Chapter 1

Introduction and summary

1.1 Introduction

In the 25 years after the general acceptance of the concept of plate tectonics we have witnessed large progress in observational, laboratory, forward modelling and inversion techniques. These provide a clear view of the immense complexities that are facing us when studying the dynamics of the interior of the Earth. Plate tectonics can be seen as both an expression of, and the mechanism controlling, the dynamic cooling of the Earth. Traditionally, the soloistic and often opposing, simplifying views have been adopted of either the 'convectionist', who sees plate tectonics merely as the surface expression of mantle convection, or the 'tectonist', who views the plates as the only dynamic component in an otherwise passive mantle. It clearly emerges from the observational data, knowledge of deformation mechanisms, and the available modelling and inversion results, that a uniform approach, combining the two views would be more appropriate to describe the dynamics of the Earth. The generalized description is made difficult by the very distinct nature of the lithosphere, as expressed by the thermal, compositional and rheological differences from the underlying mantle.

In this thesis I will present some model studies of the deformation of lithosphere and mantle, recognizing the strong influence of compositional and rheological differences. The approach is more 'convectionistic' than 'tectonistic', in that only ductile deformation is considered and that the brittle/elastic behaviour of the upper and colder lithospheric parts is ignored. Ductile creep has been used with varying success in 'tectonist' models of lithosphere dynamics, but the application of these methods to global deformation problems are, as yet, computationally too expensive.

1.2 Basic assumptions

The Earth's complicated rheological and dynamical behaviour necessitates the use of simplifying assumptions when modelling its dynamics. The next few paragraphs discuss some of the assumptions that are made here.

Slow deformation of the Earth below the upper parts of the lithosphere is governed by high temperature ductile creep. Experimental deformation work at high temperature shows that the creep behaviour of candidate mantle rocks are well described by Dorn's equation for power law creep

$$\dot{\varepsilon} = A\sigma^n \exp[-H/RT] \tag{1.1}$$

where $\dot{\varepsilon}$ is strain rate, σ applied differential stress, T temperature, R the gas constant, and n, A and H empirically determined constants [Ranalli, 1987]. Extrapolation of this creep equation from laboratory conditions to the much lower tectonic strain rates is done using theoretical creep equations, derived from microphysical models. Several mechanisms, based on movement of dislocations in crystals, can 'explain' the power law creep behaviour. The Newtonian mechanism of diffusion creep can be described by the migration of vacancies in grains and between grain boundaries. This mechanism is not often found to operate at the high strain rates normally used in laboratory experiments, but it is expected that this creep mechanism is important in the the Earth at low stresses. Although from a mechanistic point of view very different, diffusion creep can be described mathematically by the same power law creep law (1.1), for the special case $n = 1$.

The equations are solved for convection in a Boussinesq fluid at infinite Prandtl number. The narrow definition of the Boussinesq approximation implies that viscous dissipation is neglected, the fluid is incompressible and all material parameters are constant, except in the gravity term of the equation of motion [Busse, 1989]. In practice, this last condition is relaxed for material parameters other than density, allowing for e.g. variable viscosity and thermal diffusivity.

First principles are used to derive the mathematical differential equations describing the dynamics of the physical models, under the assumptions described above. In the general situation, the equations are time-dependent, non-linear and non-linearly coupled. For only a few exceptional, simplified cases a closed analytical form of the solution to the differential equations can be found. Numerical methods are required to obtain solutions to general problems.

Three-dimensional modelling has become available for simple (e.g. stationary, or isoviscous) problems. It is expected that within a few years, the progress in computational methods and increasing availability of computer power will allow for studies that can treat the full 3-dimensional time-dependent problem with realistic rheology within a reasonable production time. For the type of models used in this thesis it is still necessary, from a computational point of view, to consider 2-dimensional models only. For many applications this is a reasonable approximation, as the models can be imagined to extend in similar fashion in the third dimension.

