PERGAMON

Journal of Structural Geology 24 (2002) 25–44

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jstrugeo

Controls on lineation development in low to medium grade shear zones: a study from the Cap de Creus peninsula, NE Spain

Sandra Piazolo[1,*], Cees W. Passchier

Institut für Geowissenschaften, Johannes Gutenberg Universität, Becherweg 21, D-55099 Mainz, Germany

Received 27 July 2000; accepted 27 March 2001

Abstract

Lineations composed of similarly oriented elongate mineral aggregates or grains are a common feature in deformed rocks, but it is unclear which factors control the development of such lineations. Field observations and microstructural analysis of samples, which were taken from discrete greenschist to lower amphibolite facies shear zones of the easternmost Variscan Pyrenees, show that strain is only one of several factors that control the strength and type of a lineation. Dynamic recrystallization, metamorphic reactions and rigid body rotation are also important controlling factors for the development of lineations. The most important of these is dynamic recrystallization. The way in which dynamic recrystallization influences lineation development is largely a function of the initial fabric in a specific rock type. Different lithologies with different initial fabrics produce distinctly different types and strengths of lineations even if deformed to the same finite strain in the same shear zone. An initial fine grain size and a monomineralic composition of the parent rock type commonly hinder the development of lineations. In contrast, in initially coarse-grained polymineralic rocks, well-developed lineations commonly develop. Therefore, the ratio of initial to dynamically recrystallized grain size determines to a large extend the development of such lineations.

Keywords: Lineation; Shear zones; Dynamic recrystallization

1. Introduction

'Stretching' and 'mineral' lineations are generally regarded as reliable tools to determine tectonic transport direction and to decipher the superposition of deformation events in rocks (e.g. Sutton and Watson, 1955; Ramsay, 1958; Ellis and Watkinson, 1987; Peterson and Robinson, 1993; Shackleton, 1993). Nevertheless, the general applicability of lineations as structural tools has been questioned in some specific cases (e.g. Druguet et al., 1997; Tikoff and Greene, 1997; Fossen and Tikoff, 1998). Moreover, different rock types that experienced the same amount of finite strain within one shear zone may have different lineation 'strength' and some high-strain mylonites, especially in marbles and fine-grained chlorite schists, completely lack linear fabrics. What factors, then, control the development of lineations? The understanding of such factors is essential for the correct interpretation of lineations. In this study, we systematically describe a variety of lineations that occur in discrete low to medium grade shear zones of the Cap de Creus peninsula, Spain. Then, we discuss the factors that can play a role in the development of these lineations and propose a model for the development of different types of lineations, emphasizing the significance of recrystallization, metamorphic reaction processes and rigid body rotation.

2. Terminology of lineations

2.1. Commonly used terminology

The term lineation describes any linear feature which occurs penetratively in a rock (for a review see O'Leary et al. (1976)) and therefore excludes features like 'slickensides', 'slickenfibers' and 'striations' that are restricted to a single surface. Early descriptions of linear structures categorized lineations according to their orientation with respect to fold geometry, whereby a-lineations are perpendicular and b-lineations parallel to the fold axis (Sander, 1930). Nowadays, four main types of lineations are generally distinguished (e.g. Ramsay, 1967, pp. 183–184; Hobbs et al., 1976, pp. 267–280; Price and Cosgrove, 1990, pp. 462–465; Twiss and Moores, 1992, pp. 274–280; Park,

* Corresponding author.
E-mail address: spi@geus.dk (S. Piazolo).
[1] Present address: Dept. Geological Mapping, Geological Survey of Denmark and Greenland, Thoravej 8, 2400 Kopenhagen N, Denmark.

0191-8141/02/$ - see front matter
PII: S0191-8141(01)00045-1

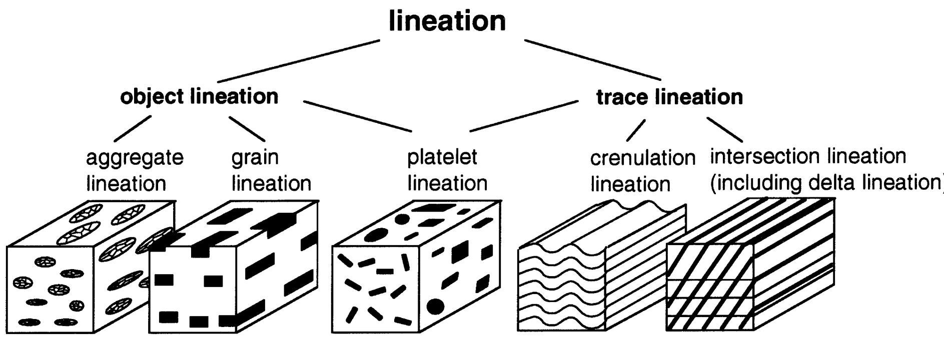


Fig. 1. The terminology for lineations used by the authors (see text for definitions).

1993, pp. 23–25; Passchier and Trouw, 1996, pp. 57–58). *Crenulation lineations* are formed by hinge lines of microfolds and/or kinkbands in the foliation plane. *Intersection lineations* are formed by two sets of intersecting surfaces. *Stretching lineations* are defined either by: (a) prolate aggregates of equidimensional or slightly elongate grains that can be distinguished from neighbouring fabric elements, or (b) prolate deformed single grains of minerals such as quartz, calcite or feldspar which normally have an equidimensional shape when undeformed (Passchier and Trouw, 1996, pp. 57–58). Deformed objects such as xenoliths in a granitoid or pebbles in a conglomerate may also form stretching lineations on a larger scale if they are present throughout a volume of rock. *Mineral lineations* (mineral grain lineation of Twiss and Moores (1992, p. 278)) are defined by the preferred orientation of single undeformed mineral grains with an elongate or platy habit. Examples are lineations of sillimanite, tourmaline or actinolite but also of mica grains that share a common axis. Additionally, rocks exhibiting linear fabrics can be classified into two different types of tectonites (LS- and L-tectonite) based on the axial ratio of elongate objects that build a lineation, as defined by Flinn (1978).

The nomenclature for lineations used today has a number of problems. One of the drawbacks of the existing terminology is the ambiguity or generic association of terms like ‘stretching’. For example, it is difficult to distinguish the second type of stretching lineation from a mineral lineation. The problem with the interpretative connotation of lineation names is demonstrated by the following example. If a polycrystalline layer in a mylonite is dismembered by shear bands, the result may be a ‘stretching lineation’ at right angles to the orientation of the longest bulk finite strain axis. Such a lineation did not develop due to stretching into an ellipsoidal shape. Due to these problems with the nomenclature for lineations, we found it useful for the present study to use a slightly different subdivision of lineations as described below.

2.2. Definitions

We define a general descriptive term *object lineation* as a lineation which is formed by parallel arrangement of distinct elongate parts of the rock with a measurable volume. In contrast, a *trace lineation* is formed by the trace of hinge lines or the intersection of surfaces (Fig. 1). Object lineations are further divided into *aggregate* and *grain lineations*. We define a *grain lineation* as a lineation that is formed by prolate single grains of a mineral whereby the long axes of the mineral grains are similarly oriented. A grain lineation may have elements from both stretching and mineral lineations and the use of this term eliminates the ambiguity mentioned above. An *aggregate lineation* is defined by prolate aggregates of grains of the same or several different minerals in which individual grains have a smaller aspect ratio than the overall aggregate. This type of lineation also includes distinct deformed objects such as pebbles and reduction spots that consist of an aggregate of grains. The term stretching lineation may also be used if the orientation with respect to the finite strain axes and mode of development can be established.

Trace lineations represent material lines of zero volume. Typical examples are *intersection lineations* between foliation planes and *crenulation lineations*.

A *platelet lineation* can be classified as an object- or trace-lineation, since such a lineation consists of platy mineral grains or fractures, which share one common axis (Fig. 1).

Although we realise that no simple terminology can capture the entire range of lineation shapes and types, we find the terminology presented here (Fig. 1) useful and sufficiently flexible for our purposes. The division into aggregate, grain, platelet, crenulation and intersection lineation is very similar to the distinction of different lineation types illustrated by Turner and Weiss (1963, p. 102) and Hobbs et al. (1976, p. 268). Within one sample, several different lineation types can be present of the same or different age, either parallel or oblique to each other. Consider the following examples. An intersection lineation consisting of two foliation planes and a grain lineation made up by elongate grains of biotite parallel to the intersection lineation could be described as “L_1 is a combined intersection lineation and parallel biotite grain lineation”. An aggregate lineation composed of quartz grains, which share a long axis (grain lineation) slightly oblique to the aggregate lineation trend could be described as “L_3 is a quartz aggregate

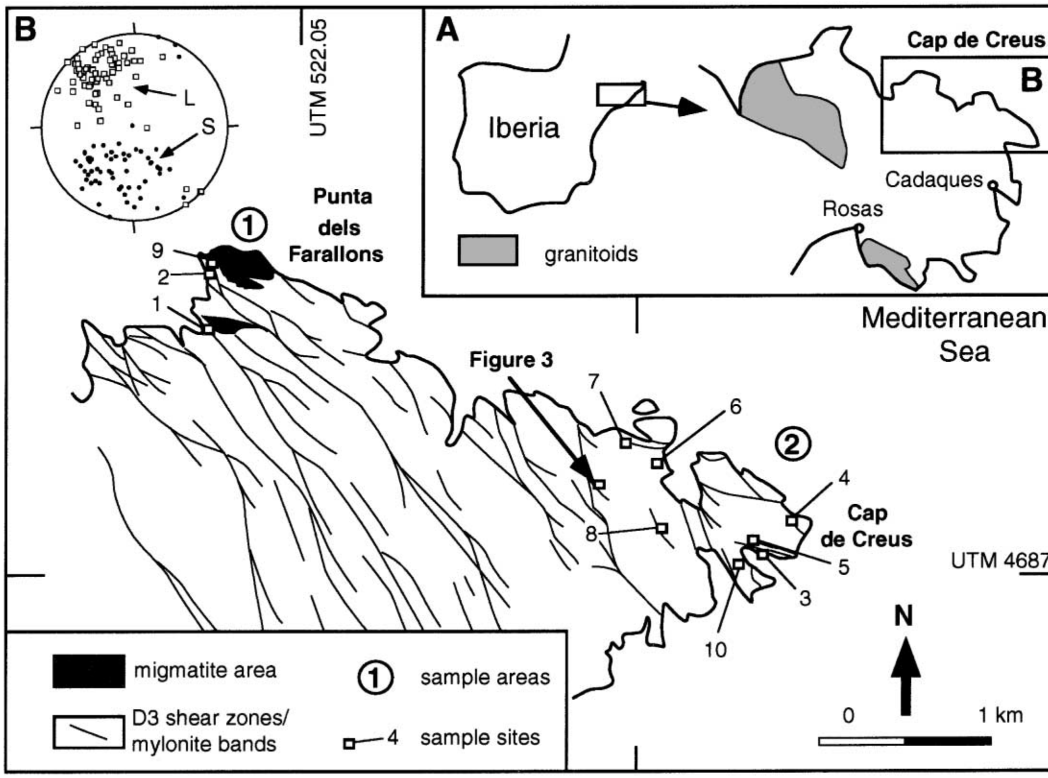


Fig. 2. Overview map of the study area; its locality within (A) Iberia, and (B) Cap de Creus peninsula. Lines correspond schematically to discrete, low to medium grade shear zones (modified after Carreras and Casas, 1987). The two sample areas are near Punta dels Farallons (1) and Cap de Creus (2). Other numbers signify shear zone numbers and sample localities discussed in the text and Table 1. The stereogram (equal area projection) shows the orientation of the mylonitic foliation (S) as black dots and of lineations (L) within the shear zones as open squares.

lineation. There is a slightly oblique quartz grain lineation within the aggregate".

The concept of a lineation is strongly dependent on the scale of observation, since this determines whether the structure is penetratively present in a rock. For example, an intersection lineation in a coarse micaschist is only present at a scale exceeding the grain scale. The descriptive terms defined here are probably most useful in the field, where it is not always possible to decide on the mechanisms of lineation development. In all cases, the nature of a lineation should be described, together with the scale of observation. We have applied the terminology described above in a study on the mechanisms that control the development of lineation in the Cap de Creus area (Spain) where different types of millimeter- to decimeter-scale lineations occur.

