experimental Needs for the 21st Century

Workshop dates: 6-7 September 2007
Workshop venue: Fort Douglas, University of Utah, UT

Co-conveners: R. N. Harris[1], A. T. Fisher[2], F. Martinez[3], and C. Ruppel[4]

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Contents

(Web published at http://www.coas.oregonstate.edu/Workshop/Futureof MarineHeatFlow.html)

Preface and Acknowledgements

This report summarizes discussion and recommendations from a NSF-sponsored workshop convened to assess scientific priorities, infrastructure and support models for the future of U.S. marine heat flow studies. The primary focus of the workshop was on scientific problems that can be addressed by the acquisition of shallow subseafloor thermal gradients and thermal conductivity data, collectively used to quantify conductive heat flow; however, the full scope of problems and techniques discussed extended well beyond this core approach.

This workshop was conceived with an emphasis on seafloor heat flow measurements as a result of two primary observations:

(1) Over the past decade there has been a resurgence of studies in which marine heat flow data play a critical role, including problems of fundamental importance to large national and international research programs, as well as the petroleum industry; and

(2) The U.S. academic research community no longer maintains the capability to execute seafloor heat flow surveys and is likely to lose access in the next few years to other heat flow instrumentation currently maintained outside the U.S.

Interest in holding a workshop like this one has been building within the community for several years, and the conveners and participants are grateful for the support and guidance of the U.S. National Science Foundation (NSF), which provided funds for planning, advertisement, travel, and related costs (OCE-0648146). Any opinions, findings and conclusions or recommendations expressed in this material are those of the conveners and/or workshop participants and do not necessarily reflect the views of the National Science Foundation.

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1. Executive Summary

A workshop held at the University of Utah in September 2007 addressed "The Future of Marine Heat Flow: Defining Scientific Goals and Experimental Needs for the 21st Century." The primary aims of the workshop were to assess (a) the state of science and future needs involving thermal studies focusing on seafloor heat flow data and (b) different approaches that might be adopted in the next several years to ensure that critical capabilities are maintained and accessible to the U.S. scientific community.

The specific questions addressed by workshop participants were:

(1) What are the fundamental science questions to be addressed using marine heat flow data in the next two decades?

(2) Which technical capabilities will be required to address these questions, and how can these capabilities be developed and sustained to assure access to critical instrumentation at reasonable cost?

Workshop participants were split into thematic and technical groups, and also met in plenary session, to address these questions. Discussions are summarized in greater detail in the rest of this report, but it is clear that there is a motivated community of active and successful researchers working within the U.S., as well as collaborating with colleagues from around the world, for whom acquisition and use of new marine heat flow data will be essential in order to address important scientific questions over the next two decades.

On the basis of these discussions, workshop participants compiled the following set of consensus statements.

Consensus #1:

We are currently in a period of enthusiastic and growing interest in marine heat flow. This interest is part of a larger need to resolve fundamental problems in Earth science that require knowledge of the thermal state of the Earth and of the material and energy fluxes between its various components.

Consensus #2:

Improvements in instrumentation, navigation, and modeling, the collection of complementary data sets, and new insights about the interrelated nature of seafloor properties and processes are leading researchers to reexamine numerous commonly accepted assumptions about a range of global, regional and local Earth processes.

Consensus #3:

The need for continued acquisition of seafloor heat flow data cuts across disciplines and programs.

Consensus #4:

The U.S. marine heat flow community suffers from a lack of access to capabilities for acquisition, processing, and interpretation of marine heat flow data.

Consensus #5:

There are several possible models for developing and sustaining the capability for the acquisition of marine heat flow data by researchers operating on UNOLS and other (conventional) research vessels at low cost, on a pay-as-you-go basis.

Consensus #6:

The U.S. community needs to move quickly to establish a basic capability, while there is still an opportunity to benefit from the present generation of experienced practitioners, so as to broaden the pool of researchers who can collect, process, and interpret marine heat flow data.

2. Introduction and Workshop Goals and Structure

2.1 Frontiers and Needs in Marine Heat Flow

Marine heat flow observations provide fundamental constraints on physical, chemical and biological processes occurring near and below the seafloor. Processes that influence and are influenced by heat transport within seafloor sediments and basement rocks include:

(1) the thermal evolution of the oceanic crust, lithosphere and Earth;

(2) the chemical evolution of the global ocean and regional seas;

(3) the geodynamics of plate boundaries and mantle convection;

(4) fluid circulation and associated impacts on water-rock interactions, seismicity, tectonics, and magmatism;

(5) establishment and maintenance of subseafloor microbial ecosystems;

(6) creation of ore, hydrocarbon and gas hydrate deposits; and

(7) the exchange of fluids and solutes across continental margins and its impact on the extent and quality of near-shore water and biological resources.

Understanding these processes involves the quantification of energy and fluid fluxes, requiring knowledge of the thermal state deduced from observations that include heat flow, sub-bottom temperature, and thermophysical rock properties. A selection of these topics, recent exciting discoveries, and potential future research projects involving marine heat flow are presented in Appendix 2 (http://www.coas.oregonstate.edu/Workshop/FutureofMarineHeatFlow.html) of this report. In addition to being scientifically important in their own right, these thermal processes and properties are also critical to numerous U.S. and international initiatives and programs, including the Integrated Ocean Drilling Program, MARGINS and InterMargins, RIDGE2000 and InterRIDGE, and the Ocean Observing Initiative [e.g., *COMPLEX*, 2000; *COMPOST*, 1993; *COMPOST II*, 1998; *FUMAGES*, 1997; *MARGINS*, 2003; *National Research Council*, 2003; *RIDGE 2000*].

For several decades beginning in the 1960s, the U.S. science community sustained expertise and capabilities in the collection, processing, and interpretation of marine heat flow data. As recently at the 1990s, there were active marine heat flow programs at Woods Hole Oceanographic Institution, Lamont-Doherty Earth Observatory, Scripps Institution of Oceanography, University of Texas, University of Miami, and the University of Washington, among others. None of these academic programs are currently operating, although marine heat probes are run in the U.S. commercially and in one military research lab. In addition, there are active heat flow programs within a few oceanographic and Earth science institutions in Canada, Europe and Asia. The loss of an U.S. academic community-based capability for the acquisition of marine heat flow data during conventional oceanographic expeditions resulted from several factors, including the retirement/death of experienced practitioners, shifting institutional priorities, and short-term changes in scientific emphases. Another challenge for sustaining the U.S. heat flow capability has been the perception of some members of the larger marine community that deep lithospheric problems, which were traditionally addressed with heat flow data, had been resolved or remained intractable. This perception is now challenged by new and higher resolution data, by greater understanding of the causes and significance of intermeasurement variability detected in marine heat flow data, and through theoretical syntheses that have led to reevaluation of long-standing thermal lithospheric reference models.

The last 10–15 years have witnessed a resurgence of interest in marine heat flow measurements, including the publication of numerous observational and theoretical studies of the thermal aspects of plate evolution [e.g., C. *Stein and Stein*, 1992; *Von Herzen et al.*, 2001; *Martinez et al.*, 2001; C. *Stein*, 2003; *Harris and Chapman*, 2004; *Ritzwoller et al.*, 2004; *Zhong et al.*, 2007] and geodynamics [e.g., *Harris et al.*, 2000a, 2000b; *DeLaughter et al.*, 2005; *Lucazeau et al.*, 2006; *Harris and*

McNutt, 2007; C. *Stein and Von Herzen*, 2007]. Among many researchers, there is also a growing realization that the intermeasurement variability that once seemed to undermine the widespread use of heat flow data actually provides important information about near-seafloor processes such as fluid flow [e.g., C. *Stein and Stein*, 1994; *Fisher et al.*, 2003a,b; *Fisher and Von Herzen*, 2005; *Grevemeyer et al.*, 2004; *He et al.*, 2007; *Stein and Fisher*, 2003; *Villinger et al.*, 2002; *Von Herzen*, 2004; *Wilson*, 2003, 2005; *Wheat et al.*, 2004], gas hydrate stability conditions, sediment dynamics, and oceanographic phenomena [e.g., *Ruppel et al.*, 1995; *Grevemeyer et al.*, 2003; *Hutchinson et al.*, in press; *Ruppel et al.*, 2005; *Hanamoto et al.*, 2005]. Today, heat flow data are commonly co-located with seafloor/subseafloor mapping, reconnaissance seismic surveys, and geochemical analyses of core material. Joint analyses of these data sets are providing insights into sources of variability stemming from both measurement uncertainties and processes, as well as ways to isolate components of these processes. New computer models allow the simulation of complex, coupled processes (tectonic-hydrologic-magmatic-biological-chemical-thermal) and yield hypotheses that can, in part, be tested by heat flow data. The renaissance of interest in marine heat flow mirrors the shift to multidisciplinary approaches to science problems in the wider community, as well as the terrestrial hydrologic community's recent focus on using heat transport as a tracer of other processes [e.g., *Anderson*, 2005; *Constantz and Stonestrom*, 2003].

To respond to the growing demand and decreasing U.S. capabilities to acquire heat flow data, U.S. practitioners have increasingly relied on relationships with non-U.S. collaborators (e.g., E. Davis of Pacific Geoscience Center, K. Louden of Dalhousie University) who maintain and operate heat flow instrumentation and have made it available at nominal cost. However, shifting scientific priorities in Canada and pending retirements threaten the availability of non-U.S. instrumentation. Furthermore, the U.S. geoscience community cannot reasonably expect to continue depending on foreign equipment and expertise for the next one to two decades. The few commercial operators of heat flow instrumentation are expensive to contract and in demand by the petroleum industry. The NRL owns and operates modern heat flow instrumentation, but making this equipment available to the community at large has proved impractical. Active heat flow programs continue at oceanographic and Earth science institutions in Canada, Europe (Germany, Italy, Spain, and the U.K.), and Asia (particularly Japan and China, and increasingly in South Korea and Taiwan) but access to instrumentation and interaction with collaborators requires identifying joint projects, navigating multiple (often simultaneous) funding pathways, and coordinating international ship scheduling priorities.

Ironically, recent use of Canadian instrumentation by several U.S. researchers has demonstrated that these systems can be operated by trained scientific personnel and their students on modest budgets and without requiring expensive shore-based or at-sea technical support. While making heat flow measurements will likely never be as routine on UNOLS ships as towing a magnetometer, neither must thermal surveys require a dedicated staff of engineers and operators, as do deep-submergence or some coring facilities.

The U.S. geoscience community has reached a critical point in its efforts to maintain a marine heat flow capability. Many participants at the workshop expressed strong interest in using marine heat flow observations to address scientifically important questions in the next two decades. However, a lack of knowledge about instrumentation and perceived lack of community expertise often impedes these researchers. Similarly, a core group of practitioners with experience in collection of marine heat flow data want to bring their expertise to high-priority research programs focused on fundamental scientific questions, but the lack of access to U.S. instrumentation frustrates these efforts. Numerous early- to mid-career scientists and students do not have experience with either data acquisition or interpretation. This is occurring against a backdrop of significant improvements in the availability and quality of navigation, mapping, seismic and other oceanographic technologies that allow thermal data to be more fully exploited and analyzed in new and exciting ways.

2.2 Workshop Goals and Structure

Thirty-eight researchers, educators, and technologists gathered for two days at Fort Douglas on the University of Utah campus in Salt Lake City, Utah, to discuss the future of U.S. marine heat flow studies. Workshop participants (Appendix 1, http://www.coas.oregonstate.edu/Workshop/FutureofMarineHeatFlow.html) came from the U.S., Canada, Germany, France, Japan, and Korea and represented many subdisciplines, including numerical modeling of geodynamical and fluid flow processes, subseafloor microbiology, and continental geothermics. Participants included representatives from universities, research institutions, U.S. government research labs, and the private sector. Of the workshop participants, more than 20% were graduate students, 15% were post-docs or junior faculty/early career scientists, and about 75% had not made seafloor heat flow measurements themselves, although they were keenly interested in using these data in their research. The broad range of disciplines and experiences represented among workshop attendees led to creative, energetic, and inspiring discussions.

The primary aims of the workshop were to look towards the next two decades of scientific research, assess the importance of marine heat flow measurements in resolving critical questions, document the technical capabilities needed by the U.S. community, and discuss funding models to sustain this capability. Prior to the workshop, participants were invited to contribute abstracts detailing a scientific or technical issue related to marine heat flow (Appendix 2, http://www.coas.oregonstate.edu/Workshop/FutureofMarineHeatFlow.html), and during the workshop many participants displayed posters outlining recent research.

While at the workshop, group discussion focused on two specific questions:

1) What are the fundamental science questions to be addressed using marine heat flow data (among other information and methods) in the next two decades?

2) Which technical capabilities will be required to address these questions, and how can these capabilities be developed and sustained to assure access to critical instrumentation at reasonable cost?

Workshop participants were split into thematic and technical groups and also met in plenary session to address these questions. The workshop schedule and general structure are listed in Appendix 3 (http://www.coas.oregonstate.edu/Workshop/FutureofMarineHeatFlow.html). Discussion during the first day focused on important scientific questions, within thematic and plenary groups, but the final section of the day included a brief presentation of tools used by several workshop participants during recent heat flow surveys. Discussion during the second day focused on technical aspects of developing and maintaining a heat flow capability within the U.S. community.

3. Thematic Discussions

Workshop participants were divided into three groups to facilitate thematic discussions, with recognition that there would be some overlap between the groups. Participants were free to circulate among the three groups, and each group reported back to the workshop as a whole, which engaged in plenary discussion of these topics. The three discussion groups were:

- thermal evolution of oceanic lithosphere;
- geodynamics; and
- advective and sedimentary systems.

3.1 Thermal Evolution of the Oceanic Lithosphere

Early studies in marine heat flow were concerned with the heat loss of the earth. The identification of higher heat flow on ridges compared to the abyssal plains [*Von Herzen*, 1959] was important for the development of ideas about seafloor spreading. Subsequently, heat flow became an important data set to understand the formation of the oceanic lithosphere.

Oceanic reference models, derived by joint inversion of both heat flow and seafloor depth data as a function of seafloor age, provide simple parameterizations of the thermal evolution of oceanic lithosphere [*Davis and Lister*, 1974; *Parsons and Sclater*, 1977; C. *Stein and Stein*, 1992]. These models provide both a uniform and consistent framework to describe the average seafloor depth and heat flow and to predict the thermal structure of the lithosphere as a function of depth and age. Reference models provide a mechanism for determining if the heat flow or bathymetry of an area is typical or anomalous relative to other areas sharing similar characteristics (e.g., age, spreading age, sediment thickness, etc.) and also a basis for constraining processes that may produce the anomaly. The success of a lithospheric reference model can be judged by its ability:

- to describe the data used to derive it (e.g., heat flow and bathymetry);
- to predict other age dependent data sets such as the geoid, geoid slope, seismic velocities, and mechanical properties (earthquake depths and flexure due to loading); and
- to isolate and describe anomalous areas that can then be interpreted in terms of Earth processes.

In this way lithospheric reference models have important implications for interpretation of physical and chemical processes involved with lithospheric formation and evolution.

Reference models may be divided into three categories. The simplest, a cooling half-space model [e.g., *Davis and Lister*, 1974], assumes a constant temperature at the base of a lithosphere proportional in thickness to the square root of the plate's age. The somewhat more complex cooling "plate" model [*Langseth et al.*, 1966; *Parsons and Sclater*, 1977; C. *Stein and Stein*, 1992] assumes a constant basal temperature at a specified depth. Alternatively, the base of the plate may be described by a constant basal heat flux [*Doin and Fleitout*, 2000; *Dumoulin et al.*, 2001]. These models describe many first-order features but do not capture the full complexity of either the observed data or the thermal evolution of plates. For example, half-space models systematically over predict seafloor depths and under predict heat flow at ages greater than about 80 million years, while the plate model assumes no further cooling once the plate has reached an asymptotical thickness (Box 1). All of these models impose highly idealized boundary conditions at the spreading centers and assume monotonic cooling with age, which may not capture variations in depth, heat flow, and geoid presumably arising due to variations in thermal evolution.

While models describing the thermal evolution of oceanic lithosphere fit first order features, observations related to plate cooling, many processes influencing the thermal state of plates remain poorly understood [e.g., *McNutt*, 1995]. These include processes adding heat to the base of the lithosphere due to possible large-scale mantle upwelling or shallow mantle processes that reheat the lithosphere. Other questions involve how to integrate depth-dependent parameters such as thermal conductivity and diffusivity and how additional data such as the geoid slope [e.g., *DeLaughter et al.*, 1999] and seismic velocities [e.g., *Ritzwoller et al.*, 2004] may be used as additional constraints on cooling models. The significance of this

Box 1. Lithospheric Reference Cooling Models and Implications for Hydrothermal Circulation

Seafloor heat flow is the most direct measure of the thermal structure of oceanic lithosphere. Seafloor bathymetry provides an integrated measure of temperature between the seafloor and the base of the lithosphere.

These two data sets have been used to develop reference models of lithospheric cooling (Figure 1.1a, b). While these models are simplistic, they provide a convenient description of seafloor cooling and subsidence.

Two features of the plate model fit to mean heat flow data are noteworthy (Figure 1.1b, c)

(1) On young seafloor (< 65 Ma) the mean values of heat flow are significantly less than predicted values, and variability is large (Figure 1.1b). This pattern is interpreted in terms of hydrothermal circulation and advective heat loss and arises because fluid flow removes significant amounts of heat through bare rock environments where conventional heat flow surveys are not possible (inset Figure 1.1b and Section 4.2.3). The variability reflects changing sediment thickness and the heterogeneity of fluid flow in a fractured media. Assuming that the difference between mean and predicted values is entirely due to hydrothermal circulation provides an estimate for global advective heat loss [e.g., *Stein and Stein*, 1994].

Hydrothermal circulation is commonly conceptualized in terms of crustal age, with the fraction of heat lost by hydrothermal circulation (Figure 1.1c) decreasing from the ridge crest until the plate is ~65 million years old. At greater ages it is assumed that little or no heat is convectively removed. However, crustal age is only a proxy for flow limiting processes such as evolution of permeability and sediment thickness. A more direct approach to understanding advective heat flow and its evolution is through a better understanding of the differences between forces driving and impeding fluid flow.

(2) On old seafloor (> 65 Ma) significant variability in heat flow remains. This variability is interpreted as indicating the persistence of hydrothermal circulation persists in some old lithosphere, with about one third of the survey sites on old crust having evidence of hydrothermal circulation [*Von Herzen*, 2004] (Figure 1.2). The interplay of crustal permeability, sediment thickness, and bathymetric relief influence the evolution of hydrothermal circulation. How this circulation changes as crustal and sediment properties evolve with age remains a fundamental question.

debate is indicated by recent analyses using larger and higher-resolution data sets and by frequent publication of papers in high-profile journals addressing these and related questions [e.g., *Hillier and Watts*, 2005; *Huang and Zhong*, 2005; *McKenzie et al.*, 2005; *Crosby et al.*, 2006; *Zhong et al.*, 2007; *Korenaga and Korenaga*, in press].

It was recognized during some of the first regional and global analyses that heat flow data from younger seafloor tended to be lower than expected and that inter-measurement variability could be extreme [*Lister*, 1972; *Sclater*, 2004]. These observations were initially interpreted as experimental uncertainty and noise, but are now understood to result mainly from the redistribution of lithospheric heat by fluid circulation in the oceanic crust (Box 1) and other shallow processes. Detailed heat flow surveys along with geochemical and direct observation of fluids exiting from the seafloor show the effects of hydrothermal circulation on and near ridge axes (Box 2).

Hydrothermal circulation within the crust evolves from advective heat extraction characterized by fluids flowing between the crust and ocean to the redistribution of heat within the crust as low permeability sediments isolate the crustal aquifer from the overlying ocean. Both processes result from crustal heating, high basement permeability, and rapid fluid flow within the crust. Widespread heat advection continues to pose challenges to the development of a lithospheric reference model because this process prevents use of heat flow data from young seafloor as a primary constraint. A better understanding of the evolution of fluid flow through oceanic crust and its impact on young seafloor is a rich research area and important for understanding older seafloor as well.

There is a small but vocal group of researchers who question the fundamental premises of the most widely accepted models, particularly the use of a thermal lithospheric reference that deviates significantly from

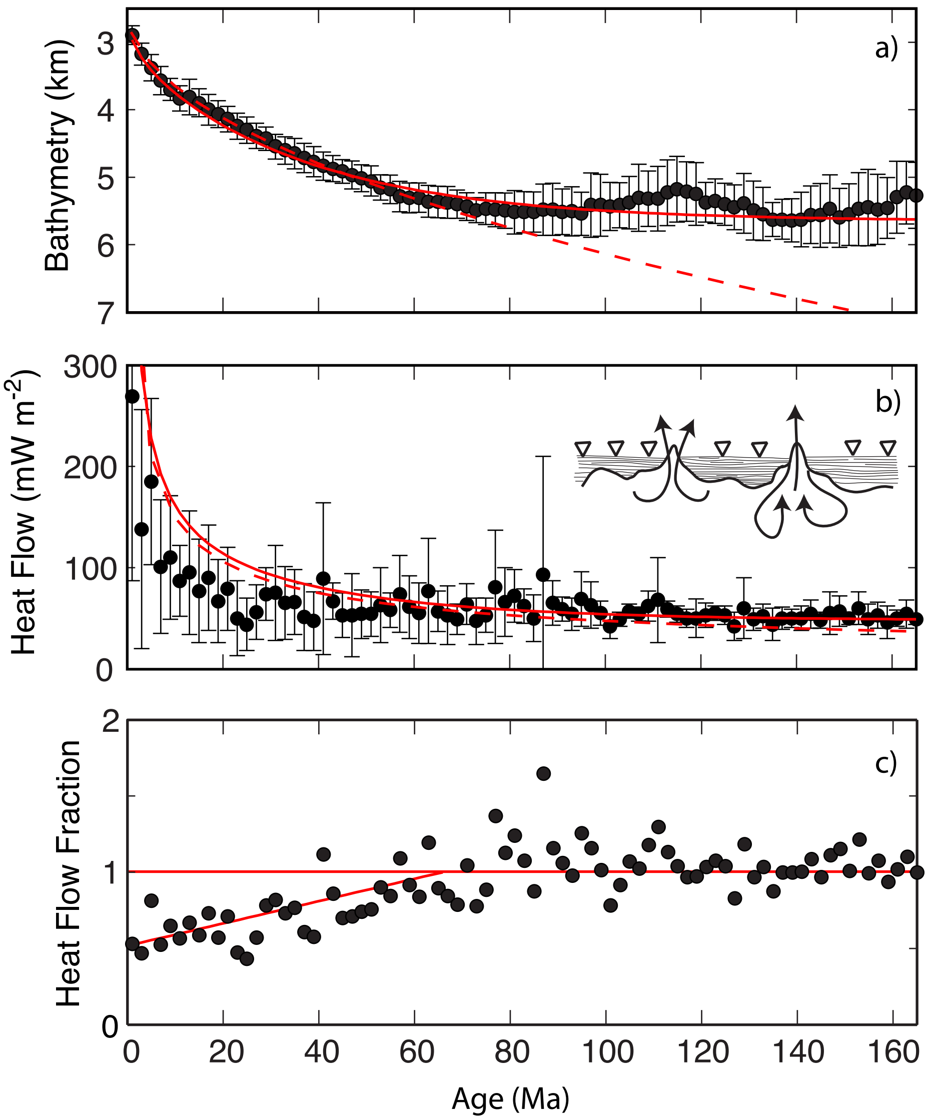


Figure 1.1

Data and reference models for ocean depth and heat flow as a function of age. Solid line shows GDH1 model [*Stein and Stein*, 1992] and dashed line shows half space cooling model. Data are averaged in two-m.y. bins, and one standard deviation about the mean value is shown.

