Chapter 2

2.1 ABSTRACT

The Sesia Zone (SEZ) in the Western Alps is a large sliver of continentally derived crustal rocks that was subducted to depth exceeding 50 km during the Cretaceous to Tertiary convergence between the Apulian microplate and the European continent. As a distal part of the rifted continental margin of the Apulian plate it was eroded during the subduction of the Piemont oceanic realm that separated the two continental domains. Because of its excellent preservation of high-pressure textures and structures in various scales, the SEZ is well-suited for the investigation of subduction- and exhumation-processes. To investigate the processes and mechanisms responsible for the subduction of light continental rocks of the SEZ and its subsequent exhumation during convergent plate motion, we carried out large scale structural mapping across large portions of the SEZ, detailed petrologic investigations of selected, structurally well defined samples as well as thermodynamic forward modelling and rheological calculations in order to better constrain the interplay of deformation, metamorphism and the physico-chemical properties of the high-pressure rocks. Our structural work involved mapping of the dominant fabrics and the development of a fabric domain map in order to correlate the complex structures within the SEZ body over regionally significant areas. Petrologic investigations concentrated on the extraction of information of multiple stages of the subduction and exhumation history from disequilibrium textures, such as zoned metamorphic minerals and relict mineral parageneses. This was done by thermodynamic forward modelling utilising the technique of Gibbs energy minimisation that involved the effect of fractional crystallisation and water fractionation on the effective bulk rock composition. Rheological calculations were performed by integrating the results from the thermodynamic models in order to constrain the influence of density changes due to retrograde metamorphism and buoyancy forces on the exhumation mechanism.

Constraints on the prograde, subduction related Alpine metamorphism in the Sesia rocks can be derived from the interpretation of garnet zonation patterns. Chemical growth zonation patterns in garnets, grown during the prograde metamorphic path from a large number of sample localities in the central SEZ have therefore been investigated. These zonation patterns show a strong

correlation between the shape of the garnet zonation and the sample locality. Garnets sampled in the vicinity of or within the so-called Monometamorphic Cover Complex (MCC), a thin band of metasediments and metabasites, that marks the tectonic contact between two subunits in the SEZ, namely the Mombarone Unit in the internal and the Bard Unit in the external part SEZ, show typical prograde chemical zonations with steadily increasing pyrope contents and increasing XMg, together with bell-shaped spessartine patterns. In contrast, garnets from the internal part of the SEZ, the Mombarone Unit, have more complex zonation patterns with a characteristic intermediate decrease in pyrope and XMg. In some cases, garnets show an abrupt compositional change between core and rim, sometimes associated with resorption textures of the garnet cores. The comparison of observed garnet zonation patterns and those from thermodynamically models shows that the different zonation patterns are strongly influenced by differences in the water content of the subducted rocks during prograde metamorphism as well as by the shape of the prograde P-T trajectory. Typical prograde garnet zonation patterns in the samples from the tectonic nappe contact can best be reproduced assuming water saturated host rocks and a low temperature subduction path. The more complex zonation patterns in samples from the Mombarone Unit can be explained by the effect of water-undersaturation of the host rocks prior to the subduction related high-pressure metamorphism. These results display strong evidence for limited water availability in the SEZ rocks during prograde metamorphism.

The water content during burial significantly influences the physical properties of the subducted rocks. Due to enhanced garnet crystallisation, water-undersaturated rocks become denser than their water-saturated equivalents, facilitating the subduction of continental material, such as the SEZ rocks. Although water-bearing phases such as phengite and epidote are stable up to eclogite facies-conditions in these rocks, dehydration reactions during subduction are lacking in water-undersaturated rocks up to the transition to the eclogite facies. Further, our calculations show that garnet zonation patterns are strongly dependent on the mineral parageneses during garnet growth and that certain co-genetic mineral assemblages cause distinct garnet zonation patterns. This enables one to interpret complex garnet growth zonation patterns in terms of garnetforming reactions and water contents during HP metamorphism, as well as to determine detailed P-T paths.