3. Geology of the Cap de Creus peninsula

3.1. General outline

The Cap de Creus peninsula is the easternmost outcrop of the Variscan axial zone of the Pyrenees in Spain and contains rocks with a complex polytectonic and polymetamorphic history (Carreras et al., 1977; Carreras and Druguet, 1994; Druguet et al., 1997 and references therein; Druguet and Hutton, 1998). During the Variscan orogeny an alternation of quartzitic, metapelitic and metapsammitic rocks and minor metacalcsilicate and amphibolite rocks was metamorphosed at low pressure resulting in a steep metamorphic gradient from chlorite–muscovite shales in the south to sillimanite–potassium feldspar bearing schists and migmatites in the north. Two small Variscan granodioritic plutons (Rosas and Rodes intrusions) intruded the rock pile in the south of the area. Numerous small volumes of quartz diorite, leucogranite and tonalite occur in the migmatitic zone. Druguet and Hutton (1998) have shown that these rock types are penecontemporaneous with the Variscan peak metamorphism. The same applies to abundant muscovite–tourmaline pegmatitic bodies that occur just south of the migmatite area (Druguet, 1997).

Two Variscan deformation events, D1 and D2 (Druguet, 1997; Druguet et al., 1997) affected pre-Variscan lithologies. According to Druguet et al. (1997), D1 produced an early foliation and boudinage of pre- or syn-D1 quartz-veins. Both S1 and the vein-boudins are parallel to bedding except in rare D1-fold closures of bedding. Relicts of D1 aggregate lineations are common in the metasedimentary sequence and in the quartz-veins.

The main phase of deformation (D2) developed during prograde metamorphism. The majority of pegmatitic bodies and at least one generation of quartz-veins are syn-D2

Table 1

Characteristics of shear zones and samples investigated in this study. Shear zone (SZ) and sample numbers correspond to those referred to in the text and figures; S2 orient. = azimuth/angle of dip of foliation outside shear zone; Smyl orient. = azimuth/angle of dip of mylonitic foliation; strain magn. = estimated strain magnitude assuming simple shear deformation; rock index = index of specific lithology within specific shear zone. Crosses in the three columns D2 fabric, SZ bend (i.e. zone where the S2 foliation is deflected) and SZ centre signify where the sample was taken. The κ-value refers to the statistical parameter κ of a von Mises distribution and signifies the degree of preferred dimensional orientation (the higher κ, the higher the degree of preferred dimensional orientation; Appendix A). Lineation type corresponds to the proposed general classification (according to Section 3.1). Seri = sericite, Am = amphibole, Fibr = fibrolite, cg. = coarse-grained, fg. = fine-grained

Sample no.	SZ no.	S2 orient.	Smyl orient.	Strain magn.	Rock type	Rock index	D2 fabric	SZ bend	SZ centre	Main mineralogy	κ	Lineation type
SP 122	1	290/25	65/60	0.0	Metapsammite	a	×			Qtz, Fsp, Bt, Ms	3.5	3.5 s-Bt grain lineation
SP 124				1.8	Metapsammite	a		×		Qtz, Fsp, Bt, Seri, Tur	1.0	1.0 i-Bt grain lineation
SP 125				1.8	Metapsammite	b		×		Bt, Seri/Chl, Fsp, Qtz, Ms, Tur	0.8	0.8 i-Bt grain lineation
SP 126				4.8	Metapsammite	a			×	Qtz, Seri/Chl, Fsp, Ms, Tur	0.5	0.5 s-Qtz aggregate lineation
SP 127				4.8	Metapsammite	b			×	Fsp, Qtz, Chl/Seri, Tur, Ms	2.6	2.6 i-Qtz aggregate lineation
SP 128A				0.0	Cg. pegmatite	c	×			Qtz, Fsp, Bt, Ms	2.3	2.3 l-Qtz grain lineation
SP 130				4.8	Qtz-rich pegmatite	c			×	Qtz	no	
SP 131				4.8	Cg. pegmatite	c			×	Qtz, Fsp, Ms	4.6	4.6 i-Qtz aggregate lineation
SP 151A	2	270/40	82/30	0.0	Granodiorite	a	×			Qtz, Fsp, Bt , Ms	1.4	1.4 i-(Qtz/Fsp) aggregate lineation
SP 151B				2.9	Granodiorite	a			×	Qtz, Fsp, Bt, Ms, Gr, Tur	3.0	3.0 i-(Qtz/Fsp) aggregate lineation
SP 160	3	260/40	20/76	5.3	Fsp-amphibole rock	a			×	Qtz, Ep, Fsp, amphibole, Ms	3.0	3.0 i-Ep grain lineation
SP 163				5.3	Fsp-amphibole rock	a			×	Qtz, Ep, Fsp, amphibole, Ms	3.4	3.4 i-Ep grain lineation
SP 191	4	140/75	40/80	0.0	Cg. metapsammite	a	×			Qtz, Fsp, Bt, Ms, Tur	1.9	1.9 s-Bt grain lineation
SP 192				3.0	Cg. metapsammite	a		×		Qtz, Fsp, Ms, Bt	3.5	3.5 s-Bt aggregate lineation
SP 193				4.1	Fg. metapsammite	b			×	Qtz, Fsp, Bt, Ms, Tur	1.6	1.6 i-Bt grain lineation
SP 194				0.0	Fg. metapsammite	b	×			Qtz, Fsp, Bt, Ms	4.4	4.4 i-Bt grain lineation
SP 195				1.6	Fg. metapsammite	b		×		Qtz, Fsp, Ms, Bt	3.9	3.9 i-Bt grain lineation
SP 197				4.1	Cg. pegmatite	c			×	Qtz, Fsp, Tur, Ms	3.0	3.0 i-(Qtz/Fsp) aggregate lineation
SP 198		164/80		0.0	Cg. pegmatite	c	×			Qtz, Fsp, Ms, Tur	1.5	1.5 i-Qtz aggregate lineation
SP 223	5	120/80	30/85	0.0	Fg. metapsammite	a	×			Fsp, Qtz, Bt	2.6	2.6 i-Bt grain lineation
SP 225				2.5	Fg. metapsammite	a		×		Qtz, Fsp, Bt, Ms	no	
SP 226				3.6	Fg. metapsammite	a			×	Qtz, Fsp, Bt/Seri/Chl, Tur	1.4	1.4 i-(Bt/Chl) aggregate lineation
SP 227				0.0	Mg. metapelite	b	×			Qtz, Fsp, Bt, Fibr, Seri	6.0	6.0 s-Bt grain lineation
SP 228				3.6	Cg. metapelite	c			×	Qtz, Fsp, Fibr, Bt, Ms, Tur	2.4	2.4 i-Fibr aggregate lineation
SP 229				0.0	Cg. metapelite	c	×			Qtz, Fsp, Ms, Bt, Fibr, And	1.2	1.2 s-Fibr aggregate lineation
SP 264	6	22/65	40/5	0.0	Qtz-vein	a	×			Qtz	no	
SP 265				1.4	Qtz-vein	a		×		Qtz	no	
SP 266				4.5	Qtz-vein	a			×	Qtz	no	
SP 267				4.5	Fg. metapelite	b			×	Qtz, Fsp, Bt, Ms, Tur	1.3	1.3 i-Bt grain lineation
SP 268				2.1	Fg. metapelite	b		×		Qtz, Fsp, Tur, Bt, Ms, Chl	1.5	1.5 i-Bt grain lineation
SP 269				0.0	Fg. metapelite	b	×			Qtz, Fsp, And, Ms, Fibr	4.8	4.8 i-Bt grain lineation
SP 270				5.1	Cg. metapelite	c			×	Qtz, Fsp, Bt, Ms	2.8	2.8 i-Bt aggregate lineation
SP 271				2.3	Cg. metapelite	c		×		Qtz, Fsp, Ms, Bt, Fibr	2.6	2.6 i-Bt grain lineation
SP 272				0.0	Cg. metapelite	c	×			Qtz, Fibr, Fsp, Tur, Ms, Bt	1.7	1.7 i-Bt grain lineation
SP 289	7	240/85	21/43	5.1	Metapelite	a			×	Qtz, Fsp, Fibr, Bt, Tur, Ms	3.2	3.2 s-Fibr aggregate lineation
SP 290				2.1	Metapelite	a		×		Qtz, Fsp, Bt, Fibr, Ms,Tur	3.0	3.0 s-Fibr aggregate lineation
SP 291				0.0	Metapelite	a	×			Qtz, Fsp, Bt, Ms, Fibr, And	1.8	1.8 s-Fibr grain lineation

Table 1 (*continued*)

Sample no.	SZ no.	S2 orient.	Smyl orient.	Strain magn.	Rock type	Rock index	D2 fabric	SZ bend	SZ centre	Main mineralogy	κ	Lineation type
				0.0							0.9	0.9 s-And grain lineation
SP 358	8	–	–	2.3	Quartzite	a	×			Qtz, Bt	2.1	2.1 s-Bt grain lineation
SP 416A	9	270/45	62/50	4.8	Granodiorite	a			×	Qtz, Fsp , Bt , Ms, Tur	2.1	2.1 i-Bt aggregate lineation
SP 416B				0.0	Granodiorite	a	×			Qtz, Fsp, Bt	1.6	1.6 s-Bt grain lineation
SP 463	10	–	–	2.3	Small qtz-vein	a	×			Qtz	2.1	2.1 i-Qtz grain lineation

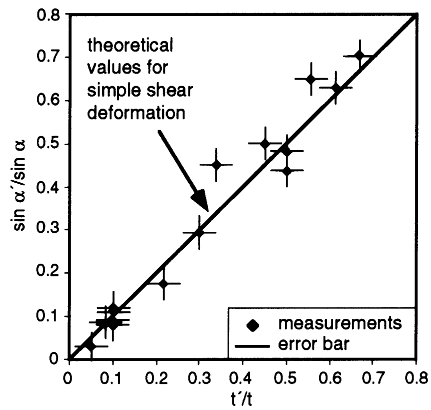


Fig. 3. Graph illustrating the type of deformation in D3 shear zones. After Ramsay (1980) an isovolumetric simple shear shear zone is characterized by $t'/t = \sin\alpha'/\sin\alpha$, whereby t' is the thickness of a layer within the shear zone, t the original thickness, α' the angle between shear zone boundary and mylonitic foliation, and α the original angle between foliation and shear zone boundary. If the shear zone is a simple shear, shear zone, values should lie on a line which has a slope of one. Measurements within error closely correspond to theoretical values and therefore D3 shear zones are deformed by simple shear deformation. Deviation from the model simple shear values are predominately to the left of the simple shear line, which signify a non-rotational flattening component perpendicular to the rock layer.

and syn-peak metamorphism. Druguet et al. (1997) proposed that D2 was a phase of highly vortical sinistral transpressional flow with a strong vertical extension component that produced a new foliation (S2) and sub-vertical lineations.

Lineations that developed during D1 and D2 exhibit variable lineation strength and are constituted of single grains or aggregates of grains. Fine-grained metasediments tend to exhibit more intense D2 lineations than coarse-grained ones. These structures are overprinted by predominantly E–W and NW–SE trending anastomosing D3-ductile shear zones of unknown age (Carreras et al., 1977; Druguet, 1997) (Fig. 2). These shear zones, which are oblique to layering and S2, developed under greenschist and lower amphibolite facies conditions. Syn- and post-tectonic fluid infiltration caused retrogression in the shear zones. Mineral assemblages with a high content of H_2O-rich minerals such as chlorite and muscovite, tourmaline form and frequently andalusite is replaced by fibrolitic sillimanite.

3.2. Characterization of deformation in D3 shear zones

The retrograde, greenschist to lower amphibolite facies D3 shear zones of the Cap de Creus area offer a unique opportunity to document and analyze the development of object lineations at low to medium metamorphic grade in different lithologies deformed in a number of spatially defined and well exposed individual shear zones (cf. Fig. 6). The shear zones are characterized by a progressive and continuous rotation of S1 and S2 towards parallelism with the shear zone boundaries. The angle between S1 or S2 and the shear zone boundaries varies from 60 to 90° and the shear zone width is up to 20 m (from first deflection of the regional foliation on the one side of the shear zone to first deflection on the other side). In the centre of the shear zones the foliation is parallel to the shear zone boundaries.