Middle panel inset shows that heat deficit arises because conventional measurements are made in sediment ponds or between exposed areas of basement where fluid discharge carries lithospheric heat away.

Bottom panel shows fractional heat flow. Fractional heat flow increases as a function of age to one at 65 ± 10 Ma where it is presumed that on average advective heat loss ceases [*Stein and Stein*, 1994].

observations on young seafloor. For example, *Hofmeister and Criss* [2005] suggest instead that convective heat transfer is not significant in young crust, meaning that the measured heat flow values represent the true lithospheric heat flow. They argue that Earth's heat loss is about 25% less than expected using reference cooling models, which has important implications for the thermal and compositional state of the earth's interior. *Von Herzen et al.* [2005] however nicely summarize the multidisciplinary evidence for large fluxes of energy and mass resulting from hydrothermal circulation. Although there are genuine disagreements between researchers currently addressing these topics, all would agree that the development of a lithospheric reference model integrating not only heat flow and depth, but also seismic, geoid, and mineral physics, is fundamentally important, both to assess how oceanic lithosphere is created and evolves and to help in resolving questions involving tectonic, magmatic, advective, and other processes.

Resolution of geodynamic questions requires acquisition of new, high-quality heat flow data from many areas. Many thermal data sets are of limited use in resolving these questions because the thermal observations lack well navigated, co-located bathymetric and seismic data sets that allow understanding of the local and regional context.

Key questions related to lithospheric reference models include:

- What are the values and distribution of physical properties influencing the thermal evolution of oceanic lithosphere, including thermal conductivity, heat

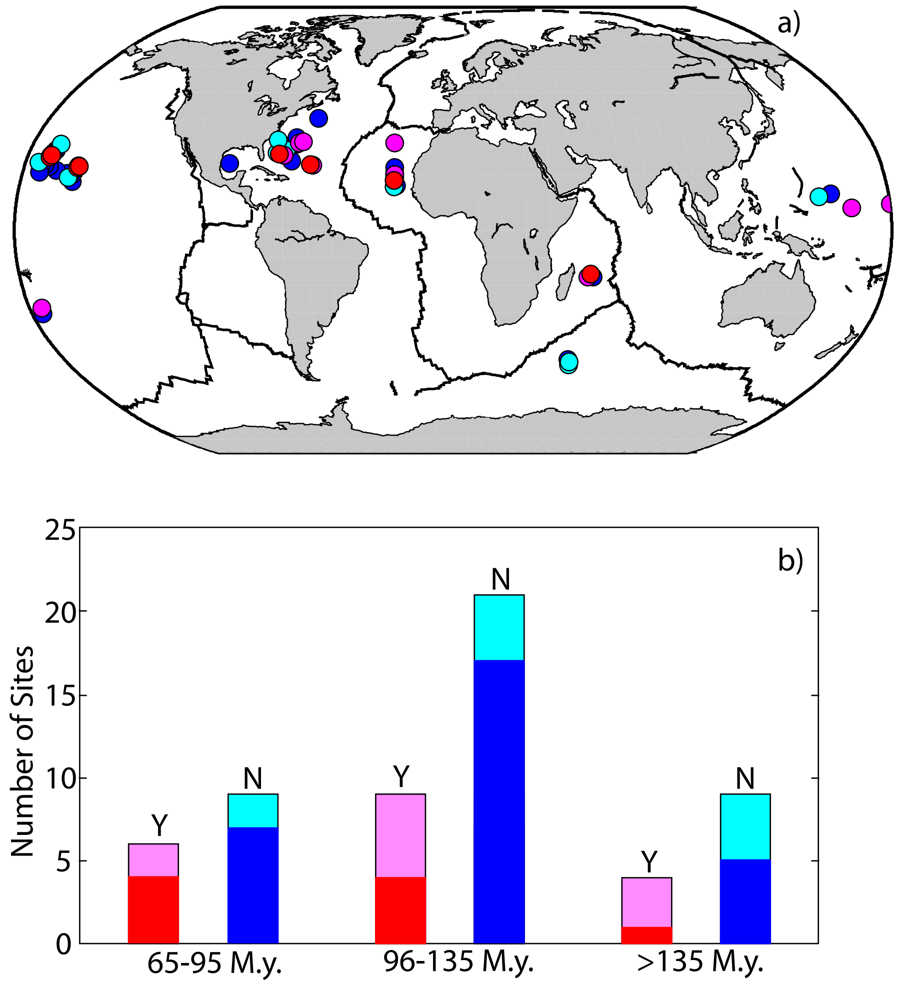


Figure 1.2

Evidence for advective fluid flow on old (> 65 Ma) seafloor [Modified from *Von Herzen*, 2006].

a) Location of marine heat flow surveys on old seafloor.

b) Number of surveys with and without evidence of hydrothermal circulation.

Red indicates sites with heat flow data indicative of advective heat transfer; magenta indicates sites with less conclusive evidence for hydrothermal circulation.

Blue indicates sites with heat flow data indicative of conductive heat transfer; cyan indicates sites with less conclusive evidence for conductive heat transfer.

capacity, thermal expansivity, strength, and seismic properties (particularly used as a proxy to determine other properties)?

- What are the fluxes of heat and mass between the lithosphere and the ocean?
- What is the distribution of lithospheric heat sources and sinks that influences both the evolution of tectonic plates and the thermal observations made at the seafloor and used to interpret lithospheric evolution? These might include solid earth components (e.g., heat input from below the lithosphere, underplating of lithospheric material), geochemical reactions that result in heat production within and below the crust, or even microbiological processes within the subseafloor biosphere.
- What causes variations in oceanic lithospheric heat flow with depth, such as those documented in Hole 504B (in the eastern equatorial Pacific Ocean), where heat flow decreases by ~50% below a fault [*Guerin et al.*, 1996]?
- What is the nature of the transition between spreading center, near-ridge, and ridge-flank thermal processes, and how are we to resolve the influence of transient, spatially distributed processes operating at different stages of lithospheric evolution?
- What is the significance of initial thermal conditions assumed at spreading centers in lithospheric cooling models? Are these conditions physically plausible, and how well constrained do they need to be in order to understand lithospheric evolution?
- Which data should be included in an integrated lithospheric reference model, and which data should be utilized to constrain model fit? How should spatially and temporally complex data be combined, filtered, or binned so as to provide a robust test of model applicability?

Box 2. Oceanic crustal hydrogeology: Heat flow data constrain hydrothermal flow paths between outcrops across 50 km on a young ridge flank

Oceanic crustal hydrogeology: Heat flow data constrain hydrothermal flow paths between outcrops across 50 km on a young ridge flank

Important questions in oceanic crustal hydrogeology that can be addressed using marine heat flow data, in conjunction with other data types, include:

- How does the vigor of hydrothermal circulation vary as a function of crustal permeability, basement relief, and variations in sediment thickness?
- What is the interplay between basement relief and sediment in isolating subseafloor aquifers from the overlying ocean?
- Across what distances and to what depths are fluid and heat transported, and what properties and processes control the length and depth scales of circulation?
- How do transmissive and storage properties evolve with continuing hydrothermal circulation as plates age, and how do these properties relate to crust alteration and other characteristics of the rock record?
- How do hydrothermal flows evolve as plates age, including changes in rates, patterns, and residence times?

Heat flow data from the eastern flank of the Juan de Fuca Ridge help to quantify the direction and rate of hydrothermal circulation in the oceanic crust, and provide critical constraints on basement hydrogeologic properties when used to calibrate coupled models (*Fisher et al.*, 2003a; *Spinelli and Fisher*, 2004; *Hutnak et al.*, 2006). Heat flow data collected adjacent to two basement outcrops on 3.5 Ma seafloor (Figure 2.1a) provide critical information: Heat flow rises abruptly from regional background values adjacent to a discharging outcrop (Figure 2.1b, Baby Bare), and drops abruptly adjacent to a recharging outcrop ~50 km to the south (Figure 2.1c, Grizzly Bare). Basement isotherms calculated from heat flow and seismic data are warped upward at Baby Bare and downward at Grizzly Bare.

Analytical calculations show that hydrothermal circulation between these outcrops can be driven by a "hydrothermal siphon" that sustains fluid flow on the basis of pressure differences between recharge and discharge sites.

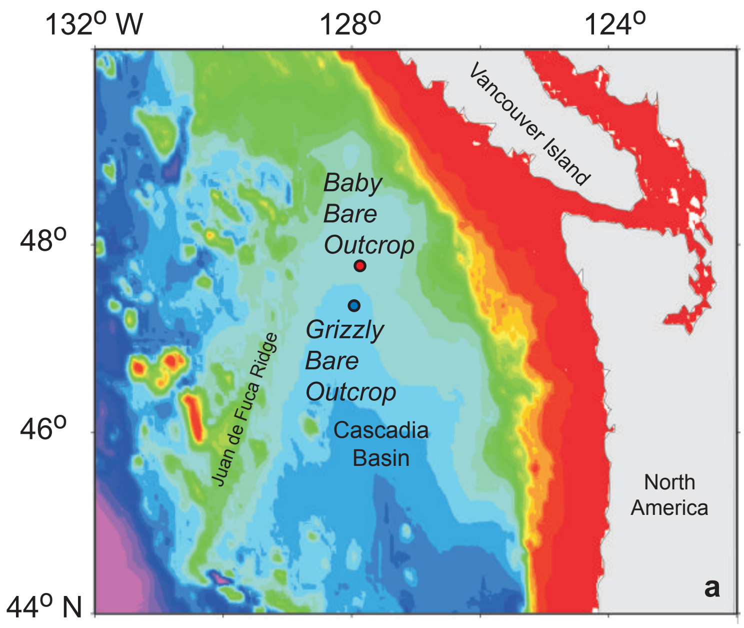
Numerical calculations show that fluid fluxes consistent with independent estimates are sufficient to match seafloor heat flow and basement temperature patterns, and require effective basement permeabilities on the order of 10^{-11} to 10^{-10} m^2.

3.2 Geodynamics

Active plate tectonic and mantle convection processes alter the flow of heat through the lithosphere relative to reference models (see Section 3.1) or regional values. Marine heat flow data can provide a quantitative measure of these perturbations and therefore help to discriminate between models of the underlying processes. A long-standing challenge has been to separate geodynamically induced, lithospheric heat-flow anomalies from surficial perturbations caused by environmental factors such as seasonal or climatic changes in bottom water temperature (BWT), sedimentation, heat refraction due to relief on the seafloor, sub-seafloor sediment and basement layers, and hydrothermal fluid flow. New instrumentation and techniques, and the use of multiple complementary data sets to assess and remove environmental effects, have made it possible to address many geodynamic problems with heat flow studies. During the workshop, the geodynamics group divided their discussions on the basis of tectonic settings, beginning with lithospheric creation, rifting and back-arc processes, and extending through transform faults and fracture zones, subduction processes, hotspots and seamounts.

Discussion of models for the construction of the lithosphere included the distribution and mechanisms of crustal cooling. Some recent seismic studies have suggested that crustal isotherms may be near-vertical and very closely spaced in the near-ridge area, perhaps extending to the base of the crust and into the upper mantle [*Dunn et al.*, 2000]. Other recent studies have suggested

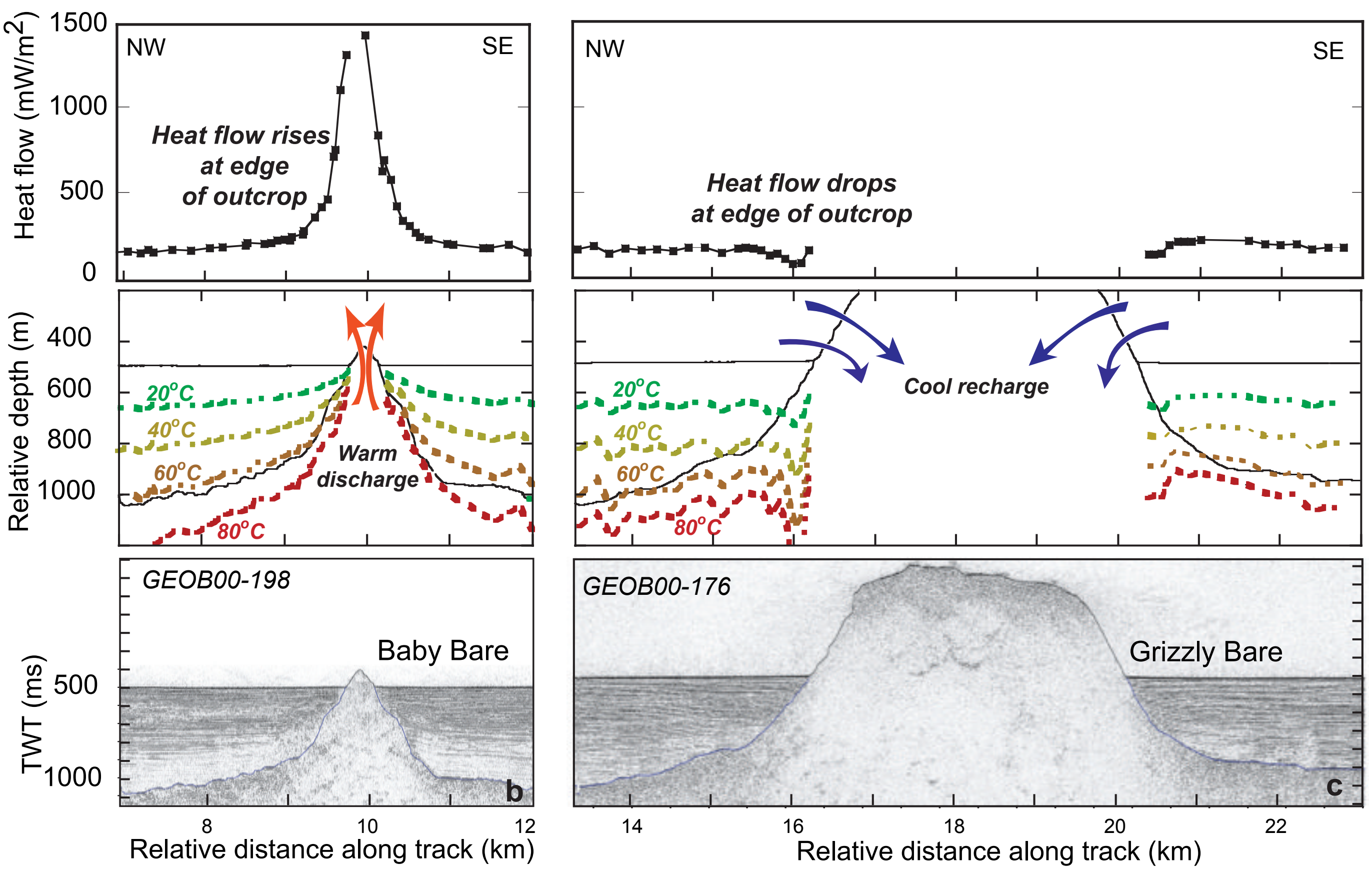
Figure 2.1



a) Regional bathymetric map of the Juan de Fuca Ridge and Cascadia Basin, northeastern Pacific Ocean.

b) Seismic reflection, heat flux, and calculated isotherms across Baby Bare outcrop. Calculated isotherms at outcrop edge are swept upward by discharging hydrothermal fluids.

c) Seismic reflection, heat flux, and calculated isotherms across Grizzly Bare outcrop. Calculated isotherms at outcrop edge are swept downward by recharging seawater..



that mantle flow and magmatic emplacement mechanisms may be highly asymmetric about spreading centers [*Toomey et al.*, 2007]. Additional important questions concern relationships between ridge segmentation, mantle flow and magmatic and heat input from depth [*Carbotte et al.*, 2004]. All of these models have thermal consequences that should be resolvable with marine heat flow measurements.

A critical challenge in addressing these topics with marine heat flow measurements is the lack of nearly continuous sediment cover at most normal seafloor spreading centers. As discussed in Section 4.2.3 on alternative and transformative instrumentation, assessing the distribution and timing of thermal output at most bare-rock spreading centers goes beyond the capabilities of conventional marine heat flow probes. However, there are environments in which conventional marine heat flow surveys can contribute to understanding the construction of oceanic lithosphere.

First, at sedimented spreading centers, such as Guaymas Basin and Middle Valley, conventional heat flow measurements can be used to assess the thermal budget of lithospheric creation, although the extent to which thermal and other processes in these areas are influenced by high sedimentation rates is an important component to understanding this environment. Similar studies might be planned for selected back-arc basins, where proximity to continents or other sediment sources may provide suitable environments for geothermal probes.

Second, in areas of high sedimentation rates but otherwise normal lithosphere (e.g., Alarcon Basin, northern East Pacific Rise), heat flow measurements have important implications for understanding near-ridge and on-ridge processes. Additional opportunities exist in areas where a ridge is propagating, but seafloor spreading and the emplacement of bare rock has not yet occurred.

Finally, measurements on ridge flanks following sedimentation can lead to important insights concerning the depth extent and efficiency of advective heat extraction and thermal rebound.

Marine heat flow should be used as one part of a broad suite of measurements along lithospheric flow lines so as to constrain the thermal evolution of a plate. Thermal studies investigating processes of oceanic rifting, including the nature of the transition between continental and oceanic lithosphere, are fundamental to understanding lithospheric deformation (Box 3). Finally, economically important links between rifting processes, the thermal evolution of passive margins, and the development of hydrocarbon, gas hydrate and ore deposits remain a scientifically and societally important area of research.

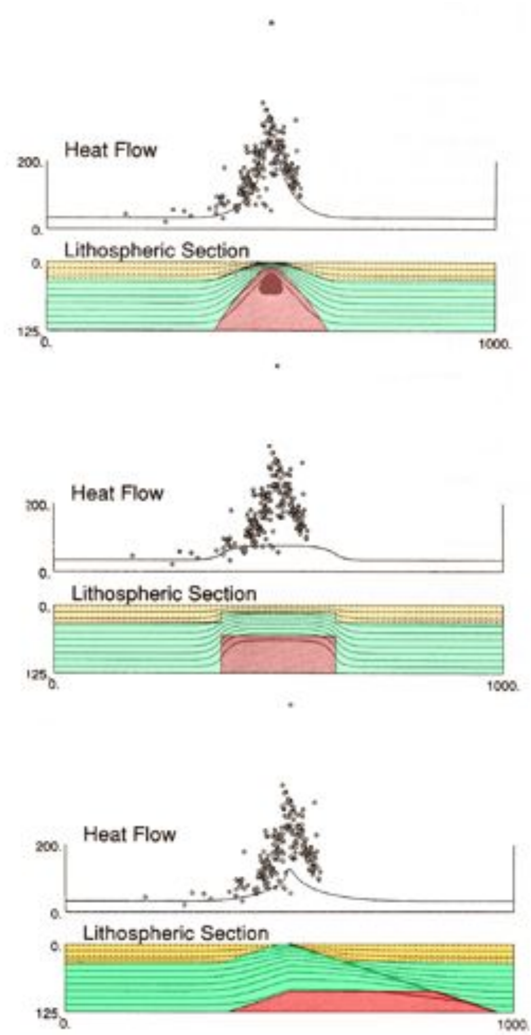
Although transform faults and fracture zones are fundamental to the thermal and mechanical architecture of oceanic lithosphere, relatively few marine heat flow data have been collected within or adjacent to these structures [*Langseth and Hobart*, 1976; *Fisher et al.*, 2003b; *Hutnak et al.*, 2007]. Strike-slip faults on land often pose significant human hazards, but resolving the thermal-tectonic relations in these continental settings is extremely complex because of the confounding influence of crustal heterogeneity and the difficulty of making systematic, closely spaced thermal measurements along different intervals of active, inactive, and creeping fault sections. Because oceanic transforms are relatively simple compared to continental strike-slip fault systems, they comprise important locations to test competing models of fault strength and friction, heat generation during seismic and aseismic events, and the thermal signature resulting from juxtaposition of lithosphere of different ages (Box 4). There are also issues to be resolved involving the magmatic transition between offset ridge segments and the extent to which the thermal signature of this offset is expressed along transforms. Transform faults and fracture zones may also allow access of fluids into the deep crust and mantle, facilitating serpentinization and associated volume changes and release of exothermic heat. As in the case of issues involving lithospheric creation, judicious selection of experimental locations and collocation of critical affiliated data (swath-mapping, seismic profiling, etc.) are important components of a program to advance understanding transform and fracture zone processes using marine heat flow observations.

