The Development of L-tectonites in High-strain Zone Settings: A Multiscale Modeling Investigation

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Graduate Program in Geology

A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

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The Development of L-tectonites in High-strain Zone Settings: A Multiscale Modeling Investigation

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by

Weiyin, Chen

Graduate Program in Geology

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Abstract

Shape fabrics in high-strain zones are commonly used to constrain deformation processes in the lithosphere. Linear fabric, as a type of shape fabric, usually indicates constrictional strain and is an important feature in orogenic belts. Among all kinds of linear fabrics, the isolated L-tectonites, which are surrounded by strong planar fabrics, are poorly understood. The isolated L-tectonites are generally developed in heterogeneous high-strain zones. Their formation involves heterogeneous and multiscale deformation processes that current single-scale kinematic models cannot explain. To relate isolated L-tectonites in a high-strain zone with its boundary conditions, I apply a multiscale approach. Isolated L-tectonites are regarded as ellipsoidal heterogeneous domains embedded in a high-strain zone. Eshelby’s formalism extended for power-law viscous materials is used to investigate the strain patterns of the partitioned flows in heterogeneous domains. It is shown that, under an imposed flattening or plane-strain deformation field at the high-strain zone scale, L-tectonites can be developed in strong domains regardless of initial shapes or orientations of the strong domains. The numerical modeling is applied to Archean greenstone belts where isolated L-tectonites are developed. The fabric set in greenstone belts has been interpreted by the gravitational sinking of greenstone rocks into the underlying granitoids. The simulations of deformation fields on different scales show that the fabric set can be well explained by transpression. The numerical modeling reproduces field-observed fabrics in greenstone belts that have remained unexplained by current kinematic models.

Keywords:
L-tectonites; Shape fabric development; Strain variation; Multiscale modeling; Greenstone belts
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Appendix A: Notation.................................................................114
1 Introduction

The fabric of a rock is defined by the spatial and geometric configuration of all those components that make up the rock (Hobbs et al., 1976, pp. 73). The main fabric elements usually refer to foliations, lineations, and lattice preferred orientations (LPO) of minerals (Passchier and Trouw, 2005, pp. 67). Fabrics are well developed in natural high-strain zones, which are also known as ductile shear zones (Passchier and Trouw, 2005, pp. 111). High-strain zones are a common feature of crustal deformation, and are usually formed by natural orogenic processes (Ramsay and Graham, 1970). Therefore, the development of fabrics is related to orogenic deformation. The study of fabrics in high-strain zones helps us understand the deformation of crustal structures and related tectonic processes.

Fabric can be defined by the preferred orientation of the shapes of 3-D elements within a rock, and in this case, it is often called a shape preferred orientation (SPO) (Passchier and Trouw, 2005, pp. 76-77). In shape fabrics, a planar fabric, such as foliation, is called $S$-fabric; a linear fabric, such as lineation, is called $L$-fabric. Tectonites, which are formed by the flow of rocks in a solid state, are pervaded by foliation and/or lineation (Turner and Weiss, 1963). There are three major types of tectonites, which are known as $S$-tectonites, $L$-tectonites and $SL$-tectonites. The terms "$S$" and "$L$" refer to foliation and lineation respectively. $S$-tectonites are characterized by strong foliation and weak or no recognizable lineation. $L$-tectonites are characterized by strong lineation and weak or no recognizable foliation (Fig. 1.1). $SL$-tectonites are characterized by both foliation and lineation (Fig. 1.2).
Fig. 1.1: L-tectonites defined by stretched pebbles in deformed conglomerates from the Cross Lake Group (a) and the Gunpoint Group (b) of the Cross Lake greenstone belt, Superior Province, Canada (photos courtesy of Dazhi Jiang).
Fig. 1.2: Schematic diagram showing the characteristics of typical SL-tectonites in a ductile shear zone. (a) 3-D block. Dashed lines represent traces of foliations, solid lines represent lineations on the foliation plane. (b) and (c) Sectional views on the vorticity-normal section (VNS) where shear sense indicators such as S-C structures (b) and kinematic indicators (c) are developed. The VNS is commonly normal to the foliation and parallel or normal to the stretching lineation depending on the history of deformation that produced the tectonites (see Chapter 2 for more discussion). (d) Lineation-normal section.
Tectonites can indicate the strain state of rock deformation because foliations and/or lineations in a tectonite are caused by significant distortion. In the study of shape fabrics, one of the goals is to interpret the magnitudes and directions of distortion that are accommodated by the development of linear fabrics and planar fabrics.

In strain analysis, the strain ellipsoid is used to illustrate the strain state of a deformed rock (Ramsay and Huber, 1983, pp. 167-195). If an original sphere in a rock deforms into an oblate strain ellipsoid, the strain of the rock is flattening. If an original sphere in a rock deforms into a prolate strain ellipsoid, the strain of the rock is constrictional. The shape of a strain ellipsoid can be plotted on a logarithm Flinn diagram (Ramsay, 1967, pp. 137-138). On a logarithm Flinn diagram, the abscissa is $\ln \frac{Y}{Z}$ and the ordinate is $\ln \frac{X}{Y}$, where X, Y and Z are the lengths of the maximum, intermediate and minimum semi-axes of a strain ellipsoid respectively. The Flinn parameter K value is defined by:

$$K = \frac{\ln \frac{X}{Y}}{\ln \frac{Y}{Z}}$$

A strain ellipsoid plotted on the K=1 line stands for plane strain. A strain ellipsoid plotted above the K=1 line stands for constrictional strain. A strain ellipsoid plotted below the K=1 line stands for flattening strain. Based on the plot of a strain ellipsoid on a logarithm Flinn diagram, structural geologists can infer the strain ellipsoid shape and strain magnitude (Fig 1.3).
Fig. 1.3: Logarithm Flinn diagram. The abscissa is $\ln \frac{Y}{Z}$, and the ordinate is $\ln \frac{X}{Y}$. The K value of a prolate strain ellipsoid is bigger than 1. The K value of an oblate strain ellipsoid is smaller than 1. The values of $\ln \frac{Y}{Z}$ and $\ln \frac{X}{Y}$ are determined by strain magnitude.

Shape fabrics in a rock usually mimic the geometry of the strain ellipsoid of the rock (Passchier and Trouw, 2005, pp. 76-77; Davis et al., 2011, pp. 520-525). In most studies, planar fabrics are commonly assumed to be parallel to the XY-plane of the strain ellipsoid, and linear fabrics are assumed to be parallel to the X-axis of the strain ellipsoid (Passchier and Trouw, 2005, pp. 76-77 and references therein). The geometric features of shape fabrics in a rock can be used to approximate the K value of the strain ellipsoid.

In general, SL-tectonites or S-tectonites indicate flattening strain and L-tectonites indicate constrictional strain (Flinn, 1965; Ramsay and Huber, 1983, pp. 167-193). SL-
tectonites or S-tectonites are common in high-strain zones and they are well studied (Ramsay and Huber, 1983, pp. 217-234 and references therein; Passchier and Trouw, 2005, pp. 118-123 and references therein). However, L-tectonites are seldom reported in the literature (Sullivan, 2013 and references therein). The rare observations of L-tectonites in high-strain zones may be due to the fact that L-tectonites are rare, and may also be due to the lack of detailed 3-D structural geology mapping (Sullivan, 2013). Nevertheless, L-tectonites are observed in a wide range of geological settings on different scales.

1.1 A brief review of studies on L-tectonites in high-strain zones

1.1.1 Field observations of L-tectonites

L-tectonites can occur over a large area. There are several examples of large regions of L-tectonites reported. L-tectonites in the Bergsdalen Nappes in Norway are characterized by quartz-feldspar ribbons and stretched pebbles (Fossen, 1993). The maximum axes of the prolate pebbles in the deformed conglomerates represent the stretching lineation. The quartz-feldspar aggregates are long on the lineation-parallel section and equidimensional on the lineation-normal section. The set of L-tectonites is believed to be produced by thrusting simple shear combined with horizontal pure shear with shortening perpendicular to the thrusting direction (Fossen, 1993). In the strongly deformed gneiss of Cristallina, Ticino, Switzerland, L-tectonites are observed and interpreted as the product of the Alpine deformation of a Hercynian basement granite (Ramsay and Huber, 1983, pp.192). Also, L-tectonites are observed in much of the deformed part of Western Gneiss Region, in the South Norway Caledonides (Fossen et al., 2013). They are mostly formed by transtensional folding and parallel to the fold hinges. The transtensional deformation is caused by orogenic collapse (Fossen et al., 2013).
L-tectonites have been often reported as localized domains in high-strain zones or within outcrop-scale fold structures. The curved segments in a shear zone favor the development of L-tectonites. For example, the Southern Knee Lake shear zone in the Superior Province in Canada is due to transpressional deformation (Lin and Jiang, 2001). In the curved segment of the shear zone, lineation is well developed but foliation is weakly developed, and strain is constrictional. The L-tectonoites there are interpreted as the product of the curved shear zone. L-tectonites can also be formed in the hinge zones of outcrop-scale folds. For example, a kilometer-wide domain of L-tectonites is developed in the hinge zone of a synform in the Eastern-Central Laramie Mountains, Wyoming (Sullivan, 2006). It results from relative thickening of fold hinge zones which are parallel to the maximum elongation direction of strain field. Overprinting deformation can also produce linear fabric. For example, pencil structure, which is a kind of linear fabrics, is formed by the intersection of foliations which are products of different deformation phases (Ramsay and Huber, 1983, pp.185; Davis et al., 2011, pp. 508-509).

Localized L-tectonite domains have also been observed in Archean greenstone belts. Based on the descriptions of the fabrics in greenstone belts (e.g. Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991; Collins et al., 1998; Lin and Jiang, 2001; Dai, 2004; Parmenter et al., 2006), I summarize a fabric set which is common in most Archean greenstone belts. Archean cratons are commonly composed of granite-greenstone-terrains (GGT). Greenstones occur as linear belts and are surrounded by granitoids. Within greenstone belts, foliation is subparallel to the contacts between greenstone belts and granitoids, and lineation plunges moderately to steeply. Shear sense indicators defined by S-C structure, rotated clasts and tails are commonly found on subhorizontal planes. Subvertical L-tectonites are usually located in rock units which are more competent than surrounding rock units. In the map view, isolated L-tectonite domains are generally dispersed in large areas of SL-tectonites or S-tectonites (Figs. 1.4 and 1.5). It is
confirmed that the formation of subvertical L-tectonites is neither due to boundary conditions of high-strain zones, nor local specific structural settings, nor overprinting deformations (Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991; Collins et al., 1998; Dai, 2004; Parmenter et al., 2006). More detailed descriptions of the fabric set in greenstone belts will be given in Chapter 4.
Fig. 1.4: The geological map of the western Cross Lake greenstone belt in the Superior Province, Canada (after Dai, 2004).
Fig. 1.5: (a) The geological map of the Warrawoona Syncline in the Pilbara Craton, Australia (after Collins et al., 1998). (b) The shape fabric pattern map of the Warrawoona Syncline (after Collins et al., 1998).
The isolated domains of L-tectonites dispersed in SL-tectonites or S-tectonites have also been observed in Proterozoic and Phanerozoic orogenies other than Archean cratons (e.g. Hossack, 1968; Holst and Fossen, 1987; Sullivan, 2008). For example, in the Raft River shear zone, Utah, USA, local domains of L-tectonites are developed in a quartz-cobble-conglomerate bed which is rheologically strong, and planar fabrics are developed in surrounding weaker phyllonites (Sullivan, 2008). Sullivan (2013) believes the phenomena that L-tectonites are surrounded by SL-tectonites or S-tectonites have commonly been overlooked in the literature. It is possible that more isolated L-tectonite domains will be found in high-strain zones once detailed mapping is carried out.