D3 deformation is weak to absent outside the D3 shear zones. In the absence of volume change, the strong localization of deformation present in these shear zones is most likely caused by simple shear flow (Ramsay, 1980; Weijermars, 1992). Carreras and Garcia (1982) investigated one specific shear zone located in one of the sampled areas (see Section 4.2) and concluded that its geometry closely corresponds to that expected for simple shear. We compared field measurements with theoretical values for isovolumetric progressive simple shear deformation (Ramsay, 1980) to investigate whether other D3 shear zones also formed by this flow type. Measurements in the shear zones are indeed close to theoretical values for zones formed by progressive simple shear (Fig. 3). The orientation and position of the investigated shear zones is not lithologically controlled. Therefore, the layered host rocks seem to have been approximately rheologically homogeneous within the active shear zones. Strain partitioning was of minor significance. This is shown by the fact that within different deformed lithologies millimeter- to centimeter-scale structures are similar and developed lineations that are colinear. Additionally, the contact between different lithologies are planar and the relative thickness of adjacent layers remains identical through the strain gradient from the undeformed host to the shear zone centre. In a shear zone that is orientated at a high angle to the initial foliation (cf. Fig. 7) strain partitioning between different lithologies would result in changes in the relative thickness of layers and development of buckle folds and boudinage that are needed to accommodate the arising space problems. Such features are not found in the shear zone segments used for this study. In many shear zones finite shear strain could be determined by measuring the displacement of marker layers (e.g. pegmatites, quartz-veins) and the shear zone width; finite shear strain varies between 50 and 250, assuming simple shear deformation.

4. Development of object lineations in shear zones at Cap de Creus

4.1. Classification of object lineations

In the low to medium grade D3 shear zones of the Cap de Creus peninsula several types of object lineations are present. In order to satisfactorily characterize these we needed to describe them accurately and to quantify their strength of development. Strength of an object lineation can be expressed by the degree of preferred dimensional orientation of the lineation as described by the statistical value κ of a von Mises distribution (Masuda et al., 1999).

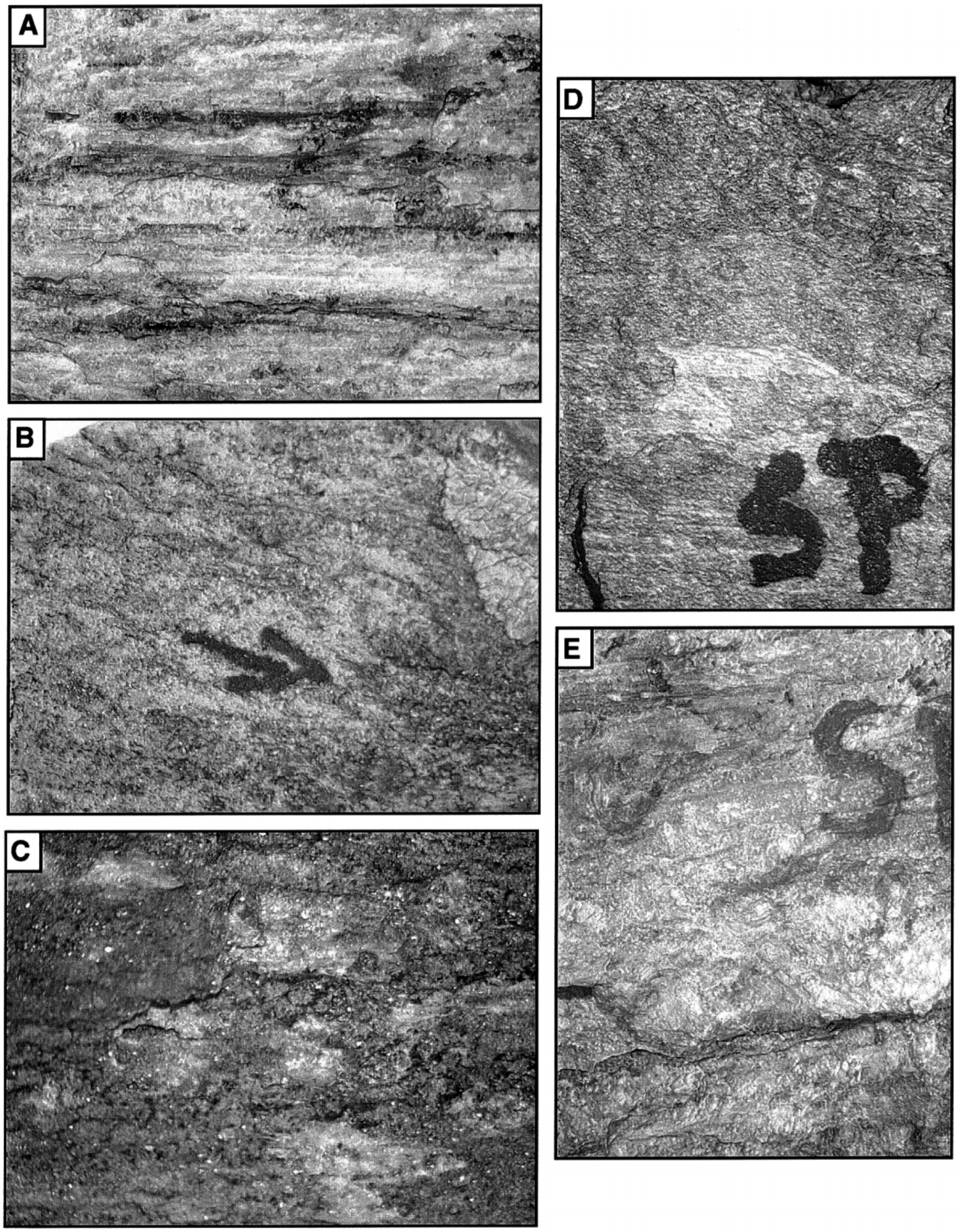


Fig. 4. Photographs of hand specimen; (A) strongly deformed pegmatite with a strong i-Qtz aggregate lineation; (B) moderate Bt grain lineation in Bt-bearing quartzite (SP 358); (C) moderate Fibr aggregate lineation (SP 290); (D) in lower third: moderate Qtz aggregate lineation in quartz-rich part of metapsammite (SP 127), in upper two thirds: no lineation in fine-grained quartz-poor part of the metapsammite (SP 126); (E) deformed granodiorite with good Fsp aggregate lineation (SP 151B); for photos (A)–(E) field of view = 2 cm.

This value is based on the common orientation of the longest axis of individual grains (grain lineation) or polycrystalline lenses (aggregate lineation). In this study, κ was determined as described in Appendix A from observation on the foliation planes of hand specimens, or in thin sections cut parallel to the foliation. Although, object lineations are penetratively present throughout a volume of rock, in many cases only part of the volume of the rock, usually a specific mineral or group of minerals, defines the actual lineation. The volume of this lineation-forming material with respect to the total volume of the rock is a measurable characteristic of a lineation.

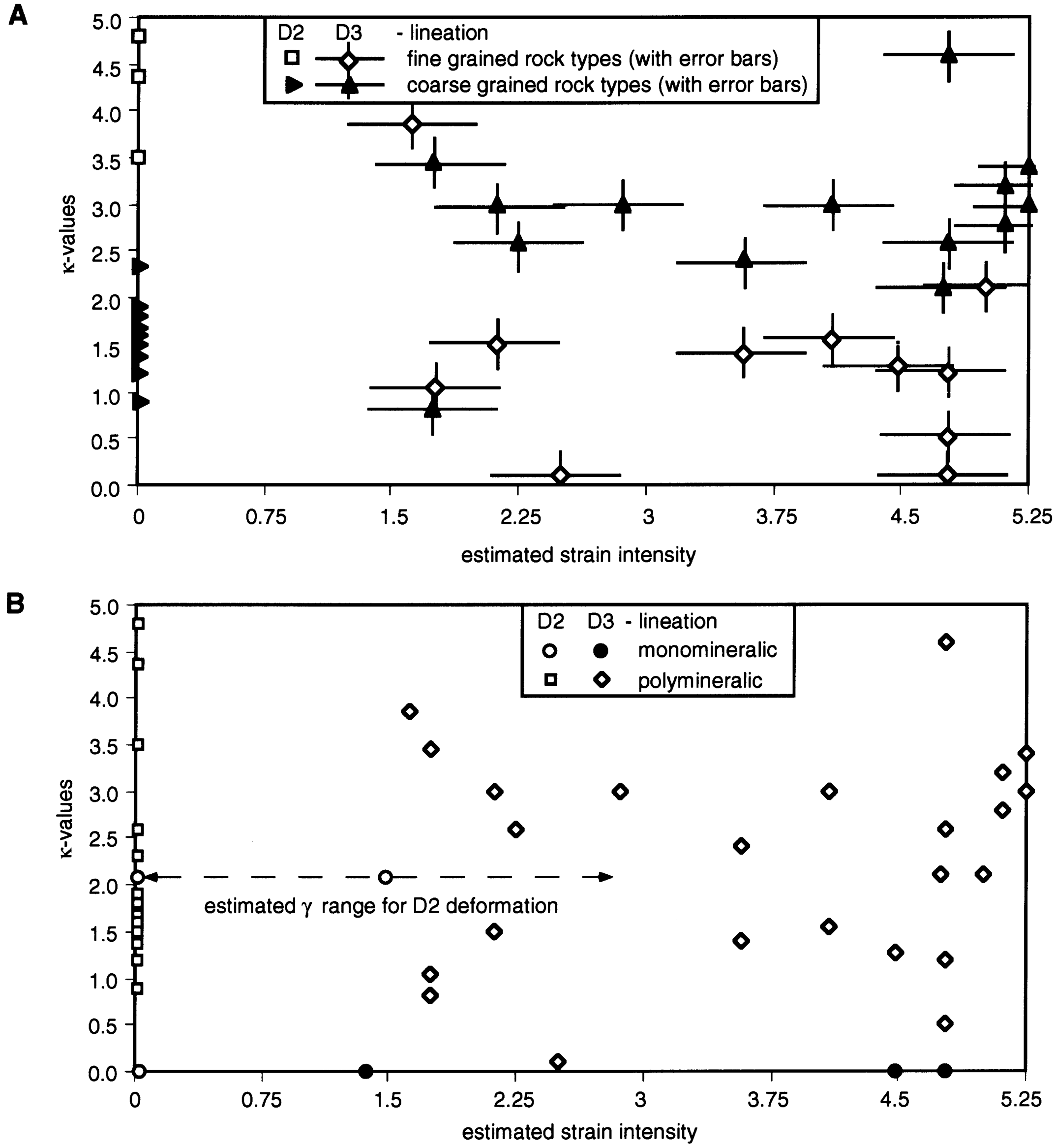


Fig. 5. (A) Graph illustrating the change in κ-values (measure of the strength of a lineation) with strain. The progressive rotation of a layer towards the mylonitic foliation provides a relative estimate of shear strain γ using the equation $\cot \alpha' = \cot \alpha \pm \gamma$ (e g. Ramsay, 1980; Lloyd et al., 1992). α is the original angle between the layer and the shear zone boundary and α' the angle between shear zone boundary and the mylonitic foliation within the shear zone. Two major rock groups are distinguished: initially coarse-grained lithologies (pegmatite, metapsammite and metapelite, granodiorite) and initially fine-grained lithologies (metapsammite and -pelite, quartzite). Note that in coarse-grained rocks κ-values increase with increasing strain, whereas in fine-grained rocks κ-values decrease. (B) Graph illustrating the change in κ-values (measure of the 'strength' of a lineation) with strain of monomineralic rocks and polymineralic rocks. Note that polymineralic rocks tend to exhibit higher κ-values than monomineralic rocks.

