Geophysical Monograph 91

Seafloor Hydrothermal Systems

Physical, Chemical, Biological, and Geological Interactions

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American Geophysical Union

Published under the aegis of the AGU Books Board

Cover: Small (about 1 meter high) white smoker chimneys at a water depth of about 3660 meters in the "Kremlin" area of the TAG active hydrothermal mound at 26°08'N on the Mid-Atlantic Ridge. Fluids with temperatures of 250°-300°C discharge from the active sphalerite-rich chimneys. Anemones (seen in the foreground) are the most abundant organism on this part of the hydrothermal mound. (Photograph courtesy of Woods Hole Oceanographic Institution.)

Library of Congress Cataloging-in-Publication Data

Seafloor hydrothermal systems : physical, chemical, biological, and geological interactions / Susan Humphris ... [et al.], editors.
p. cm. — (Geophysical monograph ; 91)
Includes bibliographical references.
ISBN 0-87590-048-8 (alk. paper)
1. Hydrothermal vents—Congresses. 2. Hydrothermal deposits——Congresses. 3. Hydrothermal vent ecology—Congresses.
I. Humphris, Susan. II. American Geophysical Union. III. Series.
GB1198.S43 1945 1995
551.46'08—dc20
95-19045
CIP

ISBN 0-87590-048-8
ISSN 0065-8448

Published by
American Geophysical Union

Printed in the United States of America.

PREFACE

Hydrothermal circulation at mid-ocean ridges is one of the fundamental processes controlling the transfer of energy and matter from the interior of the Earth to the lithosphere, hydrosphere, and biosphere. Hydrothermal interactions influence the composition of the oceanic crust and the chemistry of the oceans. In addition, hydrothermal vent fields support diverse and unique biological communities by means of microbial populations that link the transfer of the chemical energy of dissolved chemical species to the production of organic carbon.

Traditionally, the physical, chemical, biological, and geological subsystems that constitute the hydrothermal circulation process have been studied in isolation. However, understanding the transfer and fluxes of mass and energy among these subsystems requires an integrated approach and the development of models that include interactions between them. We hope that this volume broadens the understanding of hydrothermal systems beyond individual specialties and stimulates multidisciplinary studies of the linkages among physical, chemical, biological and geological processes in mid-ocean ridge hydrothermal systems.

This volume is an outgrowth of the Third RIDGE Theoretical Institute on "Physical, Chemical, Biological and Geological Interactions Within Hydrothermal Systems," which was held at Big Sky, Montana, in the summer of 1993. Composed of a four-day short course (on which most of these papers are based) and a three-day workshop (where current research and future directions were discussed), the principal goals of this Institute were to stimulate cross-disciplinary inquiry into the interactions within hydrothermal systems, and to encourage stronger links between biological/geological observations and the experimental and theoretical study of vents in order to focus future investigations on the problems that are critical to understanding the system as a whole.

The papers included in this volume provide a comprehensive and truly multidisciplinary overview of mid-ocean ridge hydrothermal systems. Since many of the papers cut across disciplines, logical sequencing of the papers is difficult. Consequently, their organization is based on interactions within different parts of the hydrothermal system, i.e., substrate, discharging fluids, and hydrothermal plumes.

The first section includes three papers that provide overviews of the global distribution of hydrothermal activity and the character of the associated biological communities. Fornari and Embley examine the spatial and temporal relations between volcanism, tectonism, and hydrothermalism at ridge crests spreading at different rates, and assess the relative contributions of volcanic and tectonic processes in controlling hydrothermal activity. Baker et al. present a synthesis of available data from spreading centers throughout the world's oceans that confirm the presence of hydrothermal plumes along segments that exhibit the entire range of spreading rates. Based on the limited amount of data available, they tentatively conclude that there may be a direct relationship between the incidence of plumes and spreading rate, as suggested by crustal evolution models that predict increased hydrothermal heat flux with increased spreading rate. Hessler and Kaharl provide an overview of the unique communities of organisms that are found associated with seafloor hydrothermal activity, and discuss the physical environment and its influence on community structure at various locations along the mid-ocean ridge system.

The second section comprises a series of five papers that address aspects of the interactions affecting hydrothermal deposits. Alt examines the mineralogical and chemical effects of hydrothermal alteration within the oceanic crust and upper mantle. He focuses on the seawater-rock reactions in the recharge, reaction, and discharge zones in the subsurface of mid-ocean ridge hydrothermal systems that ultimately determine the nature of the oceanic lithosphere and the chemistry of hydrothermal fluids actively discharging at the seafloor. Mixing of these hydrothermal fluids with seawater results in the precipitation of mineral deposits on the seafloor. The different styles of mineralization found at sites of hydrothermal venting are the subject of the paper by Hannington et al. They discuss the physical and chemical processes that control the deposition of sulfides, and follow the progressive development of vent complexes from the onset of hydrothermal activity to their eventual oxidation during seafloor weathering. Modeling hydrothermal fluid flow and chimney growth can reproduce the sequence of mineralogical precipitation observed in chimney walls, and can provide estimates of heat and mass flux through various parts of the system. Tivey reviews the combination of field, laboratory, and theoretical studies that have led to our present understanding of vent system processes, and points out the need to incorporate biological processes into the models of physical and chemical interactions at these sites. Such actively forming hydrothermal mineral deposits provide a source of energy for chemosynthesis and a substrate for colonization by vent organisms. Juniper and Sarrazin examine the evidence for interactions between mineral deposition and organism growth, and discuss the biological influences on deposit formation and destruction and, conversely, how the dynamics of chimney and mound growth affect the distribution and composition of vent communities. The paper by Shanks et al. summarizes the application of stable isotope geochemistry to studies of mid-ocean ridge hydrothermal systems. In addition to being valuable tracers of chemical sources and sinks, the fractionation of stable isotopes between co-existing phases also provides a powerful tool for understanding interactions among chemical, physical, and biological processes.

The third section examines the chemistry of hydrothermal fluids and the role of reduced chemical species in the production of organic matter. Von Damm summarizes the ranges in hydrothermal fluid chemistry measured at known venting locations, and discusses the parameters (e.g., temperature, pressure, water/rock ratio) that control the observed variations in chemical composition. The processes of phase separation and water-rock interactions are considered at some length. She also emphasizes the temporal variability in fluid compositions recently observed during the earliest stages of hydrothermal activity—a factor that complicates estimation of global chemical fluxes. Seyfried and Ding provide the connecting link between the physical/chemical conditions and fluid-crust interactions within the reaction zone, and the chemistry of the discharging hydrothermal fluid at the seafloor. They report on a series of mineral solubility experiments and theoretical phase relations that evaluate the environment and processes largely responsible for metal transport and deposition within seafloor hydrothermal systems, and discuss the role of certain fluid characteristics (e.g., redox, temperature, pH and chlorinity) on the chemistry of the discharging hydrothermal fluids. The flux of energy from geothermal sources via reduced chemical species (mainly H_2S, H_2 and CH_4) to the production of organic matter is conducted by a number of microbial processes. In his paper, Jannasch discusses the primary reactions (both aerobic and anaerobic) and their relative importance at the sites of hydrothermal venting. He also introduces the major sites of microbial interactions and discusses three of them—subsurface vent systems at elevated temperatures, microbial mats covering substrate surfaces, and the hydrothermal plumes. The fourth site—symbiotic associations with vent-specific invertebrates—is included in the paper by Fisher. Here the emphasis is on the physiological ecology of the dominant faunal groups that occur within the areas of diffuse flow, and their interactions with their temporally and spatially variable physical and chemical environment.