1.1.2 Previous interpretations and their problems

L-tectonites of large areas in high-strain zones are usually determined by bulk flows. Bulk flows, such as transtensional flows, can produce constrictional strains and hence L-tectonites. Local structural settings, such as curved shear zones, fold hinge zones, or overprinting deformations, can result in localized domains of L-tectonites.

In the above mentioned field observations, there is a group of localized L-tectonite domains which is neither caused by curved portions of a shear zone, nor fold hinge zones, nor overprinting deformations, nor bulk flows. These L-tectonites occur in isolated domains and are dispersed in SL-tectonites or S-tectonites. The shape fabric set of such L-tectonites indicates that high-strain zones have a wide range of strain geometries. The strain variation of this shape fabric set does not fit any predictions of current kinematic models (see Chapter 2 for more discussion), which makes this shape fabric set unique. In the following paragraphs, current interpretations about this unique shape fabric set and related problems will be discussed.
Vertical tectonics has been proposed to explain the development of the isolated L-tectonites in Archean greenstone belts (e.g. Dixon and Summers, 1983). In the vertical tectonic model, greenstones overlie granitoids before deformation. Due to density inversion, greenstones sink and granitoids rise. The sinking of greenstones produces constrictional strain in the sinking center and flattening strain in the surroundings. However, there are some problems with the vertical tectonic model. It cannot explain coeval non-coaxial deformation in SL-tectonites or S-tectonites. Also, the initial condition of greenstones overlying granitoids is difficult to determine. Vertical tectonics and related problems will be further discussed in Chapter 4.

In several studies, single-scale models which combine different flows are used to explain the strain variation of the unique shape fabric set (e.g. Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991). Localized constrictional deformation zones are embedded in a flattening field in order to reproduce the fabric set of greenstone belts. However, the problem of strain compatibility arises in the single-scale models when constrictional strain fields are embedded in a flattening strain field. The strain geometries must satisfy strain compatibility. Conceptual models, which are not based on a complete mechanics, cannot be expressed in a consistent formalism to allow a solution for the above strain variation.

1.2 Isolated L-tectonites and their significance

As discussed above, in the study of L-tectonites, the formation mechanism of isolated L-tectonite domains is poorly understood. In this thesis, I will focus on the development of isolated L-tectonites in high-strain zone settings.
Current kinematic models are all based on the assumption deformation is single-scale and homogenous (Davis and Titus, 2011). They are proposed for high-strain zones without heterogeneous domains. They can successfully explain fabric development in homogeneous shear zones. However, when a high-strain zone is heterogeneous, single-scale models will be inadequate to relate the deformation pattern of heterogeneous domains to the deformation pattern of the matrix.

In a lithospherical deformation zone, heterogeneous rock masses are inevitably involved. Rock deformation in the Earth’s lithosphere is thus heterogeneous (Lister and Williams, 1983; Jiang and White, 1995). In high-strain zones with isolated L-tectonite domains, lithology changes significantly from L-tectonites to SL-tectonites. The rock components of L-tectonites are usually more competent than those of SL-tectonites or S-tectonites (e.g. Dai, 2004; Sullivan, 2008), which leads to heterogeneous deformation in these high-strain zones. However, the heterogeneous deformation is often ignored in current interpretations for the development of isolated L-tectonites.

Flow field varies in a heterogeneous high-strain zone, and this is called flow partitioning (Lister and Williams, 1983). Flow partitioning results in strain variation on different scales. Fabrics in heterogeneous domains usually have different strains from regional strain. Many geologists have realized that regional deformation is not directly or simply related to local deformation and flow partitioning plays an important role in the formation of fabrics (e.g. Lister and Williams, 1983; Ishii, 1992; Goodwin and Tikoff, 2002; Jones et al., 2005; Jiang, 2014). The isolated L-tectonite domains may be caused by partitioned flows.

Isolated L-tectonites remain poorly understood. The investigation of isolated L-tectonite domains may have great significance. First, it helps us understand heterogeneous deformation in high-strain zones. Second, it helps us understand the mechanism of strain
variation in high-strain zones. Third, it will provide us a better insight into the phenomenon of flow partitioning and bridge the gap between the study of small-scale fabrics and the study of large-scale crustal structures.

1.3 A multiscale approach

In terms of distribution area, isolated L-tectonite domains are much smaller than the high-strain zone which contains them. Usually, SL-tectonites or S-tectonites occupy a large volume of a high-strain zone. In map views, SL-tectonites or S-tectonites are observed on the high-strain-zone scale. L-tectonite domains are developed in heterogeneous rock units, therefore, they are observed on the inhomogeneity scale. The linear fabrics, which define L-tectonties, are observed on the fabric-element scale. The characteristic lengths of above scales are different from each other by many orders of magnitude. If a high-strain zone has multiscale fabrics, a multiscale approach is needed to relate small-scale fabric development to the boundary condition of the high-strain zone. It will be shown in this thesis that the formation of isolated domains of L-tectonites in a high-strain zone can be well explained based on a multiscale approach. To calculate partitioned flows in heterogeneous domains, I apply the multiscale approach developed by Jiang (2013, 2014). In Jiang’s multiscale model, three scales, called the microscale, the mesoscale, and the macroscale, are considered. The characteristic lengths of the macroscale, the mesoscale and the microscale are $D$, $d$ and $\delta$ respectively (Jiang and Bentley, 2012; Jiang, 2014). The separation of the three scales can be stated by the following expression:

$$\delta \ll d \ll D \quad (1-2)$$

To apply the multiscale model, the high-strain-zone scale, the inhomogeneity scale and the fabric-element scale correspond respectively to the macroscale, the mesoscale, and the microscale. Fig. 1.6 illustrates the multiscale model.
Fig. 1.6 Schematic diagram showing the multiscale model (from Jiang, 2014). (a) The representative volume element of a crustal-scale high-strain zone has a characteristic length of D. (b) The representative volume element is composed of many rheologically different rock domains. These domains are the mesoscale. Their mean characteristic length is d. The scales for D and d were not drawn to proportion. (c), (d), (e), and (f) are microscale structures observed in different mesoscale domains. The mean characteristic length of the structures is δ. Although the structures indicate different deformation patterns, they can be related to the boundary condition of the high-strain zone by the multiscale model.

Jiang's model is based on the Eshelby theory (1957, 1959) extended for power-law viscous materials (Lebensohn and Tomé, 1993). Eshelby (1957, 1959) studied the interaction between an isolated elastic ellipsoidal domain and the surrounding
homogeneous elastic matrix. The ellipsoidal inclusion is rheologically different from the matrix. This powerful approach, known as Eshelby’s inhomogeneity solution (e.g. Qu and Cherkaoui, 2006) has been applied in structural geology. Freeman and Lisle (1987) studied the deformation path of competent pebbles in conglomerates by regarding pebbles as ellipsoidal Eshelby inhomogeneities. Mancktelow (2013) studied the SPO of mantled porphyroclasts by treating them as Eshelby inhomogeneities embedded in the rock matrix. Jiang (2013) provided a complete algorithm to numerically examine the progressive deformation of a power-law viscous ellipsoid in a power-law viscous matrix. Jiang and Bentley (2012) and Jiang (2014) made a breakthrough in the application of the extended Eshelby theory. They regard rock masses as first-order inhomogeneities which make up a high-strain zone, and regard fabric elements as second-order inhomogeneities embedded in the heterogeneous rocks. In this way, they determined the relationship between lineation variations in small domains and tectonic deformation of the Cascade Lake shear zone in the east Sierra Nevada of California, USA by using their multiscale model. Later on, Jiang's model was successfully applied to simulate the development of small-scale ductile shear zones (Xiang and Jiang, 2013), to simulate the formation of micafish in mylonites (Chen et al., 2014), and then an extended model based on a self-consistent approach was developed by Jiang (2014).

1.4 Goal and outline

The major goal of this thesis is to examine whether heterogeneous domains in high-strain zone settings favor the development of L-tectonites. In order to achieve this goal, I will investigate partitioned flows in rheologically distinctive domains of a high-strain zone. Heterogeneous domains are treated as ellipsoidal inhomogeneities in Eshelby’s sense (Eshelby, 1957; Bilby et al., 1975). A series of MathCAD (http://www.ptc.com/product/mathcad/) worksheets developed by Jiang (2013) will be
used to simulate strain fields in heterogeneous domains that are subjected to various bulk flows. The multiscale model is also applied to Archean greenstone belts, where a number of isolated L-tectonite domains are developed. By setting appropriate parameters, I will show that the strain pattern in Archean greenstone belts can be reproduced in multiscale models.

Chapter 2 presents the theoretical background of kinematic models and the numerical modeling. The difference between finite deformation and progressive deformation is demonstrated. The strain evolution and fabric development in different kinematic models are discussed. Some basic terminologies in structural analysis and in continuum mechanics are introduced.

Chapter 3 presents the numerical modeling setup and simulation results. I will show how the input parameters are set up in the model as well as their significance on the simulation results.

In Chapter 4, the formation mechanism of L-tectonites in Archean greenstone belts is discussed and the simulation results of Chapter 3 are applied to the study on Archean tectonics. In the final chapter of the thesis, the conclusions of the work are provided.
2 Theoretical background

2.1 Description of finite deformation

Finite deformation is defined as the difference in geometry of initial and final stages of a deformed rock (Passchier and Trouw, 2005, pp. 11). In the theoretical study of structural geology, geologists are concerned about finite displacement patterns of particles in a rock under different deformations. Comparing predicted finite deformation patterns with observed finite deformation in rocks, geologists can speculate the boundary condition of a high-strain zone. Ramsay and Graham (1970) applied finite deformation approach to study the strain variation in simple shear zones. Similarly, Sanderson and Marchini (1984) applied finite deformation approach to study the fold patterns in a flattening field.

The position gradient tensor, $F$, relates initial position of a particle to the final position.

The position gradient tensor is defined as:

$$ F_{ij} = \frac{\partial x_i}{\partial X_j} (i, j = 1,2,3) \tag{2-1} $$

where $\bar{X} = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix}$ is the initial position vector of a particle and $\bar{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$ is the new position vector of the particle after finite deformation. Different finite deformations can be distinguished by the components of $F$. Correspondingly, finite strain ellipsoid can be calculated from $F$. The left Cauchy Green tensor (Malvern, 1969, pp.158, 174) is defined as $FF^T$. The lengths of three principal axes of a strain ellipsoid are the square roots of the eigenvalues of left Cauchy Green tensor. The orientations of three principal axes of a strain ellipsoid correspond to the eigenvectors of left Cauchy Green tensor.
2.2 Description of progressive deformation

The accumulation of incremental deformation with time is known as progressive deformation. Not only are geologists concerned about finite deformation of rocks, but they want to figure out the deformation path of rocks. The reconstruction of the flow history of rocks is important in kinematic analysis.

The flow of a material can be described by the velocity field. The velocity field gives a velocity vector to every particle in a material. The components of a velocity gradient tensor $\mathbf{L}$ are defined as:

$$L_{ij} = \frac{\partial v_i}{\partial x_j} \quad (i, j = 1, 2, 3)$$

(2-2)

where $\mathbf{v} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$ is the velocity vector of a particle whose position vector is $\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$.