We used the following classification which is based on: (a) the lineation intensity represented either by the adjectives strong (κ-value ≥ 5), moderate ($2 \leq \kappa$-value < 5) and weak (κ-value < 2) or by the exact κ-value, (b) the modal percentage of lineation-forming material compared with matrix represented by the letters s (small; <20%), i (intermediate; 20–45%), l (large; 45–97%) and m (monomineralic; 97–100%), (c) the lineation material (one or several mineral species) written in mineral abbreviations proposed by Kretz (1983), and (d) the terminology for object lineations put forward above (see Section 2.2). A high κ-value signifies a high degree of preferred dimensional orientation, i.e. similar orientation of individual lineation elements (e.g. individual elongated grains or grain aggregates) and therefore a well developed, strong object lineation. An example of the proposed classification is '3.7 s-Sil grain lineation' for a grain lineation made of similarly oriented sillimanite grains, with a moderate degree of preferred orientation ($\kappa = 3.7$) and a small modal percentage of lineation material. Fig. 4 shows some examples of different object lineations present in the study area. This classification may seem somewhat complicated, but is

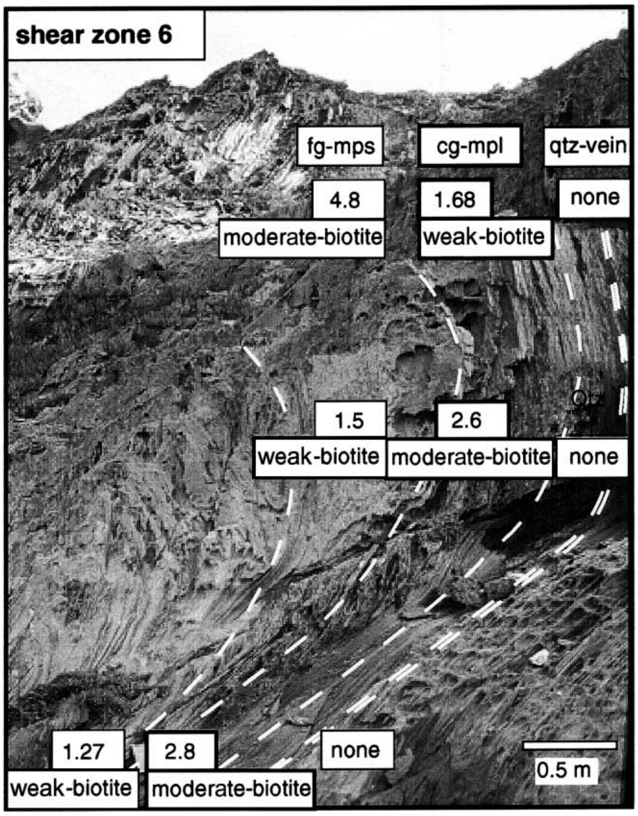


Fig. 6. Field view of shear zone 6 depicting one side of the shear zone from outer part to centre. This shear zone exhibits the development of lineations in different rock types. Numbers represent κ-values (measure of degree of dimensional preferred orientation; for further explanation see text and Appendix A) and successions of letters and numbers the lineation type using the proposed classification; cg-mpl = coarse-grained metapelite, fg-mps = fine-grained metapsammite, qtz-vein = quartz-vein; boundaries of different lithologies are outlined by dashed white lines.

necessary for an accurate and quantitative comparison of object lineations in the Cap de Creus area. It may also be useful when comparing object lineations between different areas and rock types. In the scheme proposed here, one can choose the degree of 'complexity' in nomenclature that is needed for a specific problem, i.e. either Sil grain lineation or moderate Sil grain lineation or 3.7 s-Sil grain lineation.

4.2. Sample localities

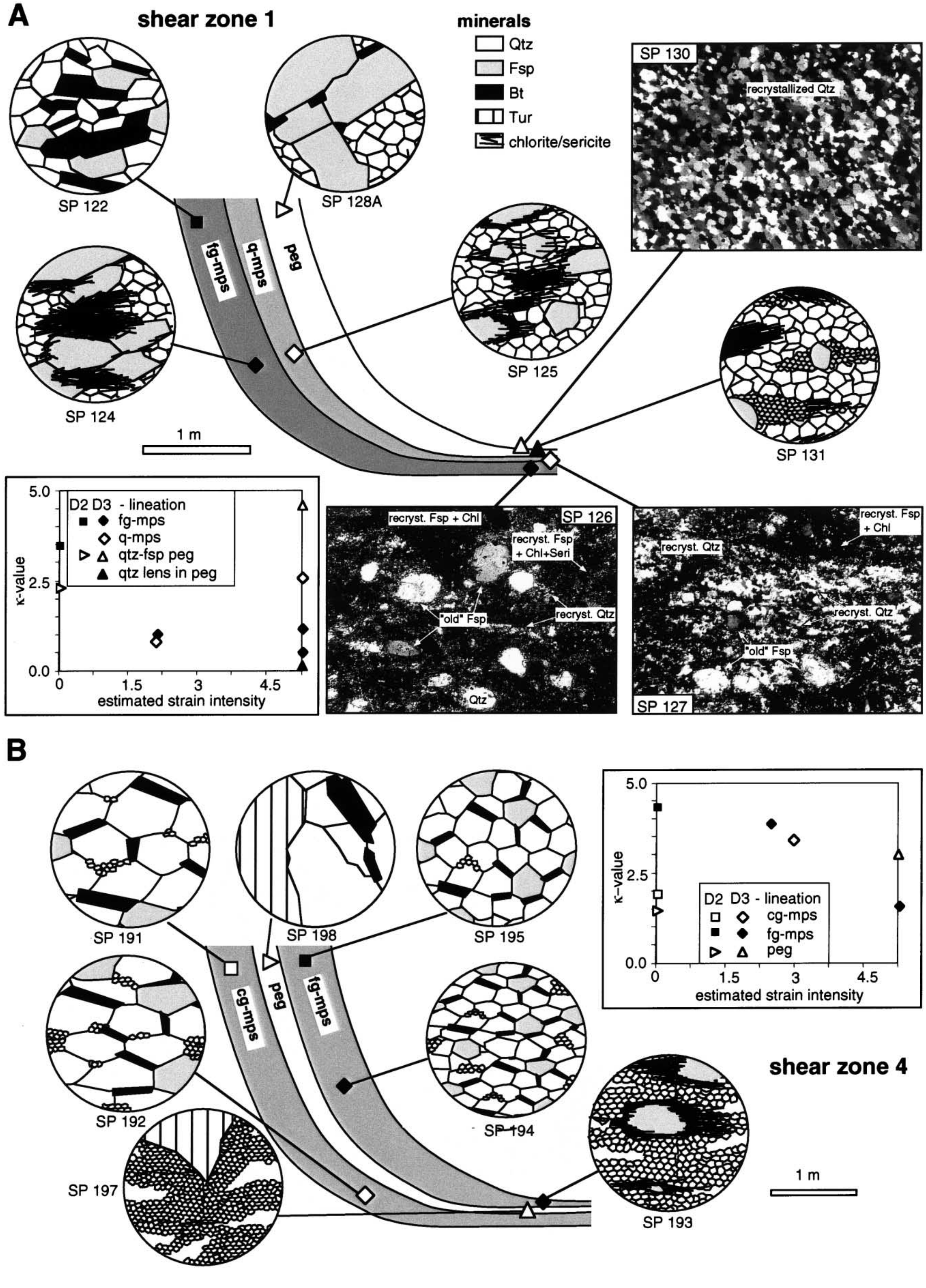
Well-exposed and homogeneously deformed sections of 10 shear zones were investigated in detail in two sample areas, which are situated in the north-eastern part of the Cap de Creus peninsula (Fig. 2). Shear zones 1, 2 and 9 lie in the northern area where pre-D3 migmatites occur (Punta dels Farallons; (1) in Fig. 2). The other shear zones are in the eastern part of the peninsula ((2) in Fig. 2). Details of the geometry of individual shear zones and object lineations are given in Table 1. Samples were collected in sections with planar, mylonitic layering devoid of folds and other disturbing features.

4.3. Object lineations in low to medium grade shear zones

Aggregate lineations are composed of elongate aggregates of minerals developed from large equidimensional parent grains by ductile deformation and associated dynamic recrystallization. Freeman and Lisle (1987) have shown that the relationship between the shape of the finite strain ellipsoid and the shape of such aggregates is complex and depends on the rheology of each rock constituent. Nevertheless, it would be expected that the strength of aggregate lineations reflects the finite strain in some way. Such a direct relationship does not exist in the Cadaques shear zones. The character of object lineations in sections through each of the investigated D3-shear zones varies significantly between different lithologies, even where finite strain values are similar (Fig. 5 and Table 1). Therefore, differences in the character of lineations in different lithologies and shear zones must, at least partly, be controlled by other parameters than finite strain.

Figs. 6 and 7 illustrate different fabrics and corresponding object lineation strength developed in three of the investigated shear zone segments (locations are given in Fig. 2). In the wall rock of shear zone 6 (Fig. 6) a moderate to strong D2 Bt grain lineation exists in the metapsammite and metapelite layers that are oriented orthogonal to the shear zone. In the coarse-grained metapelite the strength of the lineation *increases* from the shear zone boundary to the centre (Fig. 6). In the fine-grain metapsammite, however, the strength *decreases* towards the shear zone centre. In a quartz-vein present in the wall rock and the shear zone, no object lineation is present either outside or inside the zone. Grain sizes are unimodal and do not vary significantly between the three samples of the quartz-vein.

More details of the lineation development can be observed in shear zone 1 (Fig. 7A). A coarse-grained (>2 mm), feldspar–quartz–tourmaline pegmatite and two types of fine- to medium-grained metapsammite with different quartz content are deformed in this shear zone. Outside the shear zone the pegmatite body is parallel to bedding. In the central parts of this pegmatite quartz lenses (sample SP 128A) are present. In the shear zone centre, the quartz–feldspar zones of the pegmatite exhibit a well-defined aggregate lineation (SP 131), which is made up by elongated domains of recrystallized quartz interbedded with fragments of brittly deformed feldspar and aggregates of fine recrystallized grains of feldspar. In the quartz lenses, which are defined by pure fine-grained (0.02 mm) recrystallized quartz grains, no macroscopically observable object lineation forms (SP 130) in the shear zone centre. In thin section, though, a crystallographic preferred orientation is present indicating significant ductile deformation of quartz. A lineation develops only in quartz domains where a small amount of recrystallized feldspar is present. In this case, long stringers of recrystallized feldspar grains form a moderate to strong aggregate lineation. Outside the shear zone, the metapsammite with a smaller quartz content has a moderate


A
shear zone 1
minerals
Qtz
Fsp
Bt
Tur
chlorite/sericite
SP 130
recrystallized Qtz
SP 122
SP 128A
fg-mps
q-mps
peg
SP 125
SP 124
SP 131
1 m
D2 D3 - lineation
fg-mps
q-mps
qtz-fsp peg
qtz lens in peg
κ-value
5.0
2.5
0.0
0
1.5
3
4.5
estimated strain intensity
recryst. Fsp + Chl
SP 126
recryst. Fsp + Chl+Seri
"old" Fsp
recryst. Qtz
Qtz
recryst. Fsp + Chl
recryst. Qtz
SP 127
B
SP 191
SP 198
SP 195
cg-mps
peg
fg-mps
SP 192
SP 194
shear zone 4
SP 197
SP 193
D2 D3 - lineation
cg-mps
fg-mps
peg

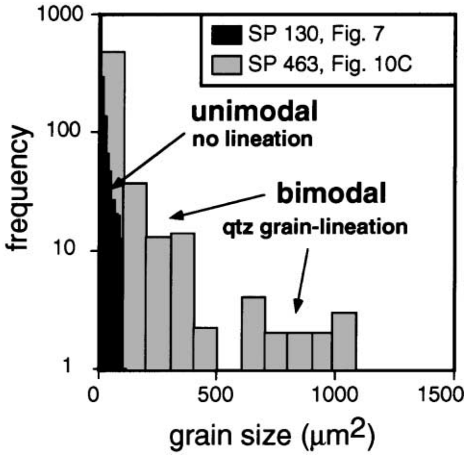


Fig. 8. Grain size distribution diagrams of two different fabrics developed in mylonitised monomineralic (Qtz) rocks; illustrated rock types are a quartz dominated part of a pegmatite (sample SP 130, cf. Fig. 7A (photomicrograph)) and a quartz-vein deformed during D2 (sample SP 463, cf. Fig. 9A (photomicrograph)).

Bt grain lineation (SP 122), whereas at the bend of the shear zone (SP 124) a weak Bt grain lineation developed (Fig. 7A). Here, quartz and biotite form aggregates of small grains, feldspar appears as small to medium-grained rounded clasts or as fine-grained constituents of the matrix. In the centre, Bt is retrogressed to sericite and chlorite and aggregates of small sericite and chlorite grains are present (SP 126). The contrast between elongate quartz aggregates and chlorite–sericite domains define a weak quartz aggregate lineation. In contrast, within the more quartz-rich metapsammite, a moderate quartz aggregate lineation is developed in the centre of the shear zone. Apparently, the modal percentage of quartz determines the lineation strength in these rocks.