The fourth section deals with hydrothermal plumes, which are the direct result of the thermal and chemical input from active vent systems into the overlying water column along the mid-ocean ridge system. Plumes are an important mechanism for the dispersal of heat, mass, and the larvae of vent-specific fauna. Studies of plumes also allow integrated estimates to be made of heat and chemical fluxes from the crust. Lupton provides an introduction to several aspects of hydrothermal plumes, ranging from the dynamics of turbulence and entrainment in the ascending plume, to the chemical characteristics of plumes and distribution of hydrothermally introduced ^3He in the world ocean. He also presents the variety of ways in which plumes can be used as tools for the study of ridge crest processes. Two papers examine the physical dynamics of hydrothermal plumes at different scales. McDuff addresses the time-averaged dynamics of the buoyant plume stage and discusses the coupling of dynamics with mixing between vent fluid and seawater and their impact on chemical processes. Helfrich and Speer focus particularly on those scales at which the rotation of the Earth becomes an important factor. They explore the idea that high-temperature hydrothermal venting can force horizontal circulation on a variety of spatial and temporal scales. The chemical and biochemical transformations in hydrothermal plumes and the consequences of fallout of particles are reviewed in two papers. Lilley et al. focus on the dissolved and particulate components that are most commonly used to detect hydrothermal venting in the deep sea. They examine the chemically and biologically induced transformations that these chemical species undergo within the plume as it ages. The fallout of hydrothermal particles after dispersion in the water column results in the wide distribution of metalliferous sediments. Mills and Elderfield trace the historical development of our understanding of the origin of hydrothermally derived metalliferous sediments. They assess the role of their formation in global geochemical budgets, which is greatest for those elements with residence times of about 10^5 years that are scavenged from seawater by particulates in hydrothermal plumes. Circulation also plays an important role in larval dispersal mechanisms, with near-bottom flow facilitating transport to neighboring vents and entrainment of larvae into the buoyant plume, resulting in retention near the source or wider dispersal in overlying currents. Mullineaux and France review recent studies of larval ecology and population genetics to examine species persistence, distribution, and dispersal at hydrothermal vents.

The final section consists of two papers that attempt to assess our understanding of global mass and energy fluxes. Stein et al. review the use of global heat flow data to estimate hydrothermal heat and water fluxes and to produce thermal models for young oceanic lithosphere that can be used to predict heat flow and hydrothermal cooling as a function of age. They conclude that about two-thirds of the hydrothermal heat loss occurs by off-ridge circulation in crust older than 1 Myr, and that beyond about 65 Myr, the observed heat flow approximately equals that predicted for cooling by conduction. The importance of off-axis circulation to hydrothermal fluxes is also stressed in the paper by Kadko et al. They assess the time scales of hydrothermal interactions relative to other oceanic processes, since these determine the importance of the hydrothermal component in global geochemical cycles, and also examine how the effects of the hydrothermal flux in past oceans might have been different from those observed today.

The editors express their gratitude to Anita Norton, who assisted throughout all stages of the preparation of this monograph. Her tremendous effort and perseverance in helping this volume come to fruition are very much appreciated. NSF grant OCE-9300080 (to Robert S. Detrick and Susan E. Humphris) for support of the Third RIDGE Theoretical Institute is gratefully acknowledged.

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Tectonic and Volcanic Controls on Hydrothermal Processes at the Mid-Ocean Ridge: An Overview Based on Near-Bottom and Submersible Studies

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INTRODUCTION

The crestal area of the mid-ocean ridge (MOR) is a stratigraphically complex and dynamic environment where new lithosphere is created through intrusive and extrusive igneous activity. Magmatic processes at ridge crests also provide the energy to drive hydrothermal circulation of seawater through the oceanic crust. These result in rock-water interactions which give rise to low-temperature (<~200°C) and high-temperature (200°C-~400°C) venting at seafloor depths ranging between approximately 3600 m to 840 m (this depth range encompasses all known high-temperature MOR crest axial vent sites in slow- to superfast-spreading environments), and contribute substantively to the Earth's heat budget. Rock-water interaction and exhalation of mantle volatiles also affect the chemical composition of the world's ocean. The permeability structure of young oceanic lithosphere controls how hydrothermal circulation will manifest itself both locally and regionally. The interplay between intrusive and extrusive igneous activity, and the inferred causal relationships between spreading-rate-controlled tectonism and the physical properties of young crust (i.e. brittle vs. ductile behavior) all influence the permeability of young ocean crust. Slow- to intermediate-rate spreading MOR constructional morphology is dominated by pillow lavas and large-scale tectonic features, while fast- and superfast-spreading ridge crests have a greater proportion of lobate, sheet and ponded lava flows erupted at high effusion rates and more subdued (<100 m high) tectonic features. The volcanic effusion style and resulting stratigraphy at MOR crests also imparts a controlling influence on the permeability structure of the shallow crust (upper ~300 m), and influences the location of hydrothermal vents.

The ridge crest environment is the largest, most continuous volcanic lineament on our planet (Figure 1), yet we have observed less than a few percent of its total surface area. Despite the lack of direct observational data on most of the global MOR crest, geological, geophysical, geochemical and ocean crustal drilling data collected during the past two decades at selected MOR sites have resulted in significant insight to ridge-crest processes. Scientists have used those data to identify many first- and second-order morphological and structural characteristics of MOR crests (Figure 2), and deduce the tectonic processes which are responsible for magmatic, volcanic and hydrothermal processes at seafloor spreading centers. For example, variations in crestal morphology and spacing between major transform faults are considered first-order properties, while smaller discontinuities in ridge crest topography at non-transform offsets and at overlapping spreading centers are second-order characteristics (see *Macdonald and Fox,* [1988] for a comprehensive discussion of this subject). The research efforts presented in the papers and reference lists of this volume, and summarized in various papers [e.g. *Macdonald*, 1982; *Haymon*, 1989; *Tivey and Johnson*, 1989; *Von Damm et al.*, 1990; *Rona and Thompson*, 1993; *Humphris*, 1995] have resulted in our present understanding of the basic magmatic and volcanic processes

