DUCTILE SHEAR ZONES
From Micro- to Macro-scales

Edited by Soumyajit Mukherjee and Kieran F. Mulchrone
DUCTILE SHEAR ZONES
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Thanks to Beth Dufour for looking at permission issues and to Alison Woodhouse for assistance in copyediting, and Kavitha Chandrasekar, Sukanya Shalisha Sam and Janyne Ste Mary for numerous help for all the chapters in this book.
Kinematics of ductile shear zones is a fundamental aspect of structural geology (e.g. Ramsay 1980; Regenauer-Lieb and Yuen 2003; Mandal et al. 2004; Carreras et al. 2005; Passchier and Trouw 2005; Mukherjee 2011, 2012, 2013, 2014a; Koyi et al. 2013; Mukherjee and Mulchrone 2013; Mukherjee and Biswas 2014; and many others). This edited volume compiles a total of 17 research papers related to various aspects of ductile shear zones.

In the first section “Theoretical Advances and New Methods”, Vitale and Mazzoli (2016) describe an inverse method to deduce the incremental strain path in heterogeneous ductile shear zones, and have applied the method in a wrench zone hosted in pre-Alpine batholiths. Field studies, analog and numerical modeling presented by Dasgupta et al. (2016) strongly indicate that volume reduction augments transpression in ductile shear zones. In addition, two parameters that control shortening perpendicular to shear zones are defined. Mulchrone et al. (2016) analytically model steady state and oblique foliation development in shear zones and present the possibility of estimating: (i) the relative strength of foliation destroying processes, (ii) the relative competency of the grains, and (iii) the kinematic vorticity number. Schrank et al. (2016) analytically model the deformation of inclusions with a hyperelastoviscoplastic rheology under ductile lithosphere conditions, and predict the evolution of the shape of the inclusion. Mukherjee and Biswas (2016) presented kinematics of layered curved simple shear zones. Considering Newtonian viscous rheology of the litho-layers, they explain how aspect ratios of inactive initially circular markers keep changing.

In the second section “Examples from Regional Aspects”, Boutonnet and Leloup (2016) discuss Quartz strain-rate-metry from shear zones at Ailao Shan–Red River (China) and Karakoram (India) and strain rate variation within these zones. They decipher high slip rates of the order of cm per year from both these zones. Applying Titanium-in-quartz thermobarometry on Scandinavian Caledonides, Wolfowicz et al. (2016) deduce a geothermal gradient and support a critical taper mechanism of deformation. Pace et al. (2016) study brittle-ductile shear zones from the Central–Northern Apennines related to frontal and oblique ramps and deduced structural inheritance of extensional faults. Sengupta and Chatterjee (2016) deduce lower amphibolites facies metamorphism in the Phulad Shear Zone (India). Antithetically oriented clasts indicate a general shear deformation; however, the method of vorticity analysis applied was found unsuitable since the deformation was heterogeneous and the shear zone contains a number of phases of folds. Chattopadhyay et al. (2016) describe how ductile shear altered the mineralogy, chemistry and texture of rocks from the South Purulia Shear Zone (India). Using phase diagrams, they also constrain the temperature of metasomatism. In a study of ductile shear zones in the Kharian basin (India), Bhadra and Gupta (2016) decipher two movement phases along the Terrane Boundary Shear Zone. Mukherjee et al. (2016) review morphology and genesis of intrafolial folds and deduce their Class 1C and Class 2 morphologies from Zanskar Shear Zone from Kashmir Himalaya. Pamplona et al. (2016) classify the Malpica Lamego Ductile Shear Zone into sectors of different deformation patterns, such as sinistral or dextral shear and flattening. Pseudosection studies by Delpino et al. (2016) for ductile shear zone in the Pringles Metamorphic Complex (Argentinia) yield thermal curves. Kanjanapayont (2016) reviews ductile shear zones in Thailand, presents structural details, and constrains and correlates when they were active. Takahashi (2016) studies the Nihonkoku Mylonite Zone (Japan) and found that its mylonitization during 55–60 Ma correlates with deformation in the Tanagura Tectonic Line. Flanking structures (Passchier 2001; Mukherjee and Koyi 2009; Mukherjee 2014b, etc.) has recently been of great interest in the context of ductile shear zones. Goswami et al. (2016) describe the geometry of flanking structures from Arunachal Pradesh, Higher Himalaya, India and use contractional flanking structures to deduce shear sense.

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PART I
Theoretical Advances and New Methods
Chapter 1
From finite to incremental strain: Insights into heterogeneous shear zone evolution

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1.1 INTRODUCTION

Heterogeneous ductile shear zones are very common in the Earth’s lithosphere and are particularly well exposed in mountain belts (e.g. Iannace and Vitale 2004; Yonkee 2005; Vitale et al. 2007a,b; Okudaira and Beppu 2008; Alsleben et al. 2008; Sarkarinejad et al. 2010; Kuiper et al. 2011; Dasgupta et al. 2012; Zhang et al. 2013; Samani 2013; Mukherjee 2013, 2014; also see Chapter 9), where they provide useful tools for a better understanding of the processes and parameters controlling strain localization, type of deformation, and rock rheology. The occurrence of strain markers such as fossils, ooids and ellipsoidal clasts in sedimentary rocks, or equant minerals, deflected veins and dykes in igneous rocks, allows one to quantify the finite strain by means of various methods (e.g. Dunnet 1969; Fry 1979; Lisle 1985; Erslev 1988; Vitale and Mazzoli 2005, 2010).