Shear zone 4, where coarse-grained and fine-grained metapsammite and a coarse-grained pegmatite are deformed, shows similar characteristics to shear zones 1 and 6 (Fig. 7B). Outside the shear zone, the fine-grained metapsammite shows a well developed Bt grain lineation of D2-age (SP 195). Moving into the outer parts of the shear zone, where the foliation is deflected, the strength of the lineation *decreases* (SP 194). In the centre of the shear zone the lineation is weakly developed (SP 193). In contrast, in the coarse-grained metapsammite, a weak Bt grain lineation of D2-age (SP 191) that is present outside the shear zone develops into a well-developed Bt aggregate lineation (SP 192) close to the centre of the zone. In the initially coarse-grained pegmatite both quartz and feldspar exhibit a strong grain size reduction in the shear zone centre (SP 197) and some quartz grains are elongate with strong undulatory extinction. Domains of very fine-grained feldspar and fine-grained quartz form a moderate quartz-feldspar aggregate lineation. A characteristic feature is that the highest percentage of fine-grained quartz and feldspar occurs close to the brittly deforming tourmaline crystals.

Similar changes in object lineations as described for these three shear zones have been observed in all of the 10 zones that were quantitatively investigated (Table 1; Appendix B), and were observed in all visited shear zones in the Cap de Creus area. In summary, although the lineation strength (κ-value) is generally dependent on finite strain, the strength gradient of object lineations from the shear zone boundary to centre is strikingly different in coarse- and fine-grained rocks (Fig. 5A). Initially coarse-grained, isotropic rocks, which lack a D1 or D2 fabric (pegmatite, granodiorite, some metapelites and -psammites) with an initial grain size of 2 mm or more exhibit a progressive *increase* in object lineation strength with strain intensity. In contrast, initially fine-grained rocks (metapelites and -psammites, quartzites or quartz-veins) with a grain size smaller than 2 mm do not develop a object lineation at all. Some initially fine-grained metapelites and metapsammites that have a D1 or D2 object lineation preserved, show a *decrease* in the strength of this lineation with increasing D3 strain.

Other factors that play a role in object lineation development are the monomineralic or polymineralic nature of a rock and the grain size distribution (Fig. 8). In mylonitised polymineralic rocks (quartzofeldspatic pegmatite, metapsammite and metapelite) moderate to strong object lineations are common. In mylonitized monomineralic rocks (some quartz-rich pegmatites and quartz-veins), which develop or retain a unimodal grain size distribution (Fig. 8), object lineations are absent or weak (e.g. monomineralic, fine-grained quartz-dominated pegmatite; SP 130; Fig. 7A). In monomineralic rocks that develop a bimodal distribution of grain size (e.g. quartz-veins such as SP 463; Figs. 8 and 9A), moderate to strong grain lineations develop. Grain size distribution therefore plays an important role in the type and strength of lineations in monomineralic rocks.

Besides these endogenous trends, mineral colour and weathering may play an important role in the visibility of object lineations. For example, bimodal grain size distribution strongly enhances heterogeneous weathering and coatings in certain areas and commonly result in object lineations that are obvious in-hand specimens. In almost monomineralic rocks with a uniform grain size distribution, an aggregate lineation may be seen as in-hand specimens

Fig. 7. Schematic diagrams of textures observed in different lithologies; diameter of circles (with textures) = 2 mm; insets show graphs plotting κ-values against estimated strain for different samples; photomicrographs (width of view (horizontal) = 0.6 mm) depict selected samples, sections are cut parallel to foliation. fg-mps = fine-grained metapsammite, q-mps = quartz-rich metapsammite, peg = pegmatite, cg-mps = coarse-grained metapsammite. (A) shear zone 1; photomicrographs: SP 126 is a fine-grained metapsammite in the centre of shear zone 1 with no statistically significant lineation, crossed nicols; SP 127 is a fine-grained metapsammite in the centre of shear zone 1, the lineation is a 2.6 s-Qtz aggregate lineation, crossed nicols; SP 130 is a Qtz dominated part of a pegmatite, no lineation is present, crossed nicols. (B) shear zone 4.

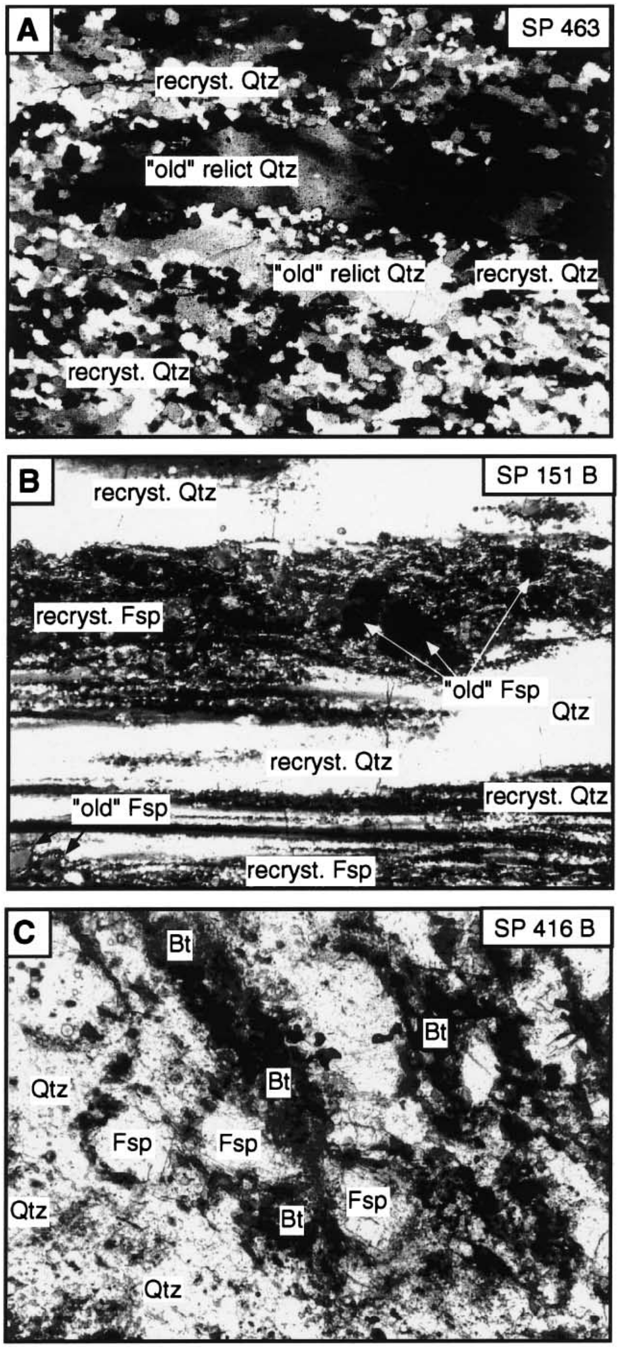


Fig. 9. Photomicrographs depicting the variable effect of dynamic recrystallization on the fabric of selected samples, sections are cut parallel to the foliation. (A) Qtz-vein deformed during D2 (sample SP 463) exhibiting a bimodal grain size distribution (cf. Fig. 8) due to moderate degrees of dynamic recrystallization dominantly at the boundaries of large, elongate relict grains; these relict grains now form a moderate Qtz grain lineation; (B) strongly deformed granodiorite (sample SP 151B) with elongate aggregates of recrystallized Fsp forming a 3.0 i-(Qtz/Fsp) aggregate lineation. Relicts of brittly deformed Fsp and Qtz ribbons are also seen. Sample is taken from central part of shear zone 2; crossed nicols; (C) strongly deformed granodiorite (sample SP 416A) with numerous small recrystallized Fsp grains and elongate aggregates of recrystallized Bt constituting a 2.1 i-Bt aggregate lineation; crossed nicols; width of view is 0.6 mm for all samples.

even if the colour of the second mineral species is similar to the rest of the rock (e.g. feldspar in quartzite) since weathering will affect the each mineral species differently.

5. Mechanisms of object lineation development

Observations from the Cap de Creus area show that elements of the initial fabric such as initial grain size, mineral composition and grain size distribution largely determine whether object lineations will develop or not. The following mechanisms of object lineation development have been described in the literature: (1) shape change by ductile deformation (e.g. Lisle et al., 1983; Paterson, 1983; Freeman and Lisle, 1987); (2) reorientation of rigid objects in a homogeneous matrix (e.g. Ferguson, 1979; Ildefonse, 1992a,b; Ježek et al., 1994, 1996); (3) growth of elongate minerals parallel to the direction of shear (e.g. Vernon, 1987); and (4) change in shape due to dissolution, precipitation and diffusion (Bell and Cuff, 1989; Azor et al., 1997). In the Cap de Creus area, three of these mechanisms seem to play a major role in the development of object lineations: shape change by ductile deformation assisted by dynamic recrystallization; growth of new mineral phases; and rigid body rotation. The way in which these processes may generally affect the development of object lineations is outlined below and supported by examples from the Cap de Creus area.

5.1. Recrystallization

Dynamic recrystallization significantly influences the formation of object lineations since it strongly affects fabric development during progressive deformation (e.g. Guillopé and Poirier, 1979; Tullis and Yund, 1985; Urai et al., 1986; Drury and Urai, 1990). At low metamorphic grade, the dominant dynamic recrystallization mechanism is rotational recrystallization (Guillopé and Poirier, 1979), also known as in situ (Sellars, 1978, p. 151), regime I (Hirth and Tullis, 1992) or regime D recrystallization (Drury and Urai, 1990). This kind of recrystallization influences grain size distribution in the rock (e.g. Means, 1981; Tullis and Yund, 1985; Trimby et al., 1998) because recrystallized grains are commonly of smaller size than 'parent' grains. The recrystallized grain size is a function of mineral species, temperature and differential stress during the deformation (e.g. Twiss, 1977; Christie and Ord, 1980; Kronenberg and Tullis, 1984; De Bresser et al., 1998); the grain size decreases with increasing stress and decreasing temperature.

In a polymineralic rock, in which the original grain size significantly exceeds that of the recrystallized grains, originally 'large' grains can develop into elongate aggregates of fine grains due to dynamic recrystallization. These aggregates then define a moderate to strong aggregate lineation. If relict grains that are surrounded by small, recrystallized grains are elongate, a moderate to strong grain lineation will also be present. However, in rocks in which the size of original grains and recrystallized grains are in the same range, such aggregates cannot form. No lineation develops, except if the small grains are already clustered into aggregates of one or several distinct mineral phases before deformation. In the latter case the effect is similar to that for an initially coarse-grained rock (i.e. high ratio of initial/recrystallized grain size) moderate to strong aggregate lineations may form.

Monomineralic rocks can develop strong *grain* lineations if the rock is only partly recrystallized and the recrystallized grain size is significantly smaller than the initial grain size. In this case, remaining larger grains are commonly elongate in shape and their preferred orientation defines a grain lineation element, well distinguishable from surrounding small grained aggregates that formed by dynamic recrystallization. However, *aggregate* lineations rarely develop in monomineralic rocks. Only, if a small fraction of a second phase is present, a moderate to strong aggregate lineation may form. This is probably the reason why some quartzites develop aggregate lineations and others do not.

Since the dynamically recrystallized grain size depends on differential stress and temperature during deformation (see above), moderate to strong aggregate lineations develop in polymineralic rocks and moderate to strong grain lineations in monomineralic rocks at high differential stress and/or low grade conditions.

Besides grain size, the degree of recrystallization (defined as the relative modal percentage of newly recrystallized grains to relict grains) can be expected to influence the strength of object lineations. In many cases, a core-and-mantle structure (Bell and Etheridge, 1973) will develop by partial recrystallization along boundaries of large old grains, and this produces weak lineations when the old grain relicts are equidimensional. However, if old grain cores are elongate and aligned, a grain lineation component will be present. This element could be parallel to an aggregate lineation component in the case of polymineralic rocks, strengthening the lineation, or could be the only object lineation element, e.g. in originally coarse-grained monomineralic rocks.