The results from the structural investigations revealed five regionally significant deformation phases that affected the SEZ rocks. Whereas eclogite-facies structures have been found to be unsuitable for a kinematic interpretation due to their polyphase retrograde overprint, blueschist- to greenschist-facies structures are well-preserved in the SEZ and the combination of existing data from the literature with new results enabled a detailed reconstruction of the deformation during the exhumation of the SEZ rocks.

Initial exhumation of the Sesia Zone from 60 to about 30 km depth occurred along steeply dipping transpressive shear zones that developed at the structural base of a weakly deformed eclogitic rock body. Retrograde P-T trajectories derived from the interpretation of chemically zoned metamorphic minerals, such as amphiboles and white mica, indicate near-isothermal decompression from 1.8 to 1.1 GPa at temperatures between 500 and 550°C during this initial stage of the exhumation. At greenschist facies conditions sub-horizontally to moderately dipping normal faults develop in the structurally highest parts of the exhumed block, indicating a significant change in the orientation of the principal stress axes and possibly a change in the exhumation scenario from buoyancy-enhanced transpressional exhumation at mantle depths to extensional exhumation along moderately dipping normal faults at mid-crustal depths. This normal faulting was related to cooling of the SEZ to temperatures between 450 and 500°C. Growth zonation patterns in calcic amphibole indicate a change from near-isothermal decompression during transpressional exhumation to cooling during exhumation along the moderately dipping normal fault. Thermal equilibration at amphibolite-facies conditions is lacking in the SEZ. This lack of an intense amphibolite facies metamorphism in the SEZ rocks, as observed in many other HP terranes, indicates that exhumation along steeply dipping structures continues till the rocks reached the middle crust, enabling a tectonically enhanced exhumation across the rigid crust-mantle transition. Extensional exhumation from mid-crustal depths associated with further cooling indicates an exhumation mechanism that is possibly enhanced by hinge roll-back. The overprinting of steeply dipping foliations active under high-pressure metamorphic conditions by the gently dipping greenschist facies normal fault marks a change in the exhumation mechanism at mid crustal depth. The latest stage of the exhumation of the Sesia rocks is then characterised by steeply dipping backthrusts that are responsible for the retro-deformation of the orogenic wedge.

These results clearly indicate that at least two different mechanisms were responsible for the exhumation of the SEZ. This is very similar to the observations from other high- and ultra-high-pressure terranes from different orogens. Shear strength calculations together with petrological and structural constraints indicate a combination of buoyancy- and tectonically-driven exhumation that enables exhumation to mid-crustal levels along transpressive shear zones followed by further exhumation along moderately dipping normal faults. Ongoing cooling during normal faulting suggests further exhumation to be caused by syn-convergent crustal scale extension most like induced by a retreating subducted slab.

Further, the numerical thermodynamic modelling conducted in this work yielded some interesting insight into the strong influence of fractional garnet crystallisation, as well as water fractionation, on garnet growth histories in high-pressure rocks. Fractional garnet crystallisation as well as disequilibrium element incorporation in garnet leads to pronounced episodic garnet growth and may even cause growth interruptions. Discontinuous growth, together with pressure- and temperature-dependent changes in garnet chemistry cause zonation patterns that are indicative of different degrees of disequilibrium element incorporation. Chemical inhomogeneities in the matrix surrounding garnet porphyroblasts strongly affect garnet growth and lead to compositional discontinuities and steep compositional gradients in the garnet zonation pattern. These typical garnet zonation patterns can be used to detect hindered element transport in metamorphic rocks. Further, this work has shown that discontinuities in garnet growth induced by limited element supply can mask traces of the thermobarometric history of the rock. Therefore, thermodynamic modelling that considers fractional disequilibrium crystallisation is required to interpret compositional garnet zonation in terms of a quantitative pressure and temperature path of the host rock.