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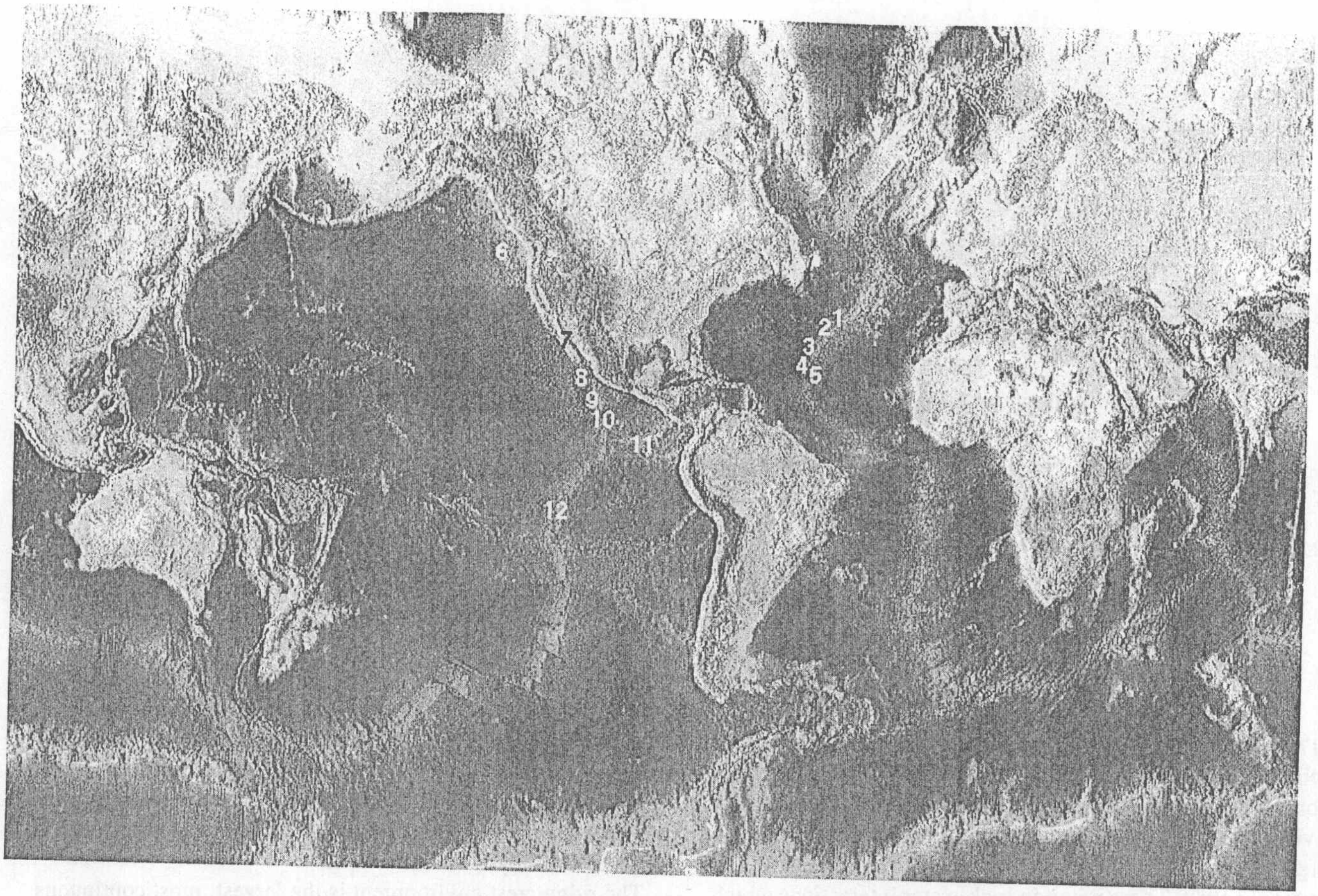

Figure 1. General location map of the world's mid-ocean ridge system showing locations of known high-temperature hydrothermal vent sites on the ridge crest. Vent sites are numbered as follows: 1= Menez Gwen, 2=Lucky Strike, 3=Broken Spur , 4=TAG, 5=Snake Pit, 6=Juan de Fuca Ridge & other Northeast Pacific Spreading Centers, 7=Guaymas Basin, 8=EPR 21°N, 9=EPR 13°N, 10=EPR 9°-10°N, 11=Galapagos Rift 86°W, 12=EPR 17°S-20° S. Gray-scale world physiography (5-minute gridded elevation/bathymetry data) is from the National Oceanic and Atmospheric Administration's digital database (*Global Relief CD-ROM*) available from the U. S. Dept. of Commerce, Washington, DC.

operating in diverse spreading-rate environments, and allowed development of conceptual models of the chemical and physical processes that drive hydrothermal circulation beneath MOR crests.

On the whole, however, investigators have been unsuccessful in identifying the specific, causal factors which determine sites of hydrothermal venting on the seafloor and consequently the 3-D organization of the circulatory plumbing system. A further complication is that ocean crust drilling at MOR crests has proved to be very difficult; hence our understanding of how hydrothermal processes affect the oceanic crustal section is rudimentary and based largely on relatively few successful deep drilling sites off-axis (e.g. DSDP/ODP Hole 504B [*Anderson et al.*, 1985a,b; *Becker et al.*, 1988, 1989], Hole 735 [*Robinson et al.*, 1991; *Dick et al.*, 1992]), or in unusual tectonic settings such as sediment covered ridges (e.g. Guaymas Basin [*Curry and Moore et al.*, 1982] and Middle Valley [*Mottl et al.*, 1993; *Davis and Fisher*, 1994]). In a few areas, multidisciplinary studies involving high-resolution sonar, remote photographic, and submersible-based mapping have been carried out with sufficient navigational accuracy, and over a long enough time period, to establish spatial relationships between volcanic features and hydrothermal vent locations and morphology. These include the Mid-Atlantic