In homogeneous steady deformation, $\mathbf{L}$ is constant everywhere in the deformation zone and keeps the same as deformation advances. If flow is heterogeneous and non-steady, $\mathbf{L}$ changes with time and also changes from locality to locality in the deformation zone.

Ramberg (1975) was the first to use the rate of deformation approach to investigate the velocity field of 2-D general shearing and found the relationship between the velocity field and the finite deformation. For a homogeneous and steady flow field, the finite deformation at time $t$ can be calculated by using equation (2-3) (Korn and Korn, 1968, pp. 422):

$$\mathbf{F}(t) = \exp(\mathbf{L} \cdot t)$$

(2-3)

where $t$ stands for time and $\mathbf{F}$ is the position gradient tensor.
The velocity gradient tensor of a flow is composed of a symmetrical strain rate tensor $\mathbf{D}$ and an asymmetrical vorticity tensor $\mathbf{W}$:

$$\mathbf{L} = \mathbf{D} + \mathbf{W} \quad (2-4)$$

where $\mathbf{D} = \frac{1}{2}(\mathbf{L} + \mathbf{L}^T)$, $\mathbf{W} = \frac{1}{2}(\mathbf{L} - \mathbf{L}^T)$. Equation (2-4) means the motion of a 3-D body can be regarded as the combination of a pure stretching $\mathbf{D}$, and a rotation $\mathbf{W}$.

The trace of $\mathbf{D}$ is the volume change rate of the deforming material during deformation. In structural geology, geologists usually assume rock materials are incompressible based on the observation that there is generally no significant change in the density of materials across strain gradients (Ramsay and Graham, 1970; Jiang, 2013). In the simulation part, I assume that the volume of a high-strain zone is constant. The trace of $\mathbf{D}$ is always set to 0.

The vorticity tensor $\mathbf{W}$ only has three independent components. The curl of the velocity field is defined by three independent components of $\mathbf{W}$ (Means et al., 1980):

$$\mathbf{\tilde{w}} = 2 \begin{bmatrix} W_{32} \\ W_{13} \\ W_{21} \end{bmatrix} \quad (2-5)$$

where $\mathbf{\tilde{w}}$ is the vorticity vector. The plane which is perpendicular to the vorticity vector is called the vorticity normal section (VNS, Jiang and Williams, 1998). On this plane, asymmetrical fabrics are best developed. $W_k$, which is called the kinematic vorticity number (Truesdell, 1991), is used to measure the degree of rotation of a flow with reference to the strain rate tensor of the flow:

$$W_k = \sqrt{\frac{-tr(W^2)}{tr(D^2)}} \quad (2-6)$$

When the vorticity number of a flow is 1, the flow is simple shearing. When the vorticity number of a flow is 0, the flow is pure shearing. For flows whose vorticity numbers are
between 0 and 1, they are composed of both a simple shear component and a pure shear component.

The vorticity of a flow depends on reference frame. When there are more than one reference frames, three principal axes of local coordinate system will rotate with respect to external fixed coordinate system. The vorticity can be decomposed into an internal vorticity and a spin (Means et al., 1980; Jiang, 1999):

\[ \mathbf{W} = \mathbf{W} + \Omega \]  

(2-7)

where \( \mathbf{W} \) is the internal vorticity tensor and \( \Omega \) is the spin tensor. Internal vorticity number is defined as:

\[ \bar{W}_k = \sqrt{\frac{-tr(\mathbf{W}^2)}{tr(D^2)}} \]  

(2-8)

The internal vorticity number \( \bar{W}_k \) is used to identify the instantaneous kinematics nature of different flows.

2.3 A review of single-scale kinematic models

2.3.1 Simple shear model

Ramsay and Graham (1970) propose the simple shear model that has been successfully applied to the study of outcrop-scale shear zones. An ideal simple shear zone is bounded by two parallel undeformed wall rocks (Fig. 2.1). The velocity gradient tensor for simple shearing flow is:

\[ \mathbf{L} = \begin{bmatrix} 0 & \dot{\gamma} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \]  

(2-9)

where \( \dot{\gamma} \) is the shear strain rate.
Fig. 2.1: (a) Simple shear model. Grey block represents the high-strain zone. Shear direction is parallel to the x-axis. Shear plane is parallel to the xz-plane. The VNS is the xy-plane. (b) Equal-area projection of the model in the xyz coordinate system. Simulation results are projected in this reference.
The K value of the strain ellipsoid in simple shear zone keeps 1 during deformation, which indicates simple shearing produces plane strain. The maximum strain rate axis (instantaneous stretching axis, Passchier and Trouw, 2005) has an angle of 45° with respect to the shear direction. The maximum axis of the strain ellipsoid rotates toward the shear direction as deformation advances (Fig. 2.2). At relatively low bulk strains, the rotation is rapid. When the maximum axis is close to the shear direction, it rotates slowly. The maximum stretching axis is always on the xy-plane. Correspondingly, the minimum axis of the strain ellipsoid rotates toward the shear plane normal (Fig. 2.2). The VNS is the xy-plane. In simple shear zone, linear fabrics are developed on the VNS and are subparallel to the shear direction, and planar fabrics are subparallel to the shear plane.

![Diagram](image)

Fig. 2.2: The orientations with progressive deformation of the maximum axis and minimum axis of the strain ellipsoid in simple shear zone plotted on an equal-area projection. Red dots refer to the maximum axis and blue dots refer to the minimum axis. The straight line refers to the shear zone boundary.
However, deformation in most high-strain zones is not planar. The simple shear model cannot deal with shear zones with significant flattening. In general cases, flow is three-dimensional. In the next sections, I will review 3-D kinematic models.

2.3.2 Monoclinic transpression model

The term "transpression" is defined in terms of kinematics. "Trans" means boundary parallel motion. "Pression" means horizontal shortening across a vertical zone. This concept was first proposed by Harland (1971) to describe the deformation where two blocks separated by a zone are approaching each other obliquely. This kind of deformation has regional tectonic meaning. Transpressional zones are developed in convergent plate boundaries. Later, Sanderson and Marchini (1984) propose a kinematic model for transpressional deformation based on mathematical description (Fig. 2.3). In the model, deformation is homogeneous and isochoric. Simple shearing and pure shearing occur simultaneously. Horizontal shortening is accommodated by vertical extrusion. The Sanderson-and-Marchini model has been successfully applied to the interpretation of large-scale ductile shear zones (e.g. the Archean greenstone belts in the Superior Province, see Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991).
Fig. 2.3: (a) Monoclinic transpression model. Grey block represents the high-strain zone. The boundary convergence velocity $V$ is oblique to the strike of the deformation zone. $\alpha$ is convergence angle. Shear direction is parallel to the $x$-axis. Shear plane is parallel to the $xz$-plane. The VNS is the $xy$-plane. (b) Equal-area projection of the model in the $xyz$ coordinate system. Simulation results are projected in this reference.
In the transpression model, the deformation zone is bounded by deformed wall rocks. The zone boundaries are stretched along the z-axis. The shear direction between the two boundaries is parallel to the x-axis. The velocity gradient tensor of a transpressional flow is defined as (Jiang, 2007c):

\[
\mathbf{L} = \begin{bmatrix}
0 & \cos(\alpha) & 0 \\
0 & -\sin(\alpha) & 0 \\
0 & 0 & \sin(\alpha)
\end{bmatrix}
\]  

(2-10)

where \( \alpha \) is the convergence angle. Fossen and Tikoff (1993) divided Sanderson-and-Marchini type transpression into pure-shear-dominated and simple-shear-dominated. Pure-shear-dominated transpression has a large convergence angle and its vorticity number is close to 0. Simple-shear-dominated transpression has a small convergence angle and its vorticity number is close to 1. The VNS of transpression is the xy-plane. If \( W_k > \sqrt{\frac{2}{3}} \), the maximum axis of the strain ellipsoid is close to the shear direction and on the VNS at relatively low bulk strains and then becomes parallel to the vorticity vector at relatively high bulk strains. If \( W_k < \sqrt{\frac{2}{3}} \), the maximum axis is always parallel to the vorticity vector. The vorticity numbers and orientations of the maximum strain rate axes for different convergence angles are listed in table 2-1.
Table 2-1: The vorticity numbers and orientations of the maximum strain rate axes for different convergence angles.

<table>
<thead>
<tr>
<th>Convergence angle</th>
<th>Vorticity number</th>
<th>Max strain rate axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>0.943</td>
<td>horizontal</td>
</tr>
<tr>
<td>20°</td>
<td>0.808</td>
<td>vertical</td>
</tr>
<tr>
<td>30°</td>
<td>0.655</td>
<td>vertical</td>
</tr>
<tr>
<td>50°</td>
<td>0.387</td>
<td>vertical</td>
</tr>
<tr>
<td>70°</td>
<td>0.179</td>
<td>vertical</td>
</tr>
</tbody>
</table>

The K values of the strain ellipsoids in transpressional zones are always smaller than 1 (Fig. 2.4). It indicates the strain of transpressional flows is generally flattening. The strain favors the development of SL-tectonites or S-tectonites. If transpression is pure-shear dominated, the history of the K values is close to the K=1 line. It indicates the strain in pure-shear dominated transpression is almost planar. When transpression is simple-shear dominated, the history of the K values is close to the K=0 line. It indicates simple-shear-dominated transpression favors the development of strong planar fabrics. For transpression with a convergence angle of 10°, the maximum axis of the strain ellipsoid is on the xy-plane and rotates toward the shear direction at relatively low bulk strains, and suddenly becomes vertical at relatively high bulk strains (Fig. 2.5). For transpression with a convergence angle of over 20°, the maximum axis of the strain ellipsoid is always vertical during deformation. The minimum axes of the strain ellipsoids in all transpressional zones rotate toward the shear plane normal. In monoclinic transpressional zone, planar fabrics are subparallel to the zone boundary, and linear fabrics plunge either horizontally or vertically.
Fig. 2.4: The shape evolution of the strain ellipsoids in monoclinic transpressional zones with different convergence angles plotted on the Logarithm Flinn diagram.
Fig. 2.5: The orientations with progressive deformation of the maximum axes and minimum axes of the strain ellipsoids in monoclinic transpressional zones with different convergence angles plotted on equal-area projections. Red dots refer to the maximum axis and blue dots refer to the minimum axis. The straight line refers to the shear zone boundary.

2.3.3 Triclinic transpression model

In the triclinic transpression model, the deformation zone is inclined (Fig. 2.6). The shear direction is oblique relative to the pure shear component. The velocity gradient tensor of a triclinic transpressional flow is defined as (Jiang, 2007c):

\[
L = \begin{bmatrix}
0 & \cos(\alpha) & 0 \\
0 & -\sin(\alpha)\sin(\beta) & 0 \\
0 & \sin(\alpha)\cos(\beta) & \sin(\alpha)\sin(\beta)
\end{bmatrix}
\] (2-11)
where $\alpha$ is the convergence angle and $\beta$ is the dip of transpressional zone.

Fig. 2.6: (a) Triclinic transpression model. Grey block represents the high-strain zone. The boundary convergence velocity $V$ is oblique to the strike of the zone. $\alpha$ is the convergence angle. $\beta$ is the dip of transpressional zone. Shear direction is parallel to the $x$-axis. Shear plane is parallel to the $xz$-plane. The VNS is oblique. (b) Equal-area projection of the model in the $xyz$ coordinate system. Simulation results are projected in this reference.
The VNS of triclinic transpression is oblique. The strain field in triclinic transpressional zones is generally flattening (Fig. 2.7). The maximum stretching direction changes smoothly from oblique to vertical (Fig. 2.8). The minimum stretching direction rotates toward the shear plane normal. Linear fabrics plunge shallowly to steeply. Planar fabrics are nearly parallel to the shear plane.

