GEOL311: Review sheet for midterm Lecture exam 1

Topic 1 - Introduction

1.1 Why study structural geology?
Earthquake hazards, find oil & gas, reconstruct 3-D geological history, investigate how Earth’s crust accommodates deformation

1.2 What is a geological structure?
Structural feature, e.g.: faults, folds, joints, foliation, lineation. Deformation is subdivided into translation, rotation, shear and dilation
Strain: change in shape or volume of a body due to stress (shear + dilation)
Stress: force per unit area acting on a surface.

1.3 Classes of structures
based on the type of structure
based on the size of the structure (macroscopic, mesoscopic, microscopic)
based on the distribution of the structure (discrete, penetrative, continuous)
based on the process of deformation (brittle, ductile)

1.4 Types of structural analysis
Descriptive analysis: characterization by type, dimensions, orientation, etc.
Strain analysis: quantitative measurement of distortion
Kinematic analysis: direction that material moves during deformation
Deformation mechanism analysis: determine temperature range of deformation
Dynamic analysis: Study of stress fields (meso- to micro-scale)
Tectonic analysis: What are the large-scale causes of deformation? (Macro-scale)

Topic 2 – Primary structures

2.1 What is a primary structure?
primary structure = structure related to formation of igneous or sed. rock
non-tectonic structure = primary structure unrelated to tectonic activity
many primary structures are geopetal, (determine way up)
Contact relations
Intrusive, faulted or depositional contact
Depositional contacts: conformable, disconformity, buttress unconformity, unconformity, nonconformity

2.2 Primary sedimentary structures
Primary sedimentary structure = syngenetic sedimentary structure determined by the conditions of deposition (primarily current velocity and sedimentation rate), developed before lithification of the rock in which it is found.
Cross-bedding: truncated top & asymptotic base, gives way-up & paleocurrent
Graded bedding: usually fining upwards
Bed-surface markings: tracks, burrows, ripple marks etc
Ripple marks: symmetric (way-up) vs. asymmetric (current direction)
Compaction / diagenetic structures: dewatering structures, convolute bedding
2.3 Salt structures
Halokinesis = deformation of halite by flowing (often in passive margin basins).
Due to density inversion, differential loading, or slope at base of salt layer
Salt diapirs – salt (halite, NaCl) flows easier than other rocks & is less dense

2.4 Primary igneous structures
A structure in an igneous rock that originated contemporaneously with
formation or emplacement of the rock, but before its final consolidation.
(a) Extrusive structures: pillow structures, ash flows, magmatic flow structures
(b) dikes, sills and laccoliths
(c) plutonic intrusions: stock, batholith, magma pressure, stoping
(d) cooling joints: columnar jointing

2.5 Impact structures
Caused by catastrophic deformation, but non-tectonic

Topic 3 – Stress

3.1 Introduction
Stress = force per unit area.
Because force is a vector, stress is also a vector. (Recall F = ma, a is also a vector)
Units = N m⁻², also known as the Pascal (Pa); 1 MPa = 10⁶ Pa; 1 GPa = 10⁹ Pa
Often find stresses cited in bars: 1 bar = 100 000 Pa (1 bar ≈ 1 atmosphere)
Stress concentration, c.f. grains and pore spaces...

3.2 Stress in two dimensions
Stress acting on a plane is a vector, which can be resolved into:
Normal stress \( \sigma_n \) - acts perpendicular to the plane.
Shear stress, \( \sigma_s \) or \( \tau \) - acts parallel to the plane
Normal force, \( F_n = F \cos \theta \), and normal stress is then \( \sigma_n = \sigma \cos^2 \theta \)
Shear force, \( F_s = F \sin \theta \), and shear stress is then \( \sigma_{1/2} \sin 2\theta \)
Note that \( F_n \) and \( \sigma_n \) have both have a maximum values at \( \theta = 0^\circ \), but \( F_s \) and \( \sigma_s \) have maximum values at different angles of \( \theta \)

3.3 Stress in three dimensions
principal stress axes are orthogonal to one another, and perpendicular to three
planes that do not contain shear stresses (the principal planes of stress)
Principal stresses \( \sigma_1 \geq \sigma_2 \geq \sigma_3 \)
Stress acting at a point - the stress ellipsoid is made up of all the stress vectors
acting on a point, from all directions. The lengths of the vectors are proportional
to the magnitude of the stresses, which vary with orientation.
Components of stress: \( \sigma_{xx} \) etc (the first letter describes the plane, the second
letter describes the direction in which the vector is acting)
There are 9 stress components all together, but only six are independent
Special stress states:
\( \sigma_1 = \sigma_2 = \sigma_3 \) Isotropic (hydrostatic) \( \sigma_1 > \sigma_2 > \sigma_3 \) Triaxial stress
\( \sigma_1 = \sigma_2 = 0; \sigma_3 < 0 \) Uniaxial tension \( \sigma_1 > 0; \sigma_2 = \sigma_3 = 0 \) Uniaxial compression
3.4 Mean and deviatoric stress

