Chapter 7: Conclusions and suggested future work

A series of simple theoretical models has been developed in an attempt to explain the structure of a subseafloor hydrothermal convection cell and its response to tidal loading at the seafloor. In addition, a discussion of the nature of tidal signals has led to the development of a new technique for the analysis of tidally modulated time-series obtained at seafloor hydrothermal systems.

The purpose of this chapter is to review the results of the preceding chapters and to suggest ways in which the work presented here could be extended in the future.

7.1 Directions for future research

7.1.1 Collection of further hydrothermal time-series

The discussion of the nature of tidal signals in Chapters 2 and 3 shows that an understanding of tidal processes can be used to advantage in the analysis of a tidally modulated data set. It is therefore hoped that future analyses of time-series data from seafloor hydrothermal systems will refer where necessary to the theory of tides. Many of the time-series examined in Chapter 4 are noisy and difficult to interpret with certainty. It may be that such noise is unavoidable but it is hoped that it will be possible to collect longer, cleaner time-series from hydrothermal systems in the future. In particular, there is a need for time-series measurements of effluent temperature which cover a time period longer than a few days. The collection of such data, however, presents considerable technical difficulties.

7.1.2 Less simplistic convection models

The convection model of Chapter 5 is deliberately simplistic but could usefully be extended in a number of ways. The assumption of a homogeneous, isotropic subseafloor is clearly an idealisation and it would be interesting to see how important these assumptions are. Thermal expansion of the rock and the subsequent alteration of porosity and permeability could also be included in future models. The most important simplification imposed in Chapter 5, however, involves the use of pure water as the convecting fluid. Pure water is a single-phase fluid at all seafloor temperatures for pressures in excess of 22 MPa (~2.2 km cold hydrostatic head), and so the considerable complication of phase separation is avoided by placing the seafloor at a depth below sea level greater than 2.2 km. It would be interesting to extend the model of Chapter 5 in two stages. Firstly, hydrothermal convection of pure water at pressures below 22 MPa could be studied to investigate the effect of phase separation on convection cell structure. Secondly, salt water could be used as the convecting fluid in place of pure water for a range of seafloor pressures. It should be noted that the second extension represents a much larger jump in physical complexity than the first.

The thermodynamic state of pure water can be fully described by two thermodynamic variables such as the pressure (p) and specific enthalpy (h). Consequently, the convection of pure water in a porous medium is governed by two conservation equations – the conservation of mass and energy – in addition to Darcy's law which expresses conservation of momentum. Furthermore, phase separation of pure water occurs at a unique temperature – the boiling point – for any given pressure below the critical pressure of 22 MPa.

In contrast to pure water, the thermodynamic state of salt water depends on a greater number of thermodynamic variables. An extra thermodynamic parameter – the salinity – is added for each extra salt which is dissolved in the water. The convection of seawater at mid-ocean ridge hydrothermal systems involves the exchange of a number of dissolved chemical species between the pore fluid and the rock. Consequently, modelling the convection of salt water in a porous medium requires that the mass of each salt be conserved in addition to fluid mass, momentum and energy. Furthermore, a full numerical simulation would need to track the exchange of dissolved salts with the rock matrix and model the subsequent changes in porosity and permeability. It is clear that the numerical modelling of reacting salt water flows constitutes a considerable challenge.

Recently, the thermodynamic properties of a salt solution containing a single salt (NaCl) have been tabulated from theoretical and experimental data (Palliser & McKibbin, 1998a: Palliser & McKibbin, 1998b: Palliser & McKibbin, 1998c). The thermodynamic properties of the solution are given as functions of the temperature (T), pressure (p) and salinity (X). The salinity is expressed a mass fraction of salt in the solution and is therefore a dimensionless number taking values between 0 and 1. Numerical codes making use of these salt water properties are currently in development and have been applied to convection at the sub-critical temperatures for which the solution remains a single phase fluid (Lowell & Xu, 2000). The modelling of salt water convection at temperatures sufficient to cause phase separation is currently being investigated (W. Xu, *pers. comm.*, 1999)