Finite strains are all quantities, directly measured or derived, related to the final state of deformation. These finite quantities, such as strain ratio, effective shear strain (sensu Fossen and Tikoff 1993), and angle $\theta'$ between the shear plane and oblique foliation in heterogeneous ductile shear zones, cannot furnish unequivocal information about the temporal strain evolution (i.e. strain path; Flinn 1962). This is because there are several combinations of deformation types such as simple shear, pure shear and volume change, that can act synchronously or at different times, leading to the same final strain configuration (Tikoff and Fossen 1993; Fossen and Tikoff 1993; Vitale and Mazzoli 2008, 2009; Davis and Titus 2011). Appropriate constraints are needed to obtain a unique solution – or at least reduce the under-determination. This also implies introducing some assumptions in the definition of the strain model. The strain path may be envisaged as a temporal accumulation of small strain increments, and the final strain arrangement as the total addition (Ramsay 1967). A possible relationship between final strain configuration and temporal evolution (i.e. incremental strains) was suggested by different authors, such as Hull (1988), Mitra (1991) and Means (1995). The latter author envisaged strain softening/hardening as the main rheological control on shear zone evolution: shear zones characterized by a thickness decreasing with time (Type II) result from strain softening, whereas shear zones characterized by increasing thickness (Type I) are produced by strain hardening (Means 1995). Based on this view, each part of a heterogeneous ductile shear zone is the result of a different strain evolution, and taken all together, the various shear zone sectors may be able to record the whole strain history.

During the last few years, several papers dealt with the possibility of calculating the incremental strain knowing the temporal and spatial evolution of the deformation. Provost et al. (2004) reconstruct the deformation history by means of the $n$ times iteration of the transforming equation characterizing the incremental strain, where $n$ is the number of deformation stages. Horsman and Tikoff (2007) focus the opportunity of separating, by previous method, the strain related to the shear zone margins, where according to Ramsay (1980) the deformation is weak, and that associated with the more deformed shear zone sectors. The authors consider heterogeneous shear zones as consisting of sub-zones, each characterized by a roughly homogeneous deformation. Based on their temporal and spatial evolution, shear zones are then classified into three main groups: (i) constant-volume deformation, (ii) localizing, and (iii) delocalizing deformation. In the first case, the shear zone boundaries remain fixed (Type III shear zone of Hull (1988); Mitra (1991); Means (1995)), whereas for the latter two groups the shear zone boundaries migrate with time, leading to decreasing (group ii) or increasing (group iii) thickness of the actively deforming zone (respectively Type II and Type I shear zones of Hull (1988); Mitra (1991); Means (1995)).

Following Means (1995), Vitale and Mazzoli (2008) provide a mathematical forward model of strain accumulation within an ideal heterogeneous shear zone by sub-dividing it into $n$ homogenously deformed layers, each one...
bound by shear planes (C-planes: Passchier and Trouw 2005) and characterized by a specific evolution, this being related to that of adjacent layers within the framework of a defined temporal succession. In the case of strain hardening, the strain evolution starts with a homogeneous deformation affecting originally a specific volume of rock (being represented by a single layer in the model). As the original “single layer” is able to accumulate only a specific amount of strain (due to strain hardening), further shearing involves new material located along the shear zone margins (Mazzoli and Di Bucci 2003; Mazzoli et al. 2004), thereby increasing the active shear zone volume (delocalizing zone) and synchronous pure shear elsewhere. The shear zone is composed of n deformed layers, each characterized by homogeneous strain. The strain evolution is illustrated in Fig. 1.1 when strain softens (localizing shear zone) and hardens (delocalizing shear zone), where matrices B_i and C_in represent finite strain within the shear zone and in the host rock in the last configuration, respectively, whereas matrices A_i and C_i are related to incremental strain.

In the case of a localizing shear zone, indicating with B_i the finite strain matrix of the i-th layer in the last configuration (n), the finite strain matrix is related to the incremental matrices by the following relationships (with i ranging between 2 to n – 1):

\[ B_i = C^{i-1} A_i \rightarrow C^{i-1} B_i = (C^{i-1})^{-1} C^{i-1} A_i \rightarrow A_i = (C^{i-1})^{-1} B_i, \]
\[ B_2 = C^{i-1} A_i A_i \rightarrow B_2 = C^{i-1} A_i (C^{i-1})^{-1} B_i \rightarrow A_2 = (C^{i-1})^{-1} B_i (B_i)^{-1} C^{i-1}, \ldots \]
\[ A_j = (C^{j-1})^{-1} B_j (B_i)^{-1} C^{j-1}. \]

Fig. 1.1. Examples of strain evolution along the xy plane of the coordinate reference frame for heterogeneous shear zones consisting of seven homogeneously deformed layers and characterized by transtension in the active shear zone and synchronous pure shear elsewhere. (a) Localizing shear zone. (b) Delocalizing shear zone.

1.2 INCREMENTAL STRAIN

To obtain a mathematical relationship between incremental and finite strain, consider the general case of deformation being localized within a heterogeneous ductile shear zone with synchronous deformation in the host rock. The shear zone is composed of n deformed layers, each characterized by homogeneous strain. The strain evolution is illustrated in Fig. 1.1 when strain softens (localizing shear zone) and hardens (delocalizing shear zone), where matrices B_i and C_in represent finite strain within the shear zone and in the host rock in the last configuration, respectively, whereas matrices A_i and C_i are related to incremental strain.

