# Chapter 2

# Introduction

## 2.1 Abstract

Modes and scales of strain localization at the brittle-viscous transition were investigated in the Northern Shear Belt, Cap de Creus, NE Spain. Field- and microstructural investigations revealed that the formation of decameter-wide mylonitic shear zones involved pressure- and temperature-sensitive deformation mechanisms. On the meter-scale, the formation and growth of mylonitic shear zone were characterized by precursory brittle fracturing and a strain-dependent brittle-viscous transition. Where shear zones interconnected and formed decameter-wide networks, fracturing was transitional to grain-size sensitive creep. As the shear zones that constitute these networks widened, the strain distribution was homogenized within the initial limits of the networks. Thereby decameter-wide shear zones formed, whose deformation was governed by a combination of viscous deformation mechanisms involving dislocation and diffusion creep. Multiscale analyses proofed that the scale-dependence of deformation mechanisms in combination with the scaling of pre-existing mechanical anisotropies, that characterize the country rock, control the spatial evolution of shear zones as they grow from millimeter- to kilometer scales.

Progressive strain localization was studied in the damage zones at the terminations of mylonitic shear zones. Discrete discontinuities that segment these tip damage zones were correlated to micro-scale shear fractures. The formation of these fractures followed strain hardening and promoted an enhanced fluid flux which accelerated the synkinematic reaction of biotite to form fine-grained aggregates of secondary biotite, muscovite, chlorite and

ilmenite. These processes accommodated strain coevally with distributed dislocation creep in quartz and fracturing of plagioclase. The relative contributions of the individual deformation mechanisms were strain-dependent, so that after a critical shear strain of $\gamma \sim 1$, the proportion of fine-grained neoblasts and dynamically recrystallized quartz in the tip damage zone was sufficient to form an interconnected weak rheological phase and accommodate all of the deformation in a narrow, softening shear zone center.

Shear zone propagation and networking were influenced by planar anisotropies that characterized the metapsammitic and metapelitic country rocks: A composite foliation on the millimeter-scale, isoclinally folded sedimentary layering on the centimeter- to decimeter-scale and layer-parallel pegmatites on the decimeter- to 10m-scale. The widths of these anisotropies correlate to the lengths of shear zones on these scales. Furthermore, the anisotropies at high angle orientations to the bulk shearing plane deflected propagating fractures antithetically and are therefore responsible for the sigmoidal geometries that characterize the investigated shear zone networks.

The shear zone networks consist of NW-trending host shear zones and W-trending step-over shear zones that formed ones host shear zones reached a critical length. Both together isolated lozenges of less-deformed country rock. Brittle step-over shear zones were precursory to extremely fine-grained millimeter-wide shear zones containing ultramylonites that probably formed by stress-driven reactions of biotite and plagioclase. These ultramylonites have deformed by viscous grain boundary sliding at temperatures of 400-500°C. Ultramylonites in step-over shear zones may have formed due to locally elevated shear stresses caused by strain compatibility problems within the shear zone network.

The interconnection of shear zones inhibited further lengthening and ongoing deformation was accommodated by homogenizing the strain distribution within the network. Strain homogenization involved the synthetic rotation of step-over shear zones, shear zone widening and the incorporation of isolated lozenges of less-deformed country rock. Shear zones widened by lateral branching of fractures from the shear zone centers and by synthetic rotation and mylonitic overprint of the drag between the fractures and shear zones. This drag truncation process allowed softening shear zones to widen. In the course of strain homogenization, decameter-wide shear zones formed whose deformation is dominated by a combination of dislocation and diffusion creep. The differential stresses driving this deformation were determined from dynamically recrystallized grain sizes in monophase quartz aggregates and yielded, in average, 22,3MPa.