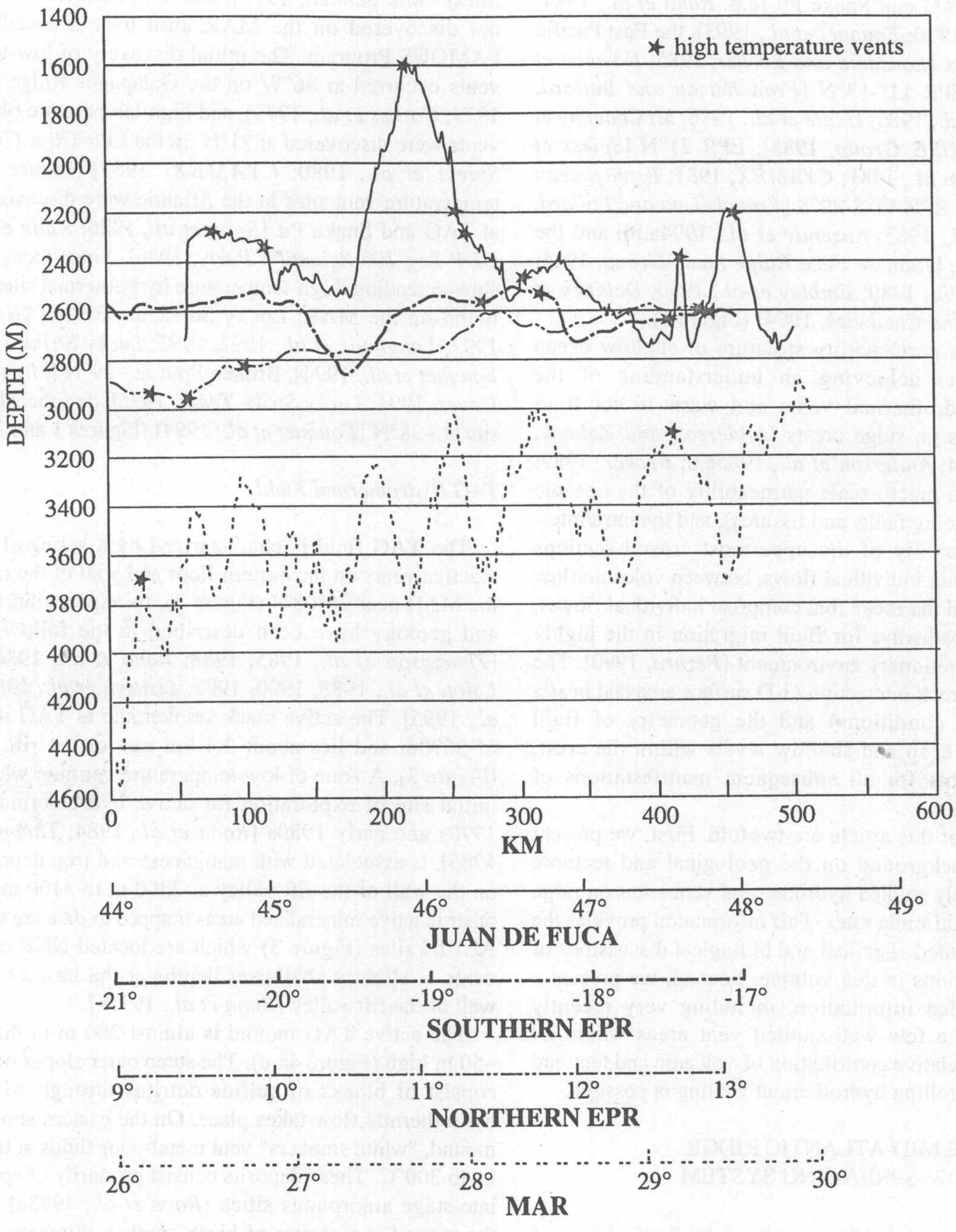

Figure 2. A. Along-strike minimum depth profiles of the Mid-Atlantic Ridge, northern East Pacific Rise, southern East Pacific Rise and Juan de Fuca Ridge in areas where high-temperature hydrothermal vents are present (stars show locations of vent sites discussed in the text). Note differences in absolute depth and wavelengths of along-axis topography from slow-spreading Mid-Atlantic Ridge, to intermediate spreading Juan de Fuca Ridge, and faster-spreading northern and southern East Pacific Rise. See text for discussion. Data sources: *Macdonald et al.* [1992]; *Scheirer and Macdonald* [1993]; *Londsale* [1985; 1989]; *Fornari et al.* [1984]; *Purdy et al.* [1990]; *Embley and Chadwick* [1994]; and R. Detrick (unpub. data).

Ridge (MAR) at TAG and Snake Pit [e.g. *Rona et al.*, 1984; *Karson and Rona*, 1990; *Fouquet et al.*, 1993], the East Pacific Rise (EPR) 9°-10°N [*Lonsdale and Becker*, 1985; *Haymon et al.*, 1991, 1993], EPR 11°-13°N [*Francheteau and Ballard*, 1983; *Hekinian et al.*, 1985; *Gente et al.*, 1986; *McConachy et al.*, 1986; *ARGO/RISE Group*, 1988]; EPR 21°N [*Spiess et al.*, 1980; *Ballard et al.*, 1981; *CYAMEX*, 1981; *Francheteau and Ballard*, 1983], EPR 17°S-20°S [*Francheteau and Ballard*, 1983; *Renard et al.*, 1985; *Auzende et al.*, 1994a,b], and the Juan de Fuca Ridge [*Juan de Fuca Ridge Study Group*, 1986; *Kappel and Franklin*, 1989; *Embley et al.*, 1990; *Delaney et al.*, 1992; *Embley and Chadwick*, 1994] (Figure 1).

Determining the permeability structure of shallow ocean crust is critical to achieving an understanding of the distribution of hydrothermal vents and warm-to-hot fluid circulation patterns on ridge crests [*Anderson and Zoback*, 1982; *Norton*, 1984; *Anderson et al.*, 1985a,b; *Becker*, 1989; *Lowell*, 1991]. The macro-scale permeability of the oceanic crust (e.g. throughgoing faults and fissures), and the intra/inter-flow micro-permeability of the uppermost crustal sections (<~300m) (e.g. within individual flows, between volcanic flow contacts, and within the rocks that comprise individual flows), provide complex pathways for fluid migration in the highly dynamic MOR accretionary environment [*Pezard*, 1990]. The conditions of fluid-rock interaction (3-D surface area and *in situ* physical-chemical conditions) and the geometry of fluid pathways, both at deep and shallow levels within the crust, provide the controls for all subsequent manifestations of hydrothermal venting.

The objectives of this article are twofold. First, we present some historical background on the geological and tectonic setting of extensively studied hydrothermal vent areas on ridge crests spreading at different rates. This information provides the context for the detailed chemical and biological discussions of the other contributions in this volume. Second, we present a selection of detailed information, including very recently collected data for a few well-studied vent areas where an assessment of the relative contribution of volcanic and tectonic phenomena to controlling hydrothermal venting is possible.

THE MID-ATLANTIC RIDGE: SLOW-SPREADING SYSTEM

The MAR (Figures 1 and 3) was one of the first portions of the MOR to be discovered [*Heezen et al.*, 1959; *Heezen and Ewing*, 1963]. It has subsequently been the most intensely studied slow-spreading (~20-40 mm yr^{-1} full-rate) ridge on the planet, and was the first portion of the MOR to have a major submersible-based science program devoted to it (FAMOUS - [*Bellaiche et al.*, 1974; *Ballard and van Andel*, 1977]) (Figure 3). Although hydrothermal venting in seafloor spreading environments was strongly suspected based on early work in the Red Sea [e.g., *Charnock*, 1964; *Degens and Ross*, 1969; *Bäcker and Schoell*, 1972], active hydrothermal venting was not discovered on the MAR until over a decade after the FAMOUS Program. The initial discovery of low-temperature vents occurred at 86°W on the Galapagos Ridge [*Lonsdale*, 1977; *Corliss et al.*, 1979], and high-temperature black smoker vents were discovered at 21°N on the EPR [*Rise Group*, 1980; *Spiess et al.*, 1980; *CYAMEX*, 1981] (Figure 1). High-temperature vent sites in the Atlantic were discovered in 1985 at TAG and Snake Pit [*Rona et al.*, 1986; *Kong et al.*, 1985; *ODP Leg 106 Scientific Party*, 1986]. Since then, three other slow-spreading, high-temperature hydrothermal sites have been found on the MAR: Lucky Strike at ~37°N [*Klinkhammer*, 1992; *Langmuir et al.*, 1992, 1993; *Lucky Strike Team*, 1995; *Fouquet et al.*, 1994], Broken Spur at ~29°N [*Murton and Van Dover*, 1994; *Lucky Strike Team*, 1995], and the Menez Gwen site at ~38°N [*Fouquet et al., 1994*] (Figures 1 and 3).

TAG Hydrothermal Field

The TAG field is characterized by a series of active and inactive vents on the eastern floor and wall of the rift valley of the MAR near 26°08'N (Figure 3). Its exploration, mineralogy and geology have been described in the following papers: [*Thompson et al.*, 1985, 1988; *Rona et al.*, 1986, 1993a,b; *Lalou et al.*, 1988, 1990, 1993; *Lisitsyn et al.*, 1989; *Tivey et al.*, 1995]. The active black smoker site at TAG is at a depth of 3670m and lies about 2.4 km east of the rift valley axis (Figure 3). A zone of low temperature venting, which was the initial site of exploration for active hydrothermalism in the 1970s and early 1980s [*Rona et al.*, 1984; *Thompson et al.*, 1985], is associated with manganese and iron deposits located on the wall of the rift valley at 2300 m to 3100 m depth. The other inactive mineralized areas mapped to date are the MIR and ALVIN sites (Figure 3) which are located NNE of the active vents at slightly shallower depths at the base of the eastern wall of the rift valley [*Rona et al.*, 1993b].

The active TAG mound is almost 200 m in diameter, and ~50 m high (Figure 4a-c). The steep outer slopes of the mound consist of blocks of sulfide detritus through which diffuse hydrothermal flow takes place. On the eastern shoulder of the mound, "white smokers" vent metal-poor fluids at temperatures up to 300°C. These deposits consist primarily of sphalerite and late-stage amorphous silica [*Rona et al.*, 1993a]. The top of the mound is a cluster of black smoker chimneys up to 15 m high discharging fluids up to 363°C. Thick clouds of particulate sulfides precipitating from the fluids often obscure the 10 m diameter summit of the mound.

