Chapter 1:   Introduction

This dissertation is concerned with the flow of water through the subseafloor at mid-ocean ridge hydrothermal systems (Section 1.1). The crustal rock and sediment which constitute the subseafloor are both permeable. Consequently, flows of interstitial water can be induced by thermal buoyancy forces and non-hydrostatic pressure gradients. The buoyancy forces are derived from the heat of upwelling magma and drive a steady convective flow (Chapter 5). In addition to this steady flow, pressure gradients induced by tidal loading drive an oscillatory flow (Chapter 6).

As water flows through the subseafloor it exchanges heat and chemical elements with the surrounding rock. Consequently, hydrothermal convection is important because it contributes to the thermal balance of the oceanic crust and the chemical balance of the oceans (Elderfield & Schultz, 1996; Schultz & Elderfield, 1997). Furthermore, the advection of heat and chemical elements by hydrothermal flow affects the distribution of these quantities within the subseafloor. A principal aim of this dissertation is to explain the subseafloor structure of hydrothermal convection cells. It is proposed that the nonlinear thermodynamic properties of water are sufficient to impose this structure (Chapter 5).

Tidally induced flows *below* the seafloor are important because they lead to observable consequences *on* the seafloor. Tidal signals have been recorded in time-series measurements of the temperature, flow rate and composition of hydrothermal fluid emerging from the seafloor. Understanding the mechanism which causes these tidal modulations is of intrinsic scientific interest, but it may also allow constraints to be placed on the properties of the subseafloor. The ocean tide constitutes an accurately known 'input signal' to a physical process whose 'output signals' are the observed tidal modulations in temperature, flow rate and composition. If the physical process and the input and output signals can all be quantified, constraints can be placed on the properties of the subseafloor. Consequently Chapter 2 is devoted to a detailed study of the characteristic features of tidal phenomena while the aim of Chapter 3 is to derive optimal techniques for extracting information from tidal signals. The principles and techniques of these two chapters are then applied to seafloor data in Chapter 4. Chapter 5 is devoted to a discussion of the steady state structure of subseafloor convection cells. Finally, in Chapter 6, the discussion returns to the subject of

tidal modulation and a model of the physical process which links the 'input' and 'output' signals is proposed.

1.1   Mid-Ocean Ridge hydrothermal systems

Mid-ocean ridges form boundaries between the rigid plates that constitute the ocean basins (Figure 1.1). Upwelling magma from the Earth's mantle creates new crust at mid-ocean ridges, and the plates are forced apart. Heat is transported to the oceans as the magma solidifies and the crust cools.
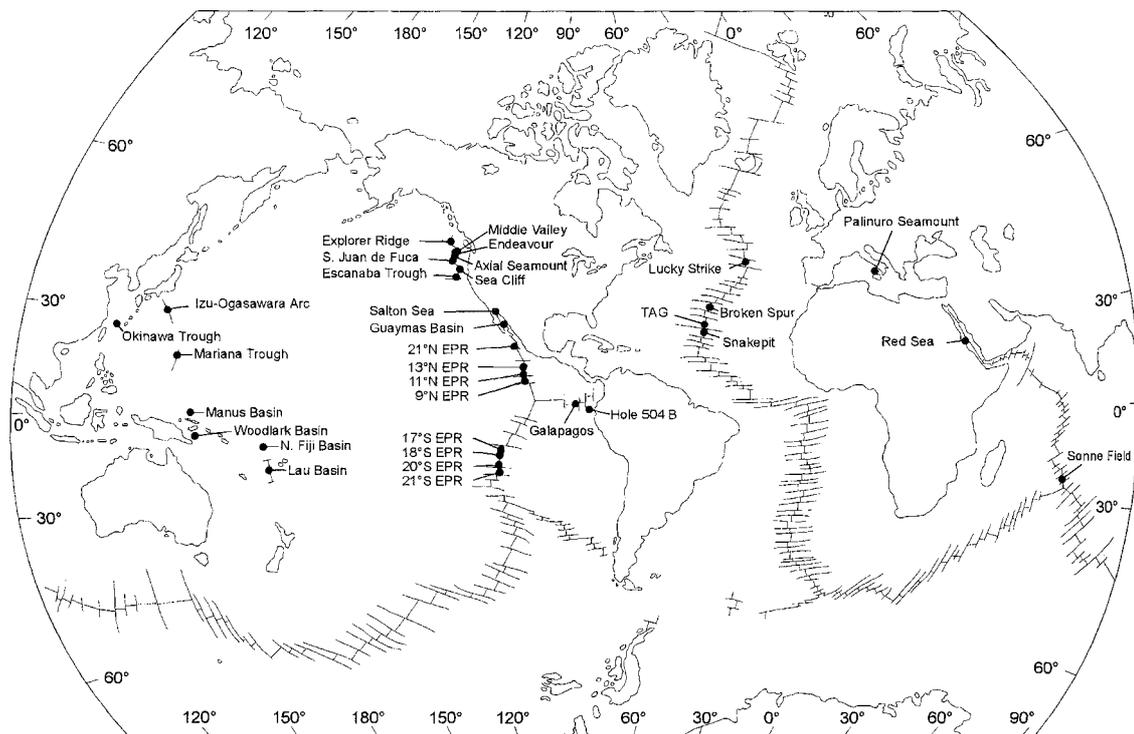
Figure 1.1:   The mid-ocean ridge system. A selection of the currently known hydrothermal systems and polymetallic massive sulphide deposits is also shown. Diagram from Herzig & Hannington (1995).