In the case of a localizing shear zone, indicating with B_i the finite strain matrix of the i-th layer in the last configuration (n), the finite strain matrix is related to the incremental matrices by the following relationships (with i ranging between 2 to n – 1):

\[ B_i = C^{i-1} A_i \rightarrow (C^{i-1})^{-1} B_i = (C^{i-1})^{-1} C^{i-1} A_i \rightarrow A_i = (C^{i-1})^{-1} B_i, \]
\[ B_2 = C^{i-1} A_i A_i \rightarrow B_2 = C^{i-1} A_i (C^{i-1})^{-1} B_i \rightarrow A_2 = (C^{i-1})^{-1} B_i (B_i)^{-1} C^{i-1}, \ldots \]
\[ A_j = (C^{j-1})^{-1} B_j (B_i)^{-1} C^{j-1}. \]
In the case of a delocalizing shear zone the relationship:

\[ A_i = B_i (C_{m-1}^{in})^{-1} C_{m-1}^{fin} (B_{i-1})^{-1} = B_i C (B_{i-1})^{-1}. \] (2)

1.2.1 Special case of no deformation in the host rock

In the case of \( C = 1 \) (identity matrix), i.e. no deformation in the host rock, Equations (1) and (2) are always substituted by the equation:

\[ A_i = B_i (B_{i-1})^{-1}. \] (3)

In this circumstance, the relationships between incremental and finite strain quantities (stretches and effective shear strains) may be directly obtained by rewriting Equation 3 in an explicit form. Consider a wrench zone in which each \( i \)-th layer is characterized by finite strain represented by the matrix (Tikoff and Fossen 1993):

\[
B_i = \begin{bmatrix}
\left( k_{fi}^{fin} \right)_{i} & \Gamma_{i}^{fin} & 0 \\
0 & \left( k_{fi}^{fin} \right)_{i} & 0 \\
0 & 0 & \left( k_{fi}^{fin} \right)_{i}
\end{bmatrix},
\] (4)

where

\[
\Gamma^{fin}_i = \ln \left( \frac{\left( k_{fi}^{fin} \right)_{i}}{\left( k_{fi}^{fin} \right)_{i-1}} \right),
\] (5)

is the \( i \)-th finite effective shear strain.

Applying Equation 3 this yields:

\[ A_i = B_i B_{i-1}^{-1} = \begin{bmatrix}
\left( k_{fi}^{fin} \right)_{i} & \Gamma_{i}^{fin} & 0 \\
0 & \left( k_{fi}^{fin} \right)_{i} & 0 \\
0 & 0 & \left( k_{fi}^{fin} \right)_{i}
\end{bmatrix},
\] (6)

where \( A_i \) is the incremental matrix referred to the \( i \)-th step.

The relationships between incremental and finite quantities are obtained:

\[
\left( k_{fi}^{incr} \right)_{i} = \frac{\left( k_{fi}^{fin} \right)_{i}}{\left( k_{fi}^{fin} \right)_{i-1}}, \quad \left( k_{fi}^{incr} \right)_{i} = \frac{\left( k_{fi}^{fin} \right)_{i}}{\left( k_{fi}^{fin} \right)_{i-1}}, \quad \left( k_{fi}^{incr} \right)_{i} = \frac{\left( k_{fi}^{fin} \right)_{i}}{\left( k_{fi}^{fin} \right)_{i-1}}.
\] (7)

and

\[ \Gamma_{i}^{incr} = \frac{\Gamma_{i}^{fin}}{\left( k_{fi}^{fin} \right)_{i-1}} - \frac{\left( k_{fi}^{fin} \right)_{i}}{\left( k_{fi}^{fin} \right)_{i-1}} \Gamma_{i}^{fin}, \] (8)

In the case of a transpressional/transtensional wrench zone with \( k_1 = 1 \) and \( k_3 = 1 \), equation (8) becomes:

\[ \Gamma_{i}^{incr} = \frac{\Gamma_{i}^{fin}}{\left( k_{fi}^{fin} \right)_{i-1}} - \frac{\left( k_{fi}^{fin} \right)_{i}}{\left( k_{fi}^{fin} \right)_{i-1}} \Gamma_{i}^{fin} \left( k_{fi}^{fin} \right)_{i-1}. \] (9)

Note that, for a deformation characterized by simple shear only \((k_1 = k_2 = k_3 = 1)\), the incremental shear strain corresponds to the finite shear strain increment.

In the case of no synchronous pure shear deformation in the host rock (i.e. \( C = 1 \)), the final strain configurations of localizing and delocalizing shear zones (Fig. 1.1) are indistinguishable. However, according to Means (1995), useful information may be obtained by the analysis of the shear strain across the shear zone. In the case of strain softening, which is assumed to control the development of localizing shear zones, the finite shear strain profile displays a peaked shape. On the contrary, in the case of strain hardening (i.e. in the case of delocalizing shear zones) the profile is flat-shaped. Therefore an accurate study of the shear strain gradient across the shear zone may effectively unravel the type of rheological behaviour (strain hardening/softening) characterizing the analysed structure.

1.3 FINITE STRAIN

It is generally very difficult to obtain all four parameters of the finite matrix (Equation 4) by analyzing naturally deformed shear zones. However, in some cases, it is possible to determine all derived strain parameters starting from measured ones. Among these, the case of a shear zone characterized by no volume variation and no stretch along the x direction \((k_1 = 1)\).

Consider a wrench zone (Fig. 1.2) where each \( i \)-th layer is characterized by synchronous simple and pure shear represented by the finite strain matrix (in order to simplify the formulae, the label \( i \) is omitted and all quantities have to be considered as finite values):

\[ B = \begin{bmatrix}
1 & \Gamma & 0 \\
0 & k_2 & 0 \\
0 & 0 & k_3
\end{bmatrix}. \] (10)