2.2 ZUSAMMENFASSUNG

Die West-alpine Sesia Zone (SEZ) ist ein großer Span kontinentaler Kruste, der während der kretazischen bis tertiären konvergenten Plattenbewegung des Apulischen Mikrokontinents und Europas in Tiefen bis über 50 km subduziert wurde. Als ein distaler Teil des gerifteten Kontinentalrandes der Apulischen Platte, wurde sie während der Subduktion des ozeanischen Bereiches, der sogenannten Piemont Einheit, die zwischen den beiden Kontinenten lag, vom Kontinentalrand erodiert und subduziert. Da in der SEZ Mineraltexturen und deformative Strukturen, die in Verbindung mit der Hochdruckmetamorphose stehen, in verschiedensten Maßstäben hervorragend erhalten sind, eignet sich die SEZ bestens zur Untersuchung von Subduktions- und Exhumierungsprozessen. Zur Untersuchung der Prozesse, die zur Subduktion und zur anschließenden Heraushebung von leichtem, kontinentalem Gesteinsmaterials geführt haben, haben wir große Teile der SEZ strukturell kartiert, haben detaillierte petrologische Untersuchungen an klar strukturell definierten Proben durchgeführt und außerdem thermodynamische und rheologische Modellierungen dieser Gesteine berechnet um ein besseres Verständnis des Zusammenspiels zwischen Deformation, Metamorphose sowie den physikalisch-chemischen Eigenschaften der Gesteine zu bekommen. Die strukturelle Arbeit umfaßte Kartierungen der Hauptgefüge und die Erstellung einer Gefügekarte im regionalen Maßstab um die sehr komplexen Strukturen innerhalb der SEZ über einen regionalen Maßstab zu korrelieren. Die petrologischen Untersuchungen konzentrierten sich vornehmlich auf die Informationsgewinnung über die Subduktions- und Exhumierungsgeschichte aus zonierten metamorph gewachsenen Mineralen. Dazu führten wir thermodynamische Modellierungen durch, die die Methode der Gibbs-Energie-Minimierung verwenden und die Effekte der fraktionierten Kristallisation und die der Wasserfraktionierung auf die Gesamtgesteinszusammensetzung berücksichtigen. Die rheologischen Berechnungen wurden unter Einbeziehung der Ergebnisse der thermodynamischen Modelle durchgeführt, um den Einfluss von Dichteunterschieden, die durch die retrograde Metamorphose entstehen, und den daraus resultierenden Auftriebskräften auf den Exhumierungsmechanismus zu untersuchen.

Erkenntnisse über die prograde, subduktionsgebundene Metamorphose der Sesia-Gesteine können aus der Interpretation von Granat-Zonierungsmustern gewonnen werden. Wir untersuchten für eine Vielzahl von Probenlokalitäten in der zentralen SEZ die chemischen Wachstumszonierungen in Granaten, die während der prograden Metamorphose gewachsen sind. Diese

Wachstumszonierungen zeigen eine deutliche Korrelation zwischen Probenort und Form der Zonierung. Granate aus der Nähe des sogenannten Monometamorphic Cover Complex, ein dünnes Band bestehend aus Metasedimenten und Metabasiten, das zwei Untereinheiten der SEZ, die Mombarone Einheit im internen Teil der SEZ und die Bard Einheit im externen Teil der SEZ, trennt, zeigen Zonierungsmuster mit kontinuierlich ansteigendem Pyropanteil und steigendem XMg, sowie glockenförmige Manganzonierungen, typisch für prograd gewachsene Granate. Im Gegensatz dazu haben Granate aus dem internen Teil der SEZ, der Mombarone Einheit, komplexere Zonierungen mit einem charakteristischen Abfall des Pyropanteils und des XMg. In manchen Fällen zeigen die Granate auch einen abrupten Wechsel in der Zusammensetzung zwischen Kern und Rand, der manchmal auch mit Resorptionserscheinungen im Kern einhergeht. Vergleiche zwischen natürlichen und modellierten Granat-Zonierungsmustern zeigen, dass die Unterschiede in der Zonierung auf unterschiedliche Wassergehalte des Wirtsgesteins und auf unterschiedliche Formen des P-T Pfades zurückzuführen sind. Die typischen prograden Zonierungsmuster aus Granaten nahe oder aus der MCC Einheit können am besten mit Wassersättigung des Wirtsgesteins und einem kalten Subduktionspfad erklärt werden. Die komplexeren Zonierungen in Granaten aus der Mombarone Einheit zeigen die Effekte von Wasseruntersättigung des Wirtsgesteins vor der prograden Metamorphose. Diese Ergebnisse sind ein deutlicher Hinweis darauf, dass die Sesia-Gesteine durch behinderte Wasserzufuhr gekennzeichnet sind.