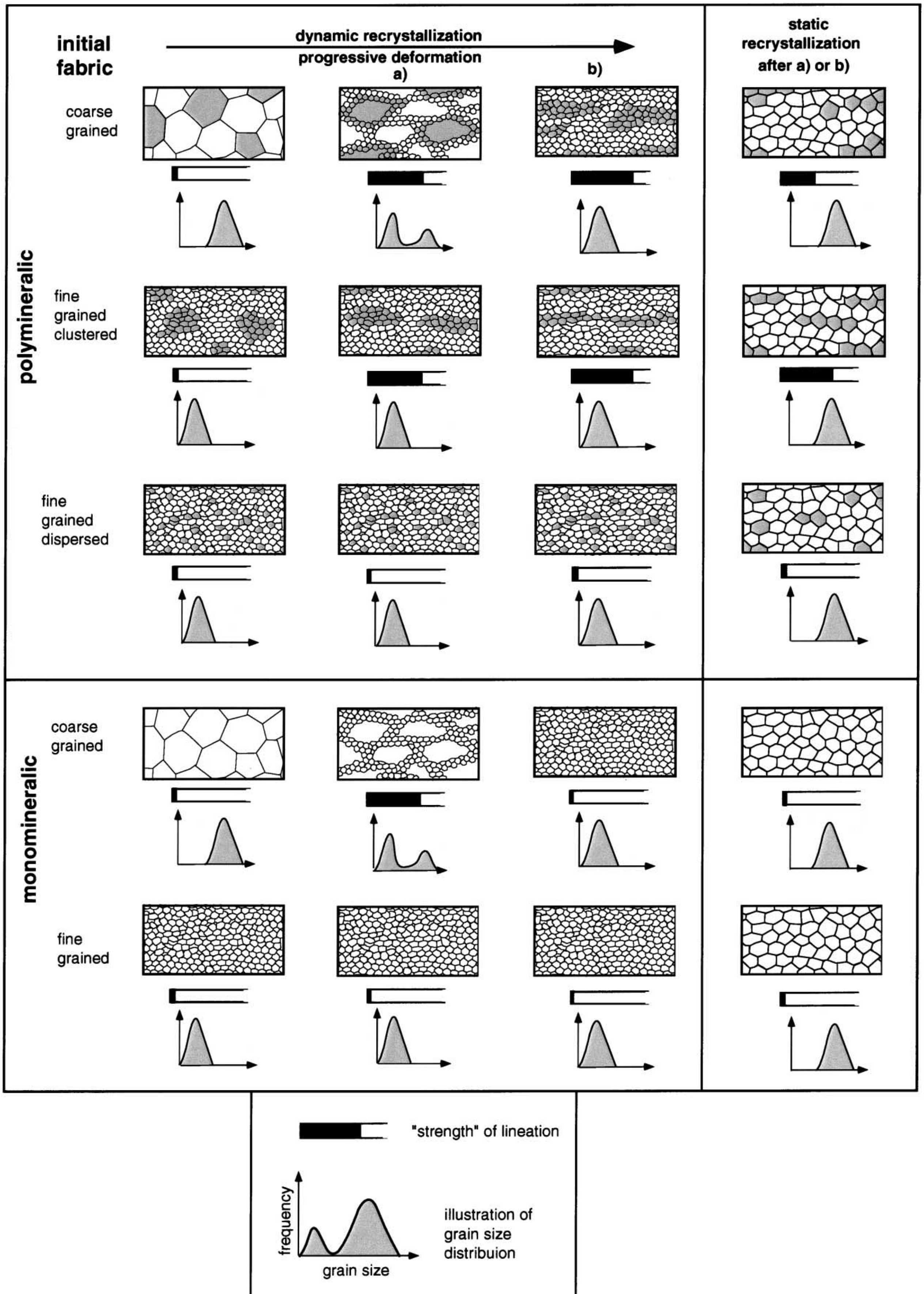
The considerations given above are confirmed by our observations in the Cap de Creus shear zones. In metapelitic, metapsammitic and metagranodioritic rocks of Cap de Creus (shear zones 1, 4, 5 and 6) quartz and feldspar are at least partly dynamically recrystallized. In polymineralic rocks recrystallized aggregates of feldspar and quartz have a mean size of 10 and 200 μm, respectively. Where the initial grain size significantly exceeds this dynamically recrystallized grain size of quartz, feldspar (Fig. 9B) or biotite (Fig. 9C) deformation and associated recrystallization result in the development of elongate aggregates, i.e. aggregate lineations. Usually, dynamic recrystallization starts at the grain boundaries resulting in a core-and-mantle structure. In quartz-dominated rocks, relict grains of such core-mantle-structures are elongate and define a grain lineation (Fig. 9A and B). In feldspar-rich rocks, relict old grains form equidimensional porphyroclasts (SP 126; SP 226) embedded in a fine-grained recrystallized matrix; thus, no grain lineation element develops.

Static recrystallization may cause obliteration or weakening of an object lineation since rock fabrics are markedly changed by associated grain growth (e.g. Bons and Urai, 1992). In monomineralic rocks, where an object lineation is defined by a bimodal grain size distribution of elongate grain relicts in a mass of fine recrystallized grains, static recrystallization will generally result in obliteration of the lineation as pervasive grain growth changes the grain size distribution from bimodal to unimodal. In polymineralic rocks, where aggregate lineations are defined by alternating strips or prolate lenses of dynamically recrystallized grains of one mineral, static recrystallization will not obliterate the lineation. Nevertheless, grain growth will change the character of the lineation because alternating aggregates of different minerals will be modified into elongate aggregates of few grains, or even single grains. The spatial distribution of the different phases and the elongate shape of the aggregates or grains may be preserved. This implies a change from an aggregate to a grain lineation.

Static recrystallization may be responsible for peculiar features of the D2-fabric in the Cap de Creus area as outlined in Section 4.3. We attribute the difference in D2 object lineation strength in fine-grained (high strength) and coarse-grained rocks (low strength) to the effect of static recrystallization. Pervasive static recrystallization acting on a deformed fine- to medium-grained rock exhibiting an object lineation will result in a coarse-grained rock with weakly developed lineations. The lineation may be preserved where static recrystallization is at least partly inhibited, e.g. because of pinning due to dispersion of other mineral phases. Static recrystallization probably occurred in the period between D2 and D3 since typical equilibrium textures (e.g. polygonal fabric with straight grain boundaries, triple junctions at 120°) are commonly seen in D2 fabrics unaffected by D3.

5.2. Growth of new phases

Metamorphic reactions change the mineral content of a rock and hence determine what minerals are available to form an object lineation. Lineation type and strength depend on the habit of minerals growing during deformation (e.g. Vernon, 1987). If at least one of the new phases is characterized by an elongate habit, a grain lineation can form due to either the oriented growth of the new mineral phase or its syntectonic rigid body rotation (Vernon, 1987). If new phases have an equidimensional habit, an aggregate lineation can form under certain circumstances. For example, clusters of newly grown equidimensional grains may form aggregate lineations during progressive deformation. Also, newly grown large grains may recrystallize dynamically during progressive deformation and form an aggregate lineation.


initial fabric
dynamic recrystallization
progressive deformation
a)
b)
static recrystallization after a) or b)
polymineralic
coarse grained
fine grained clustered
fine grained dispersed
monomineralic
coarse grained
fine grained
"strength" of lineation
frequency
grain size
illustration of grain size distribuion

In the Cap de Creus area, growth of new mineral phases is due to several retrogressive alteration reactions that took place during mylonitization: (a) plagioclase is altered to coarse muscovite (e.g. shear zone 2 and 9) or fine-grained sericite (e.g. shear zone 1 and 6); (b) potassium-rich feldspar and biotite or andalusite are altered to fibrolitic sillimanite and sericite and sometimes tourmaline (if boron-rich fluids were involved) (e.g. shear zone 5 and 7); (c) amphibole and feldspar are altered to epidote/zoisite (shear zone 3). Where these reactions led to growth of elongate minerals during deformation, existing object lineations are strengthened or new lineations are created. For example, syntectonic growth of fibrolite at the expense of andalusite results in moderate aggregate (elongate bundles of fibrolite) and grain lineations (isolated fibrolite needles) in mylonitised, initially coarse-grained metapelites. In the metapsammitic samples of shear zone 1 the contrast between quartz aggregates and chlorite/sericite domains defines an aggregate lineation whereby the presence of chlorite/sericite is a result of syntectonic metamorphic retrogression of feldspar and biotite. The amount of metamorphic replacement of one mineral by another plays a role in the strength of aggregate lineations. For example, the higher the amount of epidote/zoisite, which replaces amphibole, the higher the degree of preferred orientation. In SP 160 and SP 163 (shear zone 3) the amount of replacement of amphibole by a zoisite group mineral is 70 and 100%, respectively. This corresponds to κ-values of 3 and 3.4. Breakdown of minerals *after* deformation may weaken an object lineation that developed during deformation. For instance, weak aggregate lineations are present in SP 126 and SP 267 due to pervasive retrogression of a large percentage of the rock to fine-grained assemblages involving chlorite, quartz and sericite (Table 1).

5.3. Rigid body rotation

Rigid body rotation of mineral grains in a rock can account for an increase in the strength of an object lineation during progressive deformation since elongate mineral grains with high aspect ratios tend to rotate towards the extensional flow eigenvector. If rigid body rotation is the dominant process of object lineation development, the degree of dimensional preferred orientation depends on finite strain and on the modal amount of the lineation-forming material (Ildefonse, 1992a,b). Rigid body rotation of elongate minerals such as sillimanite and biotite may therefore result in moderate to strong grain lineations. Here again, grain size is important. Only if the matrix material enveloping the rigid mineral (e.g. biotite) is relatively fine-grained and deforms in a ductile manner, rigid body rotation can take place. Such an assumed viscous flow behaviour may be caused by dislocation climb, dynamic recrystallization and/or pressure solution. If the matrix is coarse-grained and does not deform viscously, rigid body rotation and thus the development of a grain lineation will be inhibited. Unfortunately, it is difficult in most cases to distinguish rigid body rotation from oriented growth of elongate mineral grains.

In the Cap de Creus area, we may see some effect of rigid body rotation. The sillimanite-bearing object lineations may be at least partly formed by rigid body rotation (see Section 5.2). In samples SP 227 (shear zone 5) and SP 358 (shear zone 8) biotite grains exhibit a strong preferred orientation that defines a grain lineation. This preferred orientation is probably due to rigid body rotation since biotite grains are not recrystallized while the recrystallized quartz matrix is fine-grained (0.02 mm).

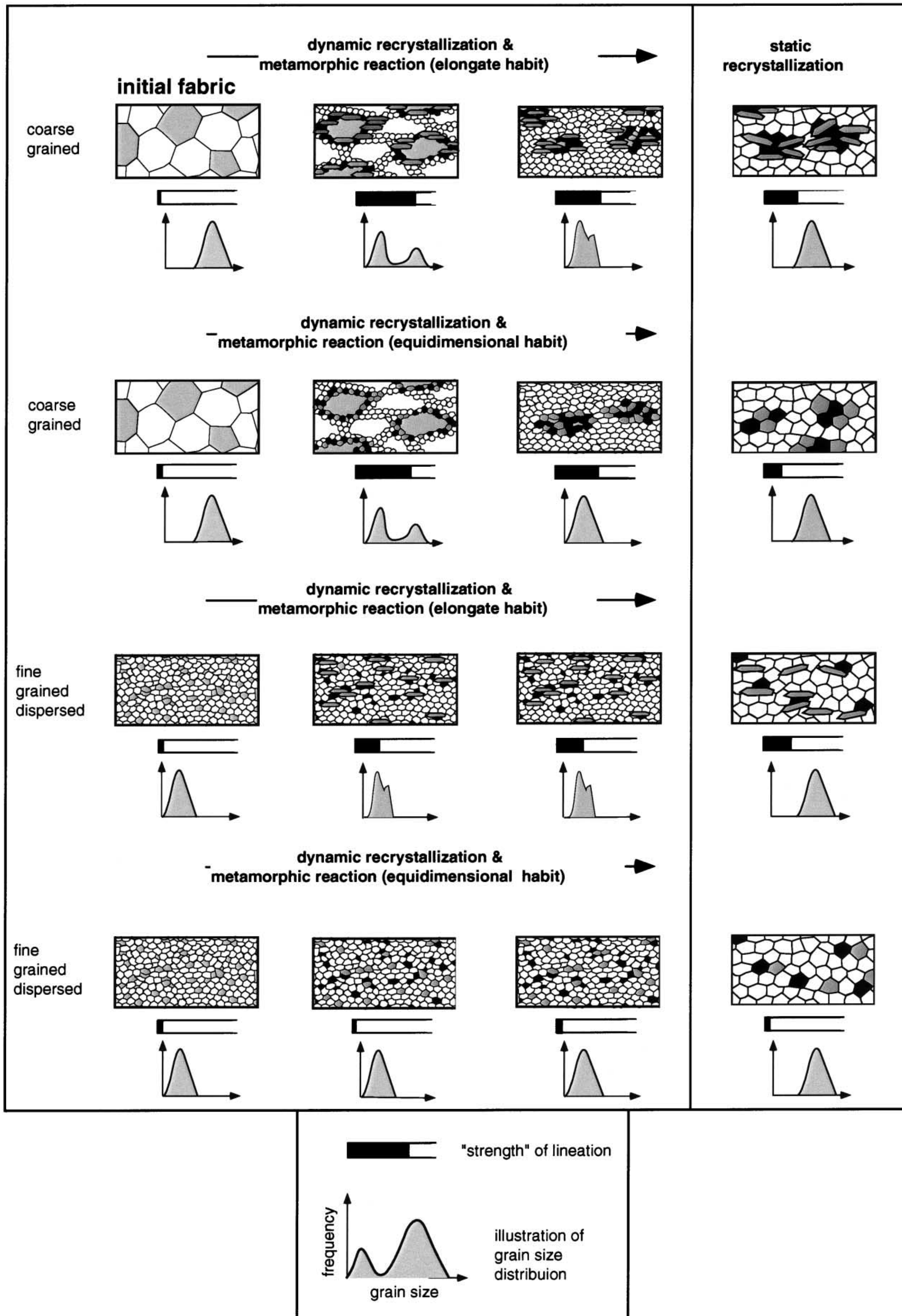
6. Conclusions — predictions for object lineation development