The mean stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$ in 3D, or $\sigma_m = (\sigma_1 + \sigma_2)/2$ in 2D

This is also known as the lithostatic (or overburden) pressure, in a rock column:

$$P_l = \rho \ g \ h,$$

where $\rho =$ density, $g =$ gravity, $h =$ thickness of rock (depth)

The total stress, $\sigma_{total} = \sigma_m + \sigma_d$ where $\sigma_d$ is the deviatoric stress

Mean stress causes volume change; deviatoric stress causes shape change

The stress tensor: not required for exam

3.5 The Mohr circle

$$\sigma_n = 1/2 (\sigma_1 + \sigma_3) + 1/2 (\sigma_1 - \sigma_3) \cos 2\theta,$$

so maximum normal stress when $\theta = 0$

$$\sigma_s = 1/2 (\sigma_1 - \sigma_3) \sin 2\theta,$$

so the maximum shear stress occurs when $\theta = 45^\circ$

Plotting $\sigma_s$ on the $y$ axis, and $\sigma_n$ on the $x$ axis, we get Mohr’s circle.

The circles intercepts the $\sigma_n$ axis at $\sigma_1$ and $\sigma_3$

For any value of $\theta$, we count round $2\theta$ from $\sigma_i$ and read off $\sigma_n$ and $\sigma_s$:

$$(\sigma_1 + \sigma_3)/2$$ is the mean stress, and is represented by the middle of the circle.

$$(\sigma_1 - \sigma_3)$$ is the differential stress ($\sigma_d$), represented by the diameter of the circle.

In tension, $\sigma_3$ would be negative and the centre would be left of the $\sigma_s$ axis.

You should be able to recognize and plot triaxial stress and hydrostatic stress on a Mohr circle. I will not ask you to plot $\sigma_2$ on a Mohr circle.

3.6 Stress measurement

Stress trajectories = lines connecting the orientation of a particular stress vector at different points within a body. Many stress trajectories gives a stress field.

Homogeneous and isotropic stress fields. Stresses can be measured in the Earth’s crust using several different methods: boreholes, hydrofracture, strain release, fault-plane solutions

Strength is the ability of a material to support differential stress.

Lithostatic stress (pressure) always increases with depth in the Earth.

Topic 4 – Strain

4.1 Deformation and strain

Deformation is comprised of: Distortion, Dilation, Translation, Rotation

Deformation describes collective displacements of points in a body relative to an external reference frame

Strain describes relative displacements of points in a body relative to each other

4.2 The strain ellipsoid

Strain may be homogeneous or heterogeneous

During homogeneous strain, straight lines remain straight, parallel lines remain parallel, circles (spheres in 3D) become ellipses (ellipsoids in 3D)

Material lines connect features (e.g. an array of grains) which are recognizable throughout the strain history. They are passive markers

In 2D, only two orientations of initially perpendicular material lines remain perpendicular after strain: these are the axes of the strain ellipse

Axes of the strain ellipsoid are labelled so that $X \geq Y \geq Z$
4.3 Strain path
Finite strain compares the initial and final states, irrespective of strain path.
The strain path is composed of many intermediate steps, each the result of an
incremental strain. Note that finite strain tells us nothing about the strain path!

4.4 Strain quantities
Note that all strains are dimensionless, i.e. no units!
Longitudinal strain: \( e = \frac{L - L_0}{L_0} = \frac{\partial L}{L_0} \)
Volumetric strain: \( \Delta = \frac{V - V_0}{V_0} = \frac{\partial V}{V_0} \)
Angular strain: \( \gamma = \tan \phi \)

4.5 Coaxial vs. non-coaxial strain
Coaxial strain vs non-coaxial strain
Internal vorticity (often reported as the kinematic vorticity number, \( \omega_k = \cos \alpha \))
Pure shear, simple shear, general shear (combination of pure and simple)

4.6 Special strain states (common terminology)
Triaxial strain (\( X > Y > Z \)), plane strain (\( X > Y=1 > Z \))
Axially symmetric elongation: extension (prolate) and contraction (oblate)
Note that any of the above can occur at constant volume (but not necessarily)
Simple elongation requires volume change

4.7 Measurement of finite homogeneous strain
Beware superimposed strain: can produce progressive strain histories that yield
apparently contradictory outcrop structures.