Our investigation confirmed that shear zones forming the BVT-segments of crustal-scale faults are characterized by coeval and subsequent brittle and viscous deformation. In the investigated shear zones the transitions between these deformation mechanisms are one-way during progressive strain localization, with brittle deformation always preceding viscous deformation. Furthermore, the transitions are restricted to specific processes in the course of the formation of decameter-wide mylonitic shear zones and thereby limited in scale. This is reflected in the scaling properties of the investigated shear zones. Comparison of shear zone area (normalized with respect to a representative reference area) with shear zone length and width revealed that shear zones on the meter- to 10m-scale preferentially lengthened, whereas shear zones on 100m to kilometer-scale grew in width.

## 2.2 Kurzfassung

Diese Untersuchung beschäftigt sich mit der Art und den Maßstäben von Verformungslokalisierung innerhalb des 'Northern Shear Belt' am Cap de Creus in NE Spanien. Feld- und mikrostrukturelle Untersuchungen haben gezeigt, dass die Entstehung von mächtigen mylonitischen Scherzonen, die den 'Northern Shear Belt' bilden, eng mit Übergängen zwischen druck- und temperatursensitiven Verformungsmechanismen zusammenhängt. Die Entstehung und das Größenwachstum von mylonitischen Scherzonen auf dem Metermaßstab waren von initialem spröden Brechen und einem verformungsbedingten Übergang hin zu mylonitischer Scherung gekennzeichnet. Spröde Brüche stellten dort, wo sich Scherzonen verbanden und Netzwerke bildeten, Vorläufer zu Scherzonen dar, in denen Verformung von viskosem Korngrenzgleiten dominiert wurde. Mit zunehmendem Breitenwachstum der vernetzten Scherzonen homogenisierte sich die Verformungsverteilung innerhalb der initialen Grenzen des Netzwerkes. Die Deformation in den dadurch gebildeten zehnermetermächtigen Scherzonen wurde von kombiniertem Dislokations- und Diffusionskriechen kontrolliert. Multiskalenanalysen haben gezeigt, dass die räumliche Entwicklung von Scherzonen während ihres Wachstums vom Millimeter- zum Kilometermaßstab von der Maßstabsgebundenheit der Verformungsmechanismen und den Maßstäben von präexistierenden mechanischen Anisotropien im Gestein kontrolliert wurde.

Die Enden von mylonitischen Scherzonen erlaubten das Studium von progressiver Verformungslokalisierung. Diese Enden sind oft von diskreten Diskontinuitäten segmentiert, von denen gezeigt wurde, dass sie mit Scherbrüchen auf dem Mikromaßstab korrelieren. Diese Brüche entstanden infolge von Kaltverfestigung ('work hardening') und sie forcierten einen erhöhten Durchsatz von Fluiden. Dieser wiederum unterstützte die deformationsinduzierte Reaktion von Biotit, aus der ein feinkörniges Aggregat von sekundärem Biotit, Muskovit, Chlorit und Ilmenit hervorging. Diese beiden Prozesse akkommodierten gemeinsam mit Dislokationskriechen in Quartz und Brechen von Plagioklas die Verformung. Die relativen Anteile der einzelnen Mechanismen variierten verformungsabhängig. Nach einer kritischen Scherung von $\gamma \sim 1$ war der Anteil von feinen Neoblasten und dynamisch rekristallisiertem Quarz im Gestein ausreichend, um ein zusammenhängendes Netzwerk zu bilden und die gesamte Verformung in einem schmalen, zunehmend weicher werdenden Scherzonenzentrum zu fokussieren.

Scherzonenwachstum und -vernetzung wurden von folgenden, in den metapelitischen und metapsammitischen Gesteinen präexistierenden, mechanischen Anisotropien beeinflusst: Einer zusammengesetzten Foliation auf dem Millimetermaßstab, dem isoklinal verfalteten sedimentären Lagenbau auf dem Zentimeter- bis Dezimetermaßstab und lagenparallelen Pegmatiten auf dem Dezimeter bis Zehnermetermaßstab. Die Breiten dieser Anisotropien korrelieren mit den Längen der Scherzonen auf diesen Maßstäben. Darüber hinaus lenkten die Anisotropien, die generell einen hohen Winkel zur Scherebene einnehmen, propagierende Brüche antithetisch ab und sind damit für die sigmoidalen Geometrien, welche die untersuchten Scherzonennetzwerke kennzeichnen, verantwortlich.