Der Wassergehalt während der Metamorphose hat signifikante Auswirkungen auf die physikalischen Eigenschaften der Gesteine. Auf Grund erhöhten Granatwachstums werden wasseruntersättigte Gesteine dichter als ihre wassergesättigten Equivalente, was die Subduktion von kontinentalem Material, wie etwa die Gesteine der SEZ, erleichtert. Obwohl wasserführende Phasen, wie beispielsweise Phengit und Epidot, bis in die Eklogit-Fazies stabil sind, finden in wasseruntersättigten Gesteinen keine Dehydratationsreaktionen statt, bis die Gesteine die Eklogit-Fazies erreichen. Des Weiteren zeigen unsere Berechnungen, dass die Granat-Zonierungsmuster stark von der co-genetischen Mineralparagenese beeinflusst sind und dass bestimmte co-genetische Mineralparagenesen bestimmte Zonierungsmuster hervorrufen. Dieser Umstand führt dazu, dass man mit Hilfe komplexer Granat-Zonierungsmuster Rückschlüsse auf granat-bildende Reaktionen und auf den Wassergehalt der Wirtsgesteine während der Hochdruckmetamorphose schließen kann und so detaillierte Druck-Temperatur-Pfade erstellen kann.

Die Ergebnisse der strukturellen Untersuchungen zeigen, dass die SEZ durch fünf regional signifikante Deformationsphasen beeinflusst wurde. Während sich, auf Grund ihrer polyphasen Überprägung, die eklogit-faziellen Deformationen als ungeeignet für eine kinematische Interpretation erwiesen, sind blau- und grünschiefer-fazielle Strukturen sehr gut in der SEZ erhalten und die Verbindung von existierenden Daten mit neuen Ergebnissen ermöglichte eine detaillierte Rekonstruktion der Deformation während der Exhumierung der SEZ.

Die erste Exhumierung der SEZ, aus Tiefen von 60 km bis etwa 30 km, fand entlang von steil stehenden transpressiven Strukturen statt. Diese Strukturen entwickelten sich an der Basis eines wenig deformierten eklogit-faziellen Gesteinskörpers. Druck-Temperatur-Pfade, die durch die Interpretation von chemisch zonierten Mineralen, wie etwa Amphibolen und Hellglimmern, gewonnen wurden, zeigen eine nahezu isothermale Dekompression von 1.8 bis etwa 1.1 GPa bei Temperaturen von etwa 500-550°C an. Unter grünschiefer-faziellen Bedingungen entwickeln sich dann in den strukturell höchsten Bereichen der SEZ sub-horizontale, in manchen Fällen auch leicht geneigte Abschiebungen, die eine Änderung der Spannungsachsen andeuten und einen Wechsel von auftriebsgesteuerter transpressiver Exhumierung unter Mantelbedingungen hin zu extensionsbetonter Exhumierung entlang von flachen Abschiebungen andeuten. Die Abschiebungen gehen einher mit einer Abkühlung der SEZ Gesteine bis hin zu Temperaturen zwischen 450 und 500°C. Wachstumszonierungen in Ca-Amphibolen deuten einen Wechsel von isothermaler Dekompression während der transpressiven Exhumierung hin zu einer Abkühlung während der Heraushebung entlang der flachen Abschiebungen. Eine thermische Angleichung an amphibolit-fazielle Bedingungen findet in der SEZ nicht statt. Das fehlen einer amphibolit-faziellen Equilibrierung, wie sie in anderen Hochdruckgesteinen häufig beobachtet wird, in den Gesteinen der SEZ, zeigt an, dass die Exhumierung entlang steil stehender Strukturen angehalten hat, bis die Gesteine die mittlere Kruste erreichten, wodurch eine auftriebsgesteuerte, tektonische Heraushebung über die rigide Kruste-Mantel Grenze ermöglicht wurde. Exhumierung entlang von flachen Abschiebungen aus der mittleren Kruste, assoziiert mit Abkühlung, lässt darauf schließen, dass die Exhumierung durch „hinge-rollback“ unterstützt wurde. Die Überprägung steil stehender Foliationen, die unter hohen Druckbedingungen aktiv waren, durch flache, grünschiefer-fazielle Abschiebungen zeiget einen Wechsel der Exhumierungsmechanismen in der mittleren Kruste an. Die letzte Phase der Exhumierung der SEZ ist durch steile Rücküberschiebungen, die verantwortlich für die rückgerichtete Deformation des Gebirgskeils sind, gekennzeichnet.

