THE MAPPING OF GEOLOGICAL STRUCTURES

Krystof Verner
Czech Geological Survey in Prague
Czech Republic
Content:

1. Part
   Introduction to structural geology
   Fabrics and structures of rocks
   Mapping techniques of field structural research

2. Part
   Field course of structural mapping

3. Part
   Tectonic evolution of the Main Ethiopian Rift (MER)
   Structural data processing and interpretation
STRUCTURAL GEOLOGY

**Structural geology** is the three-dimensional study of processes and products of deformation of sedimentary, magmatic and metamorphic rocks.

The main goal of **structural geology** is to use tectonic measurements of rock anisotropy to uncover information about the history of rock deformation and understanding the regional stress field.

**Structural geology** is also important for **engineering geology**, which is concerned with the physical and mechanical properties of natural rocks.

**Fabrics and structures of rocks** (brittle, brittle-ductile and ductile) such as e. g. faults, joints, folds and foliations are internal weaknesses of rocks which may affect the stability of underground depositories.
METHODS OF STRUCTURAL RESEARCH

Field structural mapping and microstructural analyses
Description of structures and textures including analyses of their temporal and space relationships

Application of analytical methods in structural geology

Verification of field-structures using by analytical methods
Geophysical methods such as gravity or seismic modelling
Remote sensing and image interpretation

Processing of synthetic structural map and 3D sross-sections
DEFORMATION:

Modification of shape and original structures of rock as the effect of regional stress-field

EVOLUTION DES AXES PRINCIPAUX DE LA DEFORMATION

cisaillement pur, déformation coaxiale

 cisaillement simple, déformation non coaxiale
Angles and sizes (sides) of deformed object remain unchanged
Simple Shear

Angles between the sides of the original object changes

\[
\begin{pmatrix}
1 & 0 & \gamma \\
0 & 1 & 0 \\
0 & 0 & 1 \\
\end{pmatrix}
\]
Transpression

Simple shear and pure shear act simultaneously

\[
\begin{pmatrix}
  \frac{1}{a} & g(a-1)\ln a & 0 \\
  0 & 1 & 0 \\
  0 & 0 & a \\
\end{pmatrix}
\]
Mezoscopic evidence of regional strain-field

Mezoscopic structural observation provides basic information about type, character, orientation, relationships of the fabrics or structures.
Micro-scale evidence of regional strain-field

Micro-scale observation brings additional information about evolution of rocks

Strain-rate

Mechanisms of deformation

Size

Distribution

Internal structures

Preferred orientation

PT condition of deformation

Mineral composition
DEFORMATIONAL STRUCTURES:

A. Non-tectonic structures originate close to the Earth’s surface, most likely due to gravitational forces.

B. Tectonic structures are related with regional stress-field as the response to geodynamic (tectonic) processes.
NON-TECTONIC STRUCTURES

Folds as a result of mud-flow
TECTONIC STRUCTURES:

Primary structures

Primary structures are related with the origin of rocks

Sedimentary bedding
Preferred orientation of minerals in magmatic rocks

Secondary (superimposed) structures

Their origin is related according to regional stress-field

Superimposed metamorphic foliation
Cleavage
Tectonic structures

On the basis of different strain regimes we can distinguish several deformational stages:

**Compression**
- Folding
- Faulting

**Tension**
- Stretching and thinning
- Faulting

**Shearing**
- Shearing
- Faulting

*Figure 10.6* Rocks are deformed by folding or by faulting when they are subjected to different kinds of tectonic forces. Geologists see the pattern of deformation in the field and infer the nature of the forces that caused it.
EXTENSIONAL REGIME - Rifting

Tectonic model of development of Variscan root

Extensional (transtensional structures)
Increasing heat-flow and related HT metamorphism
Magma origin and ascent and emplacement
Crustal thinning and reduction of topography
COMPRESSIVE REGIME - Collision

Tectonic model of development of Variscan root

ELEVATION

THICKENING

Compressional (transpressional) structures
Prograde metamorphism
Magma ascent and emplacement driven by tectonic forces
Thickening of the orogenic root system
Growth of the topography
The origin of tectonic structures with respect to rheology

