Naam………………………………………Studentnummer…………………..

Exam "Deformatie en Metamorfose van de Korst"
Educatorium zaal ALFA

- Do not forget to put your name and student number on each of the question and answer sheets and to return both of them.
- Answer questions 1-6 (the deformation part) and 7-10 (the metamorphism part) on separate sheets of paper.
- The maximum score per question is 10 pts.
- ***Check your answers prior to handing in the exam!***

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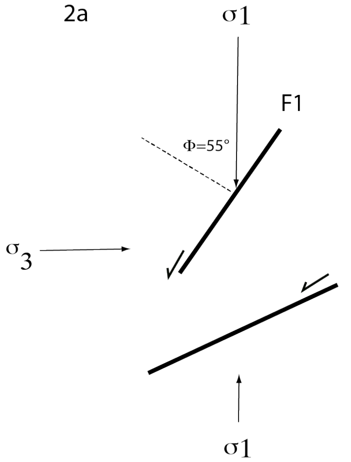
1. Give a short description of: (2 pts each)

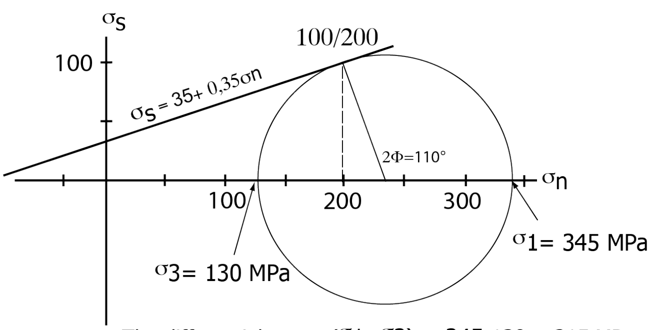
a. Body Force
Forces that affect the entire volume of a rock, eg. gravity, magnetic forces
b. Rigid body translation
Movement of a rock body without and rotation or change of shape (strain). The displacement field is marked by parallel and equally long displacement vectors
c. Stretch (b-factor)
s = 1 + e, where e is elongation (extension). Equal to the beta factor reported in regional estimates of the stretching of a basin
d. Fold hinge
The line of maximum curvature, i.e. the line defined by consecutive hinge points on a folded surface. Linear and known as the fold axis for cylindrical folds.
e. Back thrust.
Thrust displacing the hanging wall toward the hinterland, i.e. opposite to the general thrusting direction.

2. In a certain area the largest stress **σ1** is N-S oriented and horizontal. Two strike-slip faults have been mapped in this area (see map). Their strike direction is 035E (F1) and 065E (F2).

2a



2b & c



The differential stress (σ1- σ3) = 345-130 = 215 MPa

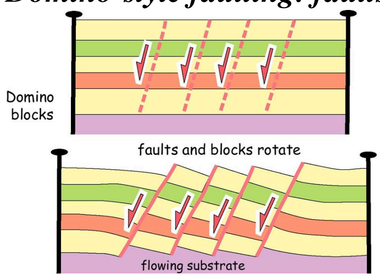
a. Indicate the sense of displacement on the faults by adding arrows in the map. Which of the two faults is more likely to be activated under the stress condition shown in the map? Explain your choice! (3pts)
The faults are sinistral strike slip faults and F1 is more likely to be activated, because the shear stress is higher on F1 compared to F2.

b. On F1 the normal stress (σn) = 200 MPa and the shear stress (σs) = 100 MPa. How large is the differential stress? ONLY use the Mohr circle construction for answering this and the following question! (4 pts)
See Figure above.

c. How large are the cohesion and the coefficient of friction of fault F1? Are these values representative for strong or weak rocks? (3pts)
See Figure above. The values are typical for fault rocks, which are generally weak.

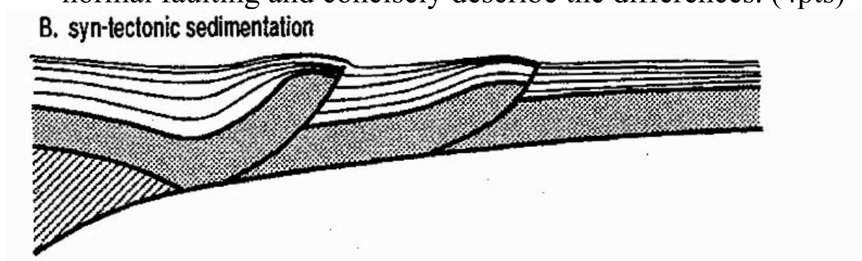
3a. Describe the differences when extension of the crust is accommodated by (a) the formation of listric faults or (b) by domino style faulting. Make sketches to illustrate the differences. (4pts)

Domino-style faulting: faults and faulted blocks rotate by the same amount.