To give an idea of the extra physics implied by the presence of salt in the convecting fluid, the equations of Palliser & McKibbin (1998a) are used to generate the state-space diagram shown in Figure 7.1. Palliser & McKibbin (1998a) publish isothermal cross-sections of the state-space which display the state of the solution as a function of pressure (p) and salinity (X). In the context of seafloor convection, however, it is more useful to examine isobaric cross-sections of the state-space which show the state of the solution as a function of pressure (p) and temperature (T), and so the diagrams in Figure 7.1 take this form. It should be noted that the salinity is shown on a logarithmic scale. The diagrams are divided into three regions. In region (1) the solution is a single phase fluid, while in region (2) it is a two-phase mixture of gas and liquid. In general the liquid and gas have different salinities, and the vertical co-ordinate represents the overall salinity of the mixture. In region (3) the system consists of solid salt and a saturated fluid solution. In other words, if salt solution is taken into region (3) of the state-space, solid salt precipitates out of solution.

It is now possible to consider the trajectory of a fluid particle through the state-space as it is heated over the range temperatures found in a seafloor convection cell. It is supposed for simplicity that the process is isobaric so that an individual diagram from Figure 7.1 can be used, and that the fluid is initially cold seawater. Bischoff & Rosenbauer (1985) suggest that a NaCl solution of salinity $X = 0.032$ is a good analogue for seawater. Consequently it is supposed that the fluid begins its passage through the convection cell at $T = 2°C$ and $\log_{10}(X) = -1.5$. As the fluid is heated at constant pressure it travels along a horizontal line in the state-space (Figure 7.1) until it reaches region (2) where phase separation occurs. At this point the fluid dynamics become complicated. The two-phase mixture is represented overall by a single point in the state-space at temperature T and salinity X, which lies in region (2). The individual gas and liquid phases, however, must lie at two distinct points on the boundary of region (2) in the state-space. At phase separation, the liquid and gas phase must both have the same temperature (T) but the liquid has a salinity X_l and the gas has a salinity X_g. If the mixture is subjected to further heating, the liquid and gas phases must be tracked separately through the state-space. Furthermore, in a convection cell, the liquid and gas phases are subject to contrasting body forces because of their different densities and could therefore move separately to regions of the seafloor with different temperatures. In the absence of numerical simulations it is not clear what the subsequent trajectory of convecting salt water through the state-space would be at super-critical temperatures. The results of numerical simulations are therefore awaited with considerable interest.