Brittle structures

Brittle-ductile structures

Ductile structures
Ductile structures

Deformational structures as the result of regional geodynamic evolution of rocks emplacement processes at higher depth (more than 15 km)

*Folded intrusive contact of and magmatic fabric defined by space orientation of K-feldspars*
Localized planar fabrics of later stages of deformation, often accompanied with retrograde metamorphism and partial recrystallization of rocks (15-10 km in depth)

Brittle-ductile structures

Shear zone with an evidence right-lateral kinematics (tonalite)

Low-temperature shear structures reflecting thrusting kinematics (migmatite)
Brittle structures

Faults and joints
Results of deformation in brittle environment

Extensional joints

Fault plane with kinematic indicators
Primary fabrics in sedimentary rocks

Sedimentary bedding
Primary accumulation planar structure in sedimentary rocks defined by bedding lithology, grain-size, grain-shape and grain-fabrics

Sedimentary structures, composition and character of material gives us information about:

Composition of source material

Processes and conditions of sedimentary deposition

Rate of sedimentation and tectonic evolution of sedimentary basins
Subhorizontal sedimentary bedding (beach sands)

Normal graded bedding
Coarse grains at the base passing upwards into finer grain sizes
Matrix supported debris-flow deposits (no structure apparent)
Current-ripple marks (fluvial sands)

Ripples of aeolian sands
Types of cross-bedding

- **Straight crested bedforms**
- **Planar cross lamination**
- **Planar cross bedding**

- **Sinuous crested and isolated bedforms**
- **Current direction**

- **Trough cross lamination**
- **Trough cross bedding**
Fabrics and structures of magmatic rocks
Types and shapes of magmatic bodies

Planar and tabular bodies:
Dikes, tabular plutons, lacolites

Elliptical and irregular boides:
stock > 10 km$^2$ > pluton > 100 km$^2$ > batholith
Batholith is a magmatic body compound of several plutons
Lacolite

Tabular body concaved upward with rigid base

Obligated to upper (brittle) – crustal conditions
Tabular body concaved downward with rigid roof restricted to upper-crustal conditions
Magmatic diapires

Steep-sided regular magmatic body with the shape of reverse tear.
Structural relationships between magmatic bodies and host rocks

Discordant bodies

Concordant bodies
Structural relationships between magmatic bodies and host rocks

Posttectonic  Syntectonic  Preteectonic
Contacts of magmatic bodies in the geological map

Contact / structural aureole

Chilled margins
Fabrics and structures of magmatic rocks

A: LINEAR
B: PLANAR
C: LINEAR-PLANAR

MAGMATIC FOLIATION
MAGMATIC LINEATION
Types of fabrics in magmatic rocks

- **Hypersolidus fabric**
  - Magmatic fabric
  - Submagmatic fabric

- **Subsolidus fabric**
  - HT
  - LT

**Melt-dominated suspension**
- Crystal-dominated suspension
- Solid state

% crystals in magma

0  50  100
Hypersolidus fabrics

No evidence or rare evidence for crystal-plastic deformation
Magmatic foliation
Porphyritic biotite granite
Flow magmatic foliation
Rhyolite
Magmatic foliation
Medium-grained tonalite
Magmatic lineation
Medium-grained weakly porphyritic granite

Plane of magmatic foliation
Magmatic foliation
Preferred orientation of mafic enclaves
Magmatic foliation
Deflection of K-feldspars around rigid objects

mafic enclave

magmatic fabric
Schlieren layers

- Gradation of the schlieren
- Younging Y
- Mafic enclave
- Continuous fade up
- Accumulation of mafic minerals
- Residues after magma mixing
Synmagmatic fracture and faults
High strain-rate
Synmagmatic fracture and faults
High strain-rate
Magmatic folds
Low strain-rate
Magmatic flow-folds
Low strain-rate

Magmatic layering
Flow foliation
Subsolidus fabrics

**HT (>450°C)**

Exclusively deformational fabrics in magmatic rocks related with recrystallization

Ductile (asymmetric folding and shearing, rotate porphyroblasts, S-C fabrics)

**LT (<450°C)**

Brittle (fracturation, segmentation of rigid parts, faulting)
Localized shear zones, S-C fabrics
Ribbons of quartz aggregates and elongated biotite
Microstructural evidence for subsolidus fabrics

