Chapter 9

Summary and Conclusions

9.1 Summary

The contents of this thesis revolve around the question of what type of geodynamics was active in the Early Earth and other terrestrial planets. The geology of the Archean (4.0-2.5 billion years before present) is quite different from recent geology, and therefore it is likely that different processes were responsible for its formation than the present-day plate tectonics. Several lines of evidence indicate internal temperatures for the early Earth significantly higher than the present. The physical consequences expected of a higher mantle temperature add arguments to the inference of a different geodynamical regime for the early Earth. Both Venus and Mars are comparable to the Earth regarding composition, and Venus also has a similar size, whereas Mars has about half the diameter of the Earth. In spite of the similarities, the surfaces of both planets look quite different from that of the Earth. For example, no evidence of recent plate tectonics is found on either planet.

In this thesis, the conditions under which plate tectonics and alternative geodynamic regimes may operate were investigated for the terrestrial planets using numerical models. For the Earth, more detailed studies of the different types of dynamics were used to compare the results of the processes that were modelled with remnants of Archean material which are still present on the surface of the Earth.

After presenting the numerical models used in this thesis, and describing the numerical methods used in getting model solutions, a number of studies were presented in which problems pertaining to the theme of the thesis are investigated.

Chapter 4 deals with conditions that allow plate tectonics to operate on the different terrestrial planets.

Plate tectonics is largely controlled by the buoyancy distribution in oceanic lithosphere, which correlates well with the lithospheric age. Buoyancy also depends on compositional layering resulting from pressure release partial melting under mid-ocean ridges, and this process is sensitive to pressure and temperature conditions that vary between the terrestrial planets and also during the secular cooling histories of the planets. In the modelling experiments, a range of values for the gravitational acceleration (representing different terrestrial planets), potential temperatures (representing different times in the history of the planets) and surface temperatures were applied in order to investigate under which conditions plate tectonics is a viable mechanism for the cooling of the terrestrial planets. Included in the models are the effects of mantle temperature on the composition and density of melt products and the thickness of the lithosphere. The results show that the onset time of negative buoyancy for oceanic lithosphere is reasonable (less than a few hundred million years) below a potential temperature of about 1500^oC for the Earth and about 1450^oC for Venus. In the reduced gravity field of Mars, a much thicker stratification is produced and the model indicates that plate tectonics could only operate on reasonable time scales at a potential mantle temperature below about $1300 - 1400^oC$.

In the following chapter (5), the cooling characteristics of plate tectonics and an alternative mechanism which is flood volcanism are quantified using parametric models.

Geophysical arguments based on buoyancy considerations against plate tectonics in a hotter Earth require an alternative means of cooling the planet from its original hot state to the present situation. Such an alternative could be extensive flood volcanism in a more stagnant-lid like setting. Starting from the notion that all heat output of the Earth is through its surface, we have constructed two parametric models to evaluate the cooling characteristics of these two mechanisms: plate tectonics and basalt extrusion / flood volcanism. Our model results show that for a steadily (exponentially) cooling Earth, plate tectonics is capable of removing all the required heat at a rate comparable to or even lower than its current rate of operation, contrary to earlier speculations. The extrusion mechanism may have been an important cooling agent in the early Earth, but requires global eruption rates two orders of magnitude greater than those of Phanerozoic flood basalt provinces. This may not be a problem, since geological observations indicate that flood volcanism was both stronger and more ubiquitous in the early Earth. Because of its reduced size, Mars is capable of cooling conductively through its lithosphere at significant rates, and as a result has possibly never required an additional cooling mechanism. Venus, on the other hand, has required the operation of an additional cooling agent for probably every cooling phase of its possibly episodic history, needing rates of activity comparable to those of the Earth.

After the conditions under which plate tectonics may operate and the cooling characteristics of both plate tectonics and flood volcanism have been studied, the flood volcanism regime is studied in more detail in chapter 6, focusing on the dynamics and geochemical effects.