The TAG deposits have been constructed by intermittent hydrothermal activity over more than 100,000 years. The hydrothermally active mound has been dated at 18Ka and the adjacent inactive mounds are as old as 140Ka [*Lalou et al.*, 1990, 1993]. The long history of hydrothermal activity at one location has given rise to the large, mineralogically zoned

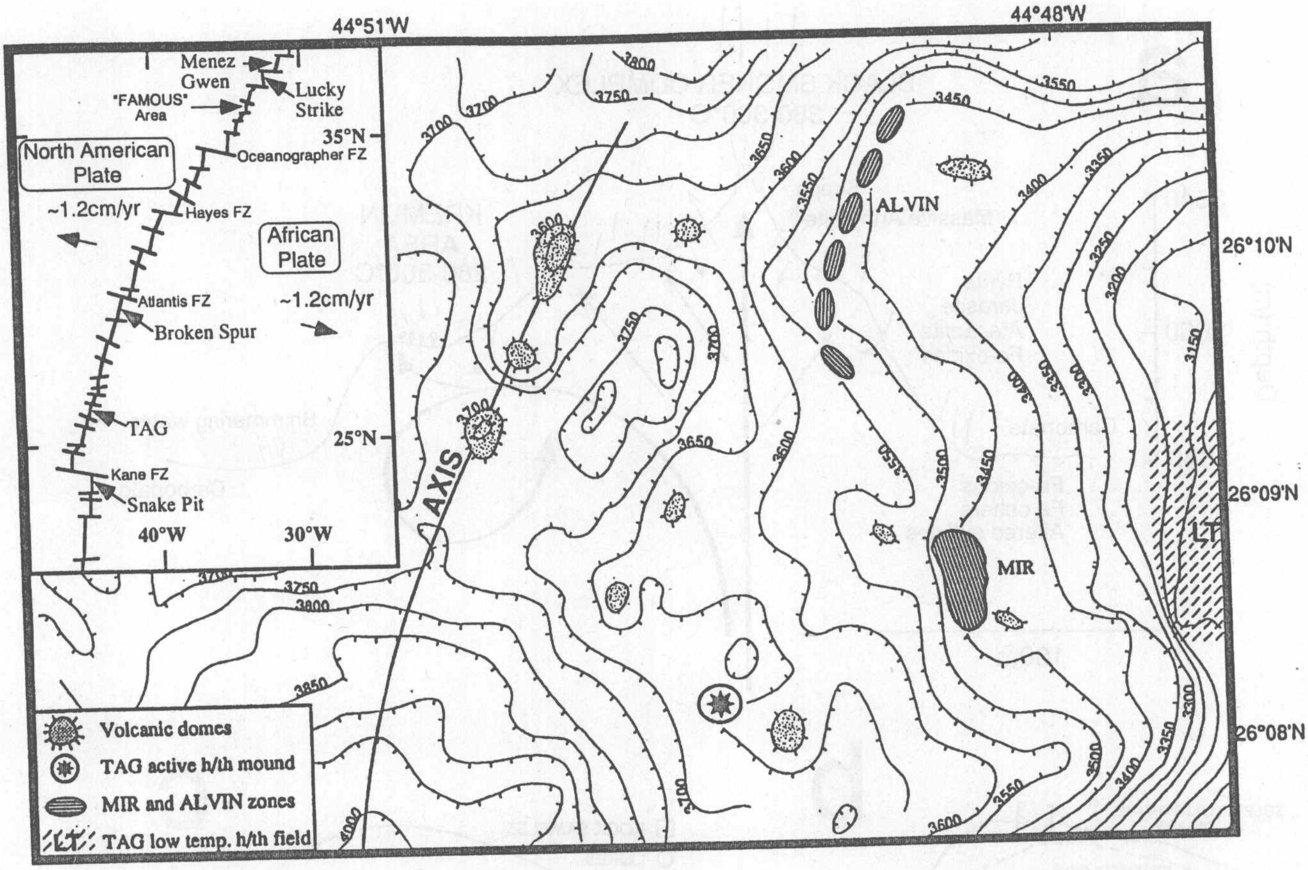

Figure 3. Bathymetric map of the TAG area on the Mid-Atlantic Ridge showing locations of active TAG mound and surrounding inactive mounds. Inset map shows relative locations of Mid-Atlantic Ridge vent sites discussed in the text and general tectonic character of the ridge. Modified from: *Thompson et al.* [1985]; and *Rona et al.* [1993b].

mound at TAG. This complex deposit has many of the morphologic and mineralogic characteristics of economic ore bodies found in ophiolites [*Pallister and Hopson*, 1981; *Haymon et al.*, 1989; *Nehlig*, 1991, 1993] and in greenstone belts on the Canadian shield [*Franklin et al.*, 1981].

Karson and Rona [1990] postulate that the TAG site is controlled by a major crustal transfer fault that bounds two half-grabens which displace the rift valley wall at ~26°08'N (Figure 5). Intermittent movement on this fault and the intersecting axis-parallel faults is believed to have maintained high-permeability zones over a long period of time at the TAG location. This model is based primarily on observations made from ALVIN and MIR submersible dives which investigated hydrothermal processes on and around the vent sites, and mapped volcanic and tectonic features elsewhere within the rift valley and walls. Recently collected 120 kHz sonar data [*Humphris et al.*, 1994; *Kleinrock et al.*, 1994] show that there is a subtle structural grain in the rift valley floor south and west of TAG that is oblique to the rift-parallel faulting, which may be the surface manifestation of cross-faults that have helped channel hydrothermal fluids to this site. Detailed geochemical studies of the hydrothermal minerals and their distribution within TAG has permitted *Tivey et al.* [1995] to infer patterns of subsurface mixing and fluid migration paths in this complex hydrothermal setting.

The rift valley at the TAG site has a number of pillow lava domes scattered within it, but no clearly defined neovolcanic zone (Figure 3). It is unclear what, if any, temporal relationship exists between volcanic and hydrothermal events at the TAG site as no detailed dating of basalts by U-Th or other disequilibrium methods has yet been carried out. The recent submersible diving by British and Japanese investigators in 1994 and high-resolution seafloor mapping investigations [*Humphris et al.*, 1994; *Kleinrock et al., 1994*], and the Ocean Drilling Program Leg 158 drilling and associated experiments at the TAG site (S. Humphris, R. Von Herzen, K. Becker, pers. commun., 1994) may provide a clearer understanding of the associations between volcanic and hydrothermal processes