Diese Ergebnisse zeigen deutlich an, dass mindestens zwei verschiedene Mechanismen für die Exhumierung der SEZ verantwortlich waren. Diese Beobachtungen stimmen mit denen überein, die in anderen Hochdruckgesteinen verschiedener Orogene gemacht wurden. Unsere Festigkeitsberechnungen zusammen mit den petrologischen und struturgeologischen Daten deuten auf eine Kombination aus auftriebs- und tektonikgetriebener Exhumierung hin, die es erlaubt, die Gesteine entlang von transpressiven Scherzonen bis in die mittlere zu bringen und dann entlang von flachen Abschiebungen weiter herauszuheben. Die stetige Abkühlung der Gesteine während der Abschiebung deutet auf eine krustenweite Dehnung hin, die wahrscheinlich durch ein Rückschreiten der subduzierten Platte hervorgerufen wurde.

Des Weiteren gaben unsere thermodynamischen Modellierungen einen interessanten Einblick in die Effekte der fraktionierten Kristallisation und der Wasserfraktionierung auf die Wachstumsgeschichte von Granat in Hochdruckgesteinen. Fraktionierte Granat Kristallisation und auch Ungleichgewichtseinbau von Elementen in Granat führt zu betont episodischem Wachstum und kann Wachstumsunterbrechungen hervorrufen. Diskontinuierliches Wachstum zusammen mit druck- und temperaturbedingten Schwankungen in der Granatzusammensetzung führen zu Zonierungsmustern, die indikativ für den Grad des Ungleichgewichts beim Einbau bestimmter Elemente in Granat. Chemische Inhomogenitäten in der Matrix um Granat-Porphyroblasten haben einen starken Einfluss auf das Granat Wachstum und führen zu steilen Konzentrationsgradienten und Konzentrationsinhomogenitäten innerhalb des Zonierungsmusters. Diese typischen Zonierungsmuster können verwendet werden um behinderten Stofftransport im Gestein zu detektieren. Außerdem hat diese Arbeit gezeigt, dass Inhomogenitäten im Granatwachstum dazu führen kann, dass bestimmte Teile der metamorphen Geschichte nicht in den Granat-Zonierungen enthalten sind. Aus diesem Grund sind thermodynamischen Modellierungen, die fraktionierte Kristallisation berücksichtigen von größter Wichtigkeit bei der Interpretation von chemischen Zonierungsmustern und beim Erstellen von quantitativen Druck- und Temperaturpfaden der Wirtsgesteine.