1.3 Scope of the thesis

In the work described in this thesis, I have developed numerical methods to model the dynamical behaviour of the Earth's lithosphere and mantle driven by thermal and compositional buoyancy forces using a non-Newtonian power law rheology. The methods have been applied to three different problems:

Salt tectonics

First, the problem of salt tectonics is considered within this framework. Rocksalt is very weak, and deforms by ductile creep even at upper crustal conditions. The formation of salt diapirs is of large economical interest, considering their role in trapping and migration of oil and gas, and in their possible use for disposal of radioactive waste and storage of energy reserves. Traditionally a constant Newtonian viscosity has been used for the salt in both laboratory and numerical modelling of salt diapirism. Here, the flow behaviour of rocksalt has been studied using an empirical creep law [Spiers et al., 1990], that describes the combined effect of dislocation and diffusion creep mechanisms that are known to occur in natural rocksalt. The effects of temperature, constitutive parameters and strain rate on the viscosity of rocksalt are considered and the rheological law has been used in numerical models of salt diapirism.

Mantle convection

Next, the influence of rheological discontinuities on large scale mantle convection is considered. The role of the transition zone between 400 and 670 km depth on mantle dynamics is still under considerable debate. The discontinuity between upper and lower mantle at 670 km has been described to be a chemical discontinuity by some [e.g. Anderson, 1989; Ita & Stixrude, 1992], and to be a mineralogical phase change by others [e.g. Ito & Takahashi, 1989], although many leave the choice between the two possibilities open [e.g. Silver et al., 1988]. The effect of the hypothesized compositional and/or phase change related discontinuity on mantle convection has been investigated in an increasing number of studies [Vening Meinesz, 1962; Verhoogen, 1965; Schubert et al., 1975; Christensen & Yuen, 1984; Liu et al., 1991; Kellogg, 1991; Zhao et al., 1992; Tackley et al., 1993]. Recent experimental results by Karato & Li [1992] show that the lower mantle might deform predominantly by diffusion creep. This opens up the possibility of a non-Newtonian upper mantle overlying a Newtonian lower mantle. The structure of stationary mantle convection using this type of depth varying rheology been investigated by Van den Berg et al. [1991]. In these models, they find the top boundary layer to behave in a plate-like fashion, that is encouraged by introducing a lithosphere with higher non-linear dependence in the flow law. Here, these studies are extended to time-dependent models, with specific attention to the interaction of an upwelling lower mantle plume with the rheologically defined transition zone.

Archaean dynamics

Finally, a model is presented that may describe the cooling of the Earth in the Archaean (approx. 3.8-2.7 billion years before present). Geological observations give contradictory indications of the thermal state of the Archaean lithosphere and mantle. The presence of komatiites with high extrusion temperatures in Archaean greenstone belts points to a maximum mantle temperature some 400-500 K higher than present day. On the other hand, the metamorphic signature of Archaean high grade terrains indicates that the continental lithosphere was thermally similar to present day's. This seeming paradox can be explained by a model in which the cratonic regions stabilized early in the Archaean and maintained relatively low temperatures at moderate depths (50-100 km). The cooling of the Earth was governed by rapid convection underneath oceanic lithosphere. Most researchers adopt the uniformitarian point of view that plate tectonics was active in the Archaean, with probably higher plate velocities to account for the rapid heat loss [e.g., Arndt, 1983; Bickle, 1986]. However, it seems very unlikely that plate tectonics can have been active in a hotter mantle. One of the consequences of higher temperatures is the increasing amount of compositionally light basalt that is generated at mid-oceanic ridges by pressure-release melting. In the present day situation, with a crustal thickness of 7 km [McKenzie & Bickle, 1988], the newly created oceanic lithosphere is stable with respect to the underlying mantle [Vlaar & Wortel, 1976; Oxburgh & Parmentier, 1977]. Subduction can only occur for lithosphere that has sufficiently cooled. The mechanical coherency of the lithosphere allows then for the rigid plate-like movement, driven by the pull of the subducting slab and the topography-induced ridge push. At the ridges, hot material fills passively the space left by the spreading plates. In a hotter mantle, pressure-release melting starts deeper and a thicker basaltic layer and depleted harzburgitic zone is created [Sleep & Windley, 1982; Vlaar, 1985; McKenzie & Bickle, 1988]. In a mantle that is hotter by 400-500 K, compared with present day's, the thickness of the basaltic layer can amount to over 50 km [Vlaar & Van den Berg, 1991], creating a permanently stably stratified oceanic lithosphere [Vlaar, 1986]. Lack of mechanical coherency of the relatively weak basalt [Hoffman & Ranalli, 1988], and absence of slab pull and ridge push makes the mechanism of plate tectonics ineffective. Here, an alternative model is presented to describe the cooling of the Archaean Earth, through thermally and compositionally driven convection in the upper mantle.