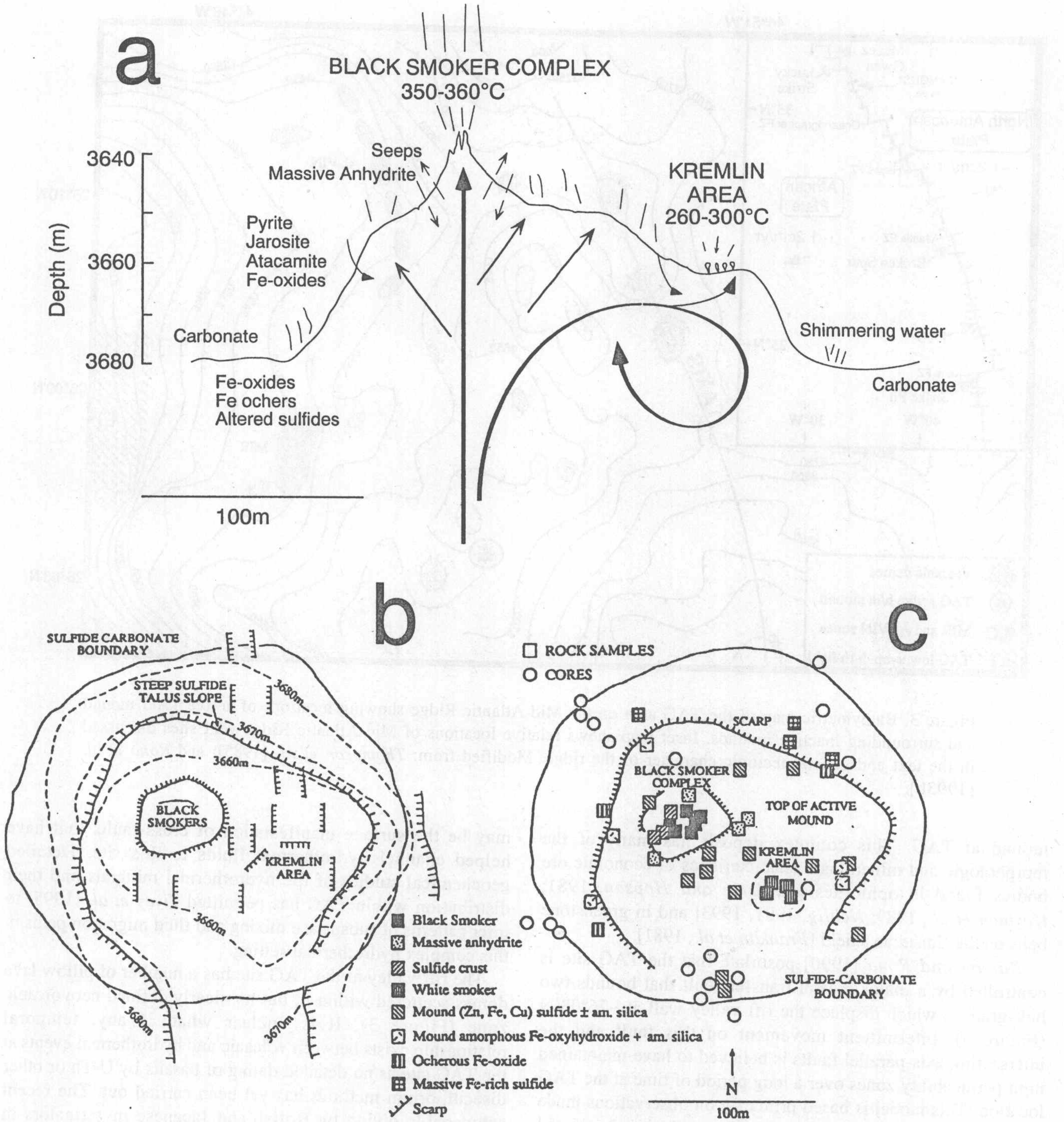

Figure 4. a) Cross-section profile across the active TAG mound from *Thompson et al.* [1985]. b) Structural features on the TAG mound. c) Geologic map showing locations of different orifices on the TAG mound, dominant mineral compositions and major morphologic features of the mound (from *Tivey et al.*, [1995]; *Thompson et al.* [1985]; and *Rona et al.* [1993b]).

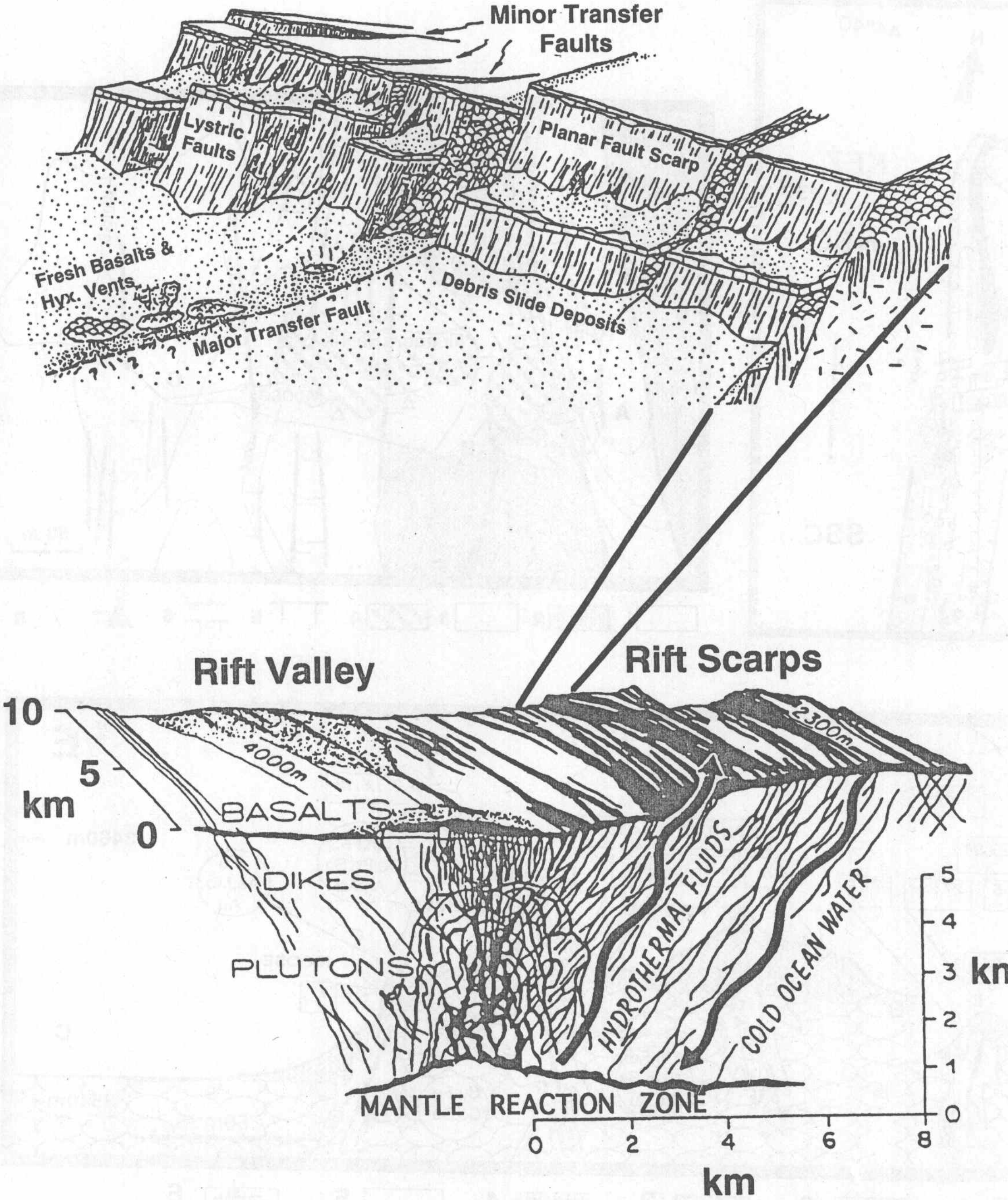

Figure 5. Drawings showing perspective models of the morphology and structure of the MAR rift valley in the TAG region (top), and inferred subseafloor fracture patterns and circulation system (bottom) associated with a slow-spreading mid-ocean ridge crest (from *Karson and Rona* [1990].

at a slow-spreading Mid-Atlantic Ridge vent site.