4.8 Strain markers
Strain markers are objects or features in rocks that indicate the finite strain.
To be useful, must know their shape or distribution before deformation
Passive strain markers are usually identical in composition to the whole rock
(must have no rheological contrast with host rock) so record total finite strain
e.g. a reduction spot
Non-passive strain markers have a different rheology to the host rock (usually
more rigid). They may record only some of the strain history, since the softer
(more ductile) matrix may flow around them, e.g. quartzite pebble in shale
Finite strain ellipsoid can be directly determined with initially spherical objects,
e.g. ooids, reduction spots, crinoid stems (2D only)
Alternatives are (i) linear features (e.g. belemnite), (ii) angular changes (e.g.
brachiopods or trilobites, fossils with an axis of symmetry), (iii) imbrication, (iv)
initially “elliptical” objects (e.g. quartz grains in deformed sandstone) and (v)
rock anisotropy.

Topic 5 – Rheology

5.1 Creep
Creep is the deformation of a sample with time.
Strain rate, \( e = \frac{\partial e}{\partial t} \) (units are \( s^{-1} \)); Shear strain rate, \( \gamma = 2 e \)
Typical geological strain rates are of the order \( 10^{-12} \) to \( 10^{-15} \) \( s^{-1} \).
5.2 Rheological relationships
rheology relates the imposed stress regime to the strain which occurs
basic rheologies: elastic (spring), viscous (dashpot), and plastic (sliding block)
elastic behaviour: fully reversible, stress proportional to strain, instantaneous
when stress applied or released
Poisson’s ratio $\nu = \text{strain perpendicular to applied stress} / \text{strain parallel to applied stress}$. $\nu = 0.25$ to 0.35 for most real rocks
viscous behaviour: irreversible, strain rate is proportional to stress, $\sigma = \eta \cdot (\partial e / \partial t)$
where $\eta$ is the viscosity of the material, measured in Pa.s
perfectly plastic behaviour: also irreversible, but a yield stress must be achieved
for any deformation to occur, e.g. sliding block on a plane (must overcome friction for movement to occur and $F$ cannot rise above the yield stress, $\sigma_y$).
For non-linear rheologies (strain rates vary with time at constant stress), can still define an effective viscosity at any point on the creep curve: $\eta_{\text{eff}} = \sigma / (\partial e / \partial t)$
visco-elastic behaviour: real rocks often behave like this under conditions of elevated temperature and pressure. Like a piston connected to a spring: gives immediate elastic response (recoverable), followed by a slower plastic response (non-recoverable), also known as relaxation

5.3 Rheology of natural materials (minerals and rocks)
Experiments are conducted in a triaxial rig
The behaviour of the sample depends on several different parameters:
Confining pressure ($P$): higher pressure increases the rock’s ability to flow
Temperature ($T$): higher temperature increases the rock’s ability to flow (yield strength decreases; ductile deformation mechanisms are thermally activated)
Strain rate ($\partial e / \partial t$): higher strain rates increase the likelihood of brittle failure
Pore fluid pressure ($P_{\text{fluid}}$): high pore fluid pressures reduce strength, promoting brittle failure ($P_{\text{eff}} = P_c - P_f$)
A typical creep curve shows varying behaviour over time:
I: primary (transient) creep, II: secondary (steady-state) creep, III: tertiary (accelerated) creep. If stress is not removed, the rock may fracture. If the stress is removed, the plastic deformation is not recovered, but elastic deformation is. The strength of a rock is the stress it can support before failure
The competency of a rock is a relative term comparing the resistance of rocks to flow (more competent = less likely to flow)
Strain hardening & strain softening
Brittle vs. ductile behaviour: Depending on parameters such as temperature, pressure, fluid pressure, and strain rate, rocks may deform in either a brittle, ductile, or intermediate (brittle-ductile) fashion
The brittle-ductile paradox: simultaneous occurrence of brittle and ductile features (e.g. folds and faults) in the same outcrop
Can be explained by variations in strain rate (since presumably $T$, $P$, and $P_{\text{fluid}}$ were similar across the outcrop)

Note: this is a comprehensive list. You should go this and see what you remember, and review anything you don’t!
The exam will be short answer questions, will start promptly at 10 am, and will end promptly at 10.50 am.
Bring compasses (for drawing circles), pens and pencils.
You will NOT need a calculator.