Fig. 2.7: The shape evolution of the strain ellipsoid in a triclinic transpressional zone with $\alpha=20^\circ$ and $\beta=70^\circ$ plotted on the Logarithm Flinn diagram.
Fig. 2.8: The orientations with progressive deformation of the maximum axis and minimum axis of the strain ellipsoid in a triclinic transpressional zone with $\alpha=20^\circ$ and $\beta=70^\circ$ plotted on an equal-area projection. Red dots refer to the maximum axis and blue dots refer to the minimum axis. The straight line refers to the shear zone boundary.

2.3.4 Monoclinic transtension model

The transtension model has been proposed for the kinematics of divergent plate boundaries (Dewey et al., 1998; Jiang and Williams, 1998; Tikoff and Fossen, 1999) (Fig. 2.9). The velocity gradient tensor of a monoclinic transtensional flow is defined as:

$$
L = \begin{bmatrix}
0 & \cos(\alpha) & 0 \\
0 & \sin(\alpha) & 0 \\
0 & 0 & -\sin(\alpha)
\end{bmatrix}
$$

(2-12)

where $\alpha$ is the divergence angle.
Fig. 2.9: (a) Monoclinic transtension model. Grey block represents the high-strain zone. The boundary divergence velocity $V$ is oblique to the strike of the zone. $\alpha$ is the divergence angle. Shear direction is parallel to the x-axis. Shear plane is parallel to the $xz$-plane. The VNS is the $xy$-plane. (b) Equal-area projection of the model in the $xyz$ coordinate system. Simulation results are projected in this reference.
The vorticity numbers and angles between the maximum strain rate axes and the shear direction for different divergent angles are listed in table 2-2. In the transtension model, the histories of the K values for different divergence angles are always above the K=1 line (Fig. 2.10). The strain in transtensional zones is generally constrictional. The maximum stretching axes for different divergent angles are always on the VNS. Their stable positions are determined by the divergent angles. The bigger the divergent angle of transtension is, the bigger the angle between the stable position of the maximum stretching direction and the shear direction is (Fig. 2.11). Transtensional deformation favors the development of strong linear fabrics. This model can be used to explain large regions of L-tectonites in a high-strain zone.

Table 2-2: The vorticity numbers and angles between the maximum strain rate axes and the shear direction for different divergence angles.

<table>
<thead>
<tr>
<th>Divergence angle</th>
<th>Vorticity number</th>
<th>Max strain rate axis</th>
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<td>50°</td>
</tr>
<tr>
<td>20°</td>
<td>0.808</td>
<td>55°</td>
</tr>
<tr>
<td>30°</td>
<td>0.655</td>
<td>60°</td>
</tr>
<tr>
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</tr>
<tr>
<td>70°</td>
<td>0.179</td>
<td>80°</td>
</tr>
</tbody>
</table>
Fig. 2.10: The shape evolution of the strain ellipsoids in monoclinic transtensional zones with different divergence angles plotted on the Logarithm Flinn diagram.
Fig. 2.11: The orientations with progressive deformation of the maximum axes and minimum axes of the strain ellipsoids in monoclinic transtensional zones with different divergence angles plotted on equal-area projections. Red dots refer to the maximum axis and blue dots refer to the minimum axis. The straight line refers to the shear zone boundary.

2.4 The limitation of single-scale models

The strain geometries predicted by current single-scale models are all monotonous: simple shearing or pure shearing produces plane strain; transpression produces flattening strain; transtension produces constrictional strain. None of them can produce a wide range of strain geometries. Current kinematic models are purely geometric and homogeneous. They work well when geologists study shape fabrics in homogeneous shear zones. If geologists work in a heterogeneous high-strain zone, they will find the
strain geometry and fabric pattern vary a lot in different outcrops and do not fit predictions of kinematic models. It is very hard to design a heterogeneous kinematic model without running into strain compatibility. To better explain strain variation on different scales, a multiscale approach is required.

2.5 Background of the numerical modeling

Before I proceed to the numerical modeling, the background of the multiscale model will be introduced.

2.5.1 The simplified treatment of rock body shapes

In order to apply the extended Eshelby theory to simulate deformation fields within heterogeneous domains of a high-strain zone, I assume the shapes of heterogeneous domains can be approximated by ellipsoids. In this section, the possibility that rock domains can be treated as ellipsoidal elements will be demonstrated.

Rock bodies in nature have irregular shapes rather than ideal geometries in 3-D space. However, the irregular shapes of rock bodies do not prevent researchers from using ellipsoids to approximate them. When researchers try to study complicated natural phenomena, they usually begin with a simplified way which is called abstraction. Abstraction is a process by which researchers reduce the observed information to retain only information which is important for solving the major problem.

There are a number of researchers who have treated individual elements as ellipsoids. Budiansky and Mangasarian (1960) were the first to regard mineral grains of a polycrystalline material as ellipsoids and applied Eshelby’s formalism to study
mechanical properties of a material. This approach was successful because it was accepted by other people (Mura, 1987, pp. 421-433; Nemat-Nasser and Hori, 1999). Besides, dislocations, stacking faults, cracks and weakened zones have been treated as ellipsoids (e.g. Mura, 1987, pp. 15-20, 240-379; Rudnicki, 1977; Healy et al., 2006; Exner and Dabrowski, 2010).

Geologists also regard rigid or deformable clasts as ellipsoids (e.g. Gay, 1968; Ghosh and Ramberg, 1976). It is confirmed by physical experiments that the motion of non-ellipsoidal bodies is very close to their best-fit ellipsoids (e.g. Ferguson, 1979; Arbaret et al., 2001; Ghosh and Ramberg, 1976). It is reasonable that the deformation path of rock bodies can be approximated by the motion of deformable ellipsoids (Jiang and Bentley, 2012; Jiang, 2013; Jiang, 2014). The partitioned flow within an ellipsoid will be insensitive to the initial aspect ratio of the ellipsoid when the initial aspect ratio is very large. Therefore, in the simulation part of the thesis, the aspect ratio of three principal axes of an ellipsoid can be set as 10:1:1 to approximate rod-like bodies, 1:1:1 to approximate spherical bodies and 10:10:1 to approximate layer-like bodies.

### 2.5.2 Extended Eshelby’s formalism for non-Newtonian viscous materials

Eshelby (1957, 1959) provided a method to relate the motion of an elastic ellipsoidal inhomogeneity embedded in the elastic matrix to the bulk deformation kinematics. He demonstrated how far-field elastic deformation is partitioned into the deformation field inside the inhomogeneity (Fig. 2.12). The stress and strain fields are uniform within the inhomogeneity. Later, his formalism was extended to Newtonian viscous materials by Bilby et al. (1975) and to power-law viscous materials by Lebensohn and Tomé (1993).
Fig. 2.12: The deformation field in an ellipsoid [strain rate, vorticity and stress ($D^E$, $W^E$ and $\sigma^E$)] is called partitioned field which is related to the bulk deformation field ($D^M$, $W^M$ and $\sigma^M$) by Eshelby’s formalism.

In the following text, tensors are represented by bold-face letters, the superscripts "E" and "M" stand for the ellipsoidal inhomogeneity and the matrix, the sign ":" stands for double contracted production of two tensors.

If both the matrix and the ellipsoid are incompressible isotropic non-Newtonian viscous materials, the relationship between the flow field within an ellipsoidal inhomogeneity and flow field of the matrix can be expressed as following equations (Jiang, 2013):

$$D^E = A : D^M$$  \hspace{1cm} (2-13)
\[ W^E = W^M + \Pi : S^{-1} : (A - J^S) : D^M \]  
(2-14)

\[ A = \left[ J^S + (n \cdot r_{eff} - 1)S \right]^{-1} : \left[ J^S + (n-1)S \right] \]  
(2-15)

where \( D \) is the strain rate tensor; \( W \) is the vorticity tensor; \( A \) is the fourth-order strain rate partitioning tensor (Jiang, 2013); \( J^S \) is the fourth-order symmetric identity tensor (Jiang, 2013); \( S \) and \( \Pi \) are the symmetric and anti-symmetric Eshelby tensors respectively; \( n \) is the power-law stress exponent of the matrix; \( r_{eff} \) is the viscosity ratio between the ellipsoid and the matrix medium in Newtonian rheology and the effective viscosity ratio in power-law rheology. Equations (2-13) and (2-14) allow us to calculate the velocity gradient tensor of the ellipsoidal inhomogeneity, \( L^E (= D^E + W^E) \), when the matrix velocity gradient tensor, \( L^M (= D^M + W^M) \), is known.

Eshelby theory is based on the assumption that there is definitely no interactions among inhomogeneities. When the volume fraction of inhomogeneities increases, the effect of interactions of inhomogeneities cannot be ignored. The mechanical property of the matrix is determined by the evolving rheology of every inhomogeneity during deformation (e.g. Nemat-Nasser and Hori, 1999). All the inhomogeneities make up a homogeneous effective matrix (HEM). Jiang (2014) applied a self-consistent approach to calculate the rheological properties of HEM and inhomogeneities. However, in this thesis, I focus on deformation fields in isolated inhomogeneities far apart from each other so that the interactions among inhomogeneities are insignificant. The self-consistent approach in Jiang's model will not be used in the simulation part.

### 2.5.3 Summary of the algorithm for the evolution of an inhomogeneity

The deformation path of an inhomogeneity is represented by the rotation and shape change of an ellipsoid. The shape evolution of an ellipsoid is represented by Flinn K
value history. I adopt the change of the orientation of an ellipsoid to describe rotational behavior of the ellipsoid. The orientation of a principal axis is defined by spherical angles \( \theta \) and \( \varphi \) in a Cartesian coordinate system (Fig. 2.13). The orientation of an ellipsoid is defined by its three mutually orthogonal axes. There are only three degrees of freedom for the orientation of an ellipsoid. Jiang (2007a, 2007b) uses a set of three spherical angles, \((\theta, \varphi_1, \vartheta)\), or \((\theta, \varphi_1, \varphi_2)\) if \(\varphi_1=90^\circ\), to define the orientation of an ellipsoid: \(\theta\) being the angle between the projection of the maximum axis in the xy-plane and the x-axis, \(\varphi_1\) being the angle between the maximum axis and the z-axis, \(\varphi_2\) being the angle between the intermediate axis and the z-axis and \(\vartheta\) being the angle between the projection of the intermediate axis in the xy-plane and the x-axis. The velocity gradient tensor of bulk flow is also defined in a Cartesian coordinate system.

![Fig. 2.13](image)

Fig. 2.13: (a) A unit vector \( \vec{u} \) is defined by spherical angles \( \theta \) and \( \varphi \) in a Cartesian coordinate system. (b) The unit vector \( \vec{u} \) is plotted on an equal-area projection.
Before deformation, the bulk flow type and initial state of an inhomogeneity (shape, orientation and effective viscosity ratio) are given as input parameters. The shape of an inhomogeneity is defined by the lengths of three semi-axes of the ellipsoid. The orientation of an inhomogeneity is defined by a set of three spherical angles of the ellipsoid.

By knowing the velocity field in an inhomogeneity, the change of the axial lengths and orientation of the ellipsoid can be tracked. By updating the shape and orientation of the ellipsoid as many steps as necessary, the deformation history of the inhomogeneity can be studied.