Seafloor heat flow data have an enormous role to play in understanding subduction processes [e.g., *Hyndman and Wang*, 1993; *Peacock and Wang*, 1999; *Oleskevish et al.*, 1999; *Moore and Saffer*, 2001; *Currie et al.*, 2002; *Von Herzen et al.*, 2001]. Marine heat flow data provide the most direct evidence of the thermal state of the plate prior to subduction and therefore help constrain initial conditions for thermal models of subduction (Box 5). The thermal state of the incoming plate may vary along strike due to hydrothermal circulation and the presence or absence of basement outcrops, and other features unrelated to subduction itself [*Harris and Wang*, 2002; *Newman et*

Box 3. Neotectonics and heat flow measurements

Tectonic deformation of the lithosphere creates transient thermal perturbations that can have distinctive spatial patterns discernable by near surface heat flow measurements. For example, the northern Red Sea is undergoing active extension and is at a late stage of continental rifting and transition to organized seafloor spreading. Heat flow measurements across the northern Red Sea (small circles) form a prominent peaked high near the center of the rift (Figure 3.1) and were used to examine the form of lithospheric extension. In the numerical models (Figure 3.1) the far-field opening is the same in each case but the geometry of extension varies. Extension and thinning of the crust (yellow) and sub-crustal lithosphere (green) is accommodated by flow of asthenosphere (red) to fill in the space and isotherms (fine lines) are calculated using a finite difference method. Extension across a lithospheric-scale detachment fault (bottom panels) predicts a narrow and low amplitude peak (solid curve) significantly lower than observed values. Pure shear extension in a widening zone (middle panels) predicts a broad low-amplitude high which also does not match observed values. Pure shear lithospheric extension within a focusing zone of extension (top panel) can match the observed heat flow pattern and also predicts the development of a zone of partial melt (dark red) in agreement with observed intrusions. [modified from *Martinez and Cochran*, 1989]. The heat flow measurements were compared to predicted patterns caused by various numerical modes of "pure shear" and "simple shear" lithospheric stretching.

Figure 3.1



Panels show 2-D finite difference calculations of the surface heat flow (solid line, in mW/m^2) generated by varying forms of lithospheric extension. Length units are km. The lithospheric cross sections each model 140 km of total extension at a rate of 1 cm/year within a 250 km total rift width, appropriate for the northern Red Sea rift. Small circles are measured marine and terrestrial heat flow values. Top panel show a case in which the zone of active extension narrows progressively with time focusing extension to the center of the rift; middle panel shows results for a widening zone of active pure shear extension yielding uniform thinning within the rift; bottom panel shows results for simple shear extension across a lithospheric-scale detachment fault dipping at 15 degrees. The case of a narrowing zone of active extension with time (top panel) best matches the observed heat flow pattern. Figure modified from *Martinez and Cochran* [1989].

5 Ma) significant variability in heat flow remains. This variability is interpreted as indicating the persistence of hydrothermal circulation persists in some old lithosphere, with about one third of the survey sites on old crust having evidence of hydrothermal circulation [*Von Herzen*, 2004] (Figure 1.2). The interplay of crustal permeability, sediment thickness, and bathymetric relief influence the evolution of hydrothermal circulation. How this circulation changes as crustal and sediment properties evolve with age remains a fundamental question.

al., 2002; *Fisher et al.*, 2003b; *Spinelli et al.*, 2006]. The thermal state of the plate and subduction thrust influences the strength of materials juxtaposed on either side of the primary plate boundary and mineralogic and fluid chemical transitions. Few margins include thermal observations that extend from the marine to the continental realm, and there is little systematic information concerning relations between the thermal state of the subducting plate and the behavior and chemistry of overlying arc systems. It has been proposed that plate flexure seaward of subduction zones can lead to the development of high-angle faults that allow the penetration of hydrothermal fluids deep into the crust and mantle [*Ranero et al.*, 2003], but it is not presently clear how fluids can flow to great depths at rates sufficient to serpentinize a large fraction of the crust or upper mantle, as is inferred in some studies [e.g., *Rupke et al.*, 2004]. Virtually all thermal models of properties and processes associated with subduction are two-dimensional and cross-sectional in geometry. Yet recent seismic anisotropy observations suggest variable mantle flow patterns above the subducting slab with strong trench-parallel components beneath and near the arc in many systems [*Russo and Silver*, 1994; *Smith et al.*, 2001]. Further, tomography based on dense networks of seismic stations in Japan resolves three-dimensional velocity variations associated with arc and rear-arc volcanism and arc melt production and migration pathways within the mantle wedge [*Hasegawa and Nakajima*, 2004; *Tamura et al.*, 2002]. Such conflicts between models and regional historic data likely require targeted thermal surveys to provide critical missing data.

Over the last decade there has been renewed interest in fundamental geodynamic processes associated with hotspots and seamounts. The origin of off-ridge volcanism, including the source of heat and mantle material that drives this activity, has been called into question in a series of recent studies, meetings, and volumes [e.g., *Foulger et al.*, 2005; *Foulger and Jurdy*, 2007]. This issue is profoundly important to understanding Earth's thermal budget, convection in the mantle, the fate of subducting slabs, and other basic processes.

A challenge in resolving deep lithospheric and mantle processes using marine heat flow is separating shallow thermal processes from deeper ones, but this has become easier with the development of new technology and the collocation of complementary measurements (Section 4.2). A related issue, at least in some cases, is the role of seamounts and other basement outcrops in allowing hydrothermal fluids to enter and exit the crust, as this can result in advective mining of lithospheric and off-axis magmatic heat. In addition, even if there is no active advective removal of heat at present, earlier stages of advective heat extraction can take millions of years to recover to thermal equilibrium if a thick sediment layer accumulates prior to the cessation of hydrothermal circulation [*Hutnak et al.*, 2007]. Recent compilations and analyses of heat flow within some of the oldest in situ seafloor suggest that hydrothermal circulation may be relatively common [e.g., *Von Herzen*, 2004] and mid-plate volcanism may leave a thermal signal that is superimposed on a longer-scale pattern of advective heat loss and redistribution. Resolving the influence of continued hydrothermal circulation on regional (and age-based) heat flow estimates is essential to testing competing models for lithospheric evolution, as discussed in Section 3.1.

Key questions related to geodynamics, particularly tectonic and magmatic processes, include:

- How does the lithosphere deform and rupture during extension, tectonic rifting, continental breakup and transition to oceanic (magmatic) seafloor spreading?
- How do the initial thermal conditions of oceanic lithosphere established at spreading centers influence the subsequent thermal history of plates, particularly with regard to ridge segmentation, spreading rate, geometry of mantle upwelling, and melt focusing, delivery and eruption at the spreading axis?
- What are the roles of off-axis volcanism, intrusion, underplating, and tectonism in influencing the thermal state of oceanic lithosphere? How important are punctuated events as opposed to more gradual processes in controlling the thermal structure of plates?
- How important are near-surface faults in redistributing heat by shallow hydrothermal circulation and deeper faults in extracting heat from great depths (i.e., the base of the crust or into the mantle) and in serpentinization of the lower crust and mantle?
- What are the roles of transform faults and fracture zones and of high-angle normal faults outboard of subduction zones, in serpentinizing the oceanic lithosphere? How cold or warm are these faults as a result of fluid, exothermic, and seismogenic processes?
- What are the 3-D (and ultimately, 4-D) distributions of heat flow associated with subduction, and how can the various heat sources be resolved (i.e., lithospheric

Box 4. Oceanic transform faults

Oceanic transform faults are likely the locus of intense heat and fluid flow from the oceanic lithosphere into the overlying water column due to their lack of sediment cover, high permeability, and the potential for exothermic serpentinization reactions occurring at depth within the fault zone. Understanding the thermal regime of transform faults is therefore critical for constraining the amount of hydration of the oceanic upper mantle, which in turn has important consequences for fault rheology and the later production of melts at subduction zones.

Yet, while fluid flow and heat transport have been studied extensively at oceanic spreading centers and ridge flanks, thermal and fluid fluxes along oceanic transform faults remain poorly constrained. Moreover, recent geodynamic models challenge the long-held paradigm that transform faults are anomalously cold relative to their surroundings, in favor of elevated temperatures along the fault resulting from the combined effects of temperature dependent viscosity and fault strength [*Behn et al.*, 2007].

Early numerical models that incorporated 3-D advective and conductive heat transport indicated that the mantle beneath oceanic transform faults is anomalously cold relative to a half-space model [*Furlong et al.*, 2001; *Phipps Morgan and Forsyth*, 1988; *Shen and Forsyth*, 1992].

This reduction in temperature resulted from two effects:

- conductive cooling from the adjacent old, cold lithosphere across the transform fault, and
- decreased mantle upwelling beneath the transform.

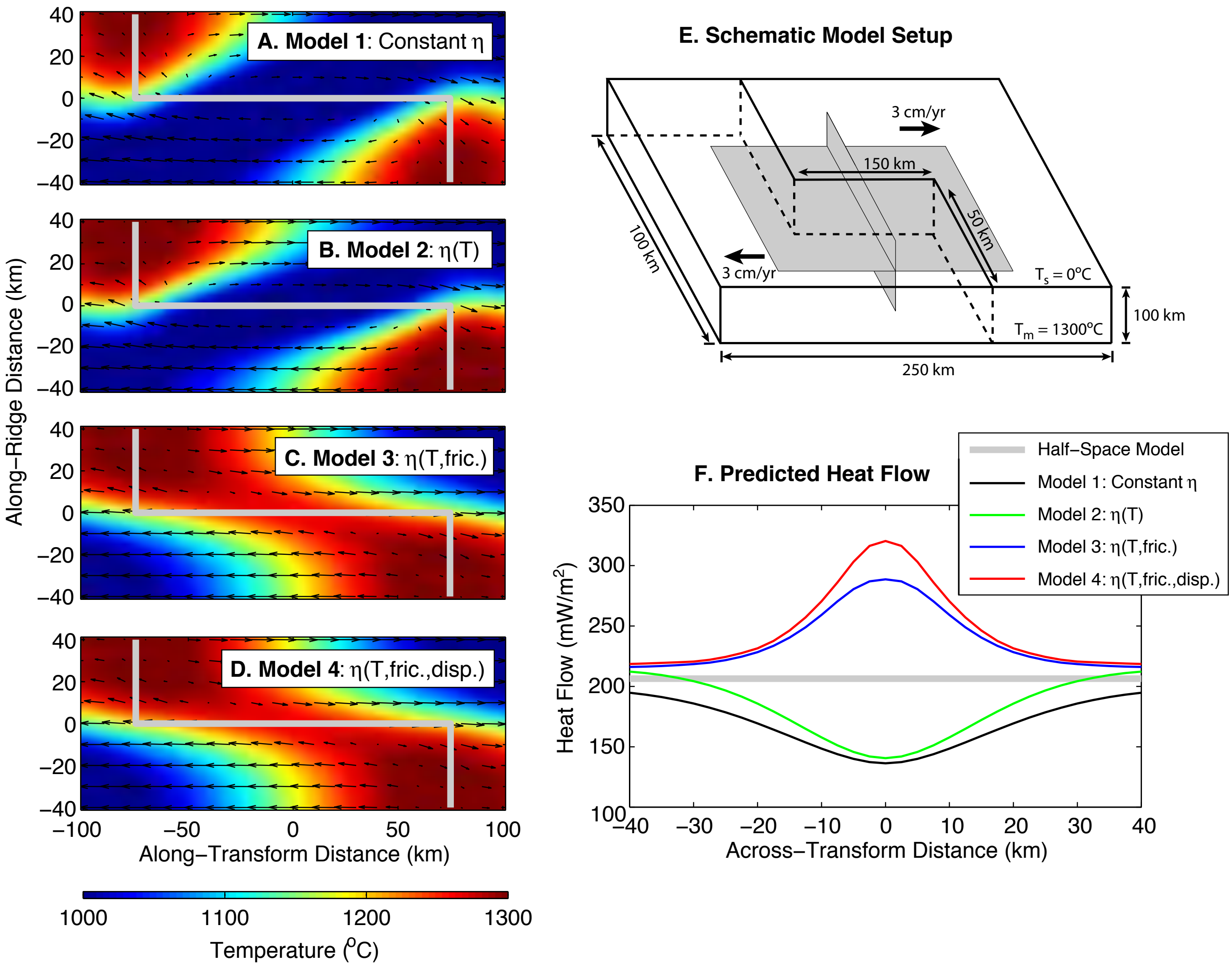
These effects were shown to result in up to a ~75% increase in lithospheric thickness beneath the center of a transform fault relative to a half-space cooling model, and significant cooling of the upper mantle beneath the ends of the adjacent spreading centers (Figure 4.1a,b).

However, correlating the maximum depth of earthquakes on transform faults with this colder thermal structure implies that the transition from stable to unstable frictional sliding occurs at ~350ºC, which is inconsistent with laboratory studies [*Jaroslow et al.*, 1996; *Warren and Hirth*, 2006] and the depth of transform and intra-plate earthquakes [*Abercrombie and Ekström*, 2001; *Bergman and Solomon*, 1988; *Chen and Molnar*, 1983; *McKenzie et al.*, 2005; *Wiens and Stein*, 1984].

Moreover, if oceanic lithosphere is cold and thick beneath transforms, it is difficult to explain the tendency for long transforms to break into en echelon zones separated by intra-transform spreading centers during changes in plate motion [*Lonsdale*, 1989; *Searle*, 1983].

To address these issues, *Behn et al.* [2007] investigated the importance of fault rheology on the thermo-mechanical behavior of transforms. They showed that brittle weakening of the lithosphere generates a region of enhanced mantle upwelling and elevated temperatures along transform faults, with the warmest temperatures and thinnest lithosphere predicted near the centers of transforms (Figure 4.1c). Incorporating shear heating along a transform further enhances the elevated temperatures along the fault (Figure 4.1d). This warmer thermal structure is more consistent with the geologic and geophysical observations from ridge-transform environments. Marine heat flow measurements would provide a direct test of these competing hypotheses and provide important constraints on the hydration and rheology of the oceanic upper mantle.

Figure 4.1



Cross-sections of mantle temperature at a depth of 20 km and a full spreading rate of 6 cm/yr for (a) Model 1: constant viscosity of 10^{19} Pa·s, (b) Model 2: temperature-dependent viscosity, (c) Model 3: temperature-dependent viscosity with a frictional failure law, and (d) Model 4: temperature-dependent viscosity with a frictional failure law and viscous dissipation (i.e., shear heating). Temperature dependence of viscosity is calculated as $\eta = \eta_o[\exp(Q_o/RT) / \exp(Q_o/RT_m)]$, where η_o is the reference viscosity of 1019 Pa·s, Q_o is the activation energy (250 kJ/mol), T_m is the mantle temperature (1300°C), and R is the gas constant. Black arrows indicate horizontal flow velocities. Grey lines show position of plate boundary. (e) Model setup. All calculations are performed for a 150-km long transform. The model space is 100 km deep and is sufficient to resolve thermal structure for a spreading rate of 6 cm/yr. Finite element grid spacing decreases toward the transform and ridge axes reaching a minimum value of 3.75 km. Locations of cross-sections used in a-d and f are shown in grey. (f) Predicted heat flow for Models 1–4 across the center of the transform fault. Grey curve shows predicted thermal structure for a half-space cooling model. Contrary to prior modeling studies, adding frictional failure in Models 3 and 4 results in a transform fault that is warmer than the surrounding lithosphere. Results after *Behn et al.* [2007].

Box 5. Marine heat flow observations and thermal modeling of subduction zones

Together with terrestrial heat flow observations, marine heat flow observations made in the offshore forearc region of convergent continental margins (Figure 5.1) are the primary constraints on subduction zone thermal models. Marine heat flow observations at ocean-ocean convergent margins are equally important. At present, detailed observations of surface heat flows are available only at a few subduction zones. A general trend in the surface heat flow pattern is observed at all subduction zones where heat flow observations have been made. The observations show that surface heat flow gradually decreases landward from the trench due primarily to the two-dimensional thermal conduction effects of the subducting slab. The surface heat flow then increases at about ~30 km trenchward of the arc and remains high in the arc-backarc region. Thermal models constrained by heat flow observations are used to investigate various important temperature-dependent processes. For example, dehydration reactions in the subducting slab control the availability of fluids, which facilitate intraslab earthquakes by elevating pore fluid pressure and promote magma generation by reducing the melting temperature of overriding mantle material. The depths of these reactions are inferred from thermal models. Thermal models are also used to constrain the location and the source of melt and are compared to petrological and geochemical studies of arc lava. However, there are large uncertainties in thermal models due to limited quantity and quality of heat flow measurements.

Critical scientific issues that require further marine heat flow observations include:

- The thermal structure of the incoming plate is a primary factor that controls the thermal regime of subduction zones. Marine heat flow observations seaward of the trench are required to determine the thermal structure of the incoming plate. Important influences on the thermal structure of the incoming plate include not only plate cooling but also hydrothermal circulation and sedimentation.
- It is hypothesized that the seismogenic zone along the plate interface is thermally controlled and occupies a temperature range of about 150-350ºC. Marine heat flow observations in the offshore forearc region are needed to understand model predictions and processes influencing the seismogenic zone.
- The magnitude of frictional heating along a subduction thrust provides important information on the strength of the thrust and earthquake rupture dynamics. Frictional heating along the seismogenic zone is constrained mainly by marine heat flow measurements. Estimates of frictional heating can be improved by better knowledge of terrigenous radiogenic heat production accumulated at the continental margin and overriding continental crust.
- Mantle wedge flow offers first-order control for the arc and back arc thermal regime. Low heat flow in the forearc region indicates a cold and stagnant mantle wedge corner, while high heat flows in the arc-back arc region indicate the presence of mantle wedge flow. Marine heat flow combined with terrestrial heat flow observations define the position and sharpness of the low-to-high heat flow transition and thus help constrain the trenchward limit of the mantle wedge flow.

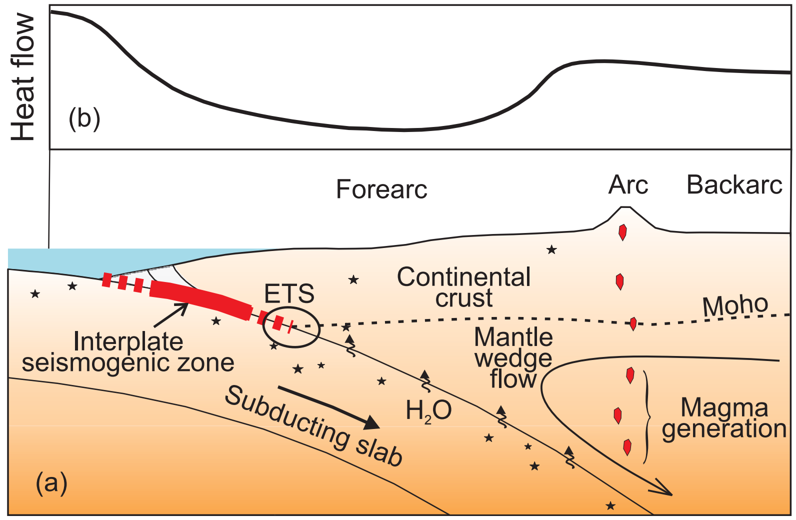
cooling, mantle wedge radioactive decay, fluid flow, frictional heating, exothermic reactions, mantle wedge and melt flow patterns)? How do the thermal characteristics of subduction influence seismogenic properties?

- Is it possible to resolve processes bringing large quantities of heat to the base of plates but which do not produce constructional magmatic features such as a seamount chain? The frequency of hotspot activity during the last 100–200 Ma can be estimated on the basis of the current distribution of seamounts, large igneous provinces, and other magmatic features. How many times during the same period has a heat source failed to cause a magmatic outpouring, yet introduced significant quantities of heat to the lithosphere?
- How can we improve our capacity to distinguish among shallow fluid processes, the thermal signature of regional- and local-scale magmatic and tectonic processes, and deeper lithospheric processes?

Figure 5.1

(a) Schematic illustration of a typical subduction zone at a continental convergent margin, showing some of subduction zone processes. Stars represent intraplate earthquakes. ETS is episodic tremor and slip events observed at northern Cascadia and Nankai, which may be temperature-dependent.

(b) A typical subduction zone surface heat flow pattern.



3.3. Near-Seafloor Processes

Near-seafloor processes (e.g., fluid advection, sedimentary, oceanographic, and climate change processes) are particularly well suited to study using marine heat flow data because of their spatial and temporal scales. Conventional heat flow measurements are based on thermal gradients in the shallow sub-bottom and are particularly sensitive to shallow thermal disturbances. Sedimentary, oceanographic, and climate change processes alter the boundary conditions at the seafloor, and advective pathways often intersect the seafloor and lead to nonlinear thermal gradients or large lateral variability across short distances. Many of these processes occur over time scales short enough to appreciably perturb the conductive thermal state in the shallow part of the subseafloor. This time scale contrasts with the millennial scale of solid Earth processes such as plate tectonic motions and mantle heat transfer. Marine heat flow measurements in the uppermost meters of the seafloor thus have a good prospect for detecting the impact of near-seafloor processes.

3.3.1 Advective Fluid Systems

Advective heat flow transfers thermal energy between the subseafloor and the overlying ocean and between and within different zones of the subseafloor (e.g., bedrock, sediment) far more efficiently than conductive heat flow. Advective heat transfer accounts for nearly 25% of the Earth's total heat flux, and approximately 33% of the heat flux through the ocean floor [*Williams and Von Herzen*, 1974; *Sclater et al.*, 1980; C. *Stein and Stein*, 1994; *Lowell et al.*, 1995]. To dissipate this amount of heat from the lithosphere, *Stein and Von Herzen* [2001] estimated that the mass of the oceans circulates through oceanic crust approximately every 1.5 to 10 Ma. Other studies have suggested a global fluid flux that is much greater [e.g., *Mottl*, 2003]. The advected heat flux though the seafloor caused by hydrothermal circulation is significant for all the major ocean basins to distances from spreading axes to seafloor ages of about 65 Ma [C. *Stein and Stein*, 1994]. An estimated one-third of the total oceanic heat flux occurs in crust younger than 1 Ma and the remaining two thirds occurs through older seafloor [*Stein and Stein*, 1994].

Because advective heat transfer occurs through the movement of fluids, measurements that estimate the advective component of heat flow provide a proxy for tracking mass transfer. Two overarching issues motivate the study of advective thermal systems:

(1) assessment of the contribution of advective heat transfer to regional or global heat flux; and

(2) determination of the role of advective processes in global (bio)geochemical cycles, particularly the carbon cycle.

The second issue highlights the inextricable link between measurements that constrain advective heat flux and other data that describe the chemistry and the biology of shallow subseafloor systems.