2.3 INTRODUCTION

The recognition that continentally derived rocks can undergo high pressure/low temperature (HP/LT) metamorphism actually came from the Western Alpine Sesia Zone (SEZ) (Ernst, 1971; Dal Piaz et al., 1972). Relics of omphacite and sodic amphibole in rocks from the internal part of the SLZ gave rise to the assumption, that continental rocks despite their compared with mantle rocks low density can be brought to depths exceeding 50 km without significant heating (Compagnoni et al., 1977; Reinsch, 1979). It was evident that such a low geothermal gradient can only be achieved by a subduction related kinematic setting (e.g. Ernst, 1971). More recent investigations show that continentally derived rocks can be subducted to depths even exceeding 100 km (Chopin, 1984; Zhang and Liou, 1994; O´Brien et al., 2001), which focused the interest of many geoscientists on the processes that lead to the subduction and subsequent rapid exhumation of such buoyant rock bodies. But despite a large number of petrologic, structural and geochronologic investigations as well as recently published numerical and analogue models (e.g. Burov et al., 2001; Bousquet et al., 1997, Roselle and Engi, 2002; Chemenda et al., 1995; Seyferth and Henk, 2004) there is still a debate about the exhumation mechanisms of such deeply buried rocks. Main problems comprise the thermal evolution of such subducted continental slices, which partly show extremely low geothermal gradients in the order of 5-10°C/km (e.g. Zhang et al. 1997; Liou et al., 2000) and are brought to depth corresponding to pressures of up to 4.5 GPa. The discovery of exsolution lamellae in Fe-Ti oxides in olivine grains from the Central Alpine Alpe Arami peridotite, which are interpreted to be the result of recrystallisation in depth of about 300 km raises the possibility that some rocks may have ascended from depths far greater that currently recognised (Ernst, 2001). Even more astonishing is the preservation of minerals indicating ultra-high pressure (UHP) metamorphism, such as diamond and coesite, because this shows that a thermal re-equilibration during exhumation of these rocks does not happen. This requires very limited heat exchange between the subducted slice and the surrounding, probably hotter mantle material. This is in agreement with the observation that the exhumation of some of the high- and ultra-high pressure rocks occurred within a very small time span (Hacker et al., 2003; Dachs and Proyer, 2002). An excellent example is the Western Alpine Zermatt Saas unit, where metamorphism in depths of about 100 km around 45 Ma was followed by a greenschist facies overprint at 38 Ma leaving only 7 Million years for the exhumation from mantle depths (Amato et al., 1999; Reddy et al., 1999). This requires exhumation velocities to be in the same order as plate motion (e.g. Rubatto and Hermann, 2001). However, in most cases relics of UHP minerals indicating subduction to mantle depths and subsequent exhumation appear in low-density quartzo-feldspatic rocks that contain smaller lenses of denser metabasic and ultrabasic rocks. This raises the assumption that buoyancy forces might play a major role in the exhumation mechanisms of such deeply buried rocks. But on the other hand buoyancy, which is the result of density contrasts between the subducted slab and the surrounding material will rapidly decrease once the exhumed continentally derived rock body reaches the lower or middle crust, because there the density contrast ceases and buoyant forces will rapidly diminish (Platt, 1993). That requires different mechanisms for the initial exhumation from mantle depths and the subsequent transcrustal exhumation. Additionally the question arises, whether buoyant forces acting on the subducted slice can exceed the shear strength of the surrounding rocks, otherwise buoyancy-driven exhumation will fail due to the frictional forces between the different lithological units.