The whole process of computation is illustrated by a flowchart (Fig. 2.14).
Fig. 2.14: Flowchart of the numerical modeling. The actual effective viscosity ratio $r_{\text{eff}}$ depends on the strain rate of the inhomogeneity, and is determined by an iterative procedure (Mancktelow, 2011; Jiang, 2013). The iterative procedure terminates when $\left| \frac{r_{\text{eff}}^{i+1}}{r_{\text{eff}}^i} - 1 \right| < 0.01$. 
To track deformation path of an inhomogeneity at different magnitudes of finite strain, the intensity of strain $N$ defined by Ramsay and Huber (1983, pp. 201-202) is used as a reference. $N$ is the measurement of finite strain state of the bulk deformation field (bulk strain):

$$N = \sqrt{\left(\frac{X}{Y} - 1\right)^2 + \left(\frac{Y}{Z} - 1\right)^2}$$

(2-16)

where $X$, $Y$ and $Z$ are the lengths of the maximum, intermediate and minimum semi-axes of a strain ellipsoid respectively.
3 Numerical modeling

In this chapter, I will simulate the deformation fields in heterogeneous high-strain zones. The major task of the simulations is to calculate the evolution of strain ellipsoids in heterogeneous domains subjected to progressive deformation.

3.1 Numerical model setup

In the numerical modeling, the velocity gradient tensor $\mathbf{L}^M$ for the bulk flow is (Equation 2-11 in Chapter 2):

$$
\mathbf{L}^M = \begin{bmatrix}
0 & \cos(\alpha) & 0 \\
0 & -\sin(\alpha)\sin(\beta) & 0 \\
0 & \sin(\alpha)\cos(\beta) & \sin(\alpha)\sin(\beta)
\end{bmatrix}
$$

(3-1)

where, as shown in Fig. 2.6, $\alpha$ is the convergence angle and $\beta$ is the dip of the shear zone boundary. The components of $-\sin(\alpha)\sin(\beta)$ and $\sin(\alpha)\sin(\beta)$ are the longitudinal strain rates parallel to the y-axis and z-axis respectively. The components of $\cos(\alpha)$ and $\sin(\alpha)\cos(\beta)$ are the shear strain rates parallel to the x-axis and z-axis respectively. The shear plane is the xz-plane. Equation (3-1) can describe different bulk flows. When $\alpha=0^\circ$ and $\beta=90^\circ$, the bulk flow is strike-slip simple shearing. When $0^\circ < \alpha < 90^\circ$ and $\beta=90^\circ$, the bulk flow is monoclinic transpression with a vertical shear boundary. When $0^\circ < \alpha < 90^\circ$ and $0^\circ < \beta < 90^\circ$, the bulk flow is triclinic transpression with an inclined shear boundary.

The power-law flow stress exponents are $n_m$ for the matrix material and $n_e$ for the ellipsoidal inhomogeneity. When $n_m$ and $n_e$ are 1, the material is Newtonian viscous. Otherwise the material is non-Newtonian viscous. The concept of viscosity ratio $r_{ef}$ is
adopted. $r_{eff}$ is defined at a reference strain rate state to describe the rheological properties of inhomogeneities (Mancktelow, 2011; Jiang, 2013). The reference state is $D^M$ of the bulk flow.

Strong domains and weak domains in a heterogeneous high-strain zone are treated as strong inhomogeneities and weak inhomogeneities embedded in the matrix. To represent the initial state of a high-strain zone containing randomly-orientated and variably-shaped heterogeneous domains, I put 50 inhomogeneities with random orientations and shapes in a bulk flow field. Before deformation, the 50 inhomogeneities are randomly oriented in 3-D space. The shapes of the 50 inhomogeneities are set as follows: the maximum and intermediate axes vary uniformly between 10 and 1, and the minimum axes are fixed at 1. The methods of generating random shapes and orientations follow Jiang (2007a, 2007b). The initial effective viscosity ratios of strong inhomogeneities vary uniformly between 2 and 10. The initial effective viscosity ratios of weak inhomogeneities vary uniformly between 0.1 and 0.5. The inhomogeneity, whose initial effective viscosity ratio is larger than 10, will behave close to a rigid body. The inhomogeneity, whose initial effective viscosity ratio is smaller than 0.1, will behave close to liquids. Both of them are unrealistic in natural high-strain zones. In Newtonian rheology cases, the viscosity ratios are constant during deformation. In non-Newtonian rheology cases, the actual effective viscosity ratios depend on the actual bulk strain rate and must therefore be updated at every step of computation using the actual bulk strain rate.

Figs. 3.1 and 3.2 show the initial shapes and orientations of the 50 inhomogeneities. The maximum and minimum axes of the 50 inhomogeneities are uniformly plotted on equal-area projections without any preferred orientations. The $K$ values of the 50 inhomogeneities range uniformly from 0 to $+\infty$, covering a variety of shapes.
Fig. 3.1: The initial orientations of the 50 inhomogeneities plotted on equal-area projections. (a) The projection of the maximum axes of the 50 inhomogeneities. (b) The projection of the minimum axes of the 50 inhomogeneities.

Fig. 3.2: The initial shapes of the 50 inhomogeneities plotted on a logarithm Flinn diagram.
I have run various simulations by systematically changing the bulk flow type, the orientation and shape of the inhomogeneity, the rheological property of the inhomogeneity, and the stress exponents of the matrix and the inhomogeneity. The purpose of changing the parameters of the numerical experiments is to examine under what conditions heterogeneous domains can favor the development of L-tectonites. 14 sets of numerical experiments are reported here (Table 3-1) that cover different flows and different inhomogeneities. The time increment for each step in all simulations is $\delta t = 0.025$ (Jiang, 2012; Jiang and Bentley, 2012). Fig. 3.3 shows the relationship between simulation steps and the bulk strain intensity.

Table 3-1: The parameters for simulations.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>bulk flow</th>
<th>stress exponent</th>
<th>inhomogeneity</th>
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<td>$\beta$</td>
<td>$W_k$</td>
</tr>
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<td>90°</td>
<td>1</td>
</tr>
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<td>90°</td>
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</tr>
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<tr>
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<td>90°</td>
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Fig. 3.3: The strain intensity $N$ of the bulk flow as a function of computation steps for various convergence angles ($\alpha$) and dip angles ($\beta$) of the high-strain zone.

### 3.2 Simulation results

Figs. 3.4-3.15 show the results of Experiment No. 1-No. 8. The results indicate that if the strong domains (the 50 strong inhomogeneities) undergo simple shearing or monoclinic transpression with low convergence angles, the strain ellipsoids in them will become prolate as deformation advances. The localization of constrictional strain in the strong domains is weakly dependent on the initial shapes and orientations of the strong domains. The higher the bulk strain intensity, the more prolate the strain ellipsoids in the strong domains. The strain magnitudes in the strong domains are smaller than that in the bulk flow field. L-tectonites can be developed in the strong domains. On the other hand, the
strain ellipsoids in the weak domains (the 50 weak inhomogeneities) tend to become more oblate as deformation advances. The strain magnitudes in the weak domains are larger than that in the bulk flow field. In the next paragraphs, I will analyze the simulation results in more detail.

Logarithm Flinn diagrams (Figs. 3.4, 3.7, 3.10, 3.13) show that even if the heterogeneous domains undergo the same bulk flow, the strain geometries in them can be significantly different. Therefore, the strain patterns in the heterogeneous domains cannot be directly related to the bulk strain. The detailed shape change of the strain ellipsoid depends on the initial orientation, shape and effective viscosity ratio of the heterogeneous domain. Although the shapes of the strain ellipsoids in the heterogeneous domains are different from each other during deformation, their plots on the logarithm Flinn diagram are in close spatial association with the plot of the bulk strain ellipsoid at each step of computation. For each bulk flow type, the plots of the strain ellipsoids of both the strong domains and the weak domains on the logarithm Flinn diagram form clusters at each step of computation, respectively. The clusters in the plots of the strong domains are generally more scattered than those of the weak domains.

The strain pattern is highly related to the rheological properties of the heterogeneous domains. The values of \( \ln(Y/Z) \) of the strain ellipsoids in the strong domains are always smaller than that in the bulk flow field. The values of \( \ln(Y/Z) \) of the strain ellipsoids in the weak domains are always bigger than that in the bulk flow field. The \( K \) values of the strain ellipsoids in the strong domains are larger than that in the bulk flow field, whereas the \( K \) values of the strain ellipsoids in the weak domains are smaller than that in the bulk flow field. No matter which bulk flow is used in the numerical experiments, the results remain the same.
The strain magnitudes in the heterogeneous domains mainly depend on the rheological properties of the heterogeneous domains. In general, the strain magnitudes in the heterogeneous domains become larger with the increase of the bulk strain intensity. The strain magnitudes in the weak domains are higher than that in the bulk flow field. The strain magnitudes in the strong domains are lower than that in the bulk flow field. Strain is more concentrated in the weak domains. The results apply to every bulk flow in the numerical experiments. The deformation field in the weak domains has been studied by Xiang and Jiang (2013). They regard small-scale ductile shear zones as weak domains to simulate the evolution of shear zones. They conclude that weak domains become zone-like features, and have higher strain intensities and non-coaxial deformation histories regardless of bulk flows or the initial conditions of the weak domains.

Figs. 3.6, 3.9, 3.12, 3.15 present the changes of orientations of the minimum axes of the strain ellipsoids in the heterogeneous domains. The minimum axes of the strain ellipsoids in Experiment No. 1-No. 8 all form point maximum on equal-area projections at each step of computation. The preferred orientations of the minimum axes of the strain ellipsoids are all subparallel to the shear plane normal. The preferred orientations of the minimum axes of the strain ellipsoids in the strong domains are more scattered compared with those in the weak domains.