Undulose extinction in quartz aggregates

Recrystallization in pressure shadows

Deformation of biotite aggregates

Grain-size reduction
Overview of possible deformational mechanisms depending on melt (%)

<table>
<thead>
<tr>
<th>Percent Melt</th>
<th>60%</th>
<th>40</th>
<th>20</th>
<th>0%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grain boundary sliding</strong></td>
<td>free rotation of crystals in melt</td>
<td>melt-enhanced gbs</td>
<td>contact melting</td>
<td>crystal plasticity</td>
</tr>
<tr>
<td><strong>Faulting</strong></td>
<td>diffuse shear</td>
<td>discreet melt-filled shear zones</td>
<td>melt-filled brittle fault</td>
<td></td>
</tr>
<tr>
<td><strong>Fracturing</strong></td>
<td>single grain melt-filled fractures</td>
<td>multigrain fractures</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Crystal tiling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Filter pressing &amp; porous flow</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Contact melting</strong></td>
<td></td>
<td></td>
<td></td>
<td>magmatic crystal plastic</td>
</tr>
<tr>
<td><strong>S-C's</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Melt-enhanced diffusion creep</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dynamic recrystallization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dislocation creep</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Embrittlement</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fabrics of magmatic rocks in the geological map.
**Fabrics of metamorphic rocks**

**FOLIATION**
A mesoscopically penetrative parallel alignment of planar fabric elements in a rock, usually a metamorphic or magmatic rock.

**LINEATION**
The subparallel to parallel alignment of elongate, linear fabric elements in rocks.

![Diagram of foliation and lineation in metamorphic rocks](image)
L, S, a LS fabrics

linear (L>S) fabrics

planar (L<S) fabrics
Metamorphic foliation

Metamorphic foliation is a penetrative planar fabrics usually produced by deformation and recrystallization of mineral grains to produce planar preferred orientation of new minerals.

Designated as „S“ (So to Sx)
Individual types of metamorphic foliation:

1. **Cleavage (slaty cleavage)**

Sharply superimposed penetrative planar fabric **in low-grade** fine-grained rocks

**Crenulation cleavage** is produced by microfolding of a preexisting foliation

**Fracture cleavage** consists of closely-spaced fractures

**Pressure-solution cleavage** produces a mineral segregation along the planes

Slaty cleavage

Cleavage plane
mikrolitón
klivavý
klivavova
doména

---

a
b

c

---

a
b
c
Cleavage (slaty cleavage)
Individual types of metamorphic foliation:

2. Metamorphic foliation

Original or superimposed planar fabric in higher-grade metamorphic rocks

**Schistosity** – foliation defined by preferred orientation of phylosilicates and/or mineral segregation into bands parallel with the foliation

**Compositional banding**

**Mylonitic foliation** – a penetrative foliation developed in zones of high-shear strain (ductile shear zones). Typical is tectonic reduction in grain-size of the rocks.
Schistosity defined by preferred orientation minerals
Compositional banding defined by preferred orientation minerals or banding parallel with the foliation
Mylonitic foliation – foliation developed in high strain shear zones.
Mylonite developed along fault zones
SUPERIMPOSITION OF METAMORPHIC FABRICS

S1
S2
S3
Metamorphic fabrics in micro-scale
Metamorphic lineation

Linear structures are important in structural mapping as than can be used to:

- distinguish various deformation phases
- determine the kinematics of deformation
**Metamorphic lineation**

- Mineral lineation
- Stretching lineation
- Crenulation lineation
- Intersection lineation
- Linear preferred orientation of boudins
FOLDS

Folds are continuous compressional structures. Their origin are related with the deformation of rocks mainly in compressional regime.