Generally one can directly measure only the \((R, \theta')\) and/or \((F', \theta')\) values, where \( R \) is the aspect ratio of the finite strain ellipse (e.g. Ramsay and Huber 1983) and \( \theta' \) is the angle between the finite strain ellipsoid XY plane and the shear plane xy (e.g. Vitale and Mazzoli 2008, 2010). \( R \) and \( \Gamma \) can be obtained using the \( R/\phi \) method.
(Dunnet 1969) and the cotangent rule (Ramsay and Huber 1983; Vitale and Mazzoli 2010), respectively. Starting from the values of $R$ and $\theta'$, let us try to find other strain parameters such as shear strain and stretches. To obtain a relationship between $k$ and $R$, let us calculate the mathematical expression of the principal strain ratios, letting $\lambda_1, \lambda_2, \lambda_3$ be the eigenvalues of the matrix $\mathbf{B}^T$ (where $\mathbf{B}^T$ is the transposed matrix of $\mathbf{B}$):

$$
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix} = \begin{bmatrix}
  (1 + \Gamma^2 - \lambda) x + \Gamma k_z x \\
  (k^2_{xy} - \lambda) y \\
  \Gamma k_x x + (k^2_{yz} - \lambda) z
\end{bmatrix} = 0,
$$

(11)

where $\mathbf{e}$ is the eigenvector and $\mathbf{I}$ is the identity matrix. The solution is:

$$
\lambda_{1,2,3} = \frac{1}{2} \left( k^2_{xy} + \Gamma^2 + 1 + \sqrt{k^4_{xy} + 2k^2_{xy}\Gamma^2 - 2k^2_{yz} + \Gamma^4 + 2\Gamma^2 + 1} \right),
$$

$$
\frac{1}{2} \left( k^2_{xy} + \Gamma^2 + 1 - \sqrt{k^4_{xy} + 2k^2_{xy}\Gamma^2 - 2k^2_{yz} + \Gamma^4 + 2\Gamma^2 + 1} \right).
$$

(12)

Indicating with $\lambda_1, \lambda_2$ and $\lambda_3$ the maximum, intermediate and minimum value, respectively (i.e. $\lambda_1 > \lambda_2 > \lambda_3$), the strain ratios of the principal finite strain ellipses are:

$$
R_{xz} = \frac{\lambda_2}{\sqrt{\lambda_1}}, R_{yz} = \frac{\lambda_1}{\sqrt{\lambda_2}}, R_{xy} = \frac{\lambda_3}{\sqrt{\lambda_1}}, R_{yz} = \frac{\lambda_1}{\sqrt{\lambda_2}}.
$$

(13)

In order to find the angle $\theta'$ between the $xz$ plane of the reference coordinate system (parallel to the shear plane) and the $XY$ plane of the finite strain ellipsoid (parallel to the foliation) from the first equation of the system (Equation 11) and choosing the appropriate value of $\lambda^*$, the angle $\theta'$ is obtained as follows:

$$
\frac{1 + \Gamma^2 - \lambda^*}{\Gamma k_z} = \frac{z}{x} = \tan \theta'.
$$

(14)

The $X$-axis of the strain ellipsoid (the maximum stretching) can lie in the $xz$ plane (Fig. 1.2b) or be parallel to the $y$-axis (Fig. 1.2c) of the reference coordinate system. In both cases the value of $\lambda^*$ in the Equation 14 is

$$
\lambda^* = \frac{1}{2} \left( k^2_{xy} + \Gamma^2 + 1 + \sqrt{k^4_{xy} + 2k^2_{xy}\Gamma^2 - 2k^2_{yz} + \Gamma^4 + 2\Gamma^2 + 1} \right).
$$

(15)

substituting the value of $\lambda^*$ of Equation 15 in the formula (Equation 14), the resulting equation is

$$
(tan \theta') k^2_{xy} - (tan \theta')^2 \Gamma^2 + (tan \theta')^2 = 0.
$$

(16)

Solving for $k_x$ yields

$$
k_x = \frac{\Gamma (tan \theta')^2 + \Gamma^2 (tan \theta')^2 + 2\Gamma^2 (tan \theta')^2 + \Gamma^2 + 4(tan \theta')^2}{2(tan \theta')^2}.
$$

(17)

and

$$
k_x = \frac{\Gamma (tan \theta')^2 - \Gamma^2 (tan \theta')^2 + 2\Gamma^2 (tan \theta')^2 + \Gamma^2 + 4(tan \theta')^2}{2(tan \theta')^2}.
$$

(18)

The solution for $k_x$ in Equation 18 provides negative values ($k_x$ being $\geq 0$), and hence has to be eliminated.

In order to find a suitable equation to join with Equation 17 in the variables $k_x$ and $\Gamma$, let us consider the strain ratio relationship

$$
R = \frac{\sqrt{k^2_{xy} + \Gamma^2 + 1 + \sqrt{k^4_{xy} + 2k^2_{xy}\Gamma^2 - 2k^2_{yz} + \Gamma^4 + 2\Gamma^2 + 1}}}{k^2_{xy} + \Gamma^2 + 1 - \sqrt{k^4_{xy} + 2k^2_{xy}\Gamma^2 - 2k^2_{yz} + \Gamma^4 + 2\Gamma^2 + 1}}.
$$

(19)

If the direction of the maximum lengthening ($x$-axis of the strain ellipsoid) lies in the $xy$ plane of the reference coordinate system (Fig. 1.2a) than the second value of $\lambda$ in the Equation 12 is the maximum one and $R = R_{xz}$, else if the $X$-axis is parallel to the $z$-axis (Fig. 1.2b), the second value of $\lambda$ is the intermediate one and $R = R_{yz}$.
\[ k_3 = \frac{\pm (-1-R^2) \pm \sqrt{1-R^2+R^4-4R^2\Gamma^2}}{2R} \]  

(20)

In order to obtain real solutions the argument of the square root must be zero or positive, hence

\[ 1 - R^2 + R^4 - 4R^2\Gamma^2 \geq 0, \]

with \( R \geq 1 \) and \( \Gamma \geq 0 \). These inequalities hold only when \( R \geq \Gamma + \sqrt{\Gamma^2 + 1} \). Under this condition, the solutions that furnish positive values are

\[ k_3 = \frac{1+R^2 - \sqrt{1-R^2+R^4-4R^2\Gamma^2}}{2R}. \]  