1.4 Summary

The mathematical equations that are derived from first principles describing the physical model are presented in chapter 2.

The finite element methods, used to solve the non-linear and time-dependent equations, are discussed in chapter 3. The equations of motion, together with the incompressibility constraint, are solved, either using a primitive variable, penalty function method or in the stream function formulation. The methods are compared to published benchmarks, from which it is concluded that the methods are very accurate in describing thermal convection in generalized Newtonian media. In the finite element methods described in chapter 3, the basic physical quantities as temperature and velocity are approximated by continuous functions. In many geophysical applications (e.g. salt diapirism), composition changes as a discontinuous function from one layer to the other. The dynamical evolution of models with discontinuously varying composition are modelled using the stream function methods in conjunction with the marker chain method. In general the viscosity and, consequently, the strain rate are discontinuous across a compositional interface and cannot accurately be modelled by the continuous low order approximation of both stream function methods, leading to non-physical oscillations in the strain rate field and, in case of non-Newtonian fluids in the viscosity field. In chapter 4 the characteristics of this oscillatory behaviour and its influence on the dynamical evolution are discussed. An alternative Lagrangian method, based on the penalty function method, is proposed and compared to the stream function methods. It is concluded that for moderate viscosity contrasts and power law indices the dynamical behaviour of the Rayleigh-Taylor instability is modelled accurately by the stream function methods.

Chapter 5 discusses the implementation of a steady state creep law, describing the two parallel mechanisms of dislocation creep and fluid-enhanced grain-boundary diffusion creep in numerical models of salt diapirism. The effective viscosity of the rocksalt depends on constitutive parameters (such as grain size, activation energy, and shear modulus), temperature and strain rate. For strain rates typical of salt diapirism driven by buoyancy alone, it is found that the average viscosity in the salt varies between 10^{17} $\mathrm{Pa \cdot s}$ (for small grain size and high temperature salt) and 10^{20} $\mathrm{Pa \cdot s}$ (for large grain size and low temperatures salt). For the larger grain sizes, the dislocation creep mechanism is effective during the most vigorous diapiric stage, At the lower strain rates, and for finer grained salts in the presence of trace amounts of water, the diffusion creep mechanism is dominant throughout the diapiric event. Values for the viscosity of rocksalt that have traditionally been used in numerical and physical modelling, are at the lower end of the range that is found from these experiments.

Chapter 6 and 7 discuss the influence of rheological discontinuities, connected with the major phase transitions, on mantle convection. Time-dependent models of plumes interacting with a rheological interface separating an upper non-Newtonian mantle and a Newtonian lower mantle are studied. It is found that pulsating diapiric structures are shedded off the rheological interface as a consequence of the drop in effective viscosity that the plume experiences, when it moves from the Newtonian lower mantle into the non-Newtonian upper mantle. The diapiric upwellings are discernible in the surface heat flow as discrete pulses, that remain relatively stationary underneath the moving surface plate. The periodicity of the pulsations depends on the Rayleigh number, the effective viscosity contrast across the interface, and, as is shown in chapter 7, the depth level of the rheological interface. Diapirs coming off a rheological boundary at the top of the transition zone are found to occur periodically with a dimensional interval of a few million years, which is comparable to the periodicity of hot spot volcanism, exemplified by the discrete nature of the Hawaiian-Emperor seamount chain.

In chapter 8, some aspects of the dynamical behaviour of the lithosphere and mantle in a hotter Earth are investigated. In an Earth that is hotter by 250-500 K than at present day, the compositional stability and lack of mechanic coherency renders plate tectonics inefficient. Decoupling between the upper and lower basaltic crust may lead to subduction of the brittle hydrated upper crust into the ductile lower crust. At lower crustal pressures, the hydrated basalt transforms efficiently into its higher pressure phase eclogite, which allows for fast recycling of the crustal material. Renewed pressure-release melting leads again to basaltic crust formation. Consumption of latent and advective cooling through magma migration is very efficient. It is proposed that this mechanism may have cooled the mantle in the Early Archaean by several hundreds of degrees.