Figs. 3.5, 3.8, 3.11, 3.14 present the changes of orientations of the maximum axes of the strain ellipsoids in the heterogeneous domains. The preferred orientations of the maximum axes of the strain ellipsoids depend on the bulk flow type. For simple shearing, the maximum axes of the strain ellipsoids form a point maxima close to the shear direction. For monoclinic transpression with a convergence angle of 10°, the maximum axes of the strain ellipsoids form a spread great circle girdle which is subparallel to the shear plane. The plunge angle of the maximum axis of the strain ellipsoid depends on the initial conditions (shape, orientation and effective viscosity ratio) of a heterogeneous
domain. For monoclinic transpression with a convergence angle of 20° or 30°, the great girdle, which is formed by the maximum axes of the strain ellipsoids, is more concentrated toward the vertical axis. At relatively high bulk strains (over 300 steps), the maximum axes of the strain ellipsoids form a point maxima, which is close to the vertical axis. At each step of computation, the variation of the preferred orientation of the maximum axes of the strain ellipsoids in the strong domains is larger than that in the weak domains.
Fig. 3.4: The shape evolution of the strain ellipsoids in the 50 heterogeneous domains plotted on the Logarithmic Flinn diagram (the results of Experiment No. 1 and Experiment No. 2 in Table 3-1). The green triangle sign stands for the corresponding bulk strain ellipsoid. (a) The strain ellipsoids in the strong domains (Experiment No. 1). (b) The strain ellipsoids in the weak domains (Experiment No. 2).
Fig. 3.5: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 heterogeneous domains (the results of Experiment No. 1 and Experiment No. 2 in Table 3-1). (a) The maximum axes of the strain ellipsoids in the strong domains (Experiment No. 1). (b) The maximum axes of the strain ellipsoids in the weak domains (Experiment No. 2). The straight line refers to the shear zone boundary.
Fig. 3.6: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 heterogeneous domains (the results of Experiment No. 1 and Experiment No. 2 in Table 3-1). (a) The minimum axes of the strain ellipsoids in the strong domains (Experiment No. 1). (b) The minimum axes of the strain ellipsoids in the weak domains (Experiment No. 2). The straight line refers to the shear zone boundary.
Fig. 3.7: The shape evolution of the strain ellipsoids in the 50 heterogeneous domains plotted on the Logarithmic Flinn diagram (the results of Experiment No. 3 and Experiment No. 4 in Table 3-1). The green triangle sign stands for the corresponding bulk strain ellipsoid. (a) The strain ellipsoids in the strong domains (Experiment No. 3). (b) The strain ellipsoids in the weak domains (Experiment No. 4).
Fig. 3.8: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 heterogeneous domains (the results of Experiment No. 3 and Experiment No. 4 in Table 3-1). (a) The maximum axes of the strain ellipsoids in the strong domains (Experiment No. 3). (b) The maximum axes of the strain ellipsoids in the weak domains (Experiment No. 4). The straight line refers to the shear zone boundary.
Fig. 3.9: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 heterogeneous domains (the results of Experiment No. 3 and Experiment No. 4 in Table 3-1). (a) The minimum axes of the strain ellipsoids in the strong domains (Experiment No. 3). (b) The minimum axes of the strain ellipsoids in the weak domains (Experiment No. 4). The straight line refers to the shear zone boundary.
Fig. 3.10: The shape evolution of the strain ellipsoids in the 50 heterogeneous domains plotted on the Logarithmic Flinn diagram (the results of Experiment No. 5 and Experiment No. 6 in Table 3-1). The green triangle sign stands for the corresponding bulk strain ellipsoid. (a) The strain ellipsoids in the strong domains (Experiment No. 5). (b) The strain ellipsoids in the weak domains (Experiment No. 6).
Fig. 3.11: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 heterogeneous domains (the results of Experiment No. 5 and Experiment No. 6 in Table 3-1). (a) The maximum axes of the strain ellipsoids in the strong domains (Experiment No. 5). (b) The maximum axes of the strain ellipsoids in the weak domains (Experiment No. 6). The straight line refers to the shear zone boundary.
Fig. 3.12: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 heterogeneous domains (the results of Experiment No. 5 and Experiment No. 6 in Table 3-1). (a) The minimum axes of the strain ellipsoids in the strong domains (Experiment No. 5). (b) The minimum axes of the strain ellipsoids in the weak domains (Experiment No. 6). The straight line refers to the shear zone boundary.
Fig. 3.13: The shape evolution of the strain ellipsoids in the 50 heterogeneous domains plotted on the Logarithmic Flinn diagram (the results of Experiment No. 7 and Experiment No. 8 in Table 3-1). The green triangle sign stands for the corresponding bulk strain ellipsoid. (a) The strain ellipsoids in the strong domains (Experiment No. 7). (b) The strain ellipsoids in the weak domains (Experiment No. 8).
Fig. 3.14: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 heterogeneous domains (the results of Experiment No. 7 and Experiment No. 8 in Table 3-1). (a) The maximum axes of the strain ellipsoids in the strong domains (Experiment No. 7). (b) The maximum axes of the strain ellipsoids in the weak domains (Experiment No. 8). The straight line refers to the shear zone boundary.
Fig. 3.15: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 heterogeneous domains (the results of Experiment No. 7 and Experiment No. 8 in Table 3-1). (a) The minimum axes of the strain ellipsoids in the strong domains (Experiment No. 7). (b) The minimum axes of the strain ellipsoids in the weak domains (Experiment No. 8). The straight line refers to the shear zone boundary.
Figs. 3.16 and 3.17 present the shape evolution of the strain ellipsoids in the strong domains undergoing pure-shear-dominated transpression. In monoclinic transpression with a convergence angle of 50°, constrictional strain is developed in the majority of the strong domains at relatively low bulk strains (over 200 steps). In monoclinic transpression with a convergence angle of 70°, the strains in all the strong domains are constrictional at relatively low bulk strains (over 100 steps).

![Diagrams showing the shape evolution of strain ellipsoids](image)

Fig. 3.16: The shape evolution of the strain ellipsoids in the 50 strong domains plotted on the logarithm Flinn diagram (the results of Experiment No. 9 in Table 3-1). The green triangle sign stands for the corresponding bulk strain ellipsoid.
Fig. 3.17: The shape evolution of the strain ellipsoids in the 50 strong domains plotted on the logarithm Flinn diagram (the results of Experiment No. 10 in Table 3-1). The green triangle sign stands for the corresponding bulk strain ellipsoid.

Constrictional strain can also be developed in the strong domains undergoing triclinic transpression with $\alpha=20^\circ$ and $\beta=70^\circ$. Figs. 3.18-3.20 present the evolution of the strain ellipsoids in Experiment No.11 (Table 3-1). The K values of the strain ellipsoids in the strong domains are larger than that in the bulk flow field at each step of computation. As deformation advances, constrictional deformation is localized in the strong domains. The
maximum and minimum axes of the strain ellipsoids in the strong domains are more scattered compared with Figs. 3.11a and 3.12a.

Fig. 3.18: The shape evolution of the strain ellipsoids in the 50 strong domains plotted on the logarithm Flinn diagram (the results of Experiment No.11 in Table 3-1). The green triangle sign stands for the corresponding bulk strain ellipsoid.
Fig. 3.19: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 strong domains (the results of Experiment No.11 in Table 3-1). The straight line refers to the shear zone boundary.
Fig. 3.20: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 strong domains (the results of Experiment No.11 in Table 3-1). The straight line refers to the shear zone boundary.

Figs. 3.21-3.27 present the evolution of the strain ellipsoids in the strong domains for non-Newtonian rheology (Experiment No.12-14 in Table 3-1). The high-strain zones are composed of power-law viscous materials. The strain magnitudes in the strong domains of such materials are smaller compared with those in the Newtonian cases. The preferred orientations of the maximum axes of the strain ellipsoids and minimum axes of the strain
ellipsoids are difficult to identify as any patterns. The strong domains in non-Newtonian rheology become rigid during deformation.

When the stress exponents of the matrix and the heterogeneous domains are both 1.5, the strain ellipsoids in the strong domains (Fig. 3.21) are more prolate than those in Experiment No. 5 (Fig. 3.10a). The preferred orientations of the maximum axes of the strain ellipsoids and minimum axes of the strain ellipsoids in Experiment No. 12 (Figs. 3.22 and 3.23) are more scattered than those in Experiment No. 5 (Figs. 3.11a and 3.12a). When the stress exponents of the matrix and the heterogeneous domains are both 3, the $K$ values of the strain ellipsoids in the strong domains are always close to 0 during deformation (Fig. 3.24). The orientations of the strain ellipsoids in the strong domains vary significantly. The strong domains hardly change their shapes and the behavior is close to rigid body deformation.

The evolution of the strain ellipsoids in the strong domains is also affected by the stress exponents. The greater the stress exponents, the less strain concentrated in the strong domains. This is due to the nonlinear interaction between the heterogeneous domains and the surrounding matrix. The increase of stress exponents of the matrix and the heterogeneous domains will result in the increase of the viscosity of the strong domain during deformation. The large effective viscosity ratio of the strong domain will make it behave like a rigid body.

When the stress exponent of the matrix is 1 and the stress exponent of the heterogeneous domains is 3, the strong domains behave differently from those in Experiment No. 13 (Figs. 3.25-3.27). The reason that the difference between Fig. 3.24c and Fig. 3.25 is significant lies in the stress exponent of the matrix. The effective viscosity ratios of heterogeneous domains are very sensitive to the stress exponent of the matrix and less sensitive to the stress exponent of the ellipsoid. When Eshelby’s formalism is extended to
non-Newtonian materials, the method of tangent linearization is used. The tangent linearization allows us to use linear equations to describe nonlinear relationships. The tangent linearization, however, leads to errors in the calculation. Gilormini and Germain (1987) and Molinari and Toth (1994) conclude that an empirical effective stress exponent $n_{\text{eff}}$ can be used instead of $n_m$ to reduce the deviation from the precise nonlinear relationship. $n_{\text{eff}}$ is between 1 and $n_m$.

Fig. 3.21: The shape evolution of the strain ellipsoids in the 50 strong domains plotted on the logarithm Flinn diagram (the results of Experiment No.12 in Table 3-1). The green triangle sign stands for the corresponding bulk strain ellipsoid.
Fig. 3.22: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 strong domains (the results of Experiment No.12 in Table 3-1). The straight line refers to the shear zone boundary.
Fig. 3.23: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 strong domains (the results of Experiment No.12 in Table 3-1). The straight line refers to the shear zone boundary.
Fig. 3.24: The results of Experiment No. 13 (Table 3-1) at step 10. During deformation, the shapes of the strain ellipsoids in the 50 strong domains are plotted close to the origin. Due to nonlinear effect, the actual effective viscosity ratios of the strong domains are much higher than the initial values. The strong domains behave like rigid bodies.
Fig. 3.25: The shape evolution of the strain ellipsoids in the 50 strong domains plotted on the logarithm Flinn diagram (the results of Experiment No.14 in Table 3-1).
Fig. 3.26: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 strong domains (the results of Experiment No.14 in Table 3-1). The straight line refers to the shear zone boundary.
Fig. 3.27: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 strong domains (the results of Experiment No.14 in Table 3-1). The straight line refers to the shear zone boundary.

3.3 Summary

I have investigated multiscale deformation fields in a high-strain zone by systematically changing input parameters of the model. The parameters include bulk flow type, the stress exponents of the matrix and the heterogeneous domains, initial conditions of the heterogeneous domains (effective viscosity ratios at the bulk strain rate, orientations and
shapes). The strain ellipsoids in the strong domains tend to become more prolate as bulk strain accumulates. The strain magnitudes in the strong domains are lower than that in the bulk flow field. Simple shearing and transpression with monoclinic or triclinic symmetry can produce constrictional strain due to flow partitioning. The development of constrictional strain in the strong domains is insensitive to initial shapes or orientations of the strong domains as bulk strain intensity increases. The results are similar both for Newtonian and non-Newtonian cases.

The results indicate that, in high-strain zones with bulk planar deformation or flattening deformation, strain geometries of heterogeneous domains cannot be approximated by the bulk strain. L-tectonites can be developed in strong domains. If a high-strain zone undergoes simple shearing, L-tectonites in strong domains are subparallel to the shear direction. If a high-strain zone undergoes transpression with a low convergence angle ($\leq 20^\circ$), L-tectonites in strong domains plunge shallowly to steeply. Although L-tectonites in different strong domains have different plunge angles ranging from $0^\circ$ to $90^\circ$, their trend angles are close to the shear direction. If a high-strain zone undergoes transpression with a large convergence angle ($\geq 20^\circ$), L-tectonites in strong domains are vertical. The isolated L-tectonites are usually found in strong rock units with weak rocks all around (e.g. Dai, 2004; Sullivan, 2008). The simulation results are consistent with field observations (Fig. 3.28).
Fig. 3.28: Schematic diagram showing the multiscale deformation fields predicted by the model.
4 Application to the development of L-tectonites in Archean greenstone belts

In this chapter, I apply the insights which are gained from the simulations in Chapter 3 to the fabric development in Archean greenstone belts. Archean tectonics has been debated for a long time (e.g. Collins et al., 1998; de Wit, 1998; Lin, 2005; Chardon et al., 2011). It will be shown that the simulations in this chapter can be used to constrain tectonics in Archean cratons.