A variety of geologic settings have thermal regimes that are dominated at least in part by advective flux. In some settings advection alters heat flow throughout a region (e.g., sediment overlying pervasively fractured basement), and in others the impact of advective flows is seemingly confined closer to focused flux features (e.g., mud volcanoes, hydrothermal vents, cold seeps). Nearly every geologic process of importance to global and regional scale solid Earth processes may be associated with some advective material flux features whose characterization provides information about the larger geologic setting. At mid-ocean ridges (MORs) and particularly at slow-spreading ridges, advective flows through hydrothermal vents, fractures, and higher permeability zones (e.g., pillow basalts) cause heat flux to be distributed heterogeneously. Assessing the contribution of such advective flux to the overall heat flow near MORs provides important clues about the thermal evolution of very young oceanic lithosphere and the establishment of normal hydrothermal circulation patterns in young crust. In these settings, suites of marine heat flow data are needed to constrain the background conductive regime as well as advective heat transfer at sites that are not characterized by seafloor fluid emissions. A variety of tools other than marine heat flow probes have been developed to constrain advective flux at the sites of focused flows at MORs and elsewhere (Section 4.2.3). On normal oceanic crust with already established hydrothermal circulation patterns, characterizing advective fluxes provides information about the role of these systems in redistributing heat and about the impact of seafloor relief (e.g., seamounts) and other features (e.g., sediment ponds) in altering shallow subseafloor hydrology. At cold seeps and mud volcanoes, distinguished from hydrothermal vents by not being connected to magmatic systems, marine heat flow surveys that delineate advective flux components are useful for determining the subseafloor extent of the flow system and detecting geologic structures (e.g., buried salt diapirs) that may partially control fluid flow patterns. On continental margins, advective flow through the shallow subseafloor links land and offshore hydrologic systems and relevance for issues such as submarine groundwater discharge (SGD) and saltwater intrusion. Heat flow measurements have generally not been used to study these geologic issues.

An important consideration when relying on conventional marine heat flow data to detect advective heat transfer is designing surveys with sufficient spatial and, in the case of repeated surveys, temporal resolution to capture at least the major details of the spatial heterogeneity and periodicity/episodicity of advective flux. The appropriate spatial scale for heat flow surveys that seek to constrain advective flow systems is strongly dependent on the geologic problem and setting. While it is impossible to devise strict guidelines for the ideal lateral spacing of heat flow measurements for each setting, acquiring data at spacings much closer than the 1 to 2 km typical of many conventional heat flow surveys is critical for characterizing the basic features of almost any shallow subseafloor advective regime. In some cases, lateral spacing of measurements may need to be as close as 50 to 100 m, which is now possible with technology that allows precise location of the probe on the seafloor. Surveys designed to study the impact of advective systems on regional thermal regimes should also adopt a strategy of nesting high resolution measurements to constrain the heterogeneity of the advective flows within a framework of lower resolution measurements designed to describe background, conductive conditions. Surveys focused on advective systems typically should be completed not along single transects, as has been traditional for heat flow surveys focused on tectonic problems. Surveys should rather adopt a mapping mode over seafloor features that are manifestations of focused advective flux or over larger areas suspected of being affected by advective flows but lacking in seafloor indicators of flux.

Marine heat flow data can be useful for detecting changes in shallow subseafloor advective systems on time scales of years. At present, marine heat flow measurements are greatly underutilized for this purpose. In geologic settings with highly dynamic hydrogeologic regimes, more studies should focus on acquiring exactly coincident thermal measurements during expeditions separated by several years or even a decade.

3.3.2 Sedimentary Processes

All sedimentary processes alter thermal regimes in the shallow subseafloor. The addition of sediment adds material at seawater temperature, while erosion exposes warmer material originally buried beneath the seafloor to bottom water temperatures. Sedimentary processes may occur sufficiently slowly that marine heat flow measurements detect only conductive (linear) gradients. Yet even the slow accumulation of sediment fundamentally alters apparent heat flow through processes such as sediment blanketing.

Numerous researchers have explored the influence of sedimentation on seafloor heat flow values [e.g., *Benfield*, 1949; *Hutchinson*, 1985; *Wang and Davis*, 1992]. These studies have shown that sedimentation corrections to marine heat flow data are generally modest, but can be significant where there is a sufficiently large sedimentation rate. A recent study extended earlier sedimentation models through inclusion of hydrothermal and transient conductive processes within basement, fluid seepage through accumulating sediments, and continuing sedimentation at globally common rates out to great seafloor ages [*Hutnak and Fisher*, 2007]. This study also explored the thermal influence of sedimentation on marine heat flow during a period of "hydrothermal rebound," when fluid pathways in and out of basement become closed by accumulating sediment. This recent work suggests that sedimentary impacts on marine heat flow data can be significant even when sedimentation rates are modest, but quantifying these effects requires access to regional information on basement relief and the history of sediment accumulation.

In general, only very rapid sedimentation or erosion, differential sedimentation and erosion over short spatial scales, or catastrophic events (e.g., slumping or removal/emplacement of submarine slide material) perturb thermal regimes sufficiently that marine heat flow data detect nonconductive gradients associated with sedimentary processes. In most cases, the impact of rapid sedimentation or erosion on thermal regimes is indistinguishable from the impact of BWT changes. For example, the temperature perturbation associated with a seafloor gouging episode might be mistaken for a decrease in BWT. Only geologic analyses of coincident cores and/or measurements of the concentrations of key pore water chemical species, whose molecular diffusivities are typically at least two orders of magnitude lower than the thermal diffusivity of saturated marine sediments, can determine whether BWT perturbations or sedimentary processes have altered thermal regimes in these cases. Catastrophic sedimentary events have a more pronounced effect than rapid sedimentation or erosion, primarily because such catastrophic events typically involve movement of a relatively thick (meters or tens of meters) sedimentary sequence. In such cases, shallow thermal regimes in the area of the slide scar and the resulting rubble field should be perturbed for several decades if conductive heat transfer dominates. To date, marine heat flow data have not successfully documented the thermal impact of such catastrophic seafloor mass movements.

Differential sedimentation and/or erosion also alter thermal regimes by producing seafloor relief and lateral variations in thermal and hydraulic conductivities. These processes have important consequences for hydrologic cycling in the shallow subseafloor. For example, the formation of sediment ponds on bare rock on the flanks of mid-ocean ridges may introduce a low permeability cap on fractured bedrock, focus fluid flow towards the side of the sediment ponds, and set up complex recharge and discharge patterns in flanking bare rock and at the edges and in the middle of sediment ponds. Marine heat flow measurements at North Pond, an isolated sediment pond near the Mid-Atlantic Ridge, have detected such fluid flow patterns [*Langseth et al.*, 1984; 1992].

One scientific issue that combines constraints on conductive sedimentary thermal regimes with an issue of importance for geohazards, global climate change, and energy resources is the distribution of marine methane hydrate deposits (Box 6). Gas hydrate forms when water and hydrocarbon gas (most often methane) combine in a clathrate structure to form an ice-like compound at pressure and temperature conditions common in marine sediments and permafrost regions. The methane contained in marine gas hydrates is most often derived from the degradation of buried organic carbon by microbes in marine sediments, but can also originate from thermogenic processes. In the present-day ocean, methane hydrates are stable in sediments lying beneath at least 300 to 500 m of water. While methane hydrate does occur at the seafloor at some sites of focused fluid flow, most methane hydrate lies within the sedimentary column in a zone bracketed at the bottom by the phase transition from methane hydrate to underlying free gas and water and at the top by a complex combination of factors that ultimately reflect the rate of methane supply. Marine heat flow surveys can provide critical information for methane hydrate studies since thermal gradients are a fundamental parameter governing gas hydrate stability [e.g., *Davis et al.*, 1990; *Grevemeyer and Villinger*, 2001; *Grevemeyer et al.*, 2003; *Kaul et al.*, 2000; *Lucazeau et al.*, 2004; *Hornbach et al.*, 2005; *Hutchinson et al.*, in press]. However, an issue in some areas is that shallowly buried carbonates and near-seafloor hydrates impede the penetration of marine heat flow probes. This can sometimes be avoided by using deep towed sidescan and camera data to choose probe penetration sites.

Box 6. Marine Methane Hydrates

Marine heat flow data have found widespread application for the study of gas hydrate provinces, whose occurrence in marine sediments is controlled by pressure (P), temperature (T), and the availability of hydrate-forming gases (e.g., methane, ethane, higher order hydrocarbons, carbon dioxide, hydrogen sulfide) in excess of their local solubility in pore waters. Such conditions often persist in the shallow (uppermost few tens to hundreds of meters) sediments on present-day continental margins. Because marine heat flow measurements directly detect thermal regimes in the shallow part of the sedimentary section, the data can often be readily and confidently extrapolated downward to constrain thermal regime and thus the stability conditions for gas hydrates.

Conversely, even without making heat flow measurements, the thermal regime in marine sediments can sometimes be estimated [e.g., *Yamano et al.*, 1982, *Kaul et al.*, 2000] when seismic data reveal a bottom simulating reflector (BSR), defined as a prominent, negative-impedance seismic reflector marking the phase boundary between hydrate-bearing sediments above and gas-charged sediments beneath (*Shipley et al.*, 1979). BSRs crosscut stratigraphic layering and approximately mimic the morphology of the seafloor, except where perturbed by fluid flow, the presence of salt diapers, or other features (see figure). Gas hydrate is typically present in sediments overlying BSRs, but gas hydrate has also been recovered where BSRs are lacking (e.g., *Paull et al.*, 1996), as they are in many gas hydrate settings.

Disparities between the BSR-constrained thermal gradient and the gradient estimated from downward extrapolation of marine heat flow data may reach ~30% [e.g., *Davis et al.*, 1990; *Wood and Ruppel*, 2000; *Grevemeyer and Villinger*, 2001]. Examination of data from many ODP sites led *Grevemeyer and Villinger* [2001] to advocate the use of marine heat flow data when seeking the most accurate estimates of geothermal gradients in gas hydrate provinces.

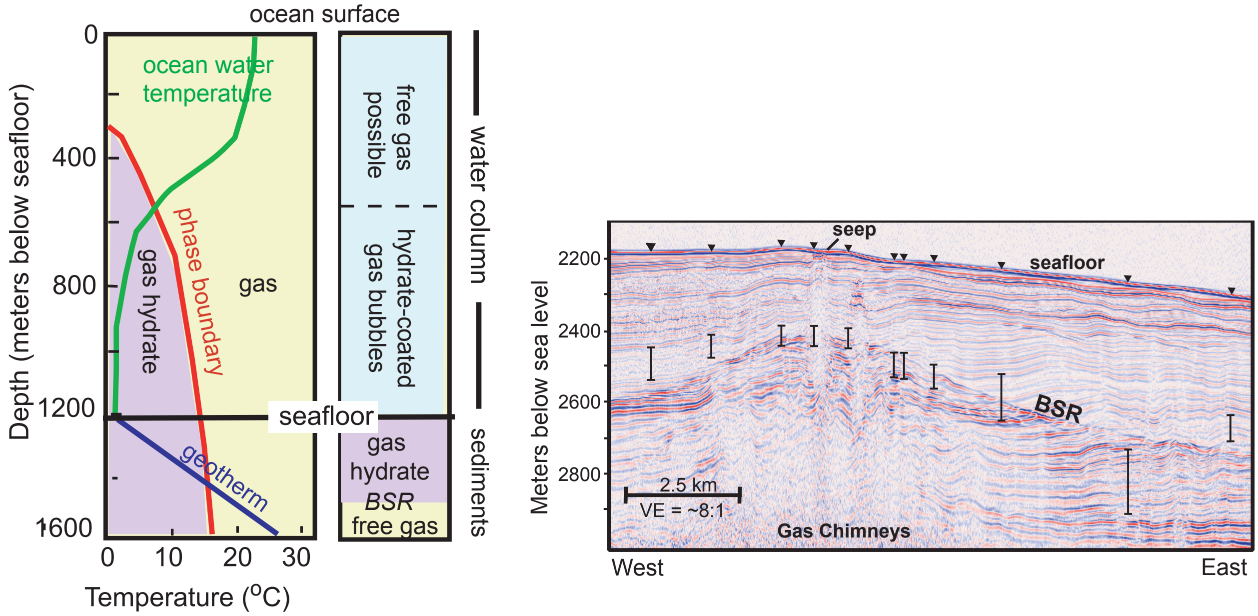
One important area of research is the degree to which disparities between BSR-predicted thermal regimes and those extrapolated from marine heat flow data or even in situ temperature measurements in boreholes [*Ruppel*, 1997, 2000] may reflect nonuniform thermal gradients within the gas hydrate stability zone or the impact of such factors as capillary pressures that inhibit gas hydrate stability in fine-grained sediments [*Clennell et al.*, 1999]. With the intense interest in gas hydrates as a potential geohazard, a nonconventional natural gas resource, and/or a factor in global climate change, the next decade is likely to see increased use of marine heat flow surveys to characterize the conditions in gas hydrate provinces on a reconnaissance basis. Combining marine heat flow data with high resolution seismic surveys and geochemical analyses of co-located piston cores is also likely to contribute to more rapid advancement of predictive models for determining gas hydrate distribution and concentration, which are known to depend on sediment permeability patterns and energy, fluid, and methane flux [e.g., *Xu and Ruppel*, 1999; *Ruppel and Kinoshita*, 2000].

3.3.3 Climate Change/Oceanographic Processes

Temperature data, particularly those recorded in continental [e.g., *Pollack and Huang*, 2000] and marine boreholes [*Ruppel*, 1997; *Fisher et al.*, 1999], are increasingly being used to study climate change at centennial or longer scales. Because marine sediments have a low thermal diffusivity, variations in BWT propagate slowly downward, perturbing the background thermal field. These temperature anomalies are a direct thermophysical consequence of a changing bottom water condition. However because conventional marine heat flow measurements are limited to the shallow sub-bottom, resolution of BWT events is more limited than deeper data acquired in continental boreholes. Nevertheless marine data have been successfully used to infer climate-related and/or oceanographic processes [e.g., *Lachenbruch and Marshall*, 1968; *Cathles and Nunns*, 1991; *Ruppel et al.*, 1995; *Fisher et al.*, 1999].

Oceanographic currents are probably the most common source of temperature perturbations detected by marine heat flow measurements. While BWT in the immediate vicinity of a vent/seep site may change dramatically (even by tens of degrees) due to variations in the temperatures of emitted fluids [e.g., *Macdonald et al.*, 2005], in most of the world's oceans short-term (e.g., <30 days) BWT

Figure 6.1



Data and reference models for ocean depth and heat flow as a function of age. Solid line shows GDH1 model [*Stein and Stein*, 1992] and dashed line shows half space cooling model. Data are averaged in two-m.y. bins, and one standard deviation about the mean value is shown.

The left panel shows the nominal thermal structure in the ocean and underlying seafloor and the temperature and depth range over which methane hydrate is stable (purple region) for a system with water depth of 1200 m.

The column to the right of the depth-temperature plot indicates where and in what form hydrate and free gas might occur in the sediment-ocean system. Note that gas hydrate or free gas can only exist in the water column or at the seafloor under very special conditions because

(a) ocean water is very undersaturated in methane;

(b) sulfate reduction in shallow subseafloor sediments in many locations almost completely consumes available methane; and

(c) microbial oxidation in some ocean water layers can further eliminate methane once it has reached the water column.

Modified from *Ruppel* [2007].

The right panel demonstrates the use of heat flow data to predict methane hydrate stability conditions. In 2000, high resolution multichannel seismic data were collected across a salt diapir within the methane hydrate province on the Inner Blake Ridge. The high conductivity salt at depth and gas chimneys that originate below the BSR and sustain a seafloor chemosynthetic community above the diapir [e.g., *Hornbach et al.*, 2007] dramatically perturb the BSR in this area.

Heat flow measurements, whose positions are denoted by triangles on the seafloor, were earlier acquired along this same transect [*Ruppel et al.*, 1995]. The BSR depths predicted by downward extrapolation of the marine heat flow data are shown on the seismic section, with error bars that reflect the combined effect of several types of uncertainties. In this case, marine heat flow data predict the base of gas hydrate stability quite well over the part of the BSR that is upwarped over the deep salt, but do more poorly on the flanks to the west and east.

Modified from *Hornbach et al.* [2005].

changes reflect the passage of deep water masses whose temperatures may differ by a few tenths of degrees to several degrees from normal temperatures. These perturbations change the boundary condition at the seafloor and lead to the development of nonuniform (concave up or down) gradients as the impact of the BWT variation propagates into the sediments. Such BWT changes do not have a long-term effect on conductive thermal gradients, and these perturbations have traditionally been viewed as noise [e.g., *Davis et al.*, 2003]. However from an oceanographic perspective these perturbations may contain important signals relating to our changing ocean climate system. If climate change events were to proceed rapidly and produce longer-term or more frequent perturbations in BWT (e.g., with the production of more cold deepwater from polar melting), marine heat flow measurements would be more strongly affected. In this case, surveys repeated several years apart may detect the impact of the evolving BWT regimes on shallow subseafloor thermal conditions.

The discussion above explored the use of marine heat flow data to assess environmental conditions, but there is also growing realization that marine (and terrestrial) heat flow may actually influence global climate conditions. One of the greatest unknowns in modeling the dynamics of ice sheets is the thermal boundary condition applied at the base [*Naslund et al.*, 2005; *Pollard et al.*, 2005]. Particularly in continental shelf areas at high latitudes, marine heat flow can be a critical factor in studies of ice sheet stability, especially with regard to the growth and impacts of ice streams [e.g., *Llubes et al.*, 2006; *van der Veen et al.*, 2007]. This issue was raised by the recent NSF-sponsored FASTDRILL workshop, which focused on interdisciplinary polar research [*Tulaczyk et al.*, 2005]. Heat flow measurements in relatively shallow water and within sediments that include dropstones and other glacial debris require surmounting some technical challenges (e.g., hard substrates) and some interpretative difficulties (e.g., impact of large BWT variations). However, time-series measurements have shown that even large seasonal thermal variations in shallow BWTs can be modeled and accurately accounted for [*Hamamoto et al.*, 2005] to yield reliable long-term heat flow values. Because there is so little heat flow data on high latitude continental shelves, even a few measurements would be extremely helpful in constraining models of ice-sheet mass balance.

3.3.4 The Deep Biosphere

The past decade has seen rapid advances in the study of the deep biosphere in marine settings [*Baker and German*, 2004]. Temperature is the most important single measurement we can make because of its capacity to constrain sources/pathways/sinks. Temperature (and its spatial gradients) drives the circulation that supports the microbiology of the ocean crust, and thermal data provide information about the loci of most vigorous circulation, which should coincide with thriving subsurface microbial communities. Coupling determinations of heat flow with surveys of microbial communities and habitats is important to quantifying and understanding the physical and chemical limits of life sustaining environments. The combination of physical, biological, and ancillary chemical approaches to this scientific problem represents the type of multidisciplinary effort that has led to so many rapid advances in geoscience in the past decade. However, the sparse nature of global heat flow dataset means that, in vast regions of the world's oceans, scientists have few constraints on such environmental parameters as temperature. Microorganisms have the potential to enhance dissolution of igneous rocks, meaning that where activity is promoted by heat-driven fluid flow, there could be high fluxes of major cations such as Ca from the crust into the oceans. Ca^{++} in the oceans is intimately connected to atmospheric carbon through the precipitation and dissolution of calcium carbonate. To some extent this connectivity is mediated by microbial activity in the ocean crust, which in turn is driven by heat flow.

To understand the potential scale of microbial impact it is important to know the depth to the 100° C (or possibly the 120° or even 130° C isotherm), which is the first order limit for the maximum temperature that can sustain life. In sedimented areas, the 100°C isotherm is usually so deep that the more critical issues for understanding the deep biosphere are the local and regional thermal gradients and the relative importance of advective fluid flow (which also affects the availability of biogeochemical substrates for microbes) in altering thermal regimes. In regions of elevated heat flow, the 100°C isotherm may lie within the sedimentary column though, making these areas ideal targets for study of the thermal limits for microbial life. To date, only a few studies have acquired marine heat flow data to constrain the thermal conditions for microbial life in the shallow subseafloor. Although microorganisms do have the potential to change the physical properties of sediments (such as permeability) no research has yet focused on whether microbial life and the associated biogeochemical processes can in turn alter the temperature structure of seafloor sediments.

4. Technical Discussions

In this section we discuss current approaches to measuring heat flow, future equipment developments, and the central issue of maintaining marine heat flow equipment for U.S. researchers. Discussions were guided by science questions and objectives posed in the preceding discussions. Different techniques are needed to measure marine heat flow in different environments, including shallow sub-surface seafloor, boreholes, and "bare" rock, and to discriminate between conductive and advective heat flow. Regardless of the approach, complementary data such as regional bathymetry, geophysical mapping and imaging, and geochemical measurements that constrain the chemistry and rate of fluid flow are important for heat flow data analyses.

4.1 Instrumentation

This group focused on heat flow instrumentation requirements to study the scientific problems discussed in the first set of breakout discussions. We concluded that the majority of these goals could be achieved with existing technology or systems modified only slightly from those used commonly during the past ten years. Other high-priority goals will require new technologies and innovations, and these are noted where appropriate in the following text.

Marine heat flow instrumentation generally fall into two classes: multipenetration heat flow probes having in-situ thermal conductivity capabilities; and autonomous outrigger probes that can be mounted on a solid shaft or core barrel, but generally lacking thermal conductivity capabilities. In this later case thermal conductivity is determined with shipboard needle-probe thermal conductivity measurements on co-located core material. Each of these instrument classes is discussed in this section. It is important to note that measurement of heat flow with either mulitpenetration probes or outrigger probes is only possible in sediments. The requirement for sediment precludes probe measurements on large areas of young seafloor and in other bare rock environments.

Downhole tools, acoustic measurements, and logging technologies can provide important scientific insights and, depending on the environment, may be more useful than shallow subsurface equipment in understanding thermal conditions. These instruments are discussed in more detail below. Other techniques to measure heat flow in bare rock environments and alternative and transformative technologies are considered in Section 4.2.3.