The oceanic crust cools as it is carried away from mid-ocean ridges by the motion of the plates. Typically the plates diverge at speeds between 1 cm.yr^{-1} and 10 cm.yr^{-1}, and so cover a distance between 10 km and 100 km every million years. Consequently, distances from the ridge are often expressed as crustal ages in millions of years.

There are two mechanisms which cool the crust – conduction and advection. The conductive transfer of heat is induced by spatial gradients in temperature and occurs throughout the crust. The conductive heat flux is greatest near mid-ocean ridges - where the lithosphere is

thin - and decays with distance away from the ridge. Advective heat transfer is a consequence of the buoyancy-driven flow of seawater within the subseafloor. The most vigorous convection occurs at the ridge axis where it is known as 'active circulation'. However, there is also significant advective heat transport in the ridge flanks - known as 'passive circulation' - for crustal ages up to 65 Ma (Stein & Stein, 1992; Stein & Stein, 1994).

This dissertation is concerned principally with the 'active' circulation which occurs in young (<1 Ma) oceanic crust. Evidence from a number of different sources suggests that a typical hydrothermal convection cell at a mid-ocean ridge has the general structure shown in Figure 1.2. In broad terms, the structure can be summarised as follows. Seawater percolates down through the crust towards a magma chamber, interacting with the surrounding rock as it flows. The interaction is both chemical and thermal. Temperature generally increases with increasing depth below the seafloor and so the fluid becomes hotter as it harvests heat from the crust. Furthermore, an exchange of chemical elements between the percolating water and the rock occurs. The fluid gains some elements and loses others, with the exact nature of the chemical transfer being temperature dependent. The fluid reaches its greatest temperature in the region above the magma chamber and begins a buoyancy-driven ascent to the seafloor. The hot fluid expelled at the seafloor is usually divided into three categories.

Firstly, the hottest fluid emerges from the seafloor through structures known as black smokers which are characterised by temperatures between 300°C and 400°C. These vents are so named because of the black "smoke" which forms when the vent water cools and mixes with cold seawater. The "smoke" is in fact due to the precipitation of metal sulphides dissolved in the vent fluid. Over time, precipitation of minerals such as anhydrite, pyrite and chalcopyrite leads to the formation of chimney structures through which the effluent fluid issues. A typical black smoker chimney has an internal diameter of ~10 cm and is a few metres in height. In the prototype example shown in Figure 1.2, several black smokers are shown within a "central black smoker complex" of a hydrothermal mound formed by the precipitation of anhydrite and metal sulphides.