(21)

Combining Equations 21 and 17 yields

\[ \frac{\Gamma \tan \theta' - \Gamma + \sqrt{\Gamma^2} \tan \theta' + 2\tan \theta' + 4\tan \theta^2}{2\tan \theta'} = \frac{1+R^2 - \sqrt{1-R^2+R^4-4R^2\Gamma^2}}{2R}. \]  

(22)

Solving for \( \Gamma \) gives the only positive and real solution

\[ \Gamma = \frac{R^2 - 1}{R} \frac{\tan \theta'}{1 + \tan \theta^2}. \]  

(23)

To find \( k_3 \), we can substitute the formula (Equation 23) into Equation 17. Furthermore, \( k_3 = k_3^{-2} \) and for the others strain quantities, such as shear strain and kinematic vorticity number, we can use the following equations, respectively:

\[ \gamma = \frac{\Gamma \log (k_3)}{1 - k_3} \]  

(24)

and

\[ W_k = \sqrt{\frac{\gamma}{2\{\log(k_3)^2 + \log(k_3')^2\}}} = \frac{\gamma}{\sqrt{4\log(k_3)^2 + \gamma^2}}. \]  

(25)

Summarizing, in the special case of \( k_3 = k_3^{-2} = 1 \), starting from the strain ratio (\( R_{yx} \), if the strain ellipsoid X-axis lies in the \( xz \) plane, or \( R_{yz} \) if the strain ellipsoid x-axis is parallel to the \( y \)-axis) and the angle \( \theta' \) that the foliation forms with the shear plane, it is possible to obtain the values of \( k_3 \) (and \( k_3^{-2} \)), \( \gamma \) and \( W_k \) by means of Equations 16, 23, 24, and 25.

### 1.4 Practical Application of Incremental and Finite Strain Analyses

The technique proposed in this study is applied to a heterogeneous ductile wrench zone (Fig. 1.3a), previously analyzed by Vitale and Mazzoli (2010), exposed in a low-strain domain of an elsewhere extensively deformed and mylonitized pre-Alpine intrusive granitoid body included within the amphibolite facies *Zentralgneiss* (Penninic units exposed within the Tauern tectonic window, Eastern Alps; Fig. 1.3c; Mancktelow and Pennacchioni 2005; Pennacchioni and Mancktelow 2007). Shear zone nucleation was controlled by the presence of precursor joints, and occurred by a widespread reactivation process that characterizes solid-state deformation of granitoid plutons also elsewhere (e.g. Pennacchioni 2005; Mazzoli et al. 2009). Wrench zones are characterized by a well-developed foliation and deformed quartz veins that are intersected by the shear zone themselves (Fig. 1.3a). Wrench zones are sub-vertical and characterized by sub-horizontal slip vectors, and sinistral and dextral sense of shear. Geochemical analyses of major and trace elements of deformed and undeformed rocks (Pennacchioni 2005), indicate no geochemical changes occurred during deformation and hence suggesting that the deformation involved no volume variation (Grant 1986).

#### 1.4.1 Finite strain

The analyzed wrench zone is characterized by localized synchronous simple shear and pure shear. The main finite strain parameters of the shear zone were evaluated by analyzing deformed planar markers (Vitale and Mazzoli 2010). In this case, the shear zone was divided into layers characterized by a roughly homogeneous internal deformation (Fig. 1.3b). For each layer, finite quantities of \( \theta' \) and \( \Gamma \) were measured and plotted in a scatter diagram (Fig. 1.4). The latter also includes a \( k_3-\gamma \) grid that was constructed considering the known conditions of no volume change (\( \Delta = 0 \)) and assuming \( k_3 = 1 \) (i.e. transpressional/transensional deformation *sensu* Sanderson and Marchini 1984) by varying the stretch \( k_3 \) and the shear strain \( \gamma \) in the equations:

\[ \Gamma = \gamma \frac{(1-k_3)}{\log(k_3)} \]  

(26)

and

\[ \theta' = \tan^{-1} \left( \frac{\Gamma^2 + 1 - \lambda_{\max}}{k_3 \Gamma} \right). \]  

(27)

The obtained data plot along a general path involving increasing shear strain \( \gamma \) and decreasing values of the stretch \( k_3 \) moving from the margin toward the shear zone centre. Using Equations 24 and 27 one can obtain the exact value of the stretch \( k_3 \) (and hence \( k_3 = k_3^{-2} \)) and of the shear strain \( \gamma \). The finite values of the strain ratios \( R_{xy}, R_{yz} \) and \( R_{zx} \) and the kinematic vorticity number \( W_k \) are obtained by applying Equations 19 and 25.

In order to smooth out the data in the incremental strain analysis that will be carried out in the following
Fig. 1.3. (a) Outcrop view of the analyzed heterogeneous dextral wrench zone deforming quartz vein. (b) Subdivision into homogeneously deformed layers. (c) Geological sketch map of part of the Eastern Alps, showing site of the structural analysis (star) (modified after Pennacchioni and Mancktelow 2007). (d) Normalized Fry plot showing finite strain measured in the host rock.

Fig. 1.4. $\Gamma$–$\theta'$ scatter diagram. The $k_2$–$\gamma$ grid was constructed for a transpressional/transtensional deformation ($\Delta = 0$ and $k_1 = 1$).
section, best-fit power-law curves are determined for the finite values of effective shear strain $\Gamma$ (Fig. 1.5a), shear strain $\gamma$ (Fig. 1.5b), strain ratio $R_{XZ}$ (Fig. 1.5c), and stretch $k_2$ (Fig. 1.5d) as a function of the angle $\theta'$. A power-law curve is used to fit the scatter data because it provides the best values of the coefficient of determination $R^2$ (which is a measure of how well the data fit the adopted statistical model).