4.1.1 Multipenetration Marine Heat Flow Probes

The most general requirements for multipenetration heat flow instrumentation (Box 7) include high accuracy and robustness. High accuracy (individual thermistor measurement resolution of 1 mK and absolute accuracy of a few mK) is required for understanding small variations in heat flow that elucidate many geodynamic and near surface processes such as the relationship between heat flow and lithospheric age, anomalous heat flow associated with hotspot swells, and advective fluid flow. To acquire data efficiently requires a robust instrument that can be inserted and pulled out of the sediment multiple times on a single lowering into the water, and can survive a modest amount of "misuse," including deployment where sediments are very thin, inadvertent extraction due to ship motion, or sustained pulling during extraction from low permeability sediments like marine clays.

A second consideration is the ability to obtain in-situ thermal conductivity measurements. Typically a calibrated heat pulse is fired after the probe has collected near-equilibrium temperatures, and the time rate of decay of the heat pulse gives a measure of thermal conductivity with absolute errors on the order of 5%. In some cases where very closely spaced measurements are made, one can determine thermal conductivity on every second or third measurement, and additional information can be gathered by measuring thermal conductivity in the laboratory on recovered cores.

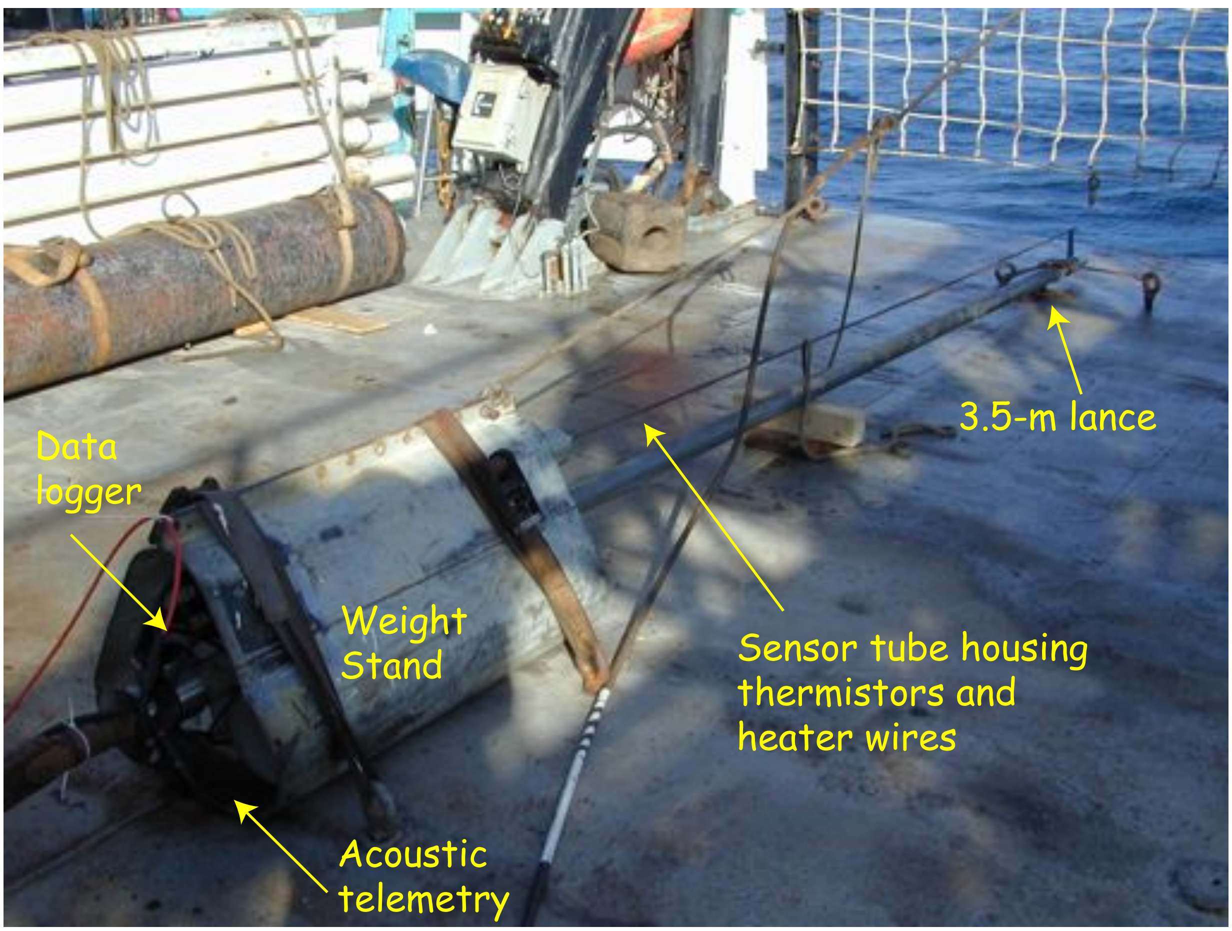
A third consideration for accurate heat flow measurements is the probe length or the subseafloor depth of measurements. Environmental disturbances such as changes in BWT or sedimentation rates are most easily eliminated by obtaining measurements beneath these disturbances. However measurement depth is restricted by local lithology and ship frame length, probe weight, and transportation considerations. In cases where variations in

Box 7. Multipenetration heat flow probes

Conductive heat flow through the seafloor is normally based on the product of the vertical temperature gradient and the thermal conductivity. Both of these measurements can be made routinely with multipenetration heat flow probes (Figure 7.1). Marine heat flow probes [Hyndman et al., 1979] generally comprise the following components: (1) a weight stand mounted on top of a lance that is at least several meters long; (2) five or more thermistor sensors arrayed along the length of the lance, either on outrigger probes or, more commonly in modern probes, in a "violin-bow" tube that houses thermistors; (3) heater wire(s) capable of generating a calibrated heat pulse, for thermal conductivity assessment; (4) data logger housed within the weight stand and including a microprocessor, analog-digital converter, power supply, and memory and; (5) telemetry system (acoustic and/or cabled) for real-time assessment of instrument performance, if not full data acquisition. Some currently-active heat flow systems exceed these basic characteristics, for example with longer lances, dozens of thermistors, or additional measurement capabilities. Battery life sufficient for at least 24-hour deployments, including the ability to generate a heat pulse is needed for thermal conductivity measurements, and would ideally extend for 48 hours, if needed.

Running a successful multipenetration heat flow survey requires certain ship and wireline tools and capabilities, mainly a trawl winch loaded with appropriate cable, a 3.5-kHz pinger attached to the wire above the probe (for evaluating probe depth and wire slack during penetration), and a suitable combination of A-frame, crane, and capstain capabilities to launch and recover the system Modern heat flow surveys also require a high geographic density of measurements to characterize the background lithospheric heat flow, the magnitude of anomalies, and a characterization of the nature of local heat flow variability. Multipenetration heat flow probes meet these requirements allowing measurements to be made efficiently and accurately.

Figure 7.1 Multipenetration heat flow probe showing its various components.



bottom water cannot be avoided, temperature loggers can be placed on the seafloor for some period of time prior to the heat flow measurements [e.g., *Hamamoto et al.*, 2005].

4.1.2 Autonomous Temperature Loggers

Another technique for obtaining heat flow values is "piggy-backing" with sediment coring programs (Box 8). With the advent of miniaturized data loggers and memory, small, highly accurate, robust, autonomous temperature loggers are now commercially available. These loggers can be attached to the outside of the core barrel to obtain temperature-depth measurements during coring operations and have been successfully used with coring programs operated from several UNOLS vessels [e.g., *Pfender and Villinger*, 2002; *Hutnak et al.*, 2007]. In this mode of operation, thermal conductivity measurements are made with needle probes on recovered cores. An advantage of this technique is the ability to obtain heat flow measurements during routine coring operations. This makes it possible to collect a small amount of heat flow data in a reconnaissance mode, without fielding a complete, multipenetration heat flow program. A set of outrigger probes, mounts, and associated hardware is considerably less expensive than a modern multipenetration heat flow system, although its applicability is also more limited.

Several successful programs have combined outrigger probes during coring with multipenetation heat flow, allowing rapid assessment of the viability and interest in running multipenetration lines at specific locations. In several of these studies, some of the highest heat flow values have come from outrigger probes, with measurements collected in places where the risk of deploying a multipenetration probe was considered to be too great [J. *Stein et al.*, 1998; J. *Stein and Fisher*, 2001; *Pfender and Villinger*, 2002; *Hutnak et al.*, 2007].

4.1.3 Thermal Conductivity Systems for Sediment Cores in the Laboratory

The standard approach for determining the thermal conductivity of marine sediments is based on the needle-probe method [*Von Herzen and Maxwell*, 1959]. A thin probe is inserted through a hole drilled in the cylindrical liner containing sediment recovered during gravity- or piston-coring. A constant heat source or calibrated heat pulse is generated with a heater wire in the probe, and the change in temperature with time is used to determine the thermal conductivity. There are two general limitations to this approach. First, because of the geometry of the experiment, the thermal conductivity determined is the geometric mean of vertical and horizontal values, whereas the vertical thermal conductivity is the value that is needed to assess conductive heat flow. This is generally not considered to be a serious shortcoming of the method when working with the upper 5–10 m of seafloor sediment, because anisotropy in thermal conductivity is generally thought to be modest except where sediments are strongly layered (e.g., turbidites). Second, thermal conductivity measurements require whole cores to equilibrate to room temperature prior to the experiment, so there is a trade-off with science that requires immediate access to cores (e.g., fluid geochemistry, microbiologic sampling). Although thermal conductivity systems were once constructed by end users, there are now several commercial systems that provide highly reliable data at reasonable cost.

4.1.4 Future Instrumentation

There was a strong consensus among workshop participants that the multipenetration shallow sediment systems described above are most critical for achieving the scientific goals described earlier in this report. However, there was also considerable discussion regarding the need to continue to innovate and improve existing technology, particularly for experiments in certain settings.

In situ measurements of additional parameters with sensors built into heat flow probes represent an area of future innovation. Pore pressure, which is also measured with probes inserted into sediments, is one of the parameters whose determination is most technically compatible with temperature and thermal conductivity measurements using lance-type probes [*Rose and Villinger*, 1999]. Indeed several community efforts in the 1990s combined pore pressure and heat flow data acquisition into a single instrument [e.g., *Davis et al.*, 1991]. The low hydraulic diffusivity of most shallow marine sediments represents a key technical challenge, since it dictates that probes remain in the seafloor much longer than necessary to measure heat flow parameters. Issues associated with long deployments needed for simultaneous heat flow and pore pressure measurements include difficulties holding the probe stationary and the potential for large pull-out tension.

Another modification that might be made to future heat flow instruments is the addition of marine cone penetrometry (CPT) technology that is already widely used for geotechnical hazards assessments of near-seafloor sediments. CPT sensors built into the tip of a redesigned heat flow probe could measure parameters such as electrical resistivity [*Jansen et al.*, 2005], which correlates with porosity (a good predictor of thermal conductivity) and permeability. Such instrumentation can yield information on pore pressure and undrained shear strength during relatively short deployments.

Other innovations discussed include real-time, two-way communication with deployed instrumentation so that measurement parameters can be modified on the fly. In addition, it takes a long time during many multipenetration heat flow surveys for the probe to position itself vertically beneath the ship. This time might be reduced for a probe designed to move through the water more efficiently or if there were active probe propulsion.

Finally, the equipment and methods discussed above require the continuous use of a ship. One new approach would be to use an autonomous underwater vehicle (AUV) to make measurements [S. *Stein et al.*, 1998]. An AUV could be deployed and then the research vessel would depart to do other projects before returning days later to recover the vehicle. There are cost savings since large heat flow data sets could be acquired while the ship is involved with other projects. Also, this approach would allow for data acquisition in settings where traditional measurements approaches are difficulty (beneath the ice and in rough higher latitude seas). However one disadvantage not yet over come with this system is that, relative to conventional heat flow probes, the depth of lance penetration is extremely shallow. Sub-bottom measurement depth is a critical concern in obtaining robust thermal gradients.

4.2 Complementary Measurements

This group was tasked with highlighting measurements that are needed to more fully interpret heat flow (i.e., thermal gradient and thermal conductivity) and surveys. This section is divided into three categories. In the first category, "Co-critical Measurements," are those measurements necessary for the design, placement, and proper interpretation of marine heat flow surveys. The second category, "Integrative Measurements," acknowledges that fundamentally heat flow is a potential field and interpretations are best when integrated with other measurements. The third category, "Alternative and Transformative Technologies" recognizes that in some important environments and systems, tools other than marine heat flow probes are needed to characterize heat transfer.

4.2.1 Co-critical Measurements

Regional geophysical surveys guide acquisition strategies for heat flow surveys through delineation of features that should be targeted or avoided and provide co-critical, contextual information for interpretation of heat flow data. In general, no heat flow survey should be completed without at least minimal regional geophysical surveying, and at a minimum heat flow measurements should be co-located with bathymetric and seismic reflection data. Such surveying can be conducted using such standard tools as multibeam and side-scan sonar for seafloor bathymetry and morphology and Chirp (3.5 kHz, 12 Hz, or towed fish) and active source seismology (single or multichannel seismic) for determining seafloor relief, sediment thickness, shallow sedimentary and tectonic structures, and/or basement characteristics. More indirect techniques might include use of magnetic intensity data to infer the location of seafloor bedrock outcrops or compilation of high-resolution seafloor maps using data acquired from ROVs.

Myriad information captured by regional geophysical surveys is critical for confidently interpreting heat flow data and may be important in applying corrections to thermal perturbations. Bathymetric data are useful in assessing the role of seafloor relief and the extent of sediment cover, both important controls on shallow fluid circulation. Sediment thickness data assist in determining the impact of thermal blanketing, the thermal perturbations associated with catastrophic sedimentary processes (e.g., submarine mass movements), or the contribution of radiogenic decay to measured heat flow in continentally derived marine sediments. Constraints on the relief of basement buried beneath sediments or the distribution of special deposits (e.g., salt) help to elucidate thermal conductivity variations, which can profoundly affect thermal gradients and fluid circulation patterns. Seafloor or subseafloor images that reveal bedrock outcrops, sedimentary or tectonic structures (e.g., faults, slump blocks), or evidence for fluid expulsion (e.g., pockmarks, mineralized deposits) may assist in identifying the loci

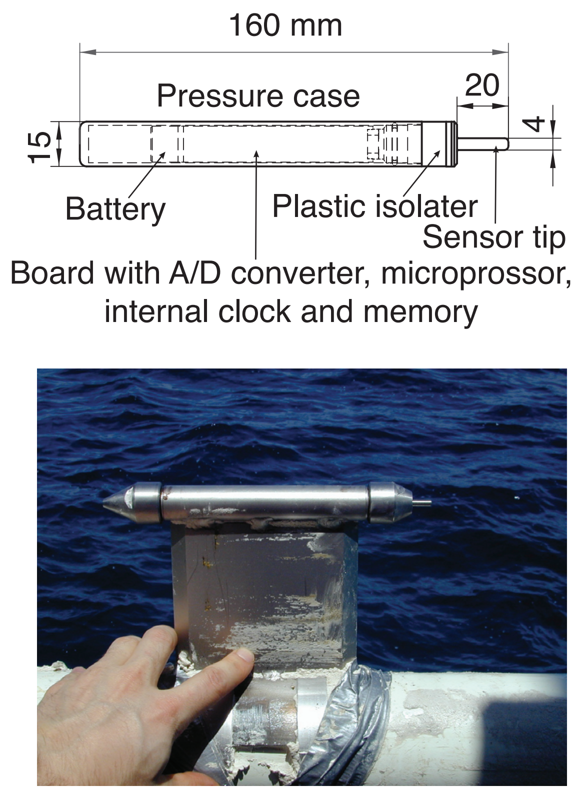
Box 8. Miniaturized temperature loggers allow routine thermal gradient measurements during coring operations

Miniaturized temperature data loggers (Figure 8.1) allow thermal gradients to be routinely measured at coring sites. These loggers consist of a 140 mm-long cylindrical body with an outside diameter of 15 mm. A thin-walled tip (20 mm long and an outside diameter of 4 mm) contains the temperature sensor. This design yields a fast response time of approximately 2 s. The pressure housing consists of high-strength corrosion resistant steel that withstands pressure equivalent to 6 km water depth. The nominal temperature measurement range is – 5° to + 60 °C, with higher sensitivity at lower temperatures. Instrument precision is 1 mK, and the absolute accuracy, based on laboratory calibration, is approximately several mK. Non-volatile memory can hold up to 18 hours of measurements collected at a sample rate of 1 s, or data from longer periods recorded at lower frequencies.

The loggers are attached to the core barrel with a fin-like attachment (Figure 8.2) in a spiral arrangement so that each logger will penetrate through undisturbed sediment. Distances between each thermistor are measured before and after each deployment and referenced to a fixed point on the core barrel. Non-vertical penetrations are accounted for with a tilt sensor placed in the core weight stand. The fin holds the logger about 10 cm away from the core barrel so that a time series of in-situ temperatures can be measured before temperatures are disturbed by the frictional heating resulting from the core barrel penetrating the sediments. After the core barrel penetrates the seafloor, it is left in place for approximately five minutes to achieve partial thermal equilibration. In-situ temperatures are extrapolated to equilibrium conditions using an asymptotic solution of the thermal decay curve for an infinitely long conductive line source [*Blackwell*, 1954; *Hyndman et al.*, 1979]. The combination of these in-situ temperatures and distances between the miniaturized temperature data loggers yields the thermal gradient. Details of temperature measurement characteristics and calibration are given in *Pfender and Villinger* [2002].

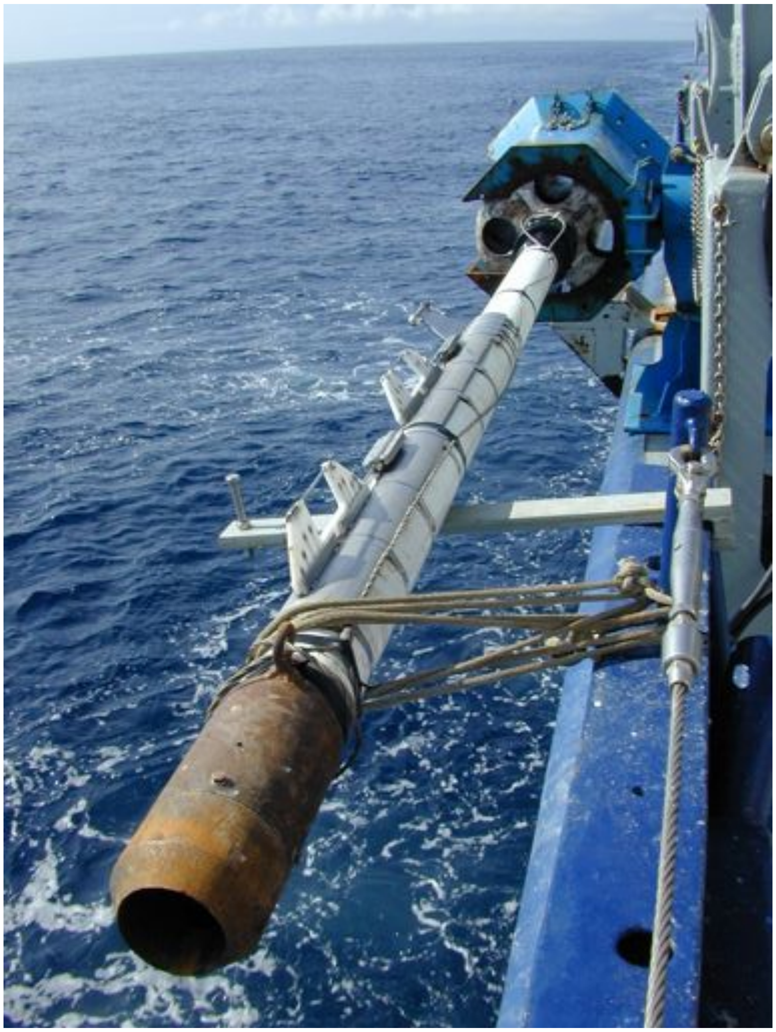
Several successful programs have shown the utility of measurements from outrigger probes during coring operations. Collocated outrigger measurements and probe measurements of thermal gradients are in good agreement. Advantages of this system include rapid assessment of potential heat flow targets, reconnaissance measurements, and the ability to make measurements in areas deemed to risky to deploy a multipenetration probe because of thin sediment cover or exposed basement. In several of these environments some of the highest heat flow values have come from outrigger probes [*Stein et al.*, 1998; *Stein and Fisher*, 2001; *Pfender and Villinger*, 2002; *Hutnak et al.*, 2007].

Figure 8.1



a) Construction sketch of logger. b) Logger protected in a fin attachment on a core barrel [*Pfender and Villinger*, 2002].

Figure 8.2



Miniaturized temperature data logger configured on core barrel. This photo shows two different configuration of data loggers, two long probes (foreground) and a short probe (background).

of fluid recharge and discharge, which can also perturb thermal regimes significantly.

The required type and extent of regional geophysical surveying are largely dictated by the scientific problem. For example, a heat flow study designed to test models of plate interaction at subduction zones might be best supported by a relatively low-resolution survey over a large area to constrain the morphology of the forearc, trench, and backarc and to identify the distribution of sediments, bedrock outcrops, fault blocks, slumps, and mud volcanoes. In contrast, a thermal study focused on shallow subseafloor fluid circulation patterns might require very detailed geophysical surveys over a small area to identify features that control recharge and discharge patterns or that represent manifestations of seafloor fluid expulsion. Typically both scales are important and can be implemented in a nested survey strategy.

4.2.2 Integrative Measurements

Heat flow is best interpreted in conjunction with other data, rendering it well-suited to integrative scientific programs. For a variety of reasons elucidated below heat flow surveys are particularly complementary to coring surveys. This is due in part to the nature of the science these tools address.

As highlighted in the scientific discussions, an important goal of many heat flow surveys involves the quantification of advective fluid flow. While much can be learned from the magnitude and variation of heat flow data coupled with modeling, chemical measurements provide important complementary information. These measurements include analyses for the basic chemistry and stable isotopes in solid phases (e.g., carbonate, barite, sulfides, diagenetic cements), the composition of gases, pore water cation/anion concentrations, and pore water stable isotope characteristics. Such suites of geochemical data have proved critical for studying processes in areas characterized by rapid fluid flux and in gas hydrate reservoirs. Heat flow data often supplement coring objectives by providing important background information and targets, while pore water geochemistry from cores, particularly concentrations of conservative species like chloride, can be used to better constrain rates of vertical fluid flux that aid the interpretation of heat flow data.