Snake Pit Hydrothermal Field

In contrast to TAG, the Snake Pit hydrothermal site (Figures 1, 3 and 6) is located in the center of the rift valley on the crest of a ~40 km-long neovolcanic ridge just south of the eastern Kane Fracture Zone - MAR intersection [*Kong et al.*, 1985; *ODP Leg 106 Scientific Party*, 1986; *Karson and Brown*, 1988; *Fouquet et al.*, 1993] (Figure 6). The

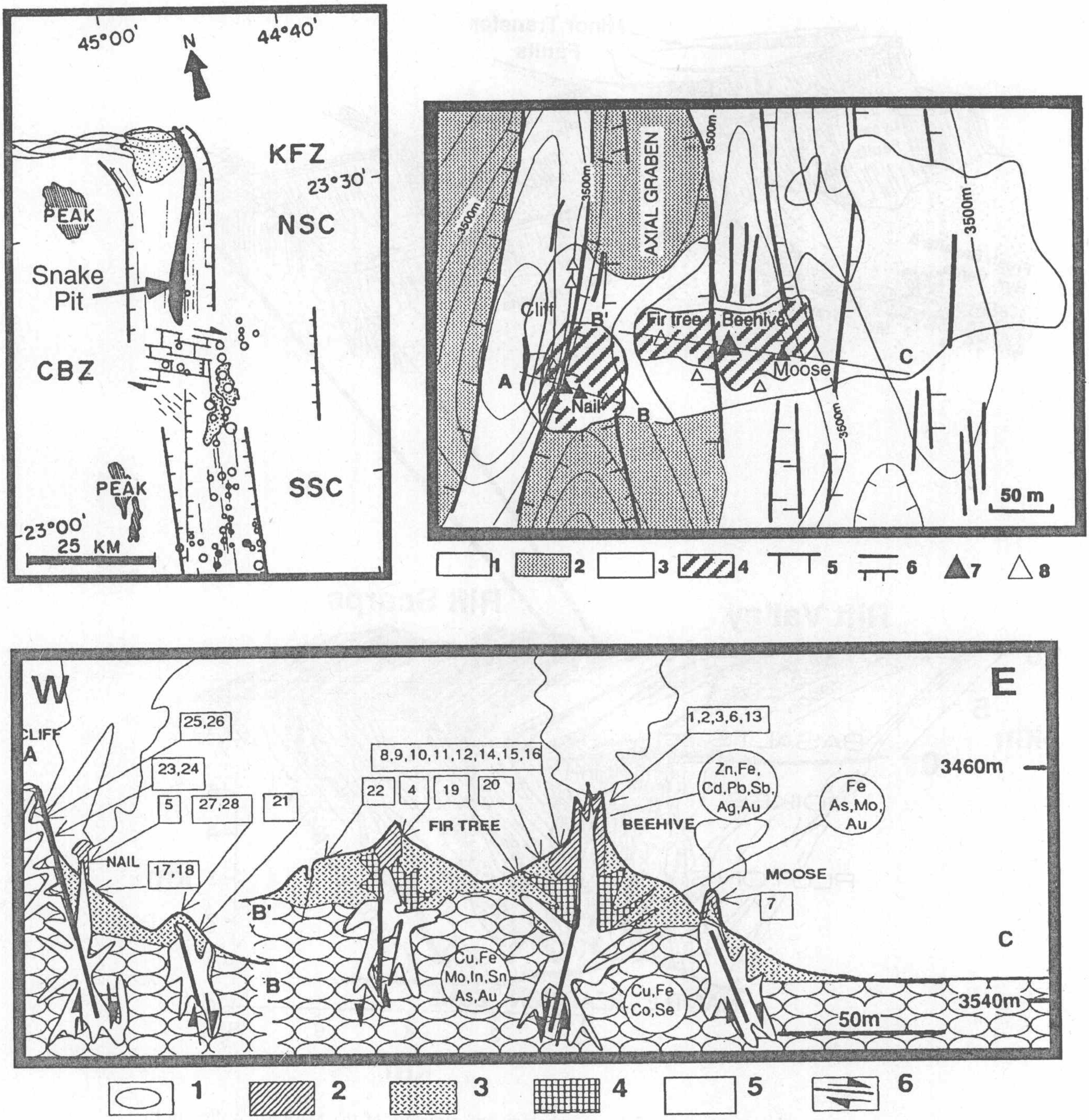

Figure 6. (upper left) Schematic morphostructural map of MARK area which includes the Snake Pit hydrothermal vent field (from *Brown and Karson* [1988]). (upper right) Geologic map of Snake Pit vent deposits from *Fouquet et al.*[1993]- Key: 1=pillow lava flows, 2=rubble, 3=hydrothermal sediments 4=sulfide mounds, 5=normal fault, 6= fissure, minor fault, 7= active black smoker, 8=inactive chimneys. (bottom) Cross section through the Snake Pit vent area showing geological and hydrothermal relationships from *Fouquet et al.* [1993]- Key: 1=pillow lava, 2=Zn-rich chimney, 3=Fe-rich massive sulfides, 4=Cu-rich massive sulfide, 5=Cu-rich sulfide of stockwork and central part of chimney, 6=normal fault.