The finite kinematic vorticity number $W_k$ increases linearly for $\theta'$, ranging from the maximum observed value (about 70°) to about 30°, becoming constant (and close to unity) for angles between about 30° and the minimum observed $\theta'$ values (<5°; Fig. 1.5e). Note that if the increase in effective shear strain, shear strain and strain ratio with decreasing $\theta'$ are somewhat expected, much less obvious is the decrease in elongation $k_2$. To evaluate finite strain in the host rock, the normalized-Fry method (Fry 1979; Erslev 1988) was applied to the rock areas surrounding the structure. The obtained values of ellipticity on the XZ plane ($R_{XZ}^{host}$) are of about 1, indicating no strain (Fig. 1.3d).

Summarizing, the ductile wrench zone is characterized by: (i) non-constant finite values of the stretches
and $k_3$, with $k_j$ values mostly larger than unity (having assumed $k_1 = 1$); (ii) localized deformation occurring within the shear zone only (i.e. undeformed host rock); and (iii) no volume variation. These features point out the occurrence of material flow along the $z$-axis of the reference frame (i.e. in the vertical direction). This effect is dominant in the low-strain parts of the shear zone (i.e. for high values of the angle $\theta'$) characterized by $k_j$ values above unity (transtensional deformation), becoming negligible for the simple shear-dominated ($W_k \approx 1$) central sector of localized high strain.

1.4.2 Incremental strain

The incremental strain analysis of the studied shear zone was carried out considering a total number of $n = 20$ steps for the application of the inverse method. For each step, discrete values of $k_j$ and $\Gamma$ were obtained from the best-fit equations (Fig. 1.5). Equation 3 has been used to calculate the incremental strain because this shear zone displays no deformation outside of it (Fig. 1.3a, d).

Figure 1.6 displays the profiles of finite and incremental values for effective shear strain $\Gamma$, shear strain $\gamma$, strain ratio $R_{xz}$, stretch $k_2$, strain ratio $R_{xz}$ and kinematic vorticity number $W_k$ versus number of steps, whereas in Fig. 1.7(a,b) finite and incremental strain paths are plotted on: (i) $\Gamma - \theta'$ and (ii) logarithmic Flinn diagrams (Flinn 1962; Ramsay 1967), respectively. It must be stressed that the first incremental strain step corresponds to the first step of finite strain (transtension); on the contrary, the subsequent incremental strain values (from 2 to 20) indicate a transpressional deformation, although the finite strain is of dominantly transtensional type. For example, the first incremental value of $k_2$ is 2.23 (transtension), whereas

Fig. 1.6. Profiles of finite and incremental values of: (a) effective shear strain $\Gamma$, (b) shear strain $\gamma$, (c) strain ratio $R_{xz}$, (d) stretch $k_2$, and (e) kinematic vorticity number $W_k$ versus layer number $n$. 

\begin{align*}
\text{(a)} & \quad \text{Finite} \quad \text{Incremental} \\
\text{(b)} & \quad \Gamma \\
\text{(c)} & \quad R_{xz} \\
\text{(d)} & \quad k_2 \\
\text{(e)} & \quad W_k
\end{align*}
the following incremental $k_2$ path (from 2 to 20 steps, Fig. 1.7a) is generally characterized by values lower than 1, decreasing toward the center of the shear zone.

Finite and incremental profiles of effective shear strain $\Gamma$, shear strain $\gamma$ and strain ratio $R_{yz}$ show similar peaked shapes, pointing out a non-linear increase during shear zone evolution (Fig. 1.6a–c). The peaked shape of the curve confirms the interpretation, already suggested, based on finite strain analysis, that shear zone rheology was characterized by strain softening, involving both simple shear and the pure shear components of the deformation. However, both finite and incremental kinematic vorticity numbers increase, up to unity, for increasing deformation (Fig. 1.6e). Therefore, the partitioning between simple shear and pure shear changed during shear zone evolution from prevailing pure shear ($W_1 \approx 0.4$) to dominant simple shear, eventually reaching conditions of simple shear alone ($W_1 \approx 1$) for the latest stages of highly localized deformation in the softened central sector of the shear zone.

The incremental strain paths plotted on the $\Gamma$– $\theta'$ diagram (Fig. 1.7a) and in the logarithmic Flinn diagram (Fig. 1.7b) confirm that the incremental strain from steps 2 to 20 consistently lies in the transpressional oblate field. Also, note that none of the incremental strain parameters holds a constant value during the temporal evolution; therefore the incremental deformation evolution is non-steady state.

As previously mentioned, the first increment points out a transtensional deformation whereas the subsequent strain increments are of transpressional type. In the case of no synchronous deformation in the host rock, the final strain configuration does not provide information about the temporal evolution of the shear zone. However, the suggested strain evolution is more consistent with a localizing shear zone (Fig. 1.1a, with $C = 1$) characterized by: (i) an early homogeneous transtensional deformation affecting the whole shear zone; and (ii) a following localization of the transpressional strain in the central part, probably driven by strain softening processes, with respect to a delocalizing shear zone (Fig. 1.1b, with $C = 1$) where an initial transtension affects the central part and subsequently migrates outward, with synchronous transpression affecting the inner sectors.