Numerical thermochemical convection models including partial melting and a simple mechanism for melt segregation and oceanic crust production were used to investigate an alternative suite of dynamics that may have been in operation in the early Earth. The modelling results show three processes that may have played an important role in the production and recycling of oceanic crust: (1) Small scale ($x \cdot 100$ km) convection involving the lower crust and shallow upper mantle with partial melting and thus crustal production in the upwelling limb and delamination of the eclogitic lower crust in the downwelling limb. (2) Large scale resurfacing events in which (nearly) the complete crust sinks into the (eventually lower) mantle, thereby forming a stable reservoir enriched in incompatible elements in the deep mantle. New crust is simultaneously formed at the surface from segregating melt. (3) Intrusion of lower mantle diapirs with a high excess temperature (about 250 K) into the upper mantle, causing massive melting and crustal growth. This allows for plumes in the Archean upper mantle with a much higher excess temperature than previously expected from theoretical considerations.

Chapter 7 looks at the formation of continental material in the geodynamical setting of the previous chapter.

Important constituents of Archean cratons, formed in the early and hot history of the Earth, are TTG plutons and greenstone belts. The formation of these granite-greenstone terrains is often ascribed to plate-tectonic processes. Buoyancy considerations, however, do not allow plate tectonics to take place in a significantly hotter Earth. Therefore, an alternative mechanism for the coeval and proximate production of TTG plutons and greenstone-like crustal successions is proposed: When a locally anomalously thick basaltic crust has been produced by continued addition of extrusive or intrusive basalts due to partial melting of the underlying convecting mantle, the transition of a sufficient amount of basalt in the lower crust to eclogite may trigger a resurfacing event, in which a complete crustal section of over 1000 km long sinks into the mantle in less than 2 million years. Pressure release partial melting in the complementary upwelling mantle produces large volumes of basaltic material replacing the original crust. Partial melting at the base of this newly produced crust may generate felsic melts that are added as intrusives and/or extrusives to the generally mafic crustal succession, adding to what resembles a greenstone belt. Partial melting of metabasalt in the sinking crustal section produces a significant volume of TTG melt that is added to the crust directly above the location of 'subduction', presumably in the form of a pluton. This scenario is self-consistently produced by numerical thermo-chemical mantle convection models including partial melting of mantle peridotite and crustal (meta-)basalt, which were presented in this chapter. The p, T-conditions under which partial melting of metabasalt takes place in this scenario are consistent with geochemical trace element data for TTG's, which indicate melting under amphibolite rather than eclogite facies. Other geodynamical settings which have also been investigated, including partial melting in small scale delaminations of the lower crust, at the base of a anomalously thick crust and due to the influx of a lower mantle diapir fail to reproduce this behaviour unequivocally and mostly show melting of metabasalt in the eclogite stability field instead. The resurfacing scenario may also have been important in Venus' history, but probably did not produce significant volumes of continental material due to the dryness of this planet.

The stability against recycling of Archean cratons is often ascribed to the presence of a low density root beneath these continental fragments. In chapter 8, the importance of different deformation processes in the formation of such a root were investigated.

A possible mechanism for adding material to a continental root is by means of upwellings from the convecting mantle subject to pressure release partial melting.

Results of numerical modelling of the interaction of melting diapirs with continental roots in an Archean setting characterized by a mantle potential temperature of 1750 ^{o}C in a 2-D Cartesian geometry are presented.

In an extension of earlier work (De Smet et al., 2000a) the influence of mantle rheology on the behaviour of diapirs has been investigated, in particular looking at the difference in behaviour of diapirs using a composite rheology combining both grainsize sensitive diffusion creep and dislocation creep mechanisms. The grain size, here taken to be uniform, was used as a control parameter to obtain model cases with varying contribution from the two creep mechanisms. The diapirs in the composite rheology model rise much faster than in a purely Newtonian model. Observed diapiric ascent times from 230 km depth to the top of the ascent path at about 80 km depth are approximately 1 Ma for a Newtonian model (averaged 14 cm/year) compared to about 50 thousand years for a composite rheology model (averaged 3 m/year) with the same parameters for the Newtonian component. This clearly indicates the large impact of the dislocation creep component of the viscous deformation process.