Recent methodical advances in geosciences, such as the better spatial resolution of geochronologic data, better knowledge of the physical properties of high- and ultra-high-pressure minerals and rocks as well as rapidly evolving databases for thermodynamic calculations brought more insight into the processes occurring in subduction zones (Peacock and Wang, 1999; Hacker et al., 2003). Detailed P-T paths, for example, which are the basis for the investigation of tectonic and mineralogical processes responsible for the rapid burial and exhumation of HP and UHP rocks in subduction zones (Peacock, 1993; Carswell and Zhang, 1999; Peacock and Wang, 1999; Liou et al. 2000; Aoya et al. 2003), can much better be derived using modern thermodynamic approaches (e.g. Spear and Selverstone, 1983; Okudaira, 1996; Konrad-Schmolke et al., 2005). Such detailed P-T paths can give insight into the subduction and exhumation processes because the shape of the P-T loop a subducted and subsequently exhumed rock passes through is defined by the depth to which it is subducted, the temperature in the surrounding mantle and the extent that heat affects the relatively cold core of the subducted slab. The latter factor is a function of the age of the slab, its heat transfer properties and the duration of metamorphism. Relict mineral parageneses and inclusion assemblages in porphyroblasts are often used to reconstruct the metamorphic evolution of the HP and UHP rock (e.g. Zhang and Liou, 1994; Enami and Nagasaki, 1999; Yoshida et al. 2004). The pressure and temperature estimates derived from these phase relations are then interpreted using equilibrium phase diagrams such as pseudosections or conventional thermobarometric methods like net-transfer- or exchange-reactions between mineral pairs (Liou and Zhang 1995; Arenas et al., 1997; Carswell and Zhang, 1999; Hoschek, 2004). Structural investigations, such as the observation of overprinting relations of regionally significant deformation phases can then be used to derive pressure-temperature-deformation (P-T-d) paths, which give insight into the depth-related thermal evolution and the kinematic framework the exhumed rocks went through on their way back to the earth's surface. Unfortunately the derivation of such P-T-d paths is no trivial task because of the lack of rock wide equilibrium in both, structural and metamorphic sense. In subduction zones, for example, disequilibrium processes, like fractional crystallisation, water fractionation and reaction overstepping, play a major role and the interpretation of conventional equilibrium phase diagrams is of limited use (e.g. John and Schenk 2003). Such disequilibrium processes are important petrologic and geophysical factors, as they are responsible for magma generation in the overriding plate caused by escaping fluids from the subducted plate, intermediate depth (70-300 km) earthquakes in some subduction zones and major volatile recycling into the mantle (Liou et al. 2000). 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 (disequilibrium) mineral reactions, phase transitions and P-T trajectories of the subducted rocks is of scientific and social relevance.

But these disequilibrium features, that appear on the first sight to be obscuring parts of the information about the rocks structural and metamorphic evolution, might turn out to be an advantage, once the fractionation processes are understood and can be quantified (e.g. Konrad-Schmolke et al., 2005). The technique of Gibbs energy minimisation, utilising internally-consistent thermodynamic datasets and relevant activity-composition models, allows the determination of equilibrium mineral modes and compositions for a fixed bulk composition at any pressure-temperature condition (e.g. de Capitani and Brown, 1987; Connolly and Kerrick, 1987; Spear and Menard, 1989). But, as mentioned above, the stage of chemical equilibrium in a rock is seldom attained, which is often documented in chemically zoned metamorphic minerals and reaction textures. Fractional crystallisation of minerals and devolatilisation reactions strongly influence the effective (reacting) bulk rock composition. In this case the chemical evolution of the rock, as well as the thermodynamic equilibrium, is a path-dependent function and can only be evaluated using thermodynamic forward models that consider these fractionation effects.

By considering that a proportion of the volume of material in slow diffusing phases, such as garnet, as being fractionated out of the effective (i.e. reacting) bulk rock composition, and calculating a series of equilibrium diagrams for small P-T steps along a given P-T trajectory with this gradually-changing bulk rock composition, it is possible to model the thermodynamic properties of the rock system affected by fractional crystallisation of various minerals along a P-T path of interest. Further, with this method it is possible to predict the zonation pattern of the metamorphic minerals that undergo fractional crystallisation and thus more confidently constrain a rock's true P-T evolution (e.g. Spear 1993, Menard and Spear 1993). The information stored in these zonation patterns can be extracted and used to interpret the chemical and P-T evolution of the host rock. The same accounts for fluid fractionation during the metamorphic evolution. By continuously removing fractions of fluids released by metamorphic reactions it is possible to calculate volume, physical and chemical properties of the released fluids as well as the thermodynamic properties of the residual mineral assemblage. Even thermodynamic calculations assuming disequilibrium distribution of certain elements, e.g. due to sluggish intercrystalline diffusion velocities in dehydrated rocks, are possible with a newly developed numerical method (Konrad-Schmolke et al., 2005). Recent publications utilising the method of Gibbs energy minimisation have already shown interesting details about the decarbonation-reactions in high-pressure rocks (Kerrick and Connolly, 1998). Therefore thermodynamic forward models that concentrate on the interpretation of growth zonation patterns in various metamorphic minerals together with detailed structural data derived from large scale structural mapping are used in this work to better constrain the pro- and retrograde metamorphic evolution of subducted continental crust in the Western Alpine Sesia Zone.

