# Chapter 7

## 7.1 SUMMARY AND OUTLOOK

This work considers various aspects of the subduction and exhumation history of continentally derived rocks of the Sesia Zone (SEZ) that were subducted to considerable depths beyond 50 km and exhumed during the convergent movement of the Apulian and European continental plates. On the one hand, a structural approach was chosen to get insight into the exhumation mechanisms that enabled the juxtaposition of large crustal blocks, such as the Austroalpine Ivrea Zone, the Piemont Ophiolites and the continentally-derived SEZ rocks, all of which have different metamorphic, structural and chronological histories. On the other hand, high resolution chemical investigations of metamorphic minerals in structurally well defined samples combined with thermodynamic and thermo-mechanical modelling was used to extract detailed information of the pressure-temperature (P-T) path, the physico-chemical evolution, such as densities and water content during the metamorphic cycle, as well as of element transport properties of the subducted rocks. In the following I will summarise and discuss the main results of this work in the light of recent investigations of subduction and exhumation processes in high- and ultra-high-pressure rock bodies of other orogens.

### 7.1.1 Structural difference and similarity between the SEZ and other high- and ultra-high-pressure terranes

The structural investigations in this work have shown that the principal stress axes or at least the direction of shortening of the SEZ body changed significantly during the exhumation process. Whereas at mantle depths exhumation occurred along steeply dipping transpressional shear zones with an oblique northward movement of the hanging wall, exhumation from mid-crustal depths occurred along moderately dipping normal faults indicating extensional exhumation. Similar tectonic evolutions have been reported from other high pressure terranes, such as the Dabie Shan (Hacker et al., 2000; Ratschbacher et al., 2000) and the Southern Urals (Echtler and Hetzel, 1997. Thus, such a change in the shortening direction, from sub-horizontal compression (or transpression) at mantle depths to sub-vertical compression associated with normal faulting seems to be a common phenomenon during the exhumation process of high-pressure rocks. Nevertheless, metamorphic conditions during subvertical shortening of exhumed high- and ultra-high pressure rocks are obviously different in different orogens. Walsh and Hacker (2004) for example report subvertical shortening of the exhumed UHP rocks from the Western Gneiss Region in Norway to have occurred at amphibolite facies condition at pressures of about 11 kbar and temperatures around 650°C. They interpret this strong metamorphic and structural overprint to be related to the underplating of the exhumed slab at the lower crust, ceased buoyancy being the cause for the hindered transcrustal exhumation of these rocks. In the case of the SEZ, the subvertical shortening occurred under greenschist facies conditions and although the pressure conditions of this deformation are poorly constrained the lack of an intense high-temperature overprint indicates that the subvertical compression took place at mid-crustal conditions rather than at the base of the lower crust. Similar observations have been made in the Dora Maira Massif (e.g. Avigad, 1993) as well as in the UHP rocks of the Dabie Shan (Hacker et al., 2000). This is strong evidence that the exhumation of the SEZ to mid-crustal depths was most likely caused by a combination of buoyancy- and tectonically-driven mechanisms. The fact that both, indications for buoyancy-driven exhumation mechanisms as well as a combination of buoyancy- and tectonically-driven exhumation mechanisms occur in different orogens, suggests that different tectonic settings might lead to the exhumation of high pressure rocks. Nevertheless, those rocks that are strongly affected by amphibolite facies metamorphism at the lower crust are most likely to be misinterpreted with respect to their geodynamic implication, because a high-temperature overprint eventually erases traces of their earlier high-pressure origin. This displays one of the main problems in many (U)HP terranes. Further research will definitely have to concentrate in particular on the faint traces of high- and ultra-high pressure metamorphism in rocks that were previously interpreted to be affected only by regional, barrovian-type metamorphism. An approach to the extraction of this P-T information, namely the method of thermodynamic forward modelling of chemical zonation patterns in metamorphic minerals, is also applied in this work and discussed in Chapter 3 and in this summary.

#### 7.1.2 The role of the slab volume during the subduction and exhumation process

The results in Chapter 3 clearly indicate that the SEZ consists of at least three different rock bodies with different metamorphic histories during their alpine evolution. This is consistent with earlier works (e.g. Venturini, 1995; Williams and Compagnoni, 1983; Passchier et al., 1981) that postulated the Sesia Zone to be an amalgamated rock body, rather than a coherent slice of the Apulian continental margin. The observation of spatially related growth zonation pattern in garnet together with detailed retrograde P-T trajectories, as presented in this work, is further evidence for a juxtaposition of three different tectonic units during the subduction and exhumation process. This has significant implications for the interpretation of the subduction and exhumation scenario and thus for the determination of exhumation processes. Ernst (2001) summarised the spatial extents of several UHP bodies and concluded that none of these exceeded a width of 5 km. If the SEZ were a coherent slice of continentally derived rocks, buoyant forces during both, subduction and exhumation, were much higher, rendering the possibility of a deep subduction due to buoyancy constraints. Additionally smaller slices of continental crust, although less buoyant, will have better chances to preserve high- and ultra-high pressure mineral assemblages due to the lower heat content in smaller slices that prevents a metamorphic re-equilibration at shallower depths. But on the other hand, as can be shown in Chapter 5, buoyant forces of thin slices of high pressure rock bodies will hardly exceed the shear strength of the surrounding mantle, thus hampering their buoyant exhumation. This fact leads back to the discussion, whether the interplay between buoyancy that is increased by the slab width and the internal amount of heat transported by the exhumed rock body that facilitates thermal re-equilibration of the high pressure mineral assemblage plays an important role during the exhumation process. With respect to that problem it might be important to compare detailed retrograde P-T trajectories that give information about the thermal evolution of the exhumed rocks and the extent of barrovian-type re-equilibration of these rock bodies in order to quantify the thermal effect of a near-adiabatic decompression.