4.1 General description of the shape fabric set in Archean greenstone belts

As mentioned in Chapter 1, the defining uniqueness of fabrics in Archean greenstone belts is that in narrow greenstone belts which are bounded by much broader granitoids, isolated L-tectonite domains are developed, surrounded by common S-tectonites or SL-tectonites, and abundant shear sense indicators are developed on subhorizontal planes (e.g. Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991; Collins et al., 1998; Dai, 2004; Parmenter et al., 2006). In the following paragraphs, I will discuss this unique shape fabric set more fully and emphasize that there is a remarkable similarity between different Archean greenstone belts in terms of fabric patterns and strain geometries.

A GGT commonly occurs as a dome-and-keel structure (Lin, 2005; Lin and Beakhouse, 2013). Greenstones are synclinal keels and are composed of low- to intermediate- grade metavolcanic and metasedimentary rocks (Lin, 2005). Domes of granitoids are composed of tonalite-trondhjemite-granodiorite (TTG) intrusions (Jahn et al., 1981). In map views, greenstone belts are generally linear or narrow and granitoids are broadly circular or elliptical. The contacts between greenstone belts and granitoid domes are usually subvertical. For example, in the northwestern Superior Province in Canada, the linear
greenstone belts are generally oriented in eastern to western directions (Fig. 4.1) and subvertical. In the Pilbara Craton in Australia, circular or ellipse-like batholith is bounded by linear steeply-dipping greenstones. High variability in the distribution of fabrics is generally observed throughout a GGT. Fabrics are weakly developed in granitoid domes whereas strongly developed in greenstone belts.

Fig. 4.1: Generalized geological map of the northwestern Superior Province (after Lin, 2005).
Transposition foliations in greenstone belts are usually defined by transposed rock units with preferred alignments of minerals (e.g. biotite and chlorite), flattened clasts and pebbles. Stretching lineations are defined by preferred orientations of stretched clasts or mineral aggregates. In granitoid domes, foliation is irregular and lineation is weakly developed (e.g. Collins et al., 1998; Lin, 2005; Lin and Beakhouse, 2013). From the central part of a granitoid dome to the boundary of a greenstone belt, the strain magnitude dramatically increases. Within a greenstone belt, large areas of SL-tectonites or ST-tectonites are developed. Foliation is subparallel to the contact between a greenstone belt and a granitoid dome and dips steeply to vertically. Lineation in such volumes generally plunges shallowly to steeply. The isolated L-tectonite domains are defined by strong subvertical linear fabrics in metaconglomerates or metabasalts. Such isolated L-tectonites are not simply associated with specific structural settings like curved segments of shear zones, hinge zones of folds, or the intersection of shear zones.

For example, the Cross Lake greenstone belt in the Superior Province has the unique shape fabric set of Archean greenstone belts (Dai, 2004, Fig. 1.4; Parmenter et al., 2006). The isolated L-tectonites there are developed in the subvertical layers of metaconglomerates (Fig. 1.1). The deformed pebbles in the metaconglomerates occur in prolate ellipsoids which are oriented vertically. L-tectonites are also defined by elongate volcanic pillows in pillow basalts and the preferred orientation of amphibole minerals in massive basalts. For the greenstone belt of the Warrawoona syncline in the Pilbara Craton (Collins et al., 1998), from the north of the greenstone belt (the Mount Edgar batholith) to the fold axis of the Warrawoona Syncline, or from the south of the greenstone belt (the Corunna Downs batholith) to the fold axis of the Warrawoona Syncline, the structural features are characterized by the change from weak, inclined S-tectonites to subvertical L-tectonites. In the fold axis of the Warrawoona Syncline, the metamorphic grade is lower, and vertical L-tectonites defined by metabasalts and cherts are developed. The aspect ratios of quartz ribbons are about 1:1:50.
Abundant shear sense indicators, such as S-C structures and rotated tails, are developed in SL-tectonites (e.g. Dai, 2004; Lin, 2005; Parmenter et al., 2006). This indicates that deformation in SL-tectonites is non-coaxial and has a large simple shear component. The major fabrics which are discussed above were mostly developed in the Neoarchean (e.g., Dai, 2004; Lin, 2005; Parmenter et al., 2006). The shape fabric set was also developed in the early Archean (e.g. Collins et al., 1998). The fabrics in Archean cratons are products of a single deformation phase rather than overprinting of different deformation phases (Chardon et al., 2002, 2011; Dai, 2004; Lin, 2005; Parmenter et al., 2006).

### 4.2 Vertical tectonics and its problems

Previously, vertical tectonics has been proposed to explain the unique shape fabric set in Archean greenstone belts (Dixon and Summers, 1983; Collins et al., 1998; Robin and Bailey 2009; Lin and Beakhouse, 2013). In this model, mafic to ultramafic greenstone rocks initially overlie felsic granitoids. Due to density inversion, greenstones sink and granitoids rise. The fabrics in Archean greenstone belts are therefore related to diapiric structures (Robin and Bailey 2009; Lin and Beakhouse, 2013). The strain field caused by gravitational instability has been modeled by Dixon and Summers (1983). Their results show that constrictional strain field in the central part of greenstones is gradational outwards into a strong flattening strain field as the granite-greenstone contact is approached (Fig. 4.2). The strain pattern predicted by their model is consistent with the development of subvertical L-tectonics embedded in SL-tectonites or S-tectonites.

However, there are some problems with applying such vertical tectonics to Archean greenstone belts. First, the initial condition of greenstones overlying granitoids is difficult to explain. Second, kinematic indicators show shear zones in greenstone belts are caused
by horizontal simple shearing. The VNS is horizontal. Vertical tectonics cannot produce regional-scale transcurrent movements along greenstone belts. Third, the structures in a GGT must correlate with the configuration of the contact between rising basement and sinking cover. Such structures are not reported in some studies, such as Collins et al. (1998), Dai (2004), Parmenter et al. (2006). Diapirism produces strain intensity gradients which are spatially related to the sinking zone. The lack of significant strain intensity pattern in most greenstone belts is against vertical tectonics (e.g. the Vermilion district greenstone belt: Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991).
Fig. 4.2: The strain pattern in a greenstone belt predicted by the vertical tectonic model (after Dixon and Summers, 1983).
4.3 New hypothesis

As emphasized in Chapter 1, the shape fabrics observed in Archean greenstone belts are on different scales. Heterogeneous domains are involved in greenstone belts. In a GGT, the geometry of a greenstone belt is observed on a high-strain-zone scale. In a greenstone belt, L-tectonites are observed on a fabric-element scale. The lithological configuration of granitoids and greenstones results in a heterogeneous GGT. In a greenstone belt, rock units are also heterogeneous. Rheological heterogeneities across a GGT lead to the variation of deformation field from one domain to another. A GGT underwent regional deformation. The geometric evolution and fabric pattern of a greenstone belt are determined by local flows. Within a greenstone belt, isolated L-tectonites are produced by microscale flows.

A large amount of planar fabrics are commonly observed in greenstone belts. Based on the kinematic models discussed in Chapter 2, a GGT may undergo transpressional flow. Abundant shear sense indicators in greenstone belts indicate that tranpressional flow has a predominant simple shear component. The vertical boundaries of greenstone belts indicate that the transpressional zone has a vertical shear zone boundary and monoclinic symmetry. It will be shown that the strain variation in greenstone belts can be well explained by simple-shear-dominated monoclinic transpression as long as flow partitioning is considered. It is not necessary to invoke unique mechanisms like vertical tectonics to explain the strain variation. The transpression model does not require the difficult initial condition of the vertical tectonic model.

Flow in greenstone belts is non-steady and heterogeneous. High-strain zones in greenstone belts cannot be bounded ideally by two parallel wall rocks as in kinematic models (Xiang and Jiang, 2013). Greenstone belts are regarded as first-order inhomogeneities (Rheologically distinct phases in Jiang, 2014) embedded in a
transpressional zone. In a greenstone belt, isolated L-tectonite domains are regarded as second-order inhomogeneities. In Chapter 3, deformation fields in a high-strain zone on two different scales were simulated. Different from the simulations in Chapter 3, the simulations in Chapter 4 covered deformation fields in a high-strain zone on three different scales (Fig. 4.3). The numerical modeling in Chapter 4 is based on the idea of embedding inhomogeneities within inhomogeneities (Jiang and Bentley, 2012; Jiang, 2014). Greenstone belts, as first-order inhomogeneities, are embedded in a transpressional zone. Isolated L-tectonite domains, as second-order inhomogeneities, are embedded in a greenstone belt.
Fig. 4.3: Schematic diagram showing the multiscale structures in an Archean craton. (a) GGTs underwent the regional flow. (b) On a high-strain-zone scale, a greenstone belt is treated as a first-order inhomogeneity. (c) On a fabric-element scale, isolated L-tectonite domains are treated as second-order inhomogeneities in the greenstone belt. (d) Shear sense indicators are developed in the matrix of the first-order inhomogeneity. (e) SL-tectonites or S-tectonites are developed in the matrix of the first-order inhomogeneity (see similar diagram Fig. 1 in Jiang, 2014).
4.4 Numerical model setup

As discussed in the last section, the flow in Archean greenstone belts is assumed to be simple-shear-dominated monoclinic transpression. The convergence angle $\alpha$ and zone dip angle $\beta$ of the bulk flow are set to $20^\circ$ and $90^\circ$ respectively. The velocity gradient tensor $L$ for the bulk flow is (Equation 2-10 in Chapter 2):

$$
L = \begin{bmatrix}
0 & \cos(20^\circ) & 0 \\
0 & -\sin(20^\circ) & 0 \\
0 & 0 & \sin(20^\circ)
\end{bmatrix}
$$

Equation (4-1) is based on Fig. 2.3. I focus on the strain pattern in different greenstone belts, and therefore, $L$ is defined in a Cartesian coordinate system instead of the geographic coordinate system. Based on the simulation results in Chapter 3, strain geometries in heterogeneous domains are similar for both Newtonian rheology and non-Newtonian rheology. Materials in Archean high-strain zones are assumed to have Newtonian rheology. The stress exponents $n_c$ and $n_m$ are set to 1. The time step for each computation is set as $\delta t = 0.025$. Because strain is usually localized in greenstone belts, first-order inhomogeneities are assumed to be weak. Their effective viscosity ratios range from 0.1 to 0.5. To represent the initial condition in which greenstone belts are randomly orientated and variably shaped, 50 first-order inhomogeneities which are randomly oriented in 3-D space are generated. The shapes of the 50 first-order inhomogeneities are set as follows: the maximum and intermediate axes vary uniformly between 10 and 1, and the minimum axes are fixed at 1. The simulation results in Chapter 3 show that L-tectonites can be developed in strong domains. Therefore one strong second-order inhomogeneity is put in each first-order inhomogeneity. The effective viscosity ratios of strong second-order inhomogeneities range from 2 to 10. The 50 second-order inhomogeneities are randomly oriented in 3-D space. The shapes of the 50 second-order inhomogeneities are set as follows: the maximum and intermediate axes vary uniformly between 10 and 1, and the minimum axes are fixed at 1.
In the numerical modeling, \( \mathbf{L} \) of the bulk flow is homogeneous and steady. \( \mathbf{L} \) is defined on a regional scale. \( \mathbf{L}' \), which is defined on a high-strain-zone scale, is the velocity gradient tensor of the partitioned flow of the regional-scale flow. \( \mathbf{L}'' \), which is defined on a fabric-element scale, is the velocity gradient tensor of the partitioned flow of the local-scale flow. To calculate the internal vorticity number of a partitioned flow, I use the method developed by Jiang (2010). The internal vorticity number can be used to identify the difference between the instantaneous kinematics nature of bulk flow and partitioned flows.