Similarly, in gas hydrate provinces, heat flow data not only constrain the background conductive thermal gradient and thus the thickness of the gas hydrate stability zone, but may also identify areas of advective flow (Box 6). The presence of solid phases like authigenic carbonates yield proof of microbially mediated processes, while barite, another solid phase, is an important marker for the base of the sulfate reduction zone. The combination of heat flow and geochemistry provides detailed information about fluid flow, biogeochemical processes (e.g., anaerobic methane oxidation and sulfate reduction) and methane flux [e.g., *Ruppel et al.*, 2005].

In addition to geochemical analyses, the accessibility to core material allows better interpretation of heat flow determinations through the collection of lithologic information such as grain size distribution, porosity, permeability, and sedimentary structures for soft sediments and rock type, textural characteristics, and vesicularity for bedrock. Physical and geotechnical measurements can constrain not only porosity and permeability, which directly affect temperature through their influence on advective fluid patterns, but also material strength, seismic wavespeeds, and geoelectrical properties, which can be used in interpretations of heat transfer characteristics.

Another area of potential integration is with paleoceanographic analyses of recovered sediment samples that typically include $\delta^{13}C$ and $\delta^{18}O$ measurements on benthic or planktonic foraminfera tests and sometimes more sophisticated analyses of Ca, Mg, Cd, or Sr isotopes. Such studies are designed to constrain ancient ocean current patterns, ocean chemistry, and water temperatures. Both the isotopic signatures recorded by benthic forams and marine heat flow data are sensitive to variations in BWT, but at very different time scales. Isotopic uptake by benthic foraminfera populations changes rapidly in response to BWT perturbations, but a BWT variation must be sustained long enough, sedimentation must be rapid enough, and preservation must be good enough for the impact of the BWT changes to be recorded at high resolution in the sediment record. The response of near seafloor thermal regimes to variations in the BWT is controlled by the thermal diffusivity of the sediments, typically on the order of $5x10^{-7}$ m^2/s for saturated marine sediments. For 50% of the effect of a sustained step-function change in BWT to propagate 1 m, 5 m, and 10 m into seafloor sediments requires approximately 25 days, 1.8 years, and 6.9 years, respectively. Instead of the continuous record of BWT variations recorded by foram tests slowly deposited on the seafloor, the thermal response is much more rapid and later changes in BWT overprint previous perturbations, with only the largest amplitude and lowest frequency BWT variations exercising a long-term impact on thermal gradients in the sediments nearest the seafloor.

Marine heat flow measurements have traditionally been limited to thermally stable deep-water areas due to perturbing effects of seasonal BWT variations on near-seafloor thermal gradients in shallow water environments. New instruments and methodologies make it feasible to make extended time-series measurements of BWT in advance of heat-flow surveys. These developments allow accurate modeling and removal of this perturbation, thereby obviating logistically difficult and/or problematic use of deep boreholes and long heat probes that can penetrate below shallow temporal variations. The ability to measure and remove seasonal thermal perturbations via time series measurements opens major societally important environments, such as continental margins and coastal areas, to heat flow studies [e.g., *Hamamoto et al.*, 2005].

A final category of in situ integrative measurements that complement heat flow studies includes monitoring of physical or chemical parameters at or near the seafloor and the use of biological experiments. For example, a thermistor installed at the seafloor can reliably and at low cost monitor BWT changes that may reflect the passage of transient deep ocean waves such as topographic Rossby waves [*Ruppel et al.*, 1995] or changes in fluid emissions from seeps/vents and that ultimately affect temperatures in the shallow subseafloor [e.g., *Haymon et al.*, 2005; *Macdonald et al.*, 2005]. The past decade has seen the development of numerous deep sea geochemical monitoring capabilities, particularly osmosampler technologies that continuously acquire a small volume of fluid emitted from the seafloor or from the walls of a borehole. Such sampling has now been carried out at the seafloor with instruments similar to seepage meters [e.g., *Tyron et al.*, 2001], in shallow sediments using instrumentation within a corer-like lance [*Lapham et al.*, 2003], and in boreholes [e.g., *Wheat et al.*, 2004]. In areas where fluid flux is neither too high nor too low, such sampling can track the chemical evolution of emitted fluids, the response of shallow subseafloor fluid circulation patterns to tides, earthquakes, and other events, and changes in fluid flux. In the biological realm, a variety of in situ experiments is under development, and the next few years will see an increase in experiments that track natural changes in microbial communities and in manipulative experiments that study the response of microbial communities to controlled perturbations.

An outcome of the geodynamic discussions was the need for multidisciplinary approaches to these problems. For example, relationships between temperature and rheology make heat flow measurements a natural complement to OBS deployments at subduction zones where inelastic processes are important. Additionally with the advent of marine geodetic technologies, heat flow surveys will likely play an important role in the interpretation of deformation data. At ridge axes, heat flow measurements aimed at understanding the geodynamics of spreading can be fruitfully combined with hard rock analyses that are aimed at understanding melt source characteristics, melt migration pathways, and crystallization parameters.

4.2.3 Alternative and Transformative Technologies

Not all environments are conducive to heat flow measurements using a standard marine probe. These environments include near axis environments such as vent fields, young and old seamounts, and other areas lacking sediment cover. The ability to drill into bare rock environments from a standard ship, drillship, or submersible to measure temperature gradients and thermal conductivity and to monitor total heat output at hydrothermal systems at seafloor observatories also remains important. In areas hosting focused or diffusive systems, measuring non-conductive components of heat flow is critical for understanding crustal processes, permeability, fluid circulation patterns, the temporal and spatial variability of heat, and understanding nutrient supplies to biological ecosystems. Measuring heat output and fluid fluxes in these environments poses considerable challenges because of their hostile environment and the complex nature of hydrothermal fluid flow.

In young, bare-rock, hydrothermal environments at oceanic spreading centers, most heat transfer is by advection through a combination of high-temperature venting and low-temperature diffuse flow. Measurements indicate that a significant fraction of the advective heat output is by diffuse flow [*Rona and Trivett*, 1992; *Schultz et al.*, 1992; *Elderfield and Schultz*, 1996; *Johnson and Pruis*, 2003; *Viers et al.*, 2006; *Ramondenc et al.*, 2006; *Lowell et al.*, Appendix C]. Metal-laden "black smoker" fluids venting through sulfide chimneys and mound structures at temperatures between 300 and 400°C provide evidence of high-temperature chemical reactions between seawater and oceanic crust. These reactions profoundly affect global geochemical cycles [*Edmond et al.*, 1979]. Moreover, these high-temperature vent systems and associated diffuse flow discharges sustain microbial and macrofaunal ecosystems. Considerable evidence suggests that life could have originated in such systems. Consequently, hydrothermal systems at oceanic spreading centers serve as real-time laboratories for investigating linkages among geological, geophysical, and biogeochemical processes of global importance.

Heat transfer measurements in young, bare-rock hydrothermal environments of ocean ridges are of critical importance to the marine science community. In this environment alternatives to traditional conductive heat flow measurements are needed (Box 9). Advective heat output from both focused and diffuse flow sites is necessary to characterize the physics of these dynamic systems [*Lowell et al.*, 1995; *Lowell and Germanovich*, 2004]. Additionally, because these systems are naturally transient on a number of time scales and undergo pronounced changes following magmatic and tectonic events, it is important to monitor changes in heat output and temperature as a function of time.

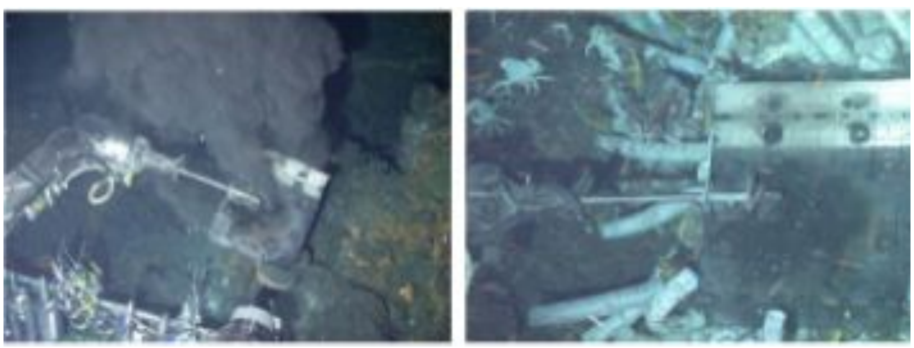
A variety of technologies are needed to detect advective heat flow at sites of focused (e.g., hydrothermal vents, cold seeps) and diffuse flow over the vent field scale and to distinguish between these two components. At present several techniques are used to determine advective heat output. These include water column measurements in the neutrally buoyant plume [e.g., *Baker et al.*, 1994, 2004], water column measurements using the AUV Autonomous Benthic Explorer [ABE; *Viers et al.*, 2006], scalar and vector measurements of vent plumes using acoustic

Box 9. Advective heat flow at spreading centers

Seafloor hydrothermal systems comprise an important component of the Earth energy budget, accounting for approximately 25% of the global heat flux. Along mid-ocean axes, high temperature venting may alone account for up 10% of the global heat loss. Understanding both the energy and mass flux requires vent field scale measurements at both focused high temperature venting sites such as chimneys and diffuse low temperature flow sites. Presently, there is considerable interest in the partitioning between focused and diffuse fluxes of heat and mass. Measurements of these fluxes are critical for an integrated understanding of ridge processes and place important constraints on crustal permeability, fluid circulation patterns and their temporal and spatial variability [Rona and Trivett, 1992; Baker et al., 1993; Converse et al., 1984; Von Damm, 2004; Ramondenc et al., 2006; Veirs et al., 2006; Baker, 2007].

Determinations of advective heat flux require coupled measurements of temperature, flow volume and velocity. Temperature measurements are made with submersibles or deep towed instruments. Measurements of flow velocity are typically made by particle or eddy tracking, and flow volume is computed based on visual inspection of orifices. While estimates of advective heat flux from focused sites are relatively straight forward, relatively low temperatures and uneven distribution make estimates of diffuse heat flux are more difficult. Recently, Ramondenc et al. [2006] used a simple and robust device to make direct measurements of advective heat output at individual vents and at one site of diffuse flow (Figure 9.1). These data constraints on the partitioning between focused and diffuse flow, and they suggest that heat flux from diffuse venting is at least an order of magnitude greater than heat flux from focused venting. Baker [2007] theorizes that small low temperature vent areas may be far more common that we realize and that resolving this issue will likely require intensive, fine-scale, near bottom surveys over entire ridge segments.

Figure 9.1



Photographs of a device from flux measurements of high-temperature vent and diffuse flow [Photos by L. Germanovich; Ramondenc et al., 2006]. The walls of the device are marked so that fluid eddies and particles may be tracked.

backscatter and of diffuse flow using acoustic scintillation [*Rona et al.*, 2006], measurements of turbulence using acoustic scintillation [*Di Iorio and Farmer*, 1994], and direct measurement of fluid flux in vent plumes and diffuse flow [*Rona and Trivett*, 1992; *Ramondenc et al.*, 2006]. All of these measurements have considerable uncertainty, and different measurement techniques often yield significantly different estimates of heat output [*Baker*, 2007]. Other suggested techniques include the use of Peltier elements and, for cold seeps, thermometry with fiber optics [*Trehu*, Appendix A3].

Due to the technical and logistical barriers to drilling even a small diameter hole in rocks on the seafloor, an alternative approach to in situ characterization of such properties as bulk permeability and porosity has been the use of noninvasive geophysical methods. Controlled source electromagnetic (CSEM) surveys, seismic velocity analyses, and magnetic intensity data can be applied independently or together as part of a program to assess shallow subseafloor fluid circulation and the role of advection in local to regional thermal regimes in hard rock settings.

Internal heat sources remain an important parameter to quantify. Although marine rocks are generally far less radiogenic than continental rocks, marine sediments consisting primarily of terrigeneous clastics and located proximal to felsic continental source rocks may contain substantial radioactivity. The heat generated in such marine sediments must be properly accounted for when calculating basement heat flow or when assessing the role of underthrust sediments in heating the overlying slab in subduction zones [*Von Herzen et al.*, 2001]. Compared to radiogenic processes, the potential for biological or chemical processes to produce heat in sediments is negligible. Yet as thermal measurements achieve higher precision, detection of endothermic/exothermic chemical or biochemical transformations may become possible.

4.3 Models for Sustainability

The main focus of this discussion was to consider different approaches to sustaining access to heat flow equipment within the U.S. research community for the next two decades. It is the consensus of the workshop participants that the community should begin modestly, through establishment of a marine heat flow capability that will serve the majority of anticipated scientific needs (i.e., based on discussions summarized earlier in this report) for surveys that sample the shallow subsurface in sedimented environments. It was also recognized that there is unlikely to be a sustained marine heat flow capability in the U.S. if it is simply left to individual investigators to develop one on their own. Although there is considerable interest in running marine heat flow surveys during the next two decades, no single investigator or group is likely to have a sufficient number of planned programs funded in advance across the timeframe of more than a decade to justify the time, effort, and cost involved in creating a pool of instruments and compiling associated documentation and support. Given the many fundamental scientific questions requiring new heat flow data discussed earlier in this report, the availability of well-maintained heat flow equipment will naturally catalyze new interest in using the technology and thus increased numbers of competitive research proposals.

There was also considerable discussion about fostering technical innovation and development to go beyond maintaining a basic capability in data acquisition with state-of-the-art equipment and to include development of enhanced tools and novel techniques. Technical enhancement and innovation can be justified and leveraged once the community has established fundamental capabilities and demonstrated necessary commitment and sustainability.

Several models for developing, managing, and sustaining access to a heat flow capability were discussed at the workshop. Considerations included:

- type of equipment;
- flexibility in scheduling equipment consistent with standard (UNOLS) practices;
- opportunities for exposure of techniques and technologies and training by the broader community, particularly students and junior researchers; and
- minimizing baseline and operating costs.

End-member models are discussed below (summarized in Table 1), including advantages and disadvantages associated with each.

Workshop participants recognize that the community might also attempt a hybrid approach, combining characteristics of two or more of the distinct support models described below. We did not make a single recommendation with regard to which model(s) should be attempted. Instead, we explored and documented factors that should be considered in creating and maintaining a capability, leaving it to individual(s) who might prepare a proposal for creation and maintenance of a marine heat flow capability to select and justify a particular model.

4.3.1 Option 1: Shipboard Scientific Equipment

With this model, a marine heat flow capability would be developed and maintained through Integrated Programs, much as other oceanographic capabilities are handled within the UNOLS fleet. Examples of other technical capabilities that have characteristics in common with marine heat flow include coring systems, portable seismic instrumentation, and gravimeters, all of which can be run from many UNOLS vessels if requested by co-PIs when a new proposal is submitted. For all of these systems, researchers need to have some basic level of expertise and understanding in order to make a strong case for use (i.e., to survive peer review and panel ranking). In many cases, it is necessary to consult in advance with others who have used or maintain the instruments prior to soliciting funding and to plan surveys in detail with ship operators once a program is approved. In addition, interested researchers need to supply a sufficient number of scientific and

Table 1. Summary of advantages and disadvantages of several possible models for developing and maintaining a U.S. marine heat flow capability

Considerations	1. Shipboard equipment	2. U.S. national facility	3. National consortium	4. International collaboration	5. Commercial lease
Baseline cost	Low-moderate	Moderate-high	Low-moderate	Low	NA
Operating cost	Low	Moderate-high	High	Low-high	High
Technical support cost	Low-moderate	High	Low	Low	Moderate-high
Shipping cost	Low-high	Low-high	Low-high	Moderate-high	Moderate-high
Scheduling flexibility	High	High	Moderate	Low	Low
Access for planning, training	High	High	Moderate	Low	Low
Integration with UNOLS operations	High	High	Moderate	Low	Low
Opportunities for innovation	Moderate	High	Low-moderate	Moderate	Low
Integrating related tools	High	Moderate-high	Low-moderate	Low-moderate	Low
Long-term maintenance opportunity	High	High	Moderate	Unclear	Unclear

technical personnel, much in the same way that the science party works on deck during core recovery and sampling or provides personnel to run seismic surveys and complete processing. There could be an option to request the participation of experienced technical support personnel from outside of the co-PI group and their colleagues, but recent experience running marine heat flow surveys suggests that in many cases this may not be necessary.

Once appropriate instruments are available to the U.S. academic community, the marine heat flow capability would ideally be affiliated with a major oceanographic or Earth science institution, where there would be access to technical expertise and facilities (e.g., machine shop, electrical technicians, storage space). Researchers who wished to make use of heat flow instrumentation and expertise would indicate this when submitting proposals to NSF or other funding sources, and costs for fielding instruments would be handled through the same mechanism that supports ship operations and technical support. This approach also offers benefits in assuring compatibility and consistency between marine heat flow and related measurements and technology (e.g., using compatible wireline terminations and wireline pingers, standardizing aspects of shipboard deployment and recovery of systems, making available appropriate acoustic receivers and display systems).

The key to making this approach work would be finding a suitable institution with scientific leadership and available technical personnel who could provide support on an as-needed basis. The ideal arrangement would include a "near-zero baseline," with financial support for fielding heat flow instrumentation ramping up or down as needed on an annual basis, depending on the number and specifics of funded programs. Personnel involved would include those having a variety of skills and responsibilities, rather than being dedicated to marine heat flow alone. It may also be possible, if a heat flow system were available at a UNOLS institution, to lease the system to non-academic U.S. users and/or to non-U.S. users on a cost-recoverable (or system-supporting, cost-plus) basis. As described below under Option 5, there is currently considerable commercial demand for marine heat flow capabilities. Finally, Option 1 (like Option 2 and possibly Options 3 and 5) offers the potential to simplify and save considerable costs in international shipping of equipment. In many cases, instrumentation and supplies can be kept in a dedicated van or on-loaded and off-loaded through U.S. ports.

4.3.2 Option 2: U. S. National Marine Heat Flow Facility

Option 2 resembles Option 1 in several respects, but has important differences, mainly related to the nature of operating personnel and costs and opportunities for future technical developments (Table 1). The creation and operation of a national facility is inherently more complex and expensive than having a pool of instruments and capabilities integrated with shipboard operations and equipment. Dedicated personnel having a specific combination of skills, experience, and interest must be hired and supported, on an ongoing basis, independent of the level of interest and funding levels within the oceanographic community from year to year. As with Option 1, a national facility could be affiliated with a major oceanographic or Earth science institution, and planning for collection of marine heat flow data could be coordinated as part of the UNOLS scheduling process.

From the perspective of end users, the primary advantage of creating a facility is in the area of technical support and innovation. End users could have the expectation of sufficient technical support to run heat flow surveys even if they personally have little or no prior experience. In addition, a national facility could include personnel who design and develop new instrumentation, so that the evolution of marine heat flow instrumentation can proceed rapidly as new technologies become available and the prices for components continue to fall.

Workshop participants note that the boundary between Options 1 and 2 is blurry: One can envision varying levels of technical support for a pool of shipboard scientific equipment or development of a bare-bones facility comprising perhaps a single individual and a single set of equipment. Yet it became clear in the discussion of scientific goals that much of what the community needs can be satisfied with a relatively low level of technical support, in part based on the ease of use of the current generation of marine heat flow technology. There was some consensus among workshop participants that the marine heat flow community needs to prove that it has the long-term commitment and wealth of important, fundable scientific ideas that are necessary to justify and sustain a facility. There could be an option to develop a facility in the future, even if the community elected to begin with a more modest model for sustainable technology and support for the near future.

4.3.3 Option 3: U. S. Marine Heat Flow Consortium

This option involves having a group of individuals, at one or more institutions, develop and maintain marine heat flow capabilities, and make these capabilities available to the community at large on an ad hoc basis. In some ways, this approach is what the community is doing now, although it should be noted that no U.S. academic institution currently has multipenetration heat flow instrumentation available. U.S. researchers do routinely borrow each other's instrumentation for attaching outrigger probes to core barrels or to measure the thermal conductivity of recovered sediment samples. In addition, U.S. researchers have repeatedly leased Canadian multipenetration heat-flow instrumentation in the past decade to complete NSF- and DOE-funded surveys. If there were a similar set of instrumentation available at one or more U.S. institutions, there could be an option to form a semi-formal or formal consortium of heat flow capabilities, with tools and documentation being made available to interested users on an as-needed basis. In some ways, this is a looser, more diffuse version of Option 1.

This approach might have relatively low baseline costs, comparable to those for Option 1, depending on which instrument sets are created and maintained by individual PIs. However, the operating costs are likely to be somewhat higher than for Option 1, as the use of equipment owned by one institution by a PI from another institution would require the expenditure of science funds, rather than shipboard operation funds, including overhead. There would also likely be considerable administrative inefficiency in this approach, requiring what amounts to a donation of time by personnel from the institution that operates the instruments, and also more limited opportunities for broad exposure and training of students and junior scientists. The laissez-faire nature of Option 3 also raises questions about whether the initial investment in instrumentation, documentation, supplies, and shipping materials would be properly maintained. It is not clear how coordination of instrumentation requests would be integrated with UNOLS scheduling, and making technical improvements to the instrument pool over time would likely be difficult.

The development of a consortium was also discussed in the context of using heat flow instrumentation owned and operated by the NRL. Unfortunately, it has proven difficult for many academic researchers to access heat flow instrumentation run by the NRL, primarily because of restrictions on transferring funds among various entities, differences in the scientific priorities and missions of the various organizations involved (e.g., shallow water versus deep water), and other administrative issues (e.g., U.S. versus international or non-U.S. waters, liability).

4.3.4 Option 4: International Collaboration

This option has U.S. researchers relying on establishing and maintaining access to instrumentation through collaboration with peer researchers working outside the U.S. In fact, many U.S. researchers are currently pursuing this approach, both as a practical means for addressing the unavailability of U.S. tools and because of the scientific and personal benefits inherent in such collaborations. Reliance on non-U.S. capabilities may have some financial advantages for U.S. researchers and funding agencies in cases where survey and equipment costs are covered externally. However, it was the consensus of workshop participants that this approach will be difficult to enhance beyond what currently occurs, which is limited, and is unlikely to provide broad U.S. access to necessary capabilities or help to train the next generation of heat flow practitioners.