The presence and strength of an object lineation in a deformed rock is not only a function of finite strain but is also strongly influenced by other factors. The two most important factors are: (a) the initial rock fabric and mineral composition, and (b) the ratio of initial grain size to dynamically recrystallized grain size. These factors determine how processes active during and after deformation will affect the development of object lineations. The most important processes are dynamic and static recrystallization, metamorphic reactions and rigid body rotation. Based on the observations in the Cap de Creus shear zones, we predict a number of trends in the development of object lineations. These trends are summarized in Figs. 10 and 11.

During deformation and dynamic recrystallization without metamorphic reactions (Fig. 10), moderate to strong aggregate lineations form in originally coarse-grained polymineralic rocks and in clustered polymineralic fine-grained rocks. Well-developed aggregate lineations cannot form in other coarse- and fine-grained rocks. In contrast, moderate to strong grain lineations may form if a coarse-grained monomineralic rock is partly recrystallized during deformation. In this case a bimodal grain size distribution develops.

During deformation and dynamic recrystallization in the presence of metamorphic reactions, the result depends on the shape of the new mineral phases. Syndeformational growth of elongate minerals causes moderate to strong grain and aggregate lineations to develop from coarse-grained rocks (Fig. 11) but if new grains are equidimensional, weak to moderate aggregate lineations will probably form. In initially fine-grained fabrics with random distribution of

Fig. 10. Diagram depicting the effect of initial fabric on the development of lineations with respect to dynamic recrystallization and static recrystallization. Represented polymineralic rocks are limited to rocks with two mineral species. Grain sizes of recrystallized grains are assumed to be of the same grain size as initially fine-grained phases. For each resultant texture a schematic grain size distribution diagram and a bar illustrating the strength of lineation is shown. The longer the black bar the stronger the lineation.


dynamic recrystallization &
metamorphic reaction (elongate habit)
static recrystallization
initial fabric
coarse grained
dynamic recrystallization &
metamorphic reaction (equidimensional habit)
coarse grained
dynamic recrystallization &
metamorphic reaction (elongate habit)
fine grained dispersed
dynamic recrystallization &
metamorphic reaction (equidimensional habit)
fine grained dispersed
"strength" of lineation
frequency
grain size
illustration of grain size distribuion

mineral phases, syntectonic growth of elongate grains results in the development of weak to moderate grain lineations. If new grains are equidimensional, object lineations are absent. If the initial fabric is fine-grained but clustered (not shown in Fig. 11) the developing lineation is weak to moderate and of the aggregate type.

Static recrystallization subsequent to deformation generally causes monomineralic rocks to exhibit a significant decrease in object lineation strength as the grain size distribution tends to become unimodal with increasing static recrystallization (Fig. 10). In polymineralic rocks, the 'strength' of an object lineation will also decrease but will still be present even after a high degree of static recrystallization, since the spatial distribution of mineral phases is not significantly affected (Figs. 10 and 11). Breakdown of minerals after deformation may alter pre-existing lineations due to changes in the grain size distribution and to overgrowth.

Due to the significant effect of other factors than finite strain on the development and strength of an object lineation, a study looking at possible strain intensity, presence and orientation of tectonic transport should preferably involve the study of several rock types.

Acknowledgements

S.P. wishes to thank Mark Jessell, Gordon Lister, Paul Bons and other members of the Earth Science Department at Monash University, Australia for making facilities available used for this study. Special thanks to Dr Malcolm Clark (Monash University, Australia) for his introduction to the statistical methods of directional data and to Elena Druguet (Universidad Autonoma, Barcelona) for introducing S.P. to the field area. Comments by the reviewers Prof. J. Hippertt, Dr I. Alsop, Dr R.J. Lisle, as well as by Dr E. Druguet, Dr K. Gessner and Dr P. Bons considerably improved earlier versions of this manuscript. For positive and negative comments concerning changes to lineation terminology we wish to thank P. Bons, H. de Bresser, B. den Brok, J. Carreras, E. Druguet, G. Gosso, H. Stünitz, S. Treagus, J. Urai, P. Williams and C. Wilson. This work was funded by the Deutsches Akademisches Auslandsamt Deutschland and the Deutsche Forschungsgemeinschaft (GRK 392/1-99).

Appendix A. Statistical evaluation of the degree of preferred dimensional orientation

Masuda et al. (1999) proposed a statistical approach to determine the degree of preferred dimensional orientation of a grain and/or aggregate lineation quantified by the concentration parameter κ. We further develop this technique by automating measurements of lineations and substituting the χ^2-test used by Masuda et al. (1999) with a Rayleigh test.

The von Mises distribution, which underlies the used statistical concept is commonly referred to as the equivalent of a normal distribution, which is specifically used to statistically evaluate circular data. The basic assumption for both distributions (normal and von Mises) is that the characteristics of the samples (in our case: measurement of the orientation of one individual mineral grain or mineral aggregate in-hand specimen or thin section) are independent from each other and that their measured values depend on a large number of factors. These assumptions only hold true if grains not directly adjacent to each other are measured, otherwise the dimensional orientation of neighbouring crystals are not necessarily independent from each other (Ildefonse et al., 1992a,b; Masuda et al., 1995). Work of Masuda et al. (1999) and tests carried out in our laboratory suggest that the distribution of the dimensional orientation of object lineations within rocks is well approximated by a von Mises distribution.

The reader is referred to Masuda et al. (1999) for the definition of the density function and other properties of a von Mises distribution. The value of the factor R, the value of the mean resultant vector describing circular data (see Masuda et al. (1999) for further explanation) provides the possibility for estimating the so-called 'concentration parameter' κ, since κ is a monotonic function of R. R ranges from zero to one whereas κ ranges from zero to infinity. The value of κ is preferable to R due to its wider range of values. The higher the κ-value the higher the preferred orientation of the measured population of elongate objects. The κ-value can be accurately determined using existing tables (Mardia, 1972, p. 298) that tabulate the relationship of R and κ. Nevertheless, we consider the following estimates sufficient for our purpose. For R values <0.45:

$$\kappa = 2R \tag{A1}$$

for $0.45 < R < 0.65$:

$$\kappa = \frac{R}{6}\left(12 + 6R^2 + 5R^4\right) \tag{A2}$$

and for $R > 0.65$ κ is approximated by:

$$\kappa = \frac{1}{2(1-R) - (1-R)^2 + (1-R)^3} \tag{A3}$$

The higher the κ-values the stronger the preferred shape orientation of a lineation as measurements are concentrated around a certain value. As a rule of thumb, if the κ-value is above one there is a noticeable but weak preferred dimensional orientation, if it is above two it is well defined, and if it is above five it is exceptionally strong. Measurements of κ

Fig. 11. Diagram depicting the effect of initial fabric, dynamic and static recrystallization and metamorphic reaction on the development of lineations during and after deformation. Two different types of metamorphic reactions are distinguished, whereby (A) one new phase is elongate, and (B) two new phases are equidimensional in shape. For each resultant texture a schematic grain size distribution diagram and a bar illustrating the strength of lineation is shown. The longer the black bar the stronger the lineation.

Table A1
Rayleigh test chart (valid for $\alpha = 0.05$) to determine if there is a significant dimensional preferred orientation or not. To use this chart, calculate the value for z with z(calculated) $= n_i \times r^2$ with n_i = number of samples and r = length of the mean vector and compare the calculated z with the $z(\alpha)$. If z(calculated) $> z(\alpha)$ then the null hypothesis is rejected which means that the distribution is *not* uniform, therefore the sample has a statistically significant shape preferred orientation. We suggest that $z(\alpha)$ with $\alpha = 0.05$ is used as such a allowance of variance is reasonable in geological applications. It should be noted that for the determination of κ-values for lineations of both in-hand specimens and thin sections can be used. For $n_i < 30$ refer to Appendix 3.5 in Mardia (1972, p. 325)

n_i	$z(\alpha) = z(0.05)$
30	2.97
50	2.98
100	2.99
200	2.99
500	2.99

in a large variety of rocks of different metamorphic grade and strain show that in natural samples κ-values commonly range between zero (no preferred dimensional orientation) and 10 (very strong lineation). To ensure a statistically significant result the number of single orientation measurements of individual grains or grain aggregates must not be less than 20 although we think one should aim for measurement numbers of at least 30. To test if there is a statistically significant shape preferred orientation, which signifies the presence of a lineation, we suggest the Rayleigh test (for details see Table A1 and explanations in Mardia (1972) and Batschelet (1981)) using a value of $\alpha = 0.05$ signifying the degree of allowable variance. A Rayleigh test chart is provided below for sample numbers $n \geq 30$ (and on the Excel spreadsheet at http://www.elsevier.nl/locate/jstrugeo. In the hopefully rare case of a single measurement number n of less than 30 the reader is referred to Mardia (1972; Table A1). As a rule of thumb, a κ-value of less than 0.2 generally signifies that there is no geologically significant preferred orientation of the measured grains or grain aggregates. The concentration parameter κ of a von Mises distribution can be estimated in the field using a chart provided at http://www.elsevier.nl/locate/jstrugeo or by a precise analytical method in a laboratory. The latter involves both visual evaluation and statistical testing and analysis as described above. Obviously, it is necessary to ensure a high number of measurements (>30) and to be aware that the outcome of measurements can be biased by selective measurements of grains with a specific orientation.

Appendix B. Detailed description of investigated shear zones (except shear zones 1, 4, 6; see text)

B.1. Shear zone 2

This D3 shear zone deforms a granodiorite. SP 151A (margin of shear zone) is characterized by large grains of Fsp and Bt and medium-grained Qtz. The magmatic texture is still well preserved in the undeformed sample. In SP 151B (centre of the shear zone) Qtz forms both stringers of small grained aggregates and medium to large elongate grains which are characterized by strong undulatory extinction. Fsp is frequently fractured, but along its rims subgrains are present and domains of very small grained equidimensional Fsp (0.01–0.06 mm) and chlorite grains are present. Domains of Fsp and white mica in contrast to recrystallized Qtz aggregates result in a 3.0 i-(Qtz/Fsp) aggregate lineation.

B.2. Shear zone 3

Samples SP 160 and SP 163 stem from the same rock unit at the centre of the shear zone. The thickness of this lithology and therefore strain differs between the two sample sites (SP 160: 6.2 cm; SP 163: 2 cm). In both samples Fsp, Qtz, Ep and minor amounts of mica are present. Fsp is strongly seriticized and only present as relicts and Qtz shows small equidimensional grains and medium size grains with irregular grain boundaries. Micas are rare and fine-grained. Mineral phases of the epidote–zoisite group appear as slightly elongated crystals and aggregates in the matrix of Qtz and Fsp (3.4 i-Ep grain lineation). In SP 163 relicts of amphiboles are present, which are rimmed by epidote. Ep forms clusters of up to 2 mm (3.0 i-Ep grain lineation).