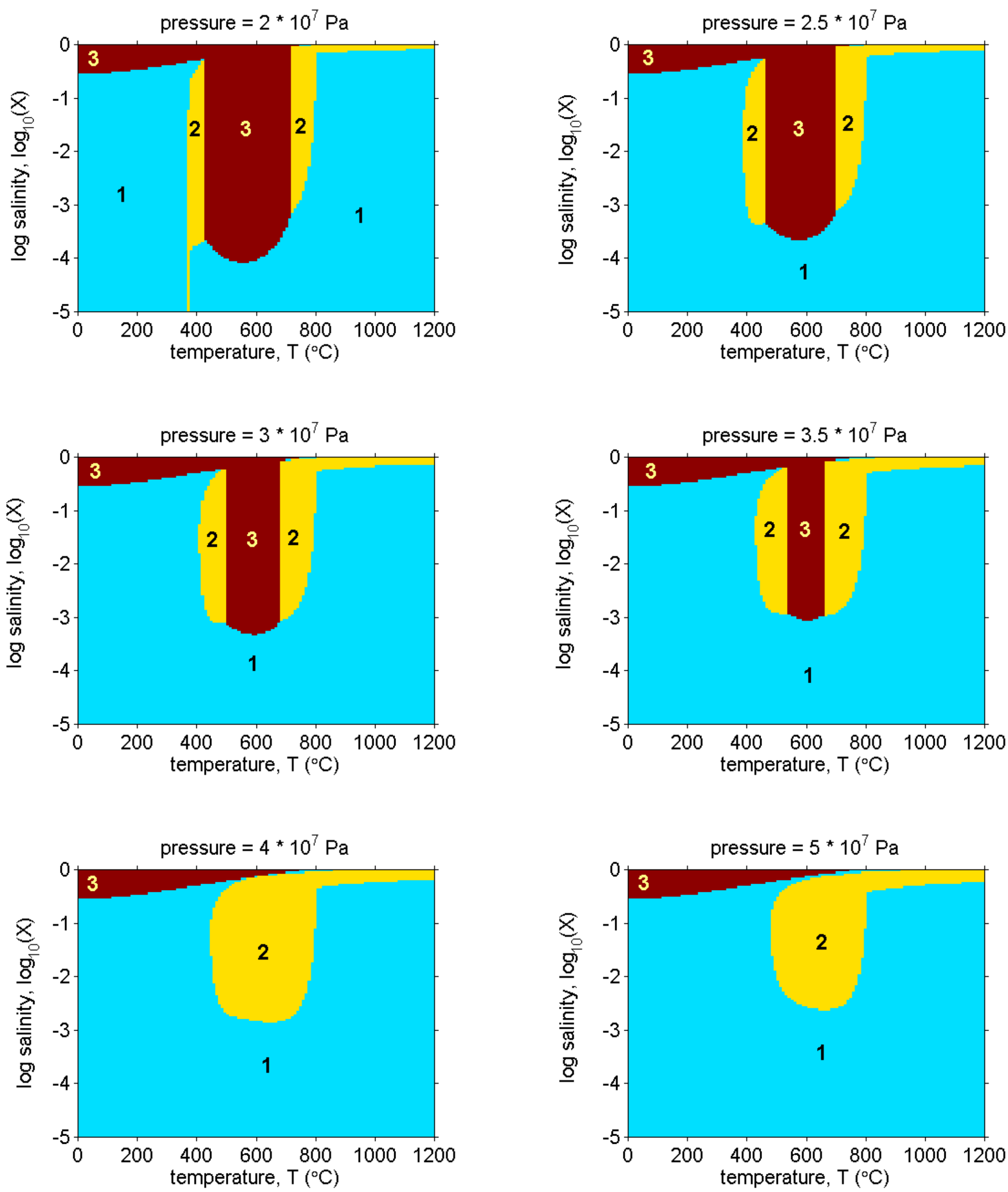

Figure 7.1: Isobaric cross-sections of the H_2O-NaCl state -pace for a range of seafloor pressures (10^7 Pa corresponds to a depth 1 km below sea level). Regions of state space are labelled as follows: **(1)** – Unsaturated single phase fluid. **(2)** – Unsaturated two-phase fluid (liquid + gas). **(3)** – Saturated single-phase fluid. Thermodynamic data from Palliser & McKibbin (1998a).

7.1.3 Direct imaging of subseafloor flow and temperature

Another area of active research relevant to this dissertation concerns the direct imaging of the subseafloor. Seismic tomography has been used for some years to constrain the depth of axial magma chambers but it does not reveal the flow or temperature structure of hydrothermal convection cells (e.g. Detrick *et al.*, 1987). However, there are two techniques which may be able to image flow and temperature structure - controlled-source electromagnetic tomography and measurement of the ζ-potential.

Controlled-source electromagnetic tomography has been used to infer the resistivity structure at an axial volcanic ridge segment of the Reykjanes Ridge at 57°45'N on the Mid-Atlantic Ridge (Sinha *et al.*, 1998; MacGregor *et al.*, 1998). If the temperature (T) is measured in °C, the resistivity of seawater (ρ_{SW}), measured in Ω.m, is given by the formula:

$$\rho_{SW} = \left(3 + \frac{T}{10}\right)^{-1} \tag{7.1}$$

for temperatures between 0°C and 350°C (Nesbitt, 1993). Consequently, tomographic estimates of crustal resistivity could be used to infer the temperature of the interstitial fluid, and hence the flow structure below the seafloor. A tomographic estimate of the width of the upflow zone could also be combined with the scaling analysis of Chapter 5 to infer subseafloor permeability. It remains to be seen whether this technique will prove practical. The structures which have been imaged previously using this method are on a significantly larger scale (1 km) than the expected width of the upflow zone (<100 m). High frequency electromagnetic signals would be required in order to resolve smaller structures, but they would attenuate more rapidly within the crust (L.M. MacGregor, *pers. comm.*, 1999).