Secondly, a lower temperature form of focussed flow emerges from structures known as white smokers which are characterised by temperatures below 300°C. In this case, the white "smoke" is produced by the precipitation of sulphates, amorphous silica and zinc sulphides.
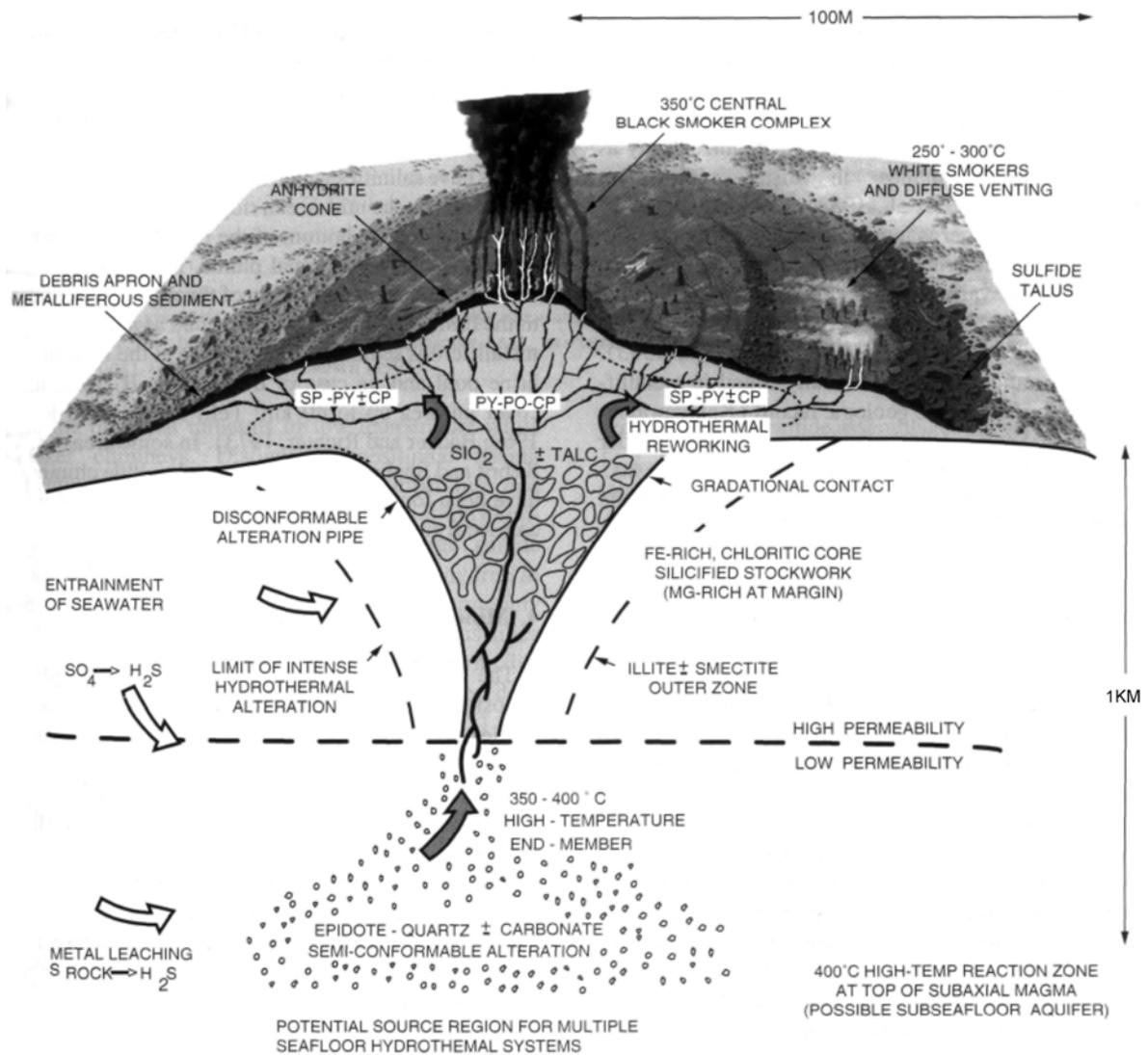
Figure 1.2:   Cross section through the seafloor, showing the principal components of a typical seafloor hydrothermal system. Diagram from Herzig & Hannington (1995).

Thirdly, the term "diffuse flow" is applied to the flow of low temperature (typically < 50°C) water which emerges from broad areas of the seafloor in the vicinity of black and white smokers. An individual area of diffuse flow typically covers an area of at most a few square metres and is identified by the appearance of "shimmering" water just above the seafloor.

The schematic picture of subseafloor structure in Figure 1.2 is derived from evidence obtained at active hydrothermal systems on the seafloor and at fossil hydrothermal systems exposed on land. At active systems, the temperature and chemistry of seafloor effluent can be measured and used to infer the conditions below the seafloor (e.g. Von Damm *et al.*, 1985). In addition, seismic studies can be used to constrain the depth of the magma chamber

below the seafloor (Morton, 1984; Morton & Sleep, 1985; Detrick *et al.*, 1987; Vera & Diebold, 1994). At fossil systems, relict hydrothermal convection cells are sometimes exposed in cross section and the subseafloor structure is revealed by examination of the metamorphic mineral assemblages (Gillis & Roberts, 1999) and by fluid inclusion geothermometry (Cowan & Cann, 1988).

1.2   Aims and dissertation outline

This dissertation is concerned with (1) the temporal variability and (2) the spatial structure of active seafloor hydrothermal systems. The spatial structure is considered on the lengthscale of an individual convection cell while the temporal variability is considered on a timescale ranging from hours to months. Spatial structure is considered in Chapter 5, while temporal variability is considered in Chapters 2, 3, 4 and 6.

The aims of this dissertation are:

1) to develop an optimal technique for analysing the tidal component of time-series collected at seafloor hydrothermal systems.

2) to apply this technique to existing seafloor datasets and assess its usefulness.

3) to develop the simplest model of hydrothermal circulation which is sufficient to explain the known subseafloor structure of convection cells.

4) to develop theoretical models of a mechanism which causes tidal modulation of the observable quantities at hydrothermal systems.