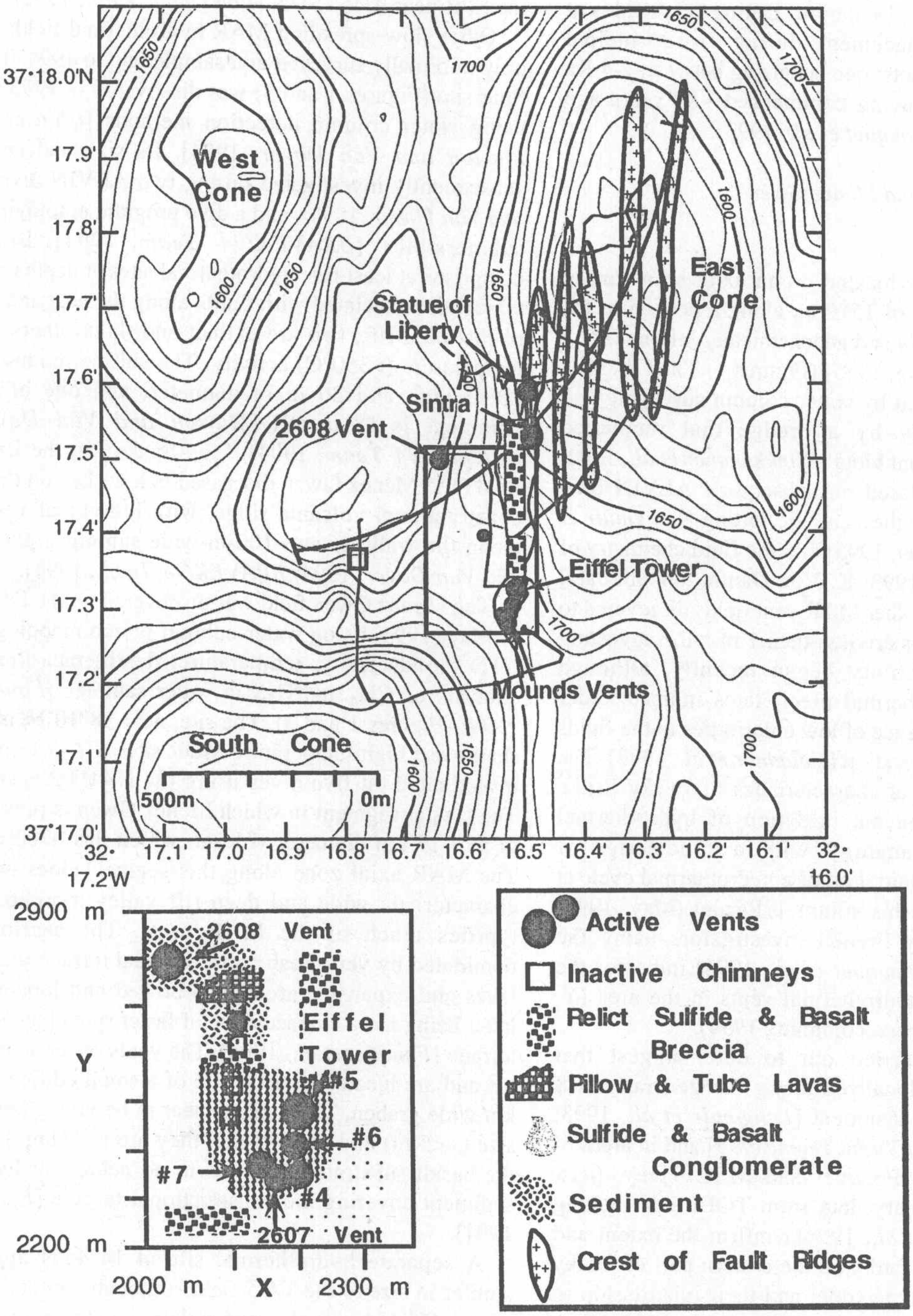

Figure 7. Distribution of active hydrothermal vents and relict sulfides in the Lucky Strike hydrothermal field based on ALVIN dive observations and sampling [*Langmuir et al.*, 1993] and *Lucky Strike Team* [submitted].

hydrothermal deposits at Snake Pit occur over an area of about 150 m x 300 m, and lie across a series of horsts and grabens within the neovolcanic zone at depths between 3465 m to 3512 m [*Fouquet et al.*, 1993]. The primary deposits are several large mounds of up to 50 m basal diameter; some are capped by active black smokers. The westernmost active mound is cut by a fault which exposes stockwork veining. *Fouquet et al.* [1993] conclude that current hydrothermal activity at Snake Pit is controlled by primary graben faults which are lenticular in plan-view. The loci of heat centers has apparently been very stable through time, providing a more-or-less steady supply of heat to drive hydrothermal circulation. Dating of sulfides at Snake Pit suggests emplacement during two principal hydrothermal/magmatic events; one occurring between 2-4 Ka and the most recent one having commenced ~80 years ago [*Lalou et al.*, 1990, 1993; *Fouquet et al.*, 1993].

Lucky Strike, Broken Spur and Menez Gwen Hydrothermal Fields

The Lucky Strike site is located on an axial seamount at 37°17.5'N at a water depth of 1570 m, along a portion of the MAR that is morphologically and geochemically influenced by the Azores hotspot [*Schilling*, 1975] (Figures 1, 3 and 7). This hydrothermal site was found by water column surveying and confirmed serendipitously by a dredge that recovered hydrothermal sulfide and vent biota [*Klinkhammer et al.*, 1992; *Langmuir et al.*, 1992]. Based on subsequent ALVIN dive observations and sampling, the geologic setting [*Langmuir et al.*, 1993; *Lucky Strike Team*, 1995] and the fluid chemistry of this site [*Colodner et al.*, 1993; K. Von Damm, unpub. data] are quite different from the other MAR vent fields discovered to date. Many of the chimneys are less than 1 m tall, suggesting that the hydrothermal activity began recently, although extensive areas of hydrothermal precipitates indicate older cycles of activity. The presence of low chlorinities in the fluids strongly suggests phase separation [*Colodner et al.*, 1993]. The morphological and chemical characteristics of Lucky Strike vents suggest relatively recent initiation of hydrothermal activity based on the analogy with a time-series of observations spanning the initiation of a hydrothermal cycle at 9°-10°N [see *Von Damm*, this volume]. Recent (May, 1994) work at Lucky Strike by French investigators using the submersible NAUTILE [*Fouquet et al.*, 1994] indicates the presence of other active hydrothermal vents in the area (Y. Fouquet and M.K. Tivey, pers. commun., 1994).

The diving studies carried out to date suggest that hydrothermal activity is localized along the generally N-S trending rift zones of the seamount [*Langmuir et al.*, 1993; *Fouquet et al., 1994*; *Lucky Strike Team*, 1995] and in areas of recent ponded lavas (Y. Fouquet and M.K. Tivey, pers. commun., 1994). Preliminary data from TOBI side-looking sonar images [*Critchley et al.*, 1994] confirm the extent and plan-view arrangement of faults on the eastern part of Lucky Strike mapped using a submersible, and their relationship to other fault structures on the floor of the eastern rift valley. Langmuir and colleagues [*Langmuir et al.*, 1993; *Lucky Strike Team*, 1995] suggest that the rifts at Lucky Strike and the principal hydrothermal lineaments may have nucleated over pre-existing faults in the rift valley. The shallow water depth of Lucky Strike results in sub-critical or near-critical subseafloor phase separation similar to that reported from some vents at 1500-2000 m depth at Axial Seamount on the Juan de Fuca Ridge [*Butterfield et al.*, 1990], and at ~2500 m depth on the EPR near 9°45'-51'N [*Von Damm et al.*, 1992].

Other slow-spreading MAR hydrothermal fields have been only minimally surveyed and sampled up to 1994. The Broken Spur site (Figures 1 and 3) was discovered in 1993 at 29°10'N using water column detection methods [*Chin et al.*, 1994; *Murton and Van Dover*, 1994]. Its size and setting were subsequently investigated during two ALVIN dives [*Murton and Van Dover*, 1994], and a dive program employing the MIR submersibles [*BRAVEX/94 Team*, 1994]. Broken Spur comprises at least five hydrothermal sites at depths of ~3000 m which are associated with faults along the east and west walls of the axial rift; two are extinct and three others have high-temperature (>350°C) activity. The sulfide mounds are up to 20 m high and 30 m in diameter, and one of the active chimneys is 18 m tall [*Murton and Van Dover*, 1994; *BRAVEX/94 Team*, 1994]. Like Snake Pit, the Broken Spur field (and Menez Gwen discussed below) lies on the crest of a constructional volcanic ridge, with individual vents located along the walls of an ~100-m-wide summit graben [*Murton and Van Dover*, 1994; *BRAVEX/94 Team*, 1994].

The Menez Gwen field was discovered on the DIVA1 cruise in May, 1994, using water-column plume mapping involving CTD (conductivity, temperature, depth) measurements and analysis of CH_4 and H_2S in water samples [*Fouquet et al., 1994*] (Figures 1 and 3). The site, near 38°10'N, is one of the shallowest high-temperature MOR sites (871-847 m), and was investigated on five dives using the NAUTILE submersible. The crestal segment in which Menez Gwen is present consists of an ~17 km diameter volcano which has ~700 m of relief. The MAR axial zone along this segment does not have the characteristic wide and deep rift valley morphology which typifies much of the MAR crest. The seafloor here is dominated by very fresh constructional terrane including lava lakes and expansive areas of pillowed and lobate flows, the latter being more characteristic of faster spreading MOR crestal terrane [*Fouquet et al.*, 1994]. The vents cover an area of ~200 m^2 and are located near the top of a small edifice within a ~2 km wide graben. The vents appear to be young based on their size (~<5 m) and the fact that they are growing directly from the basalt substrate with little to no pelagic or hydrothermal sediment covering the constructional terrane [*Fouquet et al.*, 1994].

A separate hydrothermal site at 14°45'N appears to be similar in size to the TAG field, although less active based on towed CTD/chemical scanner data, bottom photography and grab samples [*Batuyev et al.*, 1994].

Methane Venting on the Mid-Atlantic Ridge

A unique type of venting characteristic of some portions of the MAR appears to be caused by seawater interactions with ultramafic rock. Serpentinization can produce methane as part