The second technique which might be used to image subseafloor flow structure makes use of the theory of the ζ-potential (Revil & Pezard, 1998; Revil *et al.*, 1999a; Revil *et al.*, 1999b). The ζ-potential is the name given to the electrical potential generated when a charge carrying fluid is forced to move through a potential gradient. In the case of hydrothermal systems, the pore water functions as an electrolyte. The fluid motion is forced by thermal buoyancy and the potential gradient is created by polarisation due to the drag of the excess charge located at the grain-water interface of the porous medium (Revil *et al.*, 1999b). Measurements of the ζ-potential have been made at land-based geothermal systems, and are manifest as a positive potential anomaly in the ground above a discharge zone and a negative potential anomaly in the ground above a recharge zone. It is suggested that surveys of the electrical potential of the seafloor at hydrothermal sites might reveal similar behaviour and be used to infer the widths of recharge and discharge zones in hydrothermal convection cells. Revil *et al.* (1999b) point out that the magnitude of the ζ-potential is smaller for saline fluids than for fresh water, which might mean that the technique is unsuitable for seafloor use. On the other hand, phase separation in a seafloor hydrothermal system can result in the upwelling fluid having a reduced salinity.

In summary, it will be interesting to see whether electromagnetic tomography and the ζ-potential prove practical in the imaging of subseafloor flow structure.

7.2 Conclusions

In this section, the results of the preceding chapters are reviewed.

Chapter 2 contains a thorough review of the common features shared by all tidal signals. It is demonstrated that the astronomical positions of the sun and moon influence the relative magnitudes of the diurnal and semi-diurnal oscillations of which all tidal signals are composed, as well modulating their magnitudes according to the springs/neaps cycle of lunar phases. For this reason, it is recommended that time-series from hydrothermal systems be analysed with the positions of the sun and moon in mind. It is also recommended that the date and GMT time be given for all reported data so that comparison with tidal predictions can be made. The three postulated tidal inputs to a seafloor hydrothermal system – the solid tide, ocean tide and tidal streams are considered in turn. Order of magnitude calculations suggest that dilatation of the crust due to the ocean tide is far more significant than that due to the solid tide. The phase relationship between the ocean tide and tidal streams is discussed so that tidal streams may be deduced from ocean tide models when no direct measurements are available.

Chapter 3 is concerned with finding the optimal numerical techniques for the analysis of tidally modulated time-series collected at seafloor hydrothermal systems. Among non-parametric techniques for estimating power spectra, the periodogram methods used previously by some authors are shown to be unsuitable for the short, noisy time-series collected at hydrothermal systems. It is recommended that the multiple window method of Thomson (1982) be used instead. The MWPS code of A. Chave (*pers. comm.*, 1999) is ideal for this purpose. Among parametric methods for describing the tidal part of a time-series, it is argued that the Admiralty Method (Admiralty Tidal Handbook, No. 3) is optimal. This parametric description of tidal signals is used to describe the ocean tides in the world's ports and can be adapted for use with seafloor time-series. A new code – HYBRID – has been written for this purpose. Since seafloor time-series are often contaminated by drift and noise, methods to deal with these problems have been incorporated into the code. A technique derived from Bayesian statistics (Tamura *et al.*, 1991) is used to remove the drift component of the time-series, while robust section averaging methods (Chave et al. 1987) are incorporated to reduce the effect of outlier data on the estimated parameters. The HYBRID code produces a set of 8 harmonic constants which describe the tidal component of a time-series. These harmonic constants can be visualised as 4 phasors in the complex plane. Consequently, the tidal components of two time-series can be examined in terms of their phasors. It is therefore possible to compare the phasor representations of the three postulated 'input signals' (solid tide, ocean tide and tidal streams) with the tidal component of an observable 'output signal'. It can then be decided (in principle) which 'input signal' is responsible for the modulation of the 'output signal'.