Die Scherzonennetzwerke bestehen aus NW-streichenden Wirtsscherzonen und W-streichenden Verbindungsscherzonen, die sich bildeten nachdem die Wirtsscherzonen eine kritische Länge überschritten. In Kombination isolierten die beiden rhombenförmige Linsen geringer deformierten Nebengesteins. Bedingt durch spannungsinduzierte Reaktionen von Biotit und Plagioklas entstanden in spröden Verbindungsscherzonen extrem feinkörnige, ultramylonitische Lagen die durch viskoses Korngrenzgleiten bei 400°-500°C deformierten. Verbindungsscherzonen waren infolge von Kompatibilitätsproblemen innerhalb des Scherzonennetzwerkes erhöhten Scherspannungen ausgesetzt.

Die Vernetzung der Scherzonen unterband weiteres Längenwachstum. Weitere Scherung führte zur Homogenisierung der Verformung innerhalb des Netzwerkes. Diese Homogenisierung erfolgte, indem die Verbindungsscherzonen synthetisch rotierten, die Scherzonen breiter wurden und dadurch die geringer deformierten Linsen des Nebengesteins in das aktiv deformierende Gesteinsvolumen einbanden. Scherzonen verbreiterten sich, indem sich in der randlichen Schleppung der mylonitischen Scherzonen ein lateraler Bruch bildete und das dieserart vom Nebengestein isolierte Gesteinsvolumen mylonitisch überprägt wurde. Dieser Prozess erlaubte es weicher werdenden Scherzonen, in die Breite zu wachsen. Im Zuge der Verformungshomogenisierung wechselte auch der dominante Verformungsmechanismus innerhalb des Netzwerkes zu einer Kombination aus Dislokations- und Diffusions-kriechen. Die Differentialspannung, welche diese Verformung antrieb, wurde anhand der Korngrößen dynamisch rekristallisierter Quarze aus monophasen Aggregaten mit durchschnittlich 22,3MPa bestimmt.

Unsere Untersuchung hat die gängige Annahme bestätigt, dass gleichzeitige und einander nachfolgender spröde und viskose Verformung zu den Charakteristika mittelkrustaler Scherzonen am spröd-duktilen Übergang zählen. In den untersuchten Scherzonen finden Übergänge zwischen den Verformungsmechanismen nur in einer Richtung statt. Spröde Verformung geht immer der viskosen voraus. Darüber hinaus sind diese Übergänge an bestimmte Prozesse im Rahmen der Entstehung von zehnermetermächtigen Scherzonen gebunden und dadurch auf vorgegebene Maßstäbe beschränkt. Dies findet auch in den Skalierungseigenschaften der Scherzonen seinen Niederschlag. Vergleiche von, auf representative Referenzflächen normierten Flächen von Scherzonen mit ihren Längen und Breiten zeigen, dass Scherzonen auf dem Meter- bis Zehnermetermaßstab bevorzugt in die Länge wachsen, wohin-gegen Scherzonen auf dem hunderte Meter- bis Kilometermaßstab bevorzugt breiter werden.

## 2.3 Introduction

Since perfect homogeneity is never realized in nature, stresses acting on natural rocks generally lead to heterogeneous strains from the grain scale to that of tectonic plates. During such heterogeneous straining of a rock volume folds, mylonitic or brittle shear zones may form. The formation of each of these structures is linked to specific boundary conditions. Unraveling these boundary conditions by analyzing the finite shapes of these structures - nowadays exposed at the Earth's surface - is the key task of field-based structural geology.

The analysis of structures resulting from heterogeneous strains may be difficult, because even though, in their finite shapes, folds, mylonitic and brittle shear zones clearly differ from each other, the concept of ductility implies that heterogeneous deformation itself is scale-dependent. This means that any strain distribution can be considered as homogeneous if only the observational window is chosen appropriately, either small enough or large enough (Schmid & Handy, 1991, Paterson, 2001). This can be easily demonstrated by the fold shown in Fig. 2.1. The fold itself clearly reflects heterogeneous straining. Restricting the observational scale to the central limb linking the two fold hinges shows that the strain distribution there is relatively homogeneous.