Three main structural elements determine the geometry of the fold in space

**Fold axis / Hinge line/**
The line of maximal curvature

**Axial plane**
Imaginary plane defined by fold axis and interlimb angle

**Wavelength**
The distance between adjacent fold axes
Geometry of folds

- Fold plane (cleavage)
- Fold axis (b-axis)
Geometry of folds

Symmetrical folds

Asymmetrical folds

Symmetric and asymmetric folds
Fold axis and symmetry

(a) Symmetrical folds
Axial plane is vertical

(b) Asymmetrical folds
Beds in one limb dip more steeply than those in the others

(c) Overturned folds
Both limbs dip in the same direction but one limb has been tilted beyond vertical
Clasification of fold based on interlimb angle

Interlimb angle classification

- Gentle 180°–120°
- Open 120°–70°
- Close 70°–30°
- Tight 30°–0°
- Isoclinal 0°
Classification of fold based on plunge of hinge-line and dip of axial surface

**Plunge of hinge line**
- Horizontal
- Plunging

**Dip of axial surface**
- Upright folds
- Inclined folds
- Recumbent folds

**Plunge of hinge line**
- Horizontal
- Plunging
- Vertical
Shear folds

How to make a shear fold

1. Start here
2. Layer and push!

Note that layer changes thickness

PASSIVE
**Kink-bands**

*Kink-bands folds* occur in strongly foliated rocks.
Large-scale folds

syncline

anticline
Dome and basin structures

(a) Dome

Oldest formation exposed on the surface

Youngest formation

(b) Basin

Oldest formation exposed on the surface

Youngest formation
Interference of folds
Brittle structures
FAULTS

Faults are brittle to semi-brittle planar discontinuities along which significant displacement has occurred.

The origin and evolution of faults usually form in the upper crust (less than 15 km).
Identification of faults in the field

- Faults on outcrops
- Evidence for movement (slickensides)
- Brittle deformation of rocks (cataclastic deformation)
- Secondary mineralization and alteration
- Fault-related morphology
- Linear distribution of springs
Faults
Vector of displacement along the fault plane

- Displacement along the fault plane
- Dip-slip and strike-slip component
Geometric classification of faults

Anderson’s *dynamic classification of faults* considers the stress field responsible for the faulting and simple descriptive scheme based upon the geometry and separation across a fault plane.

**Normal faults**  **Strike-slip faults**  **Reverse-slip (thrust) faults**

Stereographic projection of the faults and stress systems
Translation and rotation faults
Kinematic classification of faults

**STRIKE SEPARATION**
right lateral (dextral)  
left lateral (sinistral)

**DIP SEPARATION**
normal  
reverse

**FAULTS**
- Strike-slip faults
- Oblique-slip faults
- Dip-slip faults
- Thrust
Normal fault
Normal fault as the evidence of regional extension
Thrusting fault
Thrusting fault
Brittle deformation of rocks (tectonic breccia)
Slickensides (fault lineation) on the fault plane
slickensides
Strike-slip fault

- Riedel Shears (R)
- Riedel Shears and Splays (S)
- Lower Angle Shears/First P Shears (P)
- More P Shears; First Shear Lenses (L)
- Throughgoing Fault Zone with Shear Lenses

Diagram showing stress orientations and fault patterns.
Strike-slip fault
Psedotachylites
Display of faults in geological maps and cross-sections

- Discontinuity of geological units
- Termination of geological units and bodies perpendicular to regional fabrics and lithological contacts
- Repeating of similar sedimentary layers
Large-scale faults
Joints

Joints are planar fracture (cm to km in length) with the origin related with tension (extension) often infilled with remobilised minerals.

Stretch ($\sigma_1$) is parallel to the plane of fracture. In some cases evidences of weak shear deformation can be present.

Three genetical groups of joints:

Dilational joints are extensional joints with the fracture plane normal to the principal stress ($\sigma_3$) during joint formation

Shear joints reveal small amounts of shear displacement. They are often conjugate enclosing angle of 60° or more

Hybrid joints show components of both dilatational and shear displacement
Dilational joints
Dilational joints
Shear joints

Shear joints reveal evidence for displacement (slickensides) similar to minor faults

Shear joints are often conjugate
SURFACE OF THE JOINTS
Asymmetry of the hackles indicates character of joint origin
Joints often contain some ornaments that indicate the beginning of the promotion of cracks and also show the direction in which the crack propagated.

These characters are:

**The beginnings** - the original promotion places, which are analogous to the promotion of earthquake hypocenter. These points correspond to locations of defects in the material.

"Vochle" - are straight or curved lines that begin at the beginning, to which also converge.