1.5 CONCLUSIONS

According to the Means hypothesis (Means 1975) and as suggested by Provost et al. (2004) and Horsman and Tikoff (2007), information on the incremental strain history may be obtained from the analysis of the final strain configuration in a heterogeneous shear zone. In particular, in case the structural evolution was characterized by strain softening or hardening – which are assumed to control the development of localizing and delocalizing shear zones, respectively – one can unravel the relationship between finite strain across the shear zone and incremental strains. Based on this assumption, an inverse method was derived which is able to evaluate the incremental strain matrices starting from measured finite strain quantities in a heterogeneous ductile shear zone. The proposed technique uses the finite values of the effective shear strain $\Gamma$ and the finite angle $\theta'$ (angle between the foliation, i.e. the $xy$ plane of the finite strain ellipsoid, and the shear plane) obtained for $n$ layers, in

![Fig. 1.7. (a) $\Gamma$– $\theta'$ and (b) logarithmic Flinn diagrams showing incremental and finite strain paths.](image-url)
which a shear zone may be subdivided according to homogeneity criteria. Shear zone deformation may then be described in terms of \( n \) finite strain matrices, each representing homogeneous deformation of the related layer. Starting from these matrices, it is possible to derive the incremental strain matrices. For simple cases, the proposed method furnishes symbolic formulae relating finite and incremental values of the main strain parameters, such as shear strain and stretches. The inverse method requires knowing the strain parameters, such as shear strain and stretches. In particular instances such as that analyzed in this paper, it is possible to derive all of the required strain parameters from simple formulae. For the analyzed wrench zone, characterized by no stretches along the \( x \) direction and no volume change, the incremental strain path suggests a localizing shear zone evolution characterized by an initial homogeneous transtensional deformation in the whole shear zone and a subsequent incremental transpression driven by straing softening processes affecting progressively inner sectors.

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REFERENCES


Chapter 2
How far does a ductile shear zone permit transpression?

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2.1 INTRODUCTION

Understanding the shear zone kinematics has enormous implications in interpreting a wide variety of geological processes, ranging from the exhumation of deep crustal rocks to the formation of sedimentary basins. Kinematically, ductile shear zones are defined as regions marked by localization of intense non-coaxial deformations. Considering a homogeneous strain model, Ramberg (1975) first provided a theoretical analysis of the general non-coaxial deformations by combining pure shear and simple shear flows. Based on the kinematic vorticity number, expressed as: \[ W_i = \frac{W}{2(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2)} \] (Truesdell 1954), where \( \varepsilon_i \) is the principal longitudinal strain rate and \( W \) is the magnitude of the vorticity vector, Ramberg (1975) has shown characteristic flow patterns in ductile shear zones. His analysis derives \( W_i \) as a function of the ratio \( S_i \) of pure and simple shear rates, and the orientation of the principal axes of pure shear with respect to the simple shear frame. For \( W_i = 1 \), shear zone deformations are characterized by shear-parallel flow paths, implying simple shear kinematics. On the other end, non-coaxial deformations in shear zones with \( W_i < 1 \) develop open hyperbolic particle paths, which transform into closed paths as \( W_i > 1 \). However, deformations with \( W_i > 1 \) described as a pulsating type, have been rarely reported from natural shear zones. Ramsay and his co-workers included volume strain in the kinematic analysis of ductile shear zones (Ramsay and Graham 1970; Ramsay 1980; Ramsay and Huber 1987). A range of natural structures (at both macro- and mesoscopic scales), for example, anastomose mylonitic fabrics (Gapaï et al. 1987), porphyroclast tail patterns (Ghosh and Ramberg 1976; Simpson and De Paor 1997; Passchier and Simpson 1986; Mandal et al. 2000; Kurz and Northrup 2008), and instantaneous strain axis (ISA) (Passchier and Urai 1988; Tikoff and Fossen 1993; Xypolias 2010, and references therein) have been used to explain these structures and to demonstrate the effects of pure and simple shear kinematics in ductile shear zones. Similarly, a parallel line of studies has dealt with structural (e.g. stylolites; Tondi et al. 2006) and chemical criteria (e.g. enrichment of immobile elements; O’Hara and Blackburn 1989; Mohanty and Ramsay 1994; Srivastava et al. 1995; Fagereng 2013) to determine the volume loss in shear zones.

In many tectonic settings shear zones developed under general non-coaxial deformation show components of shear and shortening parallel and orthogonal to the shear zone boundaries, respectively. From a kinematic point of view, these shear zones have been described as transpression zones, a term first coined by Harland (1971) to describe the zone of oblique convergence between two crustal blocks. Sanderson and Marchini (1984) modeled a vertical transpression zone sandwiched between two laterally moving rigid blocks, which gave rise to a strike-slip motion coupled with shortening across the zone. Their model imposes a slip boundary condition to allow the material extrusion in the vertical direction, that is, perpendicular to the shear direction. It was pointed out later that a slip boundary condition had a mechanical limitation to produce shearing motion in a transpression zone (Robin and Cruden 1994; Dutton 1997). To meet this shortcoming, they advanced the transpression model with a non-slip boundary condition, and explained the structural variations in terms of the heterogeneous flow developed in their non-slip model. A series of kinematic models have been proposed afterwards; all of them, in principle, pivot on the same theoretical formulation of Ramberg (1975) that combines the homogeneous simple shear and pure shear fields. As a consequence, the transpression can show either a monoclinic or a triclinic kinematic symmetry, depending upon the orientation of pure shear axes with respect to the simple shear (Dewey et al. 1998; Jones and Holdsworth 1998; Ghosh 2001; Fernández and Díaz-Azpiroz 2009).