**Figure 2.1:** Photograph of a (D2) fold as an example of heterogeneous strain. Hand lens for scale. Cala Serena.

But strain homogeneity is not just a matter of the scale of observation. During progressive deformation the scales of strain localization themselves, and thereby the heterogeneity of strain distribution, may change (Means, 1995). Structures that form by heterogeneous straining of a rock volume progressively evolve with strain. For example, folds may become more complex by developing different suborders of folds or even become inactive, when their limbs become parallel and deformation needs to be accommodated elsewhere. Similarly, individual mylonitic or brittle shear zones may widen or become narrower, grow in length, interact and interconnect with others or may even be deactivated. The strain-dependent evolution of these structures is influenced by a number of extrinsic and intrinsic parameters, such as stresses and strain-rates, ambient temperatures and pressures, composition and fabrics of the deforming rock and time-dependent changes in all of these quantities.

In this thesis, I investigate some of these parameters and their influence on heterogeneous strain distribution and its evolution in time upon the example of kilometer-scale strike-slip shear zones that formed in depths of 10 to 15km and are now exposed at the Cap de Creus, NE Spain. In detail, I focus on processes and parameters that control and influence the formation of these shear zones at greenschist-facies conditions in metasedimentary rocks that contain mechanical anisotropies on length scales from $\mu$m to tens of meters.

### 2.3.1 Scientific framework of this thesis

The investigation area is situated at the Cap de Creus, a small peninsula northeast of Barcelona that forms the easternmost part of mainland Spain and exhibits the most easterly outcrops of the Variscan continental basement of the Pyrenean Axial Zone (Zwart, 1986). The Cap de Creus is one of several basement massifs that characterize the formerly deep-seated crustal segments of the eastern Axial Zone along the southern branch of the Variscan mountain belt. These basement massifs share a common low-pressure/high-temperature metamorphism with high metamorphic gradients and roughly concentric isogrades around thermal domes (Druguet, 2001 and references therein).

High thermal gradients at the Cap de Creus ($> 80°C/km$) are interpreted to result from the emplacement of mantle-derived basic intrusions along subvertical transpressive shear zones and subsequent horizontal shortening (Druguet et al., 1997, Druguet & Hutton, 1998, Druguet, 2001). According to Druguet (2001) the progression of transpressive shearing during retrograde cooling and decompression resulted in narrowing of the high-grade shear zones and the formation of transpressive, strike-slip-dominated shear zone networks, the *Northern Shear Belt* (Carreras, 2001). Comparable retrograde shear belts with similar structural evolutions occur in other parts of the Pyrenean Axial zone (e.g. Banda & Wickham, 1986, Carreras & Cirés, 1986), which indicates that the general characteristics of the tectonometamorphic evolution of the Cap de Creus may be extrapolated to the entire segment of Variscan crust.

Field- and microstructural evidence indicates that the shear zones that were investigated in this thesis and are part of the Northern Shear Belt formed at greenschist-facies conditions (which were correlated to paleodepths of ∼10-15km, Druguet, 2001) during the retrograde metamorphic evolution of the rocks (Carreras & Garcia-Celma, 1982, Carreras, 2001, Druguet, 2001)[1]. Within the depth interval that comprises greenschist-facies metamorphic conditions along crustal-scale strike-slip faults in continental crust, deformation may be accommodated by pressure- and temperature-sensitive deformation mechanisms. The depth interval itself is considered as being part of the brittle-viscous transition (BVT, e.g., Handy et al., in press, and references therein), which is marked by the coexistence in space and time of brittle and viscous deformation mechanisms.