The biggest problem is that this approach relies on the willingness of non-U.S. researchers and institutions to subsidize U.S. oceanographic research or on an extremely fortuitous confluence and coincidence of international interests, funding, and ship schedules. In addition, although there would be essentially no start-up cost associated with taking this approach (leaving all capital investment to non-U.S. entities), there can be considerable administrative complexity (and potentially legal issues) involved in the international transfer of U.S. scientific operating funds. In cases where non-U.S. institutions are not able to cover field costs, these would have to be covered by U.S. PIs (and funding agencies), and these costs are likely to be relatively high.

Several U.S. researchers have leased Canadian instrumentation for marine heat flow surveys over the last decade, but this approach has involved a de-facto subsidization of U.S. research on the basis of capital costs and technical support provided by non-U.S. institutions. Reliance on international collaboration is also likely to limit access of instrumentation to U.S. researchers and students, reducing opportunities for exposure and training. Depending on the country of origin, international shipping costs (including customs brokerage and newly instituted requirements involving the transfer of electronics) may be prohibitive. It is also not clear that international partners will continue to develop and maintain instrumentation over the next two decades; there may be challenges in continuing to support this capability within individual countries if there is variable internal demand (as we have seen in the U.S.). Workshop participants certainly encourage international collaboration, and many participate in successful, ongoing scientific partnerships, but there was considerable skepticism among those present that this approach will provide the capabilities needed by the U.S. community in coming decades.

4.3.5 Option 5: Commercial Lease

There is currently one U.S. commercial company that conducts marine heat flow surveys (mainly for industrial clients) and that can make equipment available to U.S. researchers on contract. The greatest benefit to working with a commercial heat flow operator is that there is essentially no cost to the U.S. community unless and until a project is funded and the seagoing portion commences. In addition, commercial operators generally maintain technical capabilities and can field single or multiple technical support personnel, as needed and if funds are available.

Probably the greatest weakness in relying on commercial instrumentation and expertise is scheduling and competition from industry. Additionally because there is currently only one company operating heat flow gear, it leaves the U.S. academic community vulnerable to priority changes in the private sector. Commercial heat flow systems that might be available to U.S. researchers are presently in demand, being essentially scheduled 1–2 years in advance. Scheduling for use of this capability within the timeframe of UNOLS scheduling may be challenging, and there may also be serious difficulties in coordination of related technical needs with UNOLS operators. Conversely, the heat flow survey might be run on a vessel owned or leased by the commercial operator, but this can produce additional costs or difficulties (e.g., need for the ship to meet UNOLS standards if U.S. PIs are involved directly). In addition, estimated costs with this option appear to be considerably greater than those that would be associated with Options 1 or 3 (shipboard equipment or national consortium), even without considering that these funds would have to be included as direct costs on science budgets. There also appears to be limited opportunity for enhancement of current technology, and little chance for training and general exposure of a broad oceanographic community. Numerous U.S. researchers have explored use of commercial marine heat flow systems for scientific surveys, but there have been few successful examples of this model for data acquisition. It is not clear that the commercial approach could be modified to make it more compatible and economical with current and projected U.S. research planning and funding limitations.

4.4 Databases and Accessibility

It was noted during several thematic and technical sessions, and during plenary discussions, that the global heat flow database currently available to the community at large is incomplete, particularly with regard to marine heat flow data collected during the last 5–10 years. Workshop participants learned that there is an effort in the early planning stages, by members of the International Heat Flow Commission, to update the global data base, including expanding the amount and kinds of information that is stored with individual heat flow determinations. Although database development and operation is beyond the scope of primary workshop goals, participants agreed that the ongoing renaissance in marine thermal studies will place increasing demands on the existing database, and that efforts should be supported to update and maintain access to marine heat flow data. These efforts are particularly important for engaging researchers who will use existing data to constrain models and propose new experiments.

5. Toward a Sustainable U.S. Capability in Marine Heat Flow

The NSF-sponsored workshop on "The Future of Marine Heat Flow" served the purpose for which it was intended. Participants arrived with a variety of interests, expertise, and intentions with regard to collection and use of marine heat flow data. By the end of the workshop, it was clear that there is a motivated community of active and successful researchers working within the U.S., and collaborating with colleagues from around the world, for whom acquisition and use of new marine heat flow data will be essential in order to address important scientific questions over the next 10–20 years. This interest stems in part from the ability to use multiple datasets in a coordinated way to more fully exploit marine heat flow data to understand the thermal state of the Earth as well as energy and mass fluxes across its various interfaces. Ongoing improvements in instrumentation that allows more measurements with greater precision, navigation that allows closely spaced heat flow determinations and collocation with complementary data sets, together with increasing modeling power is yielding new insights and understanding of seafloor processes. These efforts have lead to the recognition that variability in closely-space heat flow data once thought to represent instrumental or environmental noise is signal that can now be interpreted. New interpretations are leading researchers to question previously held assumptions and interpretations. One global process undergoing renewed interest as a result of these advancements is the way in which hydrothermal circulation evolves and ultimately becomes shut off from the overlying ocean.

However, the lack U.S. academic based capabilities for acquisition, processing, and interpretation of marine heat flow data has weakened the community and now threatens to retard progress in these important areas. Several participants noted the perception that there is not currently U.S. sea-going expertise in conventional marine heat flow while others noted the extra real and non-monetary costs associated with leasing equipment from Canada. Participants at the workshop explored and discussed several possible models for developing and sustaining the capability for the acquisition of marine heat flow data by researchers operating on UNOLS and other (conventional) research vessels at low cost, on a pay-as-you-go basis. The U.S. community needs to move quickly to establish a basic capability, while there is still an opportunity to benefit from several generations of experienced practitioners, so as to broaden the pool of researchers who can collect, process, and interpret marine heat flow data.

References Cited

Abercrombie, R. E., and G. Ekström, 2001, Earthquake slip on oceanic transform faults, *Nature, 410*, 74–77.

Anderson, M. P., 2005, Heat as a ground water tracer, *Ground Water, 43*, 1–18.

Baker, E. T., 2007, Hydrothermal cooling of midocean ridge axes: Do measured and modeled heat fluxes agree? *Earth Planet. Sci. Lett., 263*, 140–150, doi:10.1016/j.epsl.2007.09.010

Baker, E.T., and C.R. German, 2004, On the global distribution of hydrothermal vent fields. In *Mid-Ocean Ridges: Hydrothermal interactions between the lithosphere and oceans*, C.R. German, J. Lin, and L.M. Parson (eds.), Geophys. Monogr. Ser., Vol. 148, AGU, 245–266.

Baker, E. T., R. A. Feely, M. J. Mottl, F. T. Sansone, C. G. Wheat, J. A. Resing and J. E. Lupton, 1994, Hydrothermal plumes along the East Pacific Rise, 8°40' to 11°50' N: plume distribution and relationship to the apparent magmatic budget, *Earth Planet. Sci. Lett. 128*, 1–17.

Baker, E. T., H. N. Edmonds, P. J. Michael, W. Bach, H. J. B. Dick, J. E. Snow, S. L. Walker, N. R. Banerjee and C. H. Langmuir, 2004, Hydrothermal venting in magma deserts: the ultraslow-spreading Gakkel and South West Indian Ridges, *Geochem. Geophys. Geosys., 5*, Q08002.

Behn, M. D., et al., 2007, On the thermal structure of oceanic transform faults, *Geology, 35*, 307–310.

Benfield, A.E., 1949, The effect of uplift and denudation on underground temperatures, *J. App. Phys., 20*, 66–70.

Bergman, E. A., and S. C. Solomon, 1988, Transform fault earthquakes in the North Atlantic: Source mechanisms and depth of faulting, *J. Geophys. Res., 93*, 9027–9057.

Blackwell, J. H., 1954, A transient flow method for determination of thermal constants of insulating materials in bulk, *J. Appl. Phys., 25*, 137.

Carbotte, S. M., C. Small, and K. Donnelly, 2004, The influence of ridge migration on the magmatic segmentation of mid-ocean ridges, *Nature, 429*, 743–746.

Cathles, L. M. and A. G. Nunns, 1991, A temperature probe survey on the Louisiana Shelf: effects of bottom-water temperature variations, *AAPG, 75*, 180–186.

Chen, W.-P., and P. Molnar, 1983, Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere, *J. Geophys. Res., 88*, 4183–4214.

Clennell, M. B., M. Hovland, J. S. Booth, P. Henry, and W. J. Winters, 1999, Formation of natural gas hydrates in marine sediments, 1: Conceptual model of gas hydrate growth conditioned by host sediment properties, *J. Geophys. Res., 104*, 22,985–23,003.

COMPLEX, Final Report, 2000, in *Conference on Multiplatform Exploration of the Ocean*, JAMSTEC/ORI/JOIDES, Vancouver, BC.

COMPOST, 1993, Report to the U. S. Science Advisory Committee, in *U.S. Committee on Post-1998 Ocean Drilling*, JOI, Seattle, Washington.

COMPOST II, 1998, A New Vision for Scientific Ocean Drilling, in *U.S. Committee for Post-2003 Ocean Drilling*, JOI, Miami, FL.

Constantz, J., and D. A. Stonestrom, 2003, Heat as a tracer of water movement near streams, in *Heat as a tool for studying the movement of ground water near streams*, D. A. Stonestrom, and J. Constantz, (eds.), 1–6, U. S. Geological Survey, Denver CO.

Converse, D. R., H. D. Holland, J. M. Edmond, 1984, Flow rates in the axial hot springs of the East Pacific Rise (21° N): implications for the heat budget and the formation of massive sulfides, *Earth Planet. Sci. Lett., 69*, 159–175.

Crosby, A. G., D. McKenzie, and J. G. Sclater, 2006, The relationship between depth, age and gravity in the oceans, *Geophys. J. Int., 166*, 533–573.

Currie, C. A., and R. D. Hyndman, 2006, The thermal structure of subduction zone back arcs, *J. Geophys. Res., 111*, B08404, doi:10.1029/2005JB004024.

Currie, C. A. , R. D. Hyndman, K. Wang, and V. Kostoglodov, 2002, Thermal models of the Mexico subduction zone; implications for the megathrust seismogenic zone, *J. Geophys. Res., 107*, 2370, doi:10.1029/2001JB000886,

Davis E. E., and C. R. B. Lister, 1974, Fundamentals of ridge crest topography, *Earth Planet. Sci. Lett., 21*, 405–413.

Davis, E. E., R. D. Hyndman, and H. Villinger, 1990, Rates of fluid expulsion across the Northern Cascadia accretionary prism: constraints from new heat flow and multichannel seismic reflection data, *J. Geophys. Res., 95*, 8869–8889.

Davis, E. E., Horel, G. C., MacDonald, R. D., Villinger, H., Bennett, R. H., and Li, H., 1991, Pore pressures and permeabilities measured in marine sediments with a tethered probe, *J. Geophys. Res., 96*, 5975–5984.

Davis, E. E., K. Wang, K. Becker, R. E. Thomson, and I. Yashayaev, 2003, Deep-ocean temperature variations and implications for errors in seafloor heat flow determinations, *J. Geophys. Res., 108*, 2034, doi:10.1029/2001JB001695.

DeLaughter, J., S. Stein, and C. Stein, 1999, Extraction of the lithospheric aging signal from satellite geoid data, Earth. *Planet Sci. Lett., 174*, 173–181.

DeLaughter, J., C. A. Stein, and S. Stein, 2005, Hotspots: a view from the swells, in Foulger, G. R., J. Natland, D. C. Presnall, and D. L. Anderson (eds.), Plates, plumes, and paradigms, *Geol. Soc. Am. Sp. Paper 388*, 257–278, doi: 10.1130/2005.2388(16).

Di Iorio, D., and D. Farmer, 1994, Path-averaged turbulent dissipation measurements using high-frequency acoustical scintillation analysis, *J. Acoust. Soc., Am., 96*, 1056–1069.

Doin, M.-P., and L. Fleitout, 2000, Flattening of the oceanic topography and geoid; thermal versus dynamic origin , *Geophys. J, Int., 143*, 582–594.

Dumoulin, C., M.-P. Doin, L. Fleitout, 2001, Numerical simulations of the cooling of an oceanic lithosphere above a convective mantle, *Phys. Earth Planet. Int., 125*, 45–64.

Dunn, R. A., D. R. Toomey, and S. C. Solomon, 2000, Three-dimensional seismic structure and physical properties of the crust and shallow mantle beneath the East Pacific Rise at 9 ° 30'N, *J. Geophys. Res, 105*, 23,537–23,555.

Edmond, J. M., C. Measures, R. E. McDuff, L. H. Chan, R. Collier, B. Grant, L. I. Gordon, and J. B. Corliss, 1979, Ridge crest hydrothermal activity and the balances of the major and minor elements in the ocean: The Galapagos data, *Earth Planet. Sci. Lett., 46*, 1–18.

Elderfield H., and A. Schultz, 1996, Mid-ocean ridge hydrothermal fluxes and the chemical composition of the ocean. *Annu. Rev. Earth Sci. 24*, 191–224.

Fisher, A. T., and R. P. Von Herzen, 2005, Models of hydrothermal circulation within 106 Ma seafloor: Constraints on the vigor of fluid circulation and crustal properties below the Madeira Abyssal Plain, *Geochem., Geophys., Geosystems, 6*, doi:10.1029/2005GC001013.

Fisher, A., Von Herzen, R. P., Blum, P., Hoppie, B., Wang, K., 1999, Evidence may indicate recent warming of shallow slope bottom water off New Jersey shore, EOS, *Trans. Am. Geophys. Union, 80*, 165, 172–173.

Fisher, A. T., E. E. Davis, Hutnak, M., Spiess, V., Zühlsdorff, L., Cherkaoui, A., Christiansen, L., Edwards, K. M., Macdonald, R., Villinger, H., Mottl, M., Wheat, C. G., and Becker, K., 2003a, Hydrothermal circulation across 50 km on a young ridge flank: the role of seamounts in guiding recharge and discharge at a crustal scale, *Nature, 421*, 618–621.

Fisher, A. T., C. A. Stein, R. N. Harris, K. Wang, E. A. Silver, M. Pfender, M. Hutnak, A. Cherkaoui, R. Bodzin, and H. Villinger, 2003b, Abrupt thermal transition reveals hydrothermal boundary and role of seamounts within the Cocos Plate, *Geophys. Res. Lett., 30*, doi:10.1029/2002GL016766.

Foulger, G. R., and D. M. Jurdy, (eds.), 2007, *Plates, Plumes, and Planetary Processes*, Geol. Soc. Amer. Spec. Paper 430, 998 pp.

Foulger, G.R., J. H. Natland, D. C. Presnall and D. L. Anderson, (eds.), 2005, *Plates, Plumes, and Paradigms*, Geological Society of America Special Volume 388, 881 pp.

FUMAGES, Report to the U. S. Science Advisory Committee, in *Workshop on the Future of Marine Geology and Geophysics*, NSF, Ashland Hills, OR, 1997.

Furlong, K. P., et al., 2001, Thermal-rheological controls on deformation within oceanic transforms, in *The Nature and Tectonic Significance of Fault Zone Weakening*, edited by R. E. Holdsworth, et al., pp. 65–84, Geology Society, London.

Grevemeyer, I. and H. Villinger, 2001, Gas hydrate stability and assessment of heat flow through continental margins, *Geophys. J. Int., 145*, 647–660, doi: 10.1046/j.0956-540X.2001.01404.x.

Grevemeyer, I., J. L. Diaz-Naveas, C. R. Ranero and H. W. Villinger, 2003, Heat flow over the descending Nazca plate in central Chile, 32°S to 41°S: observations from ODP Leg 202 and the occurrence of natural gas hydrates, *Earth Planet. Sci. Lett., 213*, 285—298, doi:10.1016/S0012-821X(03)00303-0.

Grevemeyer, I., A. J. Kopf, N. Feketec, N. Kaul, H. W. Villinger, M. Heesemann, K. Wallmann, V. Spieß, H.-H. Gennerich, M. Müller and W. Weinrebe, 2004, Fluid flow through active mud dome Mound Culebra offshore Nicoya Peninsula, Costa Rica: evidence from heat flow surveying, *Mar. Geo., 207*, 145–157, doi:10.1016/ j.margeo.2004.04.002

Guerin, G., K. Becker, R. Gable, P. A. Pezard, 1996, Temperature measurements and heat-flow analysis in Hole 504B, *Proc. Ocean Drill. Prog., Sci. Results 148*, 291–296.

Hacker, B. R., G. A. Abers, and S. M. Peacock, 2003, Subduction factory: 1. Theoretical mineralogy, density, seismic wave speeds, and H_2O content, *J. Geophys. Res., 108*, 2029, doi:10.1029/2001JB001127.

Hamamoto, H., M. Yamano, and S. Goto, 2005, Heat flow measurement in shallow seas through long-term temperature monitoring, *Geophys. Res. Lett., 32*, L21311, doi:10.1029/2005GL024138.

Harris, R. N., and D. S. Chapman, 2004, Deep-seated oceanic heat flow, heat deficits, and hydrothermal circulation, E.E. Davis, H. Elderfield (eds). in *Hydrogeology of the Oceanic Lithosphere*, Cambridge Univ. Press, 311–336.

Harris, R. N., and IODP Leg 306 Scientists, 2006, Borehole Observatory Installations on IODP Expedition 306Reconstruct Bottom-Water Temperature Changes in the Norwegian Sea, *Scientific Drilling, 2*, 28–31.

Harris, R. N., and M. K. McNutt, 2007, Heat flow on hot spot swells: Evidence for fluid flow, *J. Geophys. Res., 112*, B03407, doi:10.1029/2006JB004299.

Harris, R. N., and K. Wang, 2002, A thermal model of the Middle America Trench at the Nicoya Peninsula, Costa Rica, *Geophys. Res. Lett., 29(21)*, 1550, doi:10.1029/2002GL016766.

Harris, R. N., G. Garven, J. Georgen, M. K. McNutt, and R. P. Von Herzen, 2000a, Submarine hydrogeology of the Hawaiian archipelagic apron, Part 2, Numerical simulations of coupled heat transport and fluid flow, *J. Geophys. Res., 105*, 21,371–21,385.

Harris, R. N., R. P. Von Herzen, M. K. McNutt, G. Garven, and K. Jordahl, 2000b, Submarine hydrogeology of the Hawaiian archipelagic apron, Part 1, Heat flow patterns north of Oahu and Maro Reef, *J. Geophys. Res., 105*, 21,353–21,369.

Harris R. N., A. T. Fisher, and D. S. Chapman, 2004, Fluid flow through seamounts and implications for global mass fluxes, *Geology*, 725–728. doi:110.1130/G20387.1.

Hasegawa, A., and J. Nakajima, 2004, Geophysical constraints on slab subduction and arc magmatism, in *The State of the Planet: Frontiers and Challenges in Geophysics*, Geophys. Monogr. Ser., edited by R. S. J. Sparks and C. J. Hawkesworth, pp. pp. 81, American Geophysical Union, Washington, D.C.

Haymon, R. C., K. C. Macdonald,S. B. Benjamin, and C. J. Ehrhardt, 2005, Manifestations of hydrothermal discharge from young abyssal hills on the fast-spreading East Pacific Rise flank, *Geology, 33*, 153–156.

He, T., G. D. Spence, M. Riedel, R. D. Hyndman, and N. Chapman, N. R., 2007, Fluid flow and origin of a carbonate mound offshore Vancouver Island; seismic and heat flow constraints, *Mar. Geo., 239*, 83–98.

Hillier, J. K., and A. B. Watts, 2005, Relationship between depth and age in the North Pacific Ocean, *J. Geophys. Res., 110*, B02495, doi:10.1029/2004JB003406.

Hofmeister, A.M. and R.E. Criss, 2005. Earth's heat flux revised and linked to chemistry. *Tectonophys., 395*, 159–177.

Hornbach, M., C. Ruppel, D. Saffer, C.L. Van Dover, and W.S. Holbrook, 2005, Coupled geophysical constraints on heat flow and fluid flux at a salt diapir, *Geophys. Res. Lett., 32*, L24617, doi: 10.1029/2005GL024862.

Hornbach, M., C. Ruppel, and C.L. Van Dover, 2007, Three-dimensional structure of fluid conduits sustaining an active deep marine cold seep, *Geophys. Res. Lett., 34*, L05601, doi: 10.1029/2006GL028859.

Huang, J., and S. Zhong, 2005, Sublithospheric small-scale convection and its implications for residual topography at old ocean basins and the plate model, *J. Geophys. Res., 110*, B05404, doi:10.1029/2004JB003153.

Hutchinson, D., P. E. Hart, C. D. Ruppel, F. Snyder, and B. Dugan, in press, Seismic and thermal characterization of a bottom simulating reflector in the Northern Gulf of Mexico, in: *Gas Hydrates: Energy Resource Potential and Associated Geologic Hazards*, A. Johnson and T. Collett, (eds.), AAPG Hedberg Memoir.

Hutchison, I., 1985, The effects of sedimentation and compaction on oceanic heat flow, *Geophys. J. R. Astr. Soc., 82*, 439–459.

Hutnak, M., and A. T. Fisher, 2007, The influence of sedimentation, local and regional hydrothermal circulation, and thermal rebound on measurements of heat flux from young seafloor, *J. Geophys. Res.*, in press.

Hutnak, M., A. T. Fisher, C.A. Stein, R. Harris, K. Wang, E. Silver, G. Spinelli, M. Pfender, H. Villinger, R. MacKnight, P. Costa Pisani, H. DeShon, and C. Diamente, 2007, The thermal state of 18–24 Ma upper lithosphere subducting below the Nicoya Peninsula, northern Costa Rica margin, in *The Seismogenic Zone of Subduction Thrust Faults*, T. Dixon, C. Moore, (eds.), Columbia University Press, New York, 42–85.

Hutnak, M., A. T. Fisher, L. Zühlsdorff, V. Spiess, P. Stauffer, and C. W. Gable, 2006, Hydrothermal recharge and discharge guided by basement outcrops on 0.7-3.6 Ma seafloor east of the Juan de Fuca Ridge: observations and numerical models, *Geochem. Geophys. Geosyst., 7*, doi:10.1029/2006GC001242.

Hyndman, R. D., and K. Wang, 1993, Thermal constraints on the zone of major thrust earthquakes failure The Cascadia subduction zone, J. Geophys. Res., 98, 2039–2060.