The effect of an increase in the viscosity due to dehydration during partial melting was also investigated. This increase has a strong influence on the development of rising diapirs. The ascent velocity and lateral spreading of the diapirs at the end of their ascent are effectively reduced when a viscosity increase by a factor of 10 is applied, and the effect becomes stronger for larger factors. Average vertical velocities range from 1.4 cm/yr for a factor 10 to 2 mm/yr for a factor 200.

The most striking result of the viscosity increase due to dehydration is the reduction of the ascent velocity, thereby stretching the characteristic time scale of the diapiric intrusion process to a value between 5 and 50 Ma for dehydration viscosity prefactor values of 10 and 200, respectively.

In contrast with the strong difference between the Newtonian and the composite rheology models, small differences are found in the overall dynamics between the composite rheological models, characterized by different values of the uniform grainsize. The composite rheological models exhibit a selfregulating behaviour where substantial differences between the relative contributions of the two creep components result in very similar effective viscosities, due to a local dominance of dislocation creep at high stresses, and corresponding similar flow dynamics.

Stress levels and P,T-paths in the modelling results are consistent with estimates obtained from Precambrian peridotite bodies that are interpreted to have originated from asthenospheric diapirism.

9.2 Conclusions

From the various results obtained for the Earth, Venus and Mars in this thesis, tentative planetary histories may be constructed.

9.2.1 Earth

The initial stage immediately after accretion and core differentiation was probably characterized by a magma ocean (Murthy, 1992b; Abe, 1993a, 1997). After solidification of the magma ocean, the mantle was still very hot, too hot to allow plate tectonics on the basis of lithosphere buoyancy considerations (see chapter 4). However, some effective cooling mechanism was required (chapter 5), and the combination of extensive flood volcanism and periodic resurfacing probably played an important role in the dynamics, and also in cooling of the planet. Additionally, the resurfacing events generated significant volumes of felsic material that formed proto-continents (see chapter 7). When the mantle temperature dropped to about 1500^oC, oceanic lithosphere became negatively buoyant on time scale of some hundreds of million years or less, and active plate tectonics became possible (chapter 4). It is speculated that a more or less gradual transition from resurfacing dominated dynamics to plate tectonics took place around this mantle temperature, possibly during the late Archean. The advent of plate tectonics also provided an additional mechanism of continental growth through arc accretion. Continued operation of plate tectonics and resulting cooling of the mantle has brought it to its present state.

9.2.2 Venus

Though comparable in size and composition to the Earth, Venus did not undergo the same evolution. Periodic resurfacing has been suggested for Venus (Turcotte, 1995; Fowler and O'Brien, 1996), possibly by periodically operating plate tectonics (Solomatov and Moresi, 1996) or by the resurfacing mechanism presented in chapter 6. Currently, Venus is a dry planet, which would hinder plate tectonics specifically by increasing the fault strength (Nimmo and McKenzie, 1998). During its earlier history, the planet may have been less dry (Campbell and Taylor, 1983; Nimmo and McKenzie, 1998), but the mantle temperature was probably too high to allow plate tectonics (see chapter 4). It is therefore speculated that after an initial magma ocean regime during the earliest history, Venus stayed in a dynamic regime of periodic resurfacing through the process described in chapter 6 up to the present day.

9.2.3 Mars

The small size of Mars compared to Earth and Venus makes its surface to volume ratio ($\sim R^2/R^3$) much larger, making conductive cooling through the lithosphere of the planet much more efficient (see chapter 5). Observations and geophysical considerations indicate that if any large scale tectonic regime was active on Mars, it was probably during its early history (Zuber, 2001), although mantle convection models including pressure release partial melting show the rapid production of a thick thick buoyant outer shell under low gravity conditions, which would hinder plate tectonics (Schott et al., 2001). However, due to its reduced gravity compared to Earth, the operational window of potential temperatures for plate tectonics is limited to low mantle temperatures below $1300 - 1400^oC$ (chapter 5). The hotter mantle temperature expected for the early Martian history thus hinders plate tectonics. It is possible that the resurfacing mechanism of chapter 6 was active during the planet's early history. But after a potential period of this resurfacing regime, Mars probably rapidly went into the stagnant lid mode, continuing conduction-dominated cooling up to the present day.