Also important for the investigation of tectonic processes in subduction zones is the duration and the relative timing of metamorphic events along a P-T loop. The combination of pressure and temperature estimates for certain mineral parageneses with geochronological data, so called P-T-t(ime) trajectories, for the prograde and retrograde metamorphic evolution of UHP rocks can give detailed information about the processes occurring during the metamorphic loop (e.g. Jamtveit et al., 1991; Thöni and Miller, 1996; Duchêne et al. 1997; Liati and Gebauer, 1999; Willner et al., 2000; Ring et al., 2002). For a well constrained P-T-t path it is necessary to combine age determinations derived from mineral pairs that represent different stages of the metamorphic evolution as well as from isotopic systems with different resetting rates (commonly referred to as closure temperatures). Problems arising from that method are the relatively large errors in isotope geochronology and crude determinations of pressure and temperature using phase diagrams, due to large multivariant phase field for eclogitic mineral assemblages (Thöni and Jagoutz, 1992; Powell and Guiraud, 1999; Worley and Powell, 2000).

A complementary method to derive the time span of metamorphic events is so-called geospeedometry (Lasaga and Jiang, 1995; Ganguly and Tirone 1999; Perchuk and Philippot, 2000). Intracrystalline diffusional relaxation profiles in zoned metamorphic minerals can be used to constrain the duration of metamorphic events such as burial and subsequent exhumation of UHP rocks in subduction zones (Chakraborty and Ganguly 1991, Perchuk and Philippot 2000). Recent investigations using this method showed that tectonic processes in subduction zones are much faster than previously thought (Dachs and Proyer, 2002; Olker et al.; 2003). In UHP metamorphic garnets core-rim overgrowths with abrupt changes in chemical composition are very common. The relaxation of this chemical zonation pattern is best suited for geospeedometric investigations, because resorption cannot affect such an overgrowth pattern and falsify the result (Dachs and Proyer, 2002; Massonne and O´Brien, 2003). Unfortunately the petrological processes that lead to the abrupt compositional change in metamorphic minerals are poorly understood, but the technique of Gibbs energy minimisation and numerical thermodynamic models give an insight into the reasons that lead to such zonation patterns in metamorphic minerals (Konrad-Schmolke, 2005). An example of that method, applied to samples from the central Sesia Zone is given in this work.

To better define the pro- and retrograde P-T-d trajectories of exhumed continentally derived HP rocks we carried out detailed structural and petrologic investigations over a large area in the Western Alpine Sesia Zone, that displays, due to its tectonic position in the Alpine orogen and its unique preservation of structural and mineralogical information of multiple exhumation stages, a key area for the understanding of exhumation mechanisms in front of a rigid continental indenter. Structural investigations involved detailed mapping of main fabric elements over the entire Sesia Zone as well as the correlation and integration of existing structural and metamorphic data. Thermodynamic forward modelling of well-selected, structurally defined samples was carried out in order to understand the large scale structural geometries that are well preserved in the Sesia Zone, and their relation to the metamorphic evolution. Additionally, conventional thermobarometry in well equilibrated rocks is used to support the results from the forward models. Because our thermodynamic models involve physical rock-properties, such as densities and water content, we can additionally study the influence of buoyant forces acting on the low-density SLZ body along a well defined pro- and retrograde P-T trajectory.