**Ribs** - represent the position of the front propagation of cracks during the joint origin. The ribs are generally perpendicular to the vochle.
Joints

Three different genetical modes of joints:

1) Mode I. – Opening
2) Mode II. – Sliding
3) Mode III – Scissoring
Age relationships of joints

**X – intersection of joints.** It is possible to distinguish relatively younger and older system of joints

Younger joint do not generally cut older joints. They have T or H patterns (upright of the T or the cross-bar of the H)
Column joints in volcanic rocks

The origin of column joints depends on magma flow and rate of magma cooling
Joint is usually terminated by hook shape
Geological map and structural cross-section

Geological map

- Views intersection of geological bodies with the Earth's surface
- Plotted in the horizontal plane (the plane topographic maps)

Geological map provides a three-dimensional image of the distribution, age, shape and orientation of geological bodies and their contacts on the displayed area.

Geological and structural cross-section

- Display of geological structures and their relationships below the surface

Cross-section is plotted in the vertical plane (section) below the selected line in the geological map.

Blockdiagram

- The combination of geological maps and structural cross-section
Necessary field data for processing of the geological / tectonic map

Locality number

Geographic localization and coordinates

Outcrop description

Lithology and mineral composition

Description and orientation of structural data

Regional fabrics and their relationships
Lithological / tectonic contacts
Brittle structures (joints, faults)

*Drawing of schematic blockdiagram or photograph (oriented)*
Orientation data in structural geology

**Azimuth** – angle of the line from north (0 ° = 360 °), measured in the horizontal plane

**Circular data** - 2D, measured either in the horizontal plane as the azimuth or in any plane as an angle relative to the reference line

Axial data
Directional data (vectors)

**Spherical data** - orientation of structural elements in 3D
**Spherical data** - orientation of structural elements in 3D

Three the most important numbers

- Direction of the plane (azimuth)
- Dip direction of the plane (= direction + 90°)
- Dip of the plane
How to measure structures

**Foliation (S)**

*Schistosity, Schistosité, Schieferung*

**Strike and Dip**
- Strike (0°- 360°)
- Dip (0°- 90°)
- \[ S = 320°/50° \]

**Dip direction and Dip**
- Dip direction (0°- 360°)
- Dip (0°- 90°)
- \[ S = 230°/50° \]

**Lineation (L)**

\[ L = 351/53 \]

**Quadrant method:**
- \[ S = N40°W/50°SE \]

---

**Transfer:**
- The right hand rule
Strike, dip, trend, plunge, pitch

Vertical plane normal to strike of dipping plane

Line of strike for dipping plane

Trend of line

Pitch

Plunge

Plunging line

Vertical plane containing plunging line

Dipping plane

Pitch = angle between plunging line and the line of strike for the dipping plane

True dip
Display of planes and lines in the stereographic projection

Coordinate system for plane in geology

\[ \text{pole to plane} \]

\[ \text{geology = lower hemisphere, as above mineralogy = upper hemisphere} \]

For plane shown, convention for strike is:

- Right-hand convention: strike / dip = 360/20
- Left-hand convention: strike / dip = 180/20
- Dip direction & dip convention = 090/20

Strike & dip convention = 180/20E or 360/20E (least ambiguous reporting)

Coordinate system for axis (line) in geology shown within plane from (a) and (b)

Plan view stereogram

\[ \text{strike} = \text{azimuth of horizontal line on plane (360° or 180°)} \]

Plan view stereogram

\[ \text{trend of lineation} \]

\[ \text{trend of lineation} \]

\[ \text{plunge} \]

\[ \text{plunge} \]
Contour orientation diagram
Directional orientation of joints or faults

(a) All units
All brittle fractures (strikes)
Equal area, lower hemisphere
N = 938

(b) All units
Steep to vertical fractures (75°-90° dip)

N=421

Compression Direction During Alleghanian Orogeny
Principles of geological intersection
Principles of geological intersection
Summary of the field research (Arba Minch)

1. Side
   - Sedimentary sequence and normal faulting

2. Side
   - Extensional joints
   - Flow-foliation
   - Texturally different boudaries
   - Discordant trachyte dikes

3. Site

SE

NW

Scale

Schematic cross-section