Hyndman R. D., E. E. Davis, J. A. Wright, 1979, The measurement of marine geothermal heat flow by a multipenetration probe with digital acoustic telemetry and in situ thermal conductivity, *Mar. Geophys. Res., 4*, 181–205.

Hyndman, R. D., C. A. Currie, S. P. Mazzotti, 2005, Subduction zone backarcs, mobile belts, and orogenic heat, *GSA Today, 15*, 4–10.

Jansen D., B. Heesemann, M. Pfender, A. Rosenberger, H. Villinger, 2005, In situ measurement of electrical resistivity of marine sediments, results from Cascadia Basin off Vancouver Island, *Mar. Geol., 216*, 17–26.

Jaroslow, G. E., et al.,1996, Abyssal peridotite mylonites: Implications for grain-size sensitive flow and strain localization in the oceanic lithosphere, *Tectonophys., 256*, 17–37.

Johnson, H. P., and M. J. Pruis, 2003, Fluxes of fluid and heat from the oceanic crustal reservoir, *Earth Planet. Sci. Lett., 216*, 565-574, doi:10.1016/S0012-821X(03)00545-4

Kaul, N., A. Rosenberger, and H. Villinger, 2000, Comparison of measured and BSR-derived heat flow values, Makran accretionary prism, Pakistan, *Mar. Geol., 164*, 37–51.

Korenaga, T., and J. Korenaga, Subsidence of normal oceanic lithosphere, apparent thermal expansivity, and seafloor flattening," submitted to *Earth Planet. Sci. Lett.*

Lachenbruch A. H. and B. V. Marshall, 1968, Heat flow and water temperature fluctuations in the Denmark Strait, J. *Geophys. Res., 73*, 5829–5842.

Langseth, M. G., and Hobart, M. A., 1976, Interpretation of heat flow measurements in the Vema Fracture Zone, *Geophys. Res. Lett., 3*, 241–244.

Langseth, M. G., R. D. Hyndman, K. Becker, S. H. Hickman, and M. H. Salisbury, 1984, The hydrogeological regime of isolated sediment ponds in mid-oceanic ridges, in *Init. Repts., DSDP*, R. D. Hyndman, and M.H. Salisbury, (eds.) pp. 825–837, U. S. Govt. Printing Office, Washington, D. C.

Langseth, M. G., X. Le Pichon, and M. Ewing, 1966, Crustal structure of the mid-ocean ridges; 5, Heat flow through the Atlantic Ocean floor and convection currents , *J. Geophys. Res., 71*, 5321–5355.

Langseth, M. G K. Becker, R. P. Von Herzen, R. Pierre, P. Schultheiss, 1992, Heat and fluid flux through sediment on the western flank of the Mid-Atlantic Ridge; a hydrogeological study of North Pond, *Geophys. Res. Lett., 19*, 517–520.

Lapham, L.L., Chanton, J.P., Martens, C.S., Schaefer, H., Chapman, N.R., and Pohlman, J., 2003, Innovations in sampling pore fluids from deep-sea hydrate sites. *Eos Trans. Amer. Geophys. Union., 84(46)*, Fall Meet Suppl., Abstract OS52D-05, 2003.

Lister, C.R.B., 1972, On the thermal balance of a mid-ocean ridge, *Geophys. J. Int., 26*, 515–535.

Llubes, M., C. Lanseau, and F. Remy, 2006, Relations between basal condition, subglacial hydrological networks and geothermal flux in Antarctica, *Earth. Planet. Sci. Lett., 241*, 655–662.

Lonsdale, P., 1989, Segmentation of the Pacific-Nazca spreading center, 1ºN-20ºS, *J. Geophys. Res., 94*, 12,197–12,225.

Lowell, R. P. and L. N. Germanovich, 2004, Seafloor hydrothermal processes: Results from scale analysis and single-pass models, in *Mid-Ocean Ridges: Hydrothermal Interactions Between the Lithosphere and Oceans*, Geophys. Monogr. Ser., vol. 148, ed. by C.R. German, J. Lin, and L.M. Parson, pp. 219–244, AGU, Washington, D. C.

Lowell, R. P., P. A. Rona, and R. P. Von Herzen, 1995, Seafloor hydrothermal systems, *J. Geophys. Res., 100*, 327–352.

Lucazeau, F., F. Bigaud, and J. L. Bouroullec, 2004, High-resolution heat flow density in the lower Congo basin, *Geochem. Geophys. Geosys., 5*, Q03001, doi:10.1029/2003GC000644

Lucazeau, F., A. Bonneville, J. Escartin, R. P. Von Herzen, P. Gouze, H. Carton, M. Cannat, V. Vidal, and C. Adam, 2006,, Heat flow variations on a slowly accreting ridge: Constraints on the hydrothermal and conductive cooling for the Lucky Strike segment (Mid-Atlantic Ridge, 37°N), *Geochem. Geophys. Geosyst., 7*, Q07011, doi:10.1029/2005GC001178.

MacDonald, I., L. Bender, M. Vardaro, B. Bernard, and J. Brooks, 2005, Thermal and visual time-series at a gas hydrate deposit on the Gulf of Mexico slope, *Earth Planet. Sci. Lett., 233*, 45–59.

MARGINS, *Science Plans*, pp. 170, Lamont-Doherty Earth Observatory, Palisades, NY, 2003.

Martinez, F., and J. R. Cochran 1989, Geothermal measurements in the northern Red Sea: Implications for lithospheric thermal structure and mode of extension during continental rifting, *J. Geophys. Res., 94*, 12239–12265.

Martinez, F., A. M. Goodliffe, and B. Taylor, 2001, Metamorphic core complex formation by density inversion and lower-crust extrusion, *Nature, 411*, 930-934.

McKenzie, D., J. Jackson, and K. Priestley, 2005, Thermal structure of oceanic and continental lithosphere, *Earth Planet. Sci. Lett., 233*, 337–349.

McNutt, M. K., 1995, Marine geodynamics: depth-age revisited, *Rev. of Geophys., U.S. National Report Supplement*, 413–418.

Moore, J. C., and D. Saffer, 2001, Updip limit of the seismogenic zone beneath the accretionary prism of southwest Japan: An effect of diagenetic to lowgrade metamorphic processes and increasing effective stress, *Geology, 29*, 183–186.

Mottl, M., 2003, Partitioning of energy and mass fluxes between mid-ocean ridge axes and flanks at high and low temperature, in *Energy and mass transfer in submarine hydrothermal systems*, edited by P. Halbach, V. Tunnicliffe, and J. Hein, pp. 271–286, Dahlem University Press, Berlin, Germany.

Naslund, J. O., P. Jansson, J. L. Fastook, J. Johnson, and L. Andersson, 2005, Detailed spatially distributed geothermal heat-flow data for modeling of basal temperatures and meltwater production beneath the Fennoscandian ice sheet, *Ann. Glaciology, 40*, 95–101.

National Research Council, *Enabling Ocean Research in the 21st Century: Implementation of a Seafloor Observatory Network for Oceanographic Research*, 228 pp., National Research Council, Washington, D. C., 2003.

Newman, A. V., S. Y. Schwartz, V. Gonzalez, H. R. DeShon, J. M. Protti, and L. M. Dorman, 2002, Along-strike variability in the seismogenic zone below Nicoya Peninsula, Costa Rica, *Geophys. Res. Lett., 29(20)*, 1977, doi:10.1029/2002GL015409.

Oleskevich, D. A., R. D. Hyndman, and K. Wang, 1999, The updip and downdip limits to great subduction earthquakes: Thermal and structural models of Cascadia, south Alaska, SW Japan, and Chile, *J. Geophys. Res., 104*, 14,965–14,991.

Parsons, B., and J. G. Sclater, 1977, An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res., 82*, 803–827.

Paull, C. K., R. Matsumoto, P. J. Wallace, and Leg 164 Science Party, 1996, *Proceedings of the Ocean Drilling Program, Initial Reports, 164*, Ocean Drill. Program, College Station Tex.

Peacock, S. M., and K. Wang, 1999, Seismic consequences of warm versus cool subduction metamorphism; examples from Southwest and Northeast Japan, *Science, 1999*, 286, 937–939.

Pfender M., and H. Villinger, 2002, Miniaturized data loggers for deep sea sediment temperature gradient measurements, *Mar. Geol., 186*, 557–570.

Phipps Morgan, J., and D. W. Forsyth, 1988, Three-dimensional flow and temperature perturbations due to a transform offset: Effects on oceanic crust and upper mantle structure, *J. Geophys. Res., 93*, 2955–2966.

Pollack, H. N., and S. Huang, 2000, Climate reconstruction from subsurface temperatures, *Ann. Rev. Earth Planet. Sci., 28*, 339–365.

Pollard, D., R. M. DeConto, and A. A. Nyblade, 2005, Sensitivity of Cenozoic Antarctic ice sheet variations to geothermal heat flux, *Global and Planet. Change, 49*, 63–74.

Ramondenc, P., L. N. Germanovich, K. L. Von Damm, and R. P. Lowell, 2006, The first measurements of hydrothermal heat output at 9° 50'N, East Pacific Rise, *Earth Planet. Sci. Lett., 245*, 487–497, doi:10.1016/j.epsl.2006.03.023.

Ranero, C. R., J. Phipps Morgan, K. McIntosh, C. Reichert, 2003, Bending-related faulting and mantle serpentinization at the Middle America trench, *Nature, 425*, 367–373.

Richardson, W. P., S. Stein, C. A. Stein, and M. T. Zuber, 1995, Geoid data and thermal structure of the oceanic lithosphere, *Geophys. Res. Lett., 22*, 1913–1916.

RIDGE 2000, *Science Plan*, pp. 52, Pennsylvania State University, RIDGE 2000 Program Office, State College, PA, 2001.

Ritzwoller, M. H., N. M. Shapiro, and S. Zhong, 2004, Cooling history of the Pacific lithosphere, *Earth Planet. Sci. Lett., 226*, 69–84.

Rona, P. A., and D. A. Trivett, 1992, Discrete and diffuse heat transfer at ASHES vent field, Axial Volcano, Juan de Fuca Ridge, *Earth Planet. Sci. Lett., 109*, 57–71.

Rona, P. A., K. G. Bemis, C. D. Jones, D. R. Jackson, K. Mitsuzawa, and D. Silver, 2006, Entrainment and bending in a major hydrothermal plume, Main Endeavour Field, Juan de Fuca Ridge, *Geophys. Res. Lett., 33*, L19313, doi:10.1029/2006GL027211.

Rose, T., and H. Villinger, 1999, Evaluation of subseabed porewater pressures measured with PUPPI; extrapolation vs. modeling, *Phys. Chem Earth, 24*, 463–466.

Rupke, L. H., J. Phipps Morgan, M. Hort, J. A. D. Connelly, 2004, Serpentine and the subduction zone water cycle, *Earth Planet. Sci. Lett., 223*, 17–34.

Ruppel, C., 1997, Anomalously cold temperatures observed at the base of the gas hydrate stability zone on the U.S. Atlantic passive margin, *Geology, 25*, 699–702.

Ruppel, C., 2000, Thermal state of the gas hydrate reservoir, in: Max, M. editor, *Natural Gas Hydrate in Oceanic and Permafrost Environments*, Kluwer Academic Publishers, 29–42.

Ruppel, C., 2007, Tapping methane hydrates for unconventional natural gas, *Elements, 3(3)*, 193–199.

Ruppel, C. and M. Kinoshita, 2000, Heat, fluid, and methane flux on the Costa Rican active margin off the Nicoya Peninsula, *Earth Planet. Sci. Lett., 179*, 153–165.

Ruppel, C., R. P. Von Herzen, and A. Bonneville, 1995, Heat flux through an old (~175 Ma) passive margin: offshore southeastern USA, *J. Geophys. Res., 100*, 20,037–20,058, 1995.

Ruppel, C., G. Dickens, D.G. Castellini, W. Gilhooly, and D. Lizarralde, 2005, Heat and salt inhibition of gas hydrate in the northern Gulf of Mexico, *Geophys. Res. Lett., 32*, L04625, doi:10.1029/2004GL021909.

Russo, R. M., and P. G. SIlver, 1994, Trench-parallel flow beneath the Nazca plate from seismic anisotropy, *Science, 263*, 1105–1111.

Schultz A., J. Delaney, and R. McDuff, 1992, On the partitioning of heat flux between diffuse and point source seafloor venting. *J. Geophys. Res., 9*, 12,299–12,314.

Sclater, J. G., 2004, *Variability of heat flux through the seafloor: discovery of hydrothermal circulation in the oceanic crust, in Hydrology of the Oceanic Lithosphere*, E. Davis and H. Elderfield (eds.), Cambridge University Press, p 3–27.

Sclater, J. G., C. Jaupart, and D. Galson, 1980. The heat flow through oceanic and continental crust and the heat loss of the *Earth. Rev. Geophys. Space Phys., 18*, 269–311.

Searle, R. C., 1983, Multiple, closely spaced transform faults in fast-slipping fracture zones, *Geology, 11*, 607–611.

Shen, Y., and D. W. Forsyth, 1992, The effects of temperature- and pressure-dependent viscosity on three-dimensional passive flow of the mantle beneath a ridge-transform system, *J. Geophys. Res., 97*, 19,717–719,728.

Shipley, T. H., M. H. Houston, R. T. Buffler, F. J. Shaub, K. J. McMillen, J. W. Ladd, and J. L. Worzel, 1979, Seismic reflection evidence for the widespread occurrence of possible gas-hydrate horizons on continental slopes and rises, *AAPG Bull., 63*, 2204–2213.

Smith, G. P., D. A. Wiens, K. M. Fischer, L. M. Dorman, S. C. Webb, and J. A. Hildebrand, 2001, A complex pattern of mantle flow in the Lau Backarc, *Science, 292*, 713–716.

Spinelli, G .A., and A. T. Fisher, 2004, Hydrothermal circulation within rough basement on the Juan de Fuca Ridge flank, *Geochem., Geophys., Geosystems, 5*, Q02001, doi:10.1029/2003GC000616.

Spinelli G. A., D. M. Saffer, and M. B. Underwood, 2006, Hydrogeologic responses to three-dimensional temperature variability, Costa Rica subduction margin, *J. Geophys. Res., 111*, B04403, doi:10.1029/ 2004JB003436.

Stein, C. A., 2003, Heat flow and flexure at subduction zones, *Geophys. Res. Lett., 30*, 2197 doi: 10.1029/2003GL018478.

Stein, C. and S. Stein, 1992, A model for the global variation in oceanic depth and heat flow with lithospheric age, *Nature, 359*, 123–128.

Stein, C. and S. Stein, 1994, Constraints on hydrothermal flux through the oceanic lithosphere from global heat flow, *J. Geophys. Res, 99*, 3081–3095.

Stein, C. A., and R. P. Von Herzen, 2001, Geophysical Heat flow, in *Encyclopedia of the Ocean Sciences*, eds. Steele, J., Thorep, S., and K. Turekian, Academic Press Ltd, London, 1149–1157,.

Stein, C. A., and R. P. Von Herzen, 2007, Potential effects of hydrothermal circulation and magmatism on heat flow at hotspot swells, in *Plates, Plumes, and Planetary Processes*, Foulger, G. R., and Jurdy, D. M. (eds.), Geol. Soc. Am. Sp. Paper. 430.

Stein, J., and A. Fisher, 2001, Multiple scales of hydrothermal circulation in Middle Valley, northern Juan de Fuca Ridge: physical constraints and geologic models, *J. Geophys. Res., 106*, 8563–8580.

Stein, J. S., and A. T. Fisher, 2003, Observations and models of lateral hydrothermal circulation on a young ridge flank: reconciling thermal, numerical and chemical constraints, *Geochem., Geophys., Geosystems, 4*, 10.1029/2002GC000415.

Stein, J., Fisher, A., Langseth, M., Jin, W., Iturrino, G., Davis, E., 1998, Fine-scale heat flow, shallow heat sources, and decoupled circulation systems at two seafloor hydrothermal sites, Middle Valley, northern Juan de Fuca Ridge, *Geology, 26*, 1115–1118.

Stein, S., J. Lin, C. Stein, A. Bradley, R. Von Herzen, D. Yoerger, and H. Singh, 1998, An Autonomous Seafloor Heat flow Measurement System, *Eos, Trans. AGU, 79(45)*, Fall Meet. Suppl., 66.

Tamura, Y., Y. Tatsumi, D. Zhao, Y. Kido, and H. Shukuno, 2002, Hot fingers in the mantle wedge: new insights into magma genesis in subduction zones, *Earth Planet. Sci. Lett., 197*, 105–116.

Toomey, D. R., D. Jousselin, R. A. Dunn, W. S. D. Wilcock, and R. S. Detrick, 2007, Skew of mantle upwelling beneath the East Pacific Rise governs segmentation, *Nature, 446*, 409–414.

Tryon, M. D., K. M. Brown, L. M. Dorman, and A. Sauter, 2001, A new benthic aqueous flux meter for very low to moderate discharge rates, *Deep-Sea Research I, 48*, 2121–2146.

Tulaczyk, T., D. Elliott, S. W. Vogel, R. D. Powell, J. C. Priscu, and G. D. Clow, 2005, *FASTDRILL: Interdisciplinary Polar Research Based on Fast Ice-Sheet Drilling (Updated)*, pp. 263, Santa Cruz, CA.

van der Veen, C .J., T. Leftwich, R. von Frese, B. M. Csatho, and J. Li, 2007, Subglacial topography and geothermal heat flux: Potential interactions with drainage of the Greenland ice sheet, *Geophys. Res. Lett., 34*, L12501.

Veirs, S. R., R. E. McDuff and F. R. Stahr, 2006, Magnitude and variance of near-bottom horizontal heat flux at the Main Endeavour hydrothermal vent field, *Geochem. Geophys. Geosyst. 7*, Q02004, doi:10.1029/2005GC000952.

Villinger, H., I. Grevemeyer, N. Kaul, J. Hauschild, and M. Pfender, 2002, Hydrothermal heat flux through aged oceanic crust: Where does the heat escape?: *EarthPlanet. Sci. Lett., 202*, 159–170.

Von Damm, K. L., 2004, Evolution of the hydrothermal system at East Pacific Rise 9 degrees 50'N; geochemical evidence for changes in the upper oceanic crust, *Mid-Ocean Ridges: Hydrothermal Interactions Between the Lithosphere and Oceans*, Geophys. Monogr. Ser., vol. 148, AGU, Washington, DC.

Von Herzen, R. P., 1959, Heat-flow values from the south-eastern Pacific, *Nature, 183*, 882–883.

Von Herzen, R. P., 2004, Geothermal evidence for continuing hydrothermal circulation in older (> 60 M.y.) ocean crust, E.E. Davis, H. Elderfield (eds). in *Hydrogeology of the Oceanic Lithosphere*, Cambridge Univ. Press, 414–447.

Von Herzen, R. P., and A. E. Maxwell, 1959, The measurement of thermal conductivity of deep-sea sediments by a needle probe method, *J. Geophys. Res., 64*, 1557–1563.

Von Herzen, R.P., Ruppel, C., Nettles, M., Nagihara, S., Molnar, P., and Ekstrom, G., 2001, A constraint on the shear stress at the Pacific-Australia plate boundary from heat flow and seismicity at the Kermadec forearc, *J. Geophys. Res., 106*, 6817–6833.

Von Herzen, R., E. E. Davis, A. T. Fisher, C. Stein, and H. Pollack, 2005, Comments on "Earth's heat flux revised and linked to chemistry" by A. M. Hofmeister and R. E. Criss, *Tectonophysics, 409*, 193–198.

Wang, K., and E. E. Davis, 1992, Thermal effects of marine sedimentation in hydrothermally active areas, *Geophys. J. Int., 110*, 70–78.

Warren, J. M., and G. Hirth, 2006, Grain size sensitive deformation mechanisms in naturally deformed peridotites, *Earth Planet. Sci. Lett., 248*, 423–435.

Wiens, D. A., and S. Stein, 1984, Intraplate seismicity and stresses in young oceanic lithosphere, *J. Geophys. Res., 89*, 11442–11464.

Williams, D. L., and R. P. Von Herzen, R.P., 1974. Heat loss from the Earth: new estimate. *Geology, 2*, 327–330.

Wilson, A. M., 2003, The occurrence and chemical implications of geothermal convection of seawater in continental shelves, *Geophys. Res. Lett., 30*, doi:10.1029/2003GL018499.

Wilson, A. M., 2005, Fresh and saline groundwater discharge to the ocean: A regional perspective, *Water Resour. Res., 41*, doi:10.1029/2004WR003399.

Wheat, C. G., H. W. Jannasch, M. Kastner, J. N. Plant, E. H. DeCarlo, and G. Lebon, 2004, Venting formation fluids from deep-sea boreholes in a ridge flank setting; ODP Sites 1025 and 1026, *Geochem. Geophys. Geosyst, 5*, Q08007, doi:10.1029/ 2004GC000710.

Wheat, C. G., M. J. Mottl, A. T. Fisher, D. Kadko, E. E. Davis, and E. Baker, 2004, Heat flow through a basaltic outcrop on a sedimented young ridge flank, *Geochem. Geophys. Geosyst., 5*, Q12006, doi:10.1029/2004GC000700.

Wolery T. J., and N. H. Sleep, 1976, Hydrothermal circulation and geochemical flux at mid-ocean ridges, *J. Geol., 84*, 249–275.

Wood, W. and C. Ruppel, 2000, Seismic and thermal investigations of hydrate bearing sediments on the Blake Ridge Crest: A synthesis of ODP Leg 164 results, *Proc. Ocean Drilling Program, Final Reports*, 164, 253–264.

Xu, W. and C. Ruppel, 1999, Predicting the occurrence, distribution, and evolution of methane gas hydrate in porous marine sediments from analytical models, *J. Geophys. Res., 104*, 5081–5096.

Yamano, M., S. Uyeda, Y. Aoki, and T.H. Shipley, 1982, Estimates of heat flow derived from gas hydrates, *Geology, 10*, 339–343.

Zhong, S. M. Ritzwoller, N. Shapiro, W. Landuyt, J. Huang, and P. Wessel, 2007, Bathymetry of the Pacific plate and its implications for thermal evolution of lithosphere and mantle dynamics, *J. Geophys. Res., 112*, B06412, doi:10.1029/ 2006JB004628.