**4.5 Simulation results**

In this section, I will describe the deformation fields in the 50 weak first-order inhomogeneities and the 50 strong second-order inhomogeneities. To make the descriptions easy to follow, greenstone belts and strong domains are used instead of first-order inhomogeneities and second-order inhomogeneities.

Fig. 4.4 presents the shape evolution of the 50 greenstone belts. As deformation advances, the greenstone belts are commonly flattened. The plots of their shapes are all below the \( K=1 \) line. At relatively large bulk strains (over 300 steps), the ratios between the maximum axes and minimum axes are very large, and the greenstone belts have tabular zone-like features.

As for the orientations of the 50 greenstone belts (Fig. 4.5 and Fig. 4.6), the maximum and minimum axes are randomly oriented in space before deformation. During deformation, the minimum axes rotate toward the shear plane normal. At relatively high bulk strains (over 300 steps), the minimum axes form a well-defined point maxima close
to the shear plane normal. In terms of the maximum axes of the greenstone belts, they form a broad great circle girdle, spreading nearly uniformly along the shear plane. At relatively large bulk strains (over 300 steps), the broad great circle girdle becomes more concentrated near the central point of the projection.

The simulation results indicate that the greenstone belts, as weak inhomogeneities embedded in a transpressional zone, deform into flattened belts which are linear features on the horizontal section. The greenstone belts align themselves with the shear plane. The geometry evolution of the greenstone belts is insensitive to their initial shapes or orientations.
Fig. 4.4: The shape evolution of the 50 weak first-order inhomogeneities (the greenstone belts) plotted on the logarithm Flinn diagram.
Fig. 4.5: Equal-area projection of the minimum axes of the 50 weak first-order inhomogeneities (the greenstone belts). The straight line refers to the shear zone boundary.
Fig. 4.6: Equal-area projection of the maximum axes of the 50 weak first-order inhomogeneities (the greenstone belts). The straight line refers to the shear zone boundary.

Figs. 4.7-4.9 present strain geometries in the greenstone belts. The strain ellipsoids in the greenstone belts are flattened. The maximum axes of the strain ellipsoids plunge shallowly to vertically. The minimum axes form a point maxima close to the shear plane normal. The strain fields in the greenstone belts favor the development of planar fabrics which are subparallel to the boundaries of the greenstone belts, and linear fabrics which have a wide range of plunge angles.
Fig. 4.7: The shape evolution of the strain ellipsoids in the 50 weak first-order inhomogeneities (the greenstone belts) plotted on the logarithm Flinn diagram.
Fig. 4.8: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 weak first-order inhomogeneities (the greenstone belts). The straight line refers to the shear zone boundary.
Fig. 4.9: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 weak first-order inhomogeneities (the greenstone belts). The straight line refers to the shear zone boundary.

Fig. 4.10 presents the internal vorticity numbers of the partitioned flows in the greenstone belts. Initially, the internal vorticity numbers have a range from 0 to 1. At relatively low bulk strains (N>15), the internal vorticity numbers are close to 1. The flow fields in the greenstone belts are more non-coaxial than the bulk flow. This indicates that deformation in the greenstone belts is close to simple shearing. The localization of the simple shear component in the greenstone belts produces abundant shear sense indicators.
Fig. 4.10: The histogram of the internal vorticity numbers of the partitioned flows in the 50 weak first-order inhomogeneities (the greenstone belts).

In the strong domains of the greenstone belts, the strain geometries are different from those in the regional-scale and local-scale fields. Fig. 4.11 presents the shape evolution of the strain ellipsoids in the 50 strong domains. The K values of the strain ellipsoids increase as deformation advances. The development of constrictional strain is insensitive to initial shapes or orientations of the strong domains at relatively high bulk strains (over 400 steps). Comparing Fig. 4.11 with Fig. 4.7, strain magnitudes in the strong domains are generally smaller than those in the greenstone belts. Figs. 4.12 and 4.13 present the orientations of the maximum axes and minimum axes of the strain ellipsoids in the strong domains. The maximum axes form a great circle girdle at relatively low bulk strains (over 100 steps). The girdle is subparallel to the shear plane. At relatively high bulk strains (over 300 steps), the maximum axes have a preferred orientation close to the vertical axis. As for the minimum axes, they generally form a broad point maxima close to the shear plane normal.
Fig. 4.11: The shape evolution of the strain ellipsoids in the 50 strong second-order inhomogeneities (the strong domains in the greenstone belts) plotted on the logarithm Flinn diagram.
Fig. 4.12: Equal-area projection of the minimum axes of the strain ellipsoids in the 50 strong second-order inhomogeneities (the strong domains in the greenstone belts). The straight line refers to the shear zone boundary.
Fig. 4.13: Equal-area projection of the maximum axes of the strain ellipsoids in the 50 strong second-order inhomogeneities (the strong domains in the greenstone belts). The straight line refers to the shear zone boundary.

4.6 Summary

The shape fabric patterns and strain geometries predicted by the numerical modeling fit well with the field observations. The simulation results show that the fabric development in Archean cratons can be explained by transpressional deformation. In a GGT, greenstones are rheologically weaker than surrounding granitoids. Within a greenstone belt, L-tectonites are rheologically stronger than the country rocks. On a regional scale,
GGTs generally underwent monoclinic transpression with a low convergence angle. Partitioned flows on the high-strain-zone scale are responsible for the geometric configuration of narrow greenstone belts, and the development of SL-tectonites, S-tectonites and shear sense indicators. Partitioned flows on the fabric-element scale are responsible for the development of isolated subvertical L-tectonites. Fig. 4.14 shows the summary of the simulation results.
Fig. 4.14: Schematic diagram showing the strain pattern in a GGT predicted by the numerical modeling.
5 Conclusions and future work

A multiscale model developed by Jiang (2013, 2014) was applied to simulate the strain field of a heterogeneous high-strain zone in this thesis. Heterogeneous rock masses in a high-strain zone are regarded as Eshelby inhomogeneities. The multiscale model allows the strain variation on different scales to be investigated.

Isolated L-tectonite domains in a high-strain zone can be treated as rheologically strong domains embedded in a given bulk flow field. In a flattening or plane-strain field, constrictional strain is localized in strong domains. The development of constrictional strain favors the formation of strong linear fabrics.

Constrictional strain can be produced in rheologically strong domains under simple shearing or transpression macroscale deformation. The strains of strong domains are far more prolate than the bulk strain as deformation advances. The development of constrictional strain is insensitive to the initial shapes, orientations and effective viscosity ratios of strong domains. Strong domains also accumulate much less finite strains than the surrounding rocks. The results are similar both for Newtonian and power-law rheology. The simulations show that the flow field characteristics in strong domains and developing finite strain geometries are in every respect compatible with what one would expect for L-tectonites.

The pattern of the orientations of isolated L-tectonites in a high-strain zone can be used to infer the bulk flow type of the high-strain zone. The trend directions of isolated L-tectonites are close to the shear direction of a high-strain zone. Horizontal isolated L-tectonites indicate that the bulk flow is simple shearing. Isolated L-tectonites with a wide range of plunge angles in different strong domains indicate that the bulk flow is
transpression with a low convergence angle ($\leq 20^\circ$). Vertical isolated L-tectonites indicate that the bulk flow is transpression with a large convergence angle ($\geq 20^\circ$).

I applied the simulations to Archean greenstone belts by considering L-tectonites there as strong domains. The modeling reproduces the isolated L-tectonites and surrounding SL-tectonites or S-tectonites for greenstone belts. The high-strain zones in Archean cratons were caused by transpressional flows. Partitioned flows in weak greenstone belts are responsible for the strain localization and strike-slip structures there. Partitioned flows in strong domains of greenstone belts are responsible for L-tectonite development.

Isolated L-tectonite domains in high-strain zone settings are products of the partitioned flow field. Although they should not be related directly to the regional deformation, with a multiscale approach, they can be used to constrain possible regional scale deformations. For example, I related the isolated L-tectonites in greenstone belts with the regional flow field in Archean cratons. By the multiscale approach the fabric pattern constrains the regional boundary condition that could include a horizontal shortening component, although the kinematic characteristic of the isolated L-tectonite domains is close to vertical constrictional flows.

As pointed out by Schultz-Ela and Hudleston (1991), the strain compatibility problem commonly arises where a constrictional deformation zone is embedded in a planar or flattening deformation field. Regarding isolated L-tectonites as strong domains also resolves the strain compatibility problem. The modeling provides a solution which is based on physical laws for strain variations and large strain gradients in high-strain zones.

The simulations of the thesis are based on the assumption that the volume fraction of inhomogeneites is relatively low so that there is no interaction between different
inhomogeneities. If the concentration of heterogeneous rock masses is high, the rheological properties of inhomogeneities will be affected by each other. The strain fields of inhomogeneities may be different from those of isolated inhomogeneities. Future work considering inhomogeneity interactions would entail investigating the interaction of different inhomogeneities. In a transpressional zone with a low convergence angle ($\leq 20^\circ$), L-tectonites in strong domains plunge horizontally to vertically. The mechanism, which results in the wide range of plunge angles, is poorly understood. The factors which determine the plunge angles of L-tectonites in strong domains need to be further studied. Besides, isolated L-tectonites are mostly observed in Archean cratons. In the future, detailed mapping and 3-D structural analysis will be carried out to find out more isolated L-tectonite domains in Proterozoic and Phanerozoic orogenies other than Archean cratons.
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### Appendices
#### Appendix A: Notation

<table>
<thead>
<tr>
<th>Symbol quantities</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td><strong>A</strong></td>
<td>Fourth order strain-rate partitioning tensor</td>
</tr>
<tr>
<td><strong>α</strong></td>
<td>Boundary convergence angle of a transpressional zone (or divergence angle of a transtensional zone)</td>
</tr>
<tr>
<td><strong>β</strong></td>
<td>Boundary dip angle of a transpressional zone</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>Strain rate tensor in the matrix and an inhomogeneity</td>
</tr>
<tr>
<td><strong>W</strong></td>
<td>Vorticity tensor in the matrix and an inhomogeneity</td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>Symmetric Eshelby tensor</td>
</tr>
<tr>
<td><strong>Π</strong></td>
<td>Anti-symmetric Eshelby tensor</td>
</tr>
<tr>
<td><strong>J′</strong></td>
<td>Fourth order symmetric unit tensor</td>
</tr>
<tr>
<td><strong>n</strong></td>
<td>Power law stress exponent</td>
</tr>
<tr>
<td><strong>r, r_{eff}</strong></td>
<td>Viscosity ration between inhomogeneity and the matrix (Newtonian, effective where one or both the inhomogeneity and the matrix are non-Newtonian)</td>
</tr>
<tr>
<td><strong>θ, φ, θ</strong></td>
<td>Spherical angles</td>
</tr>
<tr>
<td><strong>δt</strong></td>
<td>Time step for numerical computation</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>Position gradient tensor</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>Strain intensity</td>
</tr>
<tr>
<td><strong>K</strong></td>
<td>Flinn value of an ellipsoid</td>
</tr>
<tr>
<td><strong>W_K</strong></td>
<td>Vorticity number</td>
</tr>
</tbody>
</table>

**Superscript labelling**

| **E**             | ellipsoid |
| M       | matrix |
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