As part of crustal-scale strike-slip faults the BVT is spatially related to the lower boundary of the seismogenic zone where the largest earthquakes nucleate (e.g. Sibson, 1982, Das & Scholz, 1983). The exact depth interval in which brittle and viscous deformation coexist varies in location and width during the earthquake cycle (e.g. Scholz, 1988, Handy and Brun, 2004). Especially the lower boundary of this interval is depressed downwards during large (strike-slip-related) earthquakes due to the rate-dependence of strength. Following an earthquake, the BVT recovers to its long-term, interseismic level (Tse & Rice, 1986, Trepmann & Stoeckhert, 2003, Ellis & Stoeckhert, 2004, Handy & Brun, 2004, Rolandone et al., 2004).

The BVT is influenced by several factors, the most important being the deforming lithology (i.e. modes and compositions of the constituent minerals), temperature, effective pressure, shear stress, strain rate, strain,

[1]Even though the investigated shear zones formed in mechanically anisotropic rocks containing pre-existent fabrics resulting from deformation, most of them are not related to earlier synmagmatic shear-related structures, as suggested by Druguet, 2001.

the presence of a fluid phase and syntectonic metamorphic reactions (Rutter 1986, Handy et al., in press). This view of the BVT was engendered by laboratory (Byerlee, 1968, Rutter, 1972, Brodie & Rutter, 1985, Jordan, 1987, Shimamoto, 1989, Bauer et al., 2000a&b, Ellis & Stoeckhert, 2004, Rolandone et al., 2004, Holyoke & Tullis, 2006a and b), theoretical (Sibson, 1980a, Scholz, 1988, Handy, 1990) and field studies (e.g. Passchier, 1982, 1984, Mitra, 1984, Hobbs et al., 1986, Goodwin & Wenk, 1995, Stoeckhert et al., 1999, Stewart et al., 2000, Imber et al., 2001, Handy & Stünitz, 2002, Trepmann & Stoeckhert, 2003, Gueydan et al., 2004).

Most field studies of fossil mid-crustal shear zones that formed at the BVT were done either on thrust- (e.g. Passchier, 1982, 1984, Mitra, 1984, Hobbs et al., 1986, Goodwin & Wenk, 1995, Tourigny & Tremblay, 1997) or detachment-systems (e.g. Séranne & Séguret, 1987, Lister & Davis, 1989, Jolivet et al., 1991, 1998, Gueydan et al., 2005), both of which may be expected to show pronounced structural and rheological asymmetries between their hanging- and footwalls resulting from a long-term temperature difference between the warm and the cold fault block. For the investigation of the coeval activity of pressure- and temperature-sensitive deformation mechanisms these effects are disturbing. The few studies on BVT segments of transcrustal strike-slip shear zones were restricted to specific scales of observation (e.g. kilometer- and micro-scale, Stöckhert et al., 1999, Trepmann & Stöckhert, 2003, or meter- and micro-scale, Stewart et al., 2000) and their data density is therefore too incoherent to draw conclusions on the cross-scale evolution of strain localization.

To better define the evolution of strain heterogeneity in space and time I and my coauthors investigated parts of the Northern Shear Belt, the fossil BVT-segment of a crustal-scale strike-slip shear zone, from the micro- to the kilometer-scale. In particular, we studied how brittle and viscous deformation mechanisms interacted during progressive strain localization to form decameter-wide shear zones that constitute the belt. The exceptional outcrop conditions in the investigation area allow to delineate how the formation of these micro- to kilometer-scale shear zones was influenced by mechanical anisotropies that characterize the country rocks. Our cross-scale approach required detailed field work and mapping to formulate a field-based model for the structural evolution of the investigated shear zones (Chapter 3). Field work involved sampling of key outcrops and structures. Optical and scanning electron microscopy as well as microprobe analyses were performed on these samples to test and refine the field-based models, as well as to investigate, on a microscale, how different deformation mechanisms interacted during deformation at the BVT and to determine syndeformational temperatures and differential stresses (Chapters 4 and 5). To be able to evaluate and quantify heterogeneous deformation in shear zones from micro- to kilometer scales we developed several parameters that allowed us to perform a multiscale analysis of strain localization from field- and image data as well as from maps (Chapter 6).