Chapter 4 comprises a review of the previously observed tidal modulations observed in time-series collected at seafloor hydrothermal systems. The chapter also contains the results obtained when the principles of Chapter 2 and the techniques of Chapter 3 are applied to real data collected on the seafloor. It is shown that use of the multiple window method of spectral estimation can result in very different power spectra than are obtained from a simple periodogram analysis. It is also demonstrated that the ocean tide at a hydrothermal site may be very different from the ocean tide at the nearest coastal port. It is therefore unwise to infer the nature of the ocean tide at a hydrothermal site from coastal tide tables. Furthermore the tidal streams on the seafloor cannot necessarily be obtained simply by differentiating the ocean tide with respect to time. The theory of tidal streams quoted in Chapter 2 should be consulted before an estimation of seafloor currents is attempted. The HYBRID code is used to estimate the Admiralty Method harmonic constants of a number of data time-series. The quality of the results is variable and depends to a large extent of the noisiness of the original signal. The Bayesian drift removal technique, in particular, is shown to be inappropriate when the signal-to-noise ratio of the data is low. However, the estimation of Admiralty Method harmonic constants using the Bayesian drift removal technique is shown to be very successful for the clean tidal signal obtained from current meter measurements at the Lucky Strike hydrothermal site. In general it is shown that effluent temperatures display greater similarity with the ocean tide than with the solid tide. This conclusion is consistent with the order of magnitude argument presented in Chapter 2. It is therefore proposed that the tidal modulation of effluent temperature at seafloor hydrothermal systems is caused by the tidal loading of the seafloor. The tidal modulation of ambient bottom water temperatures, on the other hand, is often caused by the lateral advection of warm water by tidal streams. The time-series data for effluent velocity are insufficiently comprehensive for any firm conclusion to be drawn.

Chapter 5 examines the effect which the nonlinear thermodynamic properties of water have on the steady-state structure of a subseafloor hydrothermal convection cell. It is shown that these thermodynamic properties are sufficient to impose a structure on the convection cell which is consistent with the known constraints. For simplicity, a homogeneous isotropic seafloor is assumed and the convecting fluid is taken to be pure water above the critical pressure of 22 MPa. A numerical simulation and analysis of the governing equations are used to explain how the thermodynamic properties of water impose an upper limit of ~400°C on the temperature of black smokers. It is predicted that temperatures greater than ~400°C are confined to a thin boundary layer at the base of the convection cell which can be identified with the reaction zone observed in ophiolites. A scaling analysis is presented which calculates the width of the discharge zone and the thickness of the reaction zone as functions of the bulk permeability. The predicted residence times of fluid in the reaction and discharge zones are also estimated.

Chapter 6 investigates the tidal loading of a hydrothermal convection cell by the changing tidal pressure field on the seafloor. The convection cell structure derived in Chapter 5 is shown to lead to a dichotomy between regions of the cell where water is liquid-like (<400°C) and regions of the cell where water is gas-like (>400°C). The dependence of the important poroelastic parameters on fluid temperature is discussed. In general terms, the interstitial fluid bears a high proportion of the applied load when cold and a low proportion of the applied load when hot. Consequently, at high tide, the incremental pore pressure is highest where the fluid is cold and a flow is induced from cold regions to hot regions. The one-dimensional incremental pore pressure solution of Van der Kamp and Gale (1983) is extended to yield expressions for the incremental fluid velocity and incremental temperature due to tidal loading. In the case of an infinite halfspace, the incremental fluid velocity at the seafloor is shown to lag the ocean tide by a phase angle of 135°. If the permeable seafloor is of finite vertical extent, this phase lag is shown to lie in the range [90°, 135°]. A simple model in which temperature and pressure are linear with depth predicts that the incremental temperature lags the incremental velocity by a phase angle in the range [45°, 90°] depending on the permeability. Consequently, the incremental temperature is predicted to lag the ocean tide by a phase angle in the range [180°, 225°] for an infinite half-space, and a phase angle in the in the range [135°, 225°] for a finite permeable layer. These predictions are shown to be consistent with some of the data presented in Chapter 4.

It is hoped that the theoretical principles outlined in this dissertation will prove useful to future investigators. The physics of seafloor hydrothermal systems are only partially understood, and it is certain that the coming years will see the publication of new data and more sophisticated models. There is much to learn.