### 7.1.3 Thermo-mechanical models

Although the material parameters used to calculated the shear strength of rocks have many sources of error due to the procedure by which they are determined (cf. Means, 1990) and are highly debated (e.g. Burov, 2003; Ranalli, 2003), the calculations in this work show that hydration and grain size reduction might play an important role for the shear zone development during the exhumation of HP rocks and therefore must be considered in thermo-mechanical models. Apart from the already complicated structure of algorithms used to numerically model the thermo-mechanical behaviour of rocks (e.g. Regenauer-Lieb and Yuen, 2003) and the complex interplay between metamorphic reactions and the mechanical rock-properties (e.g. Gerya and Yuen, 2003), the influence of changing deformation mechanisms as well as of pre-existing anisotropies (e.g. Cosgrove, 1997) on the rheology of the deformed rocks even more hampers the interpretation of numerical models at the present state. Therefore it is most important to better integrate the observations from field-based geology and petrology into the numerical models as well as to concentrate on the capacity of numerical models to work out and quantify the first order parameters of tectonic and metamorphic processes. On the other hand, numerical models, together with rapidly evolving remote sensing techniques, such as seismic reflection and refraction profiling is often the only possibility to get insight into important processes occurring in the inaccessible deeper parts of the earths crust and mantle (e.g. Karato et al., 2001; Solomatov, 2001) and therefore need to be an inherent part of geosciences.

### 7.1.4 Thermodynamic forward modelling

Thermodynamic forward modelling in this work concentrated mainly on the extraction of P-T information as well as of the physico-chemical evolution of the subducted rocks. In general, as a result of the fast burial of a slab into the mantle, mineral reactions and phase transitions often occur in chemical and thermodynamic disequilibrium. These disequilibrium reactions involve fractional crystallisation, reaction overstepping and volume changes due to devolatilisation of hydrous minerals in the subducted plate. Such disequilibrium processes are important petrologic and geophysical factors, as they are responsible for magma generation in the overriding plate, intermediate depth (70-300 km depth) earthquakes in some subduction zones as well as for the subsequent rapid exhumation of ultra-high pressure (UHP) rocks. Due to the limited possibility to quantify these disequilibrium conditions by conventional thermodynamic calculations, the mineralogical processes during deep subduction are poorly understood, but knowledge about the linkage between mineral reactions, phase transitions and P-T trajectories of the subducted rocks is of scientific and social relevance. The results of this study have shown that with the aid of thermodynamic forward modelling that considers fractional crystallisation as well as volatile fractionation detailed P-T trajectories of the prograde (subduction) path as well as of the retrograde (exhumation) path can be derived. The results shown in Chapter 5 show that the interpretation of chemical zonation patterns in metamorphic minerals that are affected by retrograde modification, either by the growth of newly formed material or by a diffusional modification along element pathways yields insight into the shape and slope of the P-T trajectory. Although applied in several other metamorphic terranes (Spear and Selverstone, 1983; Spear et al., 1984; Menard and Spear 1993; Okadaira, 1996; Ayres and Vance, 1997; Enami, 1998; Cooke et al., 2000; Escuder-Viruete et al., 2000) this technique has never been tested in detail in continentally derived high-pressure/low-temperature rocks. Because the temperatures during subduction related metamorphism are sufficiently low to preserve chemical zonation patterns even in minerals with higher intracrystalline diffusion velocities are preserved in the SEZ rocks and can be used for an interpretation in terms of the P-T-X history of the host rocks. Further development of that technique, e.g. a combination of thermodynamic modelling with thermo-mechanical calculations will be an important task for geoscientists on their way to model the kinematics in subduction zones and other lithosphere-scale processes. Recent publications (e.g. Gerya and Yuen, 2003) already successfully tried to combine these two techniques, but further development with respect to thermodynamic databases, solid solution models of complex minerals as well as increased computational capacities is necessary to numerically simulate large scale geodynamic processes.

### 7.1.5 The effect of the water content of subducted rocks

As shown in Chapter 3 it seems to be very likely that at least large parts of the SEZ body consisted of relatively dry rocks. This is indicated by the interpretation of the prograde garnet growth zonation patterns as well as other mineralogical evidence in rocks from the Mombarone Unit. Low water contents during burial seems to be a common feature in many high- and ultra-high pressure rocks and is, in case of the SEZ likely the result of its pre-alpine high temperature metamorphism. Whether or not the resulting enhanced garnet growth, which theoretically leads to a higher density of the continentally derived rocks, is responsible for the initial subduction must remain uncleared, particularly since a structural record of the early stages of the subduction history are either lacking or kinematically not interpretable due to later structural overprint (Chapter 4). Thus the reason for the onset of the subduction in the Western Alps cannot be revealed in the SEZ. But erosion of continental material during the subduction of oceanic crust in the hanging wall seems to be a common process in plate tectonics (Scheuber et al., 1994).

Nevertheless, the results from the thermodynamic forward modelling (Chapter 3) clearly indicate that the volatile content of the subducted rocks does not only influence the surrounding rocks by infiltration of liberated fluids, but has also significant effect on the physico-chemical properties of the subducted slab itself. Therefore, further research (e.g. thermodynamic calculations) must incorporate the effect of changing water contents of rocks that undergo prograde high pressure metamorphism.