Despite an enormous volume of research work over the last several decades, there have been so far few attempts to analyze the mechanics and to estimate the degree of transpression physically possible in a ductile...
shear zone. Flow modeling for a viscous layer sandwiched between two rigid walls (Mandal et al. 2001) show that the viscous extrusion is much more energetically expensive, as compared to the gliding motion of the rigid blocks. According to Mandal et al. (2001), this contrasting energetics thus leads to dominantly simple shear kinematics even when the bulk compression is at a high angle to the shear zone. This theoretical prediction is in good agreement with the dominantly simple shear kinematics of deep-crustal ductile shear zones reported from high-grade metamorphic terrains (Puelles et al. 2005). Furthermore, our own field observations of centimeter to meter scale shear zones from the Chotanagpur Granite Gneiss Complex point to limited flattening. In contrast, many field studies have documented a range of structural evidences in support of the transpressional kinematics (Ghosh and Sengupta 1987; Sengupta and Ghosh 2004; Zák et al. 2005; Massey and Moecher 2013). A revisit to the problem of transpressional movement in ductile shear zones is needed to address such apparently contradictory field observations. Using analog experiments the present study aims to physically evaluate how much flattening is possible in a coherent ductile shear zone hosted in an undeformable medium. Our experimental results confirm earlier theoretical predictions that shear zones with large aspect ratios are unlikely to undergo significant flattening. We also demonstrate from the laboratory experiments that appreciable flattening can occur under specific geometrical conditions. Finite element model simulations were performed to substantiate these findings.

Section 2.2 presents a set of field examples of small scale shear zones along with a qualitative evaluation of their flattening. Section 2.3 deals with analog modeling, giving a quantitative estimation of flattening as a function of shear zone geometry. In Section 2.4, we discuss simulated ductile shear zones in finite element (FE) models, considering physical properties approximated to the crustal rheology. In Section 2.5 we discuss the experimental findings in the context of actual field observations, and propose syn-shearing volume changes as a mechanically potential mechanism for transpression in ductile shear zones. Section 2.6 concludes the principal outcomes of this work.

2.2 FIELD OBSERVATIONS: GEOMETRIC ANALYSIS

We investigated outcrop-scale ductile shear zones in the Chotanagpur Granite Gneiss Complex (CGGC) terrain, lying north of the Singhbhum Proterozoic mobile belt (Fig. 2.1). The dominant mineral constituents of the CGGC rocks are quartz, feldspars, micas and garnet with secondary phases, such as tourmaline and amphibole. Petrological studies suggest that the terrain has undergone a peak metamorphism ($P \approx 6 \text{ kbar}, T \approx 850^\circ\text{C}$) in granulite facies (Maji et al. 2008), and regional deformations under N–S convergence, giving rise to an overall E–W structural trend (Fig. 2.1). The CGGC in the study area recorded four major ductile deformation episodes (Mahmoud, 2008). In the course of these ongoing events, the terrain has experienced regionally a brittle–ductile transition, producing vertical shear zones on centimeter to meter scales. In the western part of Purulia district the gneissic rocks display excellent outcrops of such shear zones, broadly in two sets, trending NNE–SSW and NE–SW, showing both dextral and sinistral strike–slip motion, as revealed from the deflection of dominant gneissic foliations or markers, like quartz veins.

The deflection patterns of mylonitic foliation produced by the motion of the shear zones were used to undertake a qualitative analysis of the shear zone kinematics. We assumed that the distortion pattern of transverse markers is a function of the ratio ($S_t$) between pure and simple shear rates (Mandal et al. 2001; Puelles et al. 2005). The distortion of a passive marker at an instant can be reconstructed from the following velocity equations (after Jaeger 1969) in a Cartesian space ($x$, $y$):

\begin{align}
\begin{align}
u &= 3\dot{\varepsilon}_b x \left[ \frac{1}{2} \left( \frac{y}{T} \right)^2 \right] + \dot{\gamma}_b x \\
v &= \frac{1}{2} \dot{\gamma}_b y \left[ \left( \frac{y}{T} \right)^2 - 3 \right].
\end{align}
\end{align}

Where, $\dot{\varepsilon}_b$ and $\dot{\gamma}_b$ are the bulk flattening and shear rates, $u$ and $v$ are the components of velocity along the $x$ and $y$ directions, respectively and $t$ is the instantaneous shear zone thickness. Using Equations 1 and 2, it can be demonstrated that a line parallel to the $y$-axis will be distorted with outward convexity, the symmetry of which depends on the ratio of pure and simple shear rates ($S_t = \frac{\dot{\varepsilon}_b}{\dot{\gamma}_b}$) and the initial orientation of markers with the shear direction. To investigate the distortion pattern, we chose a set of lines across the shear zone (Fig. 2.2) described by the following equation:

\begin{align}
y = m(x - C)
\end{align}

where, $m = \tan \theta$; $\theta$ and $C$ are the initial angles of lines with respect to the shear direction and their distance from the shear zone center along the shear direction, respectively (Fig. 2.2). The lines were deformed by incremental displacements by using the velocity function in Equations 1 and 2. All the parameters, such as shear zone thickness $t$ were modified at each step of the iterations.

Using this theoretical approach we obtained the distortion patterns of a set of parallel passive markers as a function of $S_t$ and $\theta$, and compared them with those observed in natural shear zones. For $S_t = 0$, the markers show angular deflections without any distortion, irrespective of their initial orientation ($\theta$). The degree of outward convexity decreases with decreasing values of
both $S_r$ and $\theta$ (Fig. 2.2). The graphical plots indicate that markers oriented initially normal to the shear zone boundaries ($\theta = 90^\circ$) do not show any appreciable outward convexity for $S_r$ values less than 0.05.

Figure 2.3(a) shows an isolated shear zone at a right angle to the foliation, with an aspect ratio of 10.8. The foliation marker has been deflected in a sinistral sense by an angle of about $70^\circ$. A close inspection of the distorted pattern of foliation markers within the shear zone reveals that they maintain their planar geometry along the entire length of the shear zone. Comparing the distortion patterns with the corresponding theoretical one (Fig. 2.2), the shear zone is predicted to have undergone little flattening, and evolved dominantly by simple shear (i.e. $S_r \sim 0$).