B.3. Shear zone 5

Outside the shear zone the fine-grained metapsammite shows a D2, 2.6 i-Bt grain lineation formed by oriented Bt grains (0.5–1 mm). In the outer parts of the shear zone the lineation is deflected and Bt are recrystallized at their rims. At the centre of the shear zone Bt is completely recrystallized and Fsp breaks down to Ab-rich Fsp and white mica. Dynamically recrystallized grains are very fine-grained (0.01–0.02 mm) and relict Fsp and Qtz crystals (0.2–0.4 mm) are predominantly rounded (SP 225). Here, the rock does not exhibit a statistically significant preferred dimensional orientation. In the centre of the shear zone a lineation is again developed, this time the lineation is formed by aggregates of recrystallized Bt and chlorite flakes make up 1.4 i-(Bt/Chl) aggregate lineation.

The medium-grained metapelite initially exhibits a D2, strong Bt grain lineation where Bt grains are aligned in a matrix of medium-grained Fsp and Qtz.

The coarse-grained metapelite has a weak D2 lineation outside the shear zone formed by fibrolite (1.2 i-Fibr aggregate lineation). In the centre of the shear zone the strength of lineation increases ($\kappa = 2.6$) as Fibr is aligned and clusters of fibrolite become more and more elongate and similarly oriented.

B.4. Shear zone 7

In SP 291 (outside shear zone) some grains of And and a few aggregates of fibrolite are present. In SP 290 and SP 289, which are from the outer part and the centre of the shear zone, respectively, no relict And crystals remain and Fibr aggregates form elongate-shaped bundles. These aggregates show a high degree of preferred dimensional orientation (3.2 s-Fibr aggregate) in contrast to the 0.9 i-And grain lineation and 1.8 i-Fibr aggregate lineation of sample SP 291.

B.5. Locality 8

A quartzite layer which was deformed during D1 and D2 but not during D3 has small amounts of Bt. It shows a 2.1 s-Bt grain lineation due to small Bt grains (0.1 mm) in a matrix of fine-grained Qtz (0.02 mm).

B.6. Shear zone 9

The shear zone deforms a granodiorite. Outside the shear zone at Fsp (Ø ≈ 5 mm) rims Bt is abundant in up to 1-mm-sized grains (SP 416B) and Qtz is medium-grained or partly recrystallized. The Bt mineral lineation is a 1.6 s-Bt grain lineation. In SP 416A (centre of shear zone) no Fsp grains larger than 0.5 mm in diameter occur and a well-developed Bt aggregate lineation is present (2.1 i-Bt aggregate lineation). The total amount of mica increased from 18 to 47%. Individual grains and aggregates of Bt are aligned alongside Fsp grains and dynamically recrystallized Qtz aggregates show a well defined preferred dimensional orientation.

B.7. Locality 10

A quartzite layer was deformed during D1 and D2. Elongation of old medium to large Qtz grains and aggregates of small grains and the bimodal distribution of grain sizes result in a well defined lineation (2.1 i-Qtz grain lineation; SP 463).

References

Azor, A., Simancas, J.F., Exposito, I., Lodeiro, F.G., Poyatos, D.J.M., 1997. Deformation of garnets in a low-grade shear zone. Journal of Structural Geology 19, 1137–1148.

Batschelet, E., 1981. Circular Statistics in Biology. Academic Press, London.

Bell, T.H., Etheridge, M.A., 1973. Microstructures of mylonites and their descriptive terminology. Lithos 6, 337–348.

Bell, T.H., Cuff, C., 1989. Dissolution, solution transfer, diffusion versus fluid flow and volume loss during deformation and metamorphism. Journal of Metamorphic Geology 7, 425–447.

Bons, P.D., Urai, J.L., 1992. Syndeformational grain growth: microstructures and kinetics. Journal of Structural Geology 14, 1101–1109.

Carreras, J., Garcia, A., 1982. Quartz *c*-axis fabric variation at the margins of a shear zone developed in schists from Cap de Creus (Spain). Acta Geol. Hisp. 17, 137–149.

Carreras, J., Casas, J.M., 1987. On folding and shear zone development: a mesoscale structural study on the transition between two different tectonic styles. Tectonophysics 135, 87–98.

Carreras, J., Druguet, E., 1994. Structural zonation as a result of inhomogeneous non-coaxial deformation and its control on syntectonic intrusions: an example from the Cap de Creus area (eastern-Pyrenees). Journal of Structural Geology 16, 1525–1534.

Carreras, J., Estrada, A., White, S., 1977. The effects of folding on the *c*-axis fabrics of a quartz mylonite. Tectonophysics 39, 3–24.

Christie, J.M., Ord, A., 1980. Flow stress from microstructures of mylonites: example and current assessment. Journal of Geophysical Research 85, 6253–6262.

De Bresser, J.H.P., Peach, C.J., Reijs, J.P.J., Spiers, C.J., 1998. On dynamic recrystallization during solid state flow: effects of stress and temperature. Geophysical Research Letters 25, 3457–3460.

Druguet, E., 1997. The structure of the NE Cap de Creus peninsula. Relationships with metamorphism and magmatism. Unpubl. Thesis, Univ. Autònoma de Barcelona.

Druguet, E., Hutton, D.H.W., 1998. Syntectonic anatexis and magmatism in a mid-crustal transpressional shear zone: an example from the Hercynian rocks of the eastern Pyrenees. Journal of Structural Geology 20, 905–916.

Druguet, E., Passchier, C.W., Carreras, J., Victor, P., den Brok, S., 1997. Analysis of a complex high-strain zone at Cap de Creus, Spain. Tectonophysics 280, 31–45.

Drury, M.R., Urai, J.L., 1990. Deformation-related recrystallization processes. Tectonophysics 172, 235–253.

Ellis, M., Watkinson, A.J., 1987. Orogen-parallel extension and oblique tectonics: the relation between stretching lineations and relative plate motions. Geology 15, 1022–1026.

Ferguson, C.C., 1979. Rotations of elongate rigid particles in slow non-newtonian flows. Tectonophysics 60, 247–262.

Flinn, D., 1978. Construction and computation of three-dimensional progressive deformations. Journal of the Geological Society of London 135, 291–305.

Fossen, H., Tikoff, B., 1998. Extended models of transpression and transtension, and application to tectonic settings. In: Holdsworth, R.E., Strachan, R.A., Dewey, J.F. (Eds.), Continental Transpressional and Transtensional Tectonics. Geological Society, London, Special Publications 135, pp. 15–33.

Freeman, B., Lisle, R.J., 1987. The relationship between tectonic strain and the three-dimensional shape fabrics of pebbles in deformed conglomerates. Journal of the Geological Society of London 144, 635–639.

Guillopé, M., Poirier, J.P., 1979. Dynamic recrystallization during creep of single crystalline halite: an experimental study. Journal of Geophysical Research 4, 5557–5567.

Hirth, G., Tullis, J., 1992. Dislocation creep regimes in quartz aggregates. Journal of Structural Geology 14, 145–159.

Hobbs, B.E., Means, W.D., Willians, P.F., 1976. An Outline of Structural Geology. Wiley, New York.

Ildefonse, B., Launeau, P., Bouchez, J.-L., Fernandez, A., 1992a. Effect of mechanical interactions on the development of shape preferred orientations: a two-dimensional experimental approach. Journal of Structural Geology 14, 73–83.

Ildefonse, B., Sokoutis, D., Mancktelow, N., 1992b. Mechanical interactions between rigid particles in a deforming ductile matrix. Analogue experiments in simple shear flow. Journal of Structural Geology 14, 1253–1266.

Ježek, J., Melka, R., Schulmann, K., Venera, Z., 1994. The behaviour of rigid triaxial ellipsoidal particles in viscous flows — modeling of fabric evolution in a muliparticle system. Tectonophysics 229, 165–180.

Ježek, J., Schulmann, K., Segeth, K., 1996. Fabric evolution of rigid inclusions during mixed coaxial and simple shear flows. Tectonophysics 257, 203–221.

Kretz, R., 1983. Symbols for rock-forming minerals. American Mineralogist 68, 277–279.

Kronenberg, A.K., Tullis, J., 1984. Flow strengths of quartz aggregates: grain size and pressure effects due to hydrolic weakening. Journal of Geophysical Research 89, 4281–4297.

Lisle, R.J., Rondeel, H.E., Doorn, D., Brugge, J., van de Gaag, P., 1983. Estimation of viscosity contrast and finite strain from deformed elliptical inclusions. Journal of Structural Geology 5, 603–609.

Lloyd, G.E., Law, R.D., Mainprice, D., Wheeler, J., 1992. Microstructural and crystal fabric evolution during shear zone formation. Journal of Structural Geology 14, 1079–1100.

Mardia, K.V., 1972. Statistics of Directional Data. Academic Press, London.

Masuda, T., Kugimiya, Y., Aoshima, I., Hara, Y., Ikei, H., 1999. A statistical approach to determination of mineral lineation. Journal of Structural Geology 21, 467–472.

Masuda, T., Michibayashi, K., Ohta, H., 1995. Shape preferred orientation of rigid particles in a viscous matrix: re-evaluation to determine kinematic parameters of ductile deformation. Journal of Structural Geology 17, 115–130.

Means, W.D., 1981. The concept or steady-state foliation. Tectonophysics 78, 179–199.

O'Leary, D.W., Friedman, D.E., Pohn, H.A., 1976. Lineament, linear, lineation: some proposed new standards for old terms. Geological Society of American Bulletin 87, 1463–1469.

Park, R.G., 1993. Foundations of Structural Geology. Chapman and Hall, New York.

Passchier, C.W., Trouw, R.A.J., 1996. Microtectonics. Springer, Berlin.

Paterson, S.R., 1983. A comparison of methods used in measuring finite strains from ellipsoidal objects. Journal of Structural Geology 5, 611–618.

Peterson, V.L., Robinson, P., 1993. Progressive evolution from uplift to orogen-parallel transport in a late-acadian, upper amphibolite- to granulite-facies shear zone, south-central Massachusetts. Tectonics 12, 550–567.

Price, N.J., Cosgrove, J.W., 1990. Analysis of Geological Structures. Cambridge University Press, Cambridge.

Ramsay, J.G., 1958. Superposed folding in Loch Monar, Inverness-shire and Ross-shire. Quarterly Journal of the Geological Society of London 113, 271–308.

Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw-Hill, New York.

Ramsay, J.G., 1980. Shear zone geometry: a review. Journal of Structural Geology 2, 83–99.

Sander, B., 1930. Gefügekunde der Gesteine. Springer Verlag, Wien.

Sellars, C.M., 1978. Recrystallization of metals during hot deformation. Philosophical Transactions of the Society of London 288, 147–158.

Shackleton, R., 1993. Tectonics of the lower crust: a view from the Usambara Mountains, NE Tanzania. Journal of Structural Geology 15, 663–671.

Sutton, J., Watson, J., 1955. The structure and stratigraphic succession of the Moines of Fannich Forest and Strath Bran, Ross-shire. Quarterly Journal of the Geological Society of London 110, 21–53.

Tikoff, B., Greene, D., 1997. Stretching lineations in tranpressional shear zones: an example from the Sierra Nevada Batholith, California. Journal of Structural Geology 19, 29–39.

Trimby, P.W., Prior, D.J., Wheeler, J., 1998. Grain boundary hierarchy development in a quartz mylonite. Journal of Structural Geology 20, 913–935.

Tullis, J., Yund, R.A., 1985. Dynamic recrystallization of feldspar: a mechanism for ductile shear zone formation. Geology 13, 238–241.

Turner, F.J., Weiss, L.E., 1963. Structural Analysis of Metamorphic Tectonites. McGraw-Hill, New York.

Twiss, R.J., 1977. Theory and applicability of recrystallized grain size paleopiezometer. Pure and Applied Geophysics 115, 199–226.

Twiss, R.J., Moores, M.E., 1992. Structural Geology. W.H. Freeman and Company, New York.

Urai, J.L., Means, W.D., Lister, G.S., 1986. Dynamic recrystallization of minerals. American Geophysical Union Geophysical Monograph 36, 161–199.

Vernon, R.H., 1987. Growth and concentration of fibrous sillimanite related to heterogeneous deformation in K-feldspar–sillimanite metapelites. Journal of Metamorphic Geology 5, 51–68.

Weijermars, R., 1992. Progressive deformation in anisotropic rocks. Journal of Structural Geology 14, 723–742.