Chapter 2 contains a review of the theory of tides and tidal signals. All tidal signals share a common cause – the well known astronomical motions of the sun and moon – and it is helpful to consider the features which all tidal signals are expected to share. There are two obvious mechanisms by which the tides might deform the seafloor and influence hydrothermal systems. Firstly, the direct action of tidal forces on the seafloor causes a deformation known as the solid tide. Secondly, the rise and fall of the ocean surface (the ocean tide) imposes a time-dependent load on the seafloor. This causes a deformation known as the load tide. Order of magnitude calculations suggest that the load tide produces much larger strains in oceanic crust than the solid tide. It is therefore expected that the tidal signals observed at hydrothermal systems are correlated with the load (i.e. ocean) tide rather than the solid tide. This expectation is tested in Chapter 4. A third mechanism by which tidal processes might influence hydrothermal systems is provided by tidal streams - the lateral motion of ocean waters induced by the ocean tide. The characteristic features of each of the

three plausible 'input signals' – solid tide, ocean tide and tidal streams – are considered in turn from a theoretical standpoint. Consequently the tidal component of any seafloor time-series (the 'output signal') can be compared with each of the postulated 'input signals' in order to constrain the physical process linking input and output.

Chapter 3 is concerned with finding the best way to extract useful information from a time-series with a tidal component. Methods of time-series analysis are divided into two classes – parametric and non-parametric. Non-parametric methods are used to estimate the power spectrum of a time-series. Most previous analyses of tidal modulation at seafloor hydrothermal systems have relied on non-parametric methods based on the periodogram. However, it is argued that the multiple window method (Thomson, 1982) is much better suited to the analysis of the short noisy datasets which are typically obtained at the seafloor. It is therefore recommended that the multiple window method should be used in all future analyses. Parametric methods are used to derive parameters which describe the information content of a time-series, if it is assumed that the time-series takes a particular functional form. Previous analyses of hydrothermal time-series data have used a discrete Fourier series (referred to as the Harmonic Method) as a parametric model for tidal data. It is argued here that the Admiralty Method is simpler and likely to yield more useful information from a limited dataset. The Admiralty Method has long been used to describe the nature of the ocean tides in the world's ports (Doodson & Warburg, 1941; Admiralty Tidal Handbook, No. 1; Admiralty Tidal Handbook, No. 3). It is recommended here that the Admiralty Method should be used to describe the tidal component of time-series obtained at the seafloor. Previously, the Harmonic Method has been combined with a Bayesian technique for removing the drift from a time-series to produce a parametric algorithm for tidal analysis (Tamura *et al.*, 1991). Here the Bayesian drift removal technique is instead combined with the Admiralty Method to produce a new parametric algorithm for tidal analysis. This algorithm has been combined with the robust data analysis technique of Huber weighting (Chave *et al.*, 1987) to produce a new computer code – HYBRID – which is recommended for the parametric analysis of tidally modulated time-series from seafloor hydrothermal systems.

Chapter 4 presents a review of the tidally modulated signals which have been obtained at seafloor hydrothermal systems. In the cases where these data are readily available, they are examined in the light of the theory presented in Chapter 2, by using the techniques described in Chapter 3. Some of the data discussed in Chapter 4 is presented here for the first time. In

addition, previously published data are re-examined. In some cases, the conclusions based on the theory of Chapters 2 and 3 are different to those of the authors who originally analysed the data. The results of the data analysis are used to determine which 'input signal' (solid tide, ocean tide, tidal streams) is most likely to have caused the tidal modulations in the data. Finally, the efficacy of the techniques recommended in Chapter 3 is discussed in the light of their application to real data.

Chapter 5 examines the structure of hydrothermal convection cells. A simple model of subseafloor convection - incorporating the full nonlinear thermodynamic properties of water - is examined using numerical simulations and analysis of the governing equations. It is argued that the nonlinear thermodynamic properties of water are sufficient to explain the structure of convection cells and the observed upper limit to black smoker temperatures (~400°C). A scaling analysis is derived to quantify how the lengthscales and timescales of a subseafloor convection cell depend on the bulk crustal permeability.

Chapter 6 draws together the concepts of the previous chapters. The convection cell structure derived in Chapter 5 is considered in the context of tidal loading of the seafloor. The equations of poroelasticity are reviewed in order to examine how the thermodynamic properties of water influence the response of a hydrothermal system to an applied tidal load. An analytical solution describing the diffusion of fluid pressure in a tidally loaded one-dimensional halfspace is reviewed (Van der Kamp & Gale, 1983). This solution is then extended in a number of ways. Firstly, expressions for the tidally induced variations in temperature and flow are derived from the established expression for the pressure variations. Secondly, analogous expressions are derived for a layer of finite thickness. Thirdly, the theory is extended to two-dimensions where it is illustrated with numerical simulations. These simulations are used to show how the convection cell derived in Chapter 5 is affected by tidal loading of the seafloor.

Finally, Chapter 7 contains a summary of the preceding chapters and a brief discussion of the suggested directions for future research.