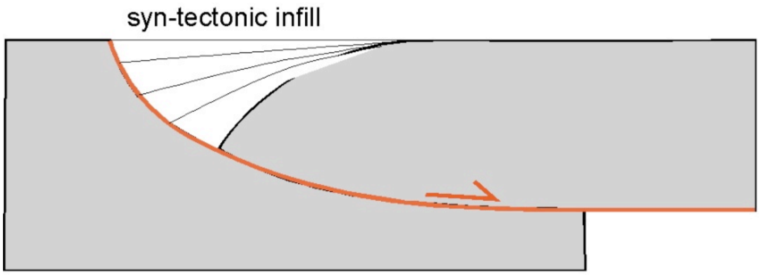


Listric faulting: Hangingwall accommodation is by the formation of roll over structures or antithetic faults. The fault does not rotate.

b. How can you infer that movement of a fault occurred at the same time as deposition of sediments. Make sketches for the cases of thrusting and of normal faulting and concisely describe the differences. (4pts)



In the case of thrust faults, syn-tectonic sediments are thicker in the footwall of the fault and thicken towards the hangingwall block. Faults cut through part of the succession.

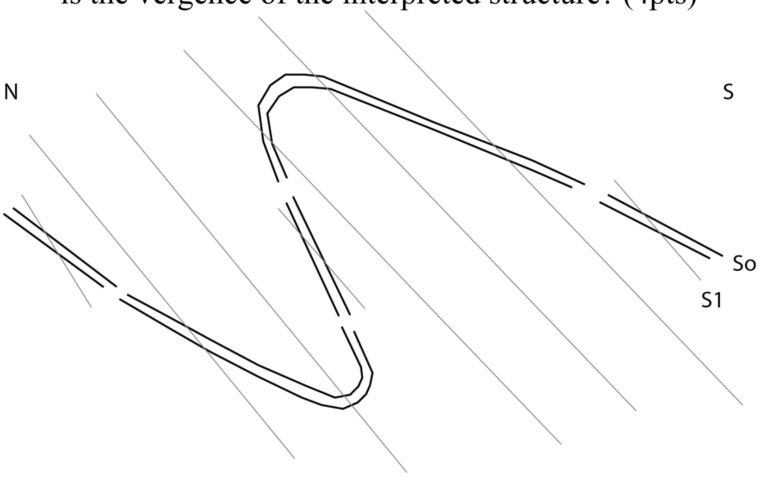


In the case of normal faults, syn-tectonic sediments are thicker in the hangingwall of the fault and thicken towards the footwall. Faults cut through part of the succession.

c. How do faults grow? Describe the main mechanisms and elaborate on their differences. (2pts)

Faults can grow by: 1. stick slip mechanisms (sudden slip followed by no slip period.
2. stable sliding or aseismic slip (slip occurs at a constant rate).
Stable sliding seems to be favoured when (a) the normal stress on the fault is small (this is the case in the shallow part of the crust or when pore fluid pressure reduces the normal stress component) and (b) the lithologies are clay-rich and/or porous.

4a. The figure below displays a bedding (S_0) – cleavage (S_1) relation observed along a road section. Complete the profile based on these observations. What is the vergence of the interpreted structure? (4pts)



This is a N-vergent structure

b. What is the direction of shortening for the situation depicted in your interpretation above and what is the orientation of the fold axes? (2pts)

The direction of shortening is N-S and the fold axes trend E-W. The asymmetry of the fold suggests that shortening was accompanied by a shear component.

c. Which observations in the field will allow you to discriminate folds developed by "neutral surface folding" from those formed by "flexural slip folding"? (2pts)

Flex. Slip: slickensides on s-planes, fold geometry often of chevron type. Neutral surface folding: extension structures at outer arc (tension gashes often filled with quartz or calcite); compressive structures at inner arc (fault and shear structures, crennulations).

d. What is the difference between cylindrical and non-cylindrical folds? (2pts)
Cylindrical folds have a straight hingle line wheras that of non-cylindrical folds is curved.

5a. Describe and sketch 4 criteria you can use to infer the sense of shear in ductile shear zones. (2 pts per criteria)
Drag of existing foliation, change in orientation of newly formed foliation, displaced markers, shear bands, sc-fabrics, porphyrocalst systems (sigma, delta clasts), asymmetric folds, mica fish, oblique foliation;

5b. Which parameters control the shape of boudinage structures? (2pts)
Viscosity contrast between boudinaged layer and surrounding matrix.

6a. What are favourable conditions for the initiation of subduction zones? (2pts)
Favourable conditions are: density and strength contrasts across plate boundaries or within plates; the existence of pre-existing structures and loads like at passive margins.

b. What is the tectonic significance of ophiolites and of which rock types are they made off? (6pts)
Ophiolites contain information on the formation of oceanic lithosphere and they provide evidence for the existence of past oceans, which have largely been subducted.
Ophiolite sequences consist of: mantle rocks (peridotites), (layered) gabbros; sheeted dykes, pillow lavas, deep sea sediments.

c. Which mechanisms lead to the exhumation of metamorphic rocks? (2pts)
Normal faulting and erosion are the most efficient exhumation mechanisms.

7. Give short answers to the following questions;

a) What is the definition of metamorphism and what grain-scale processes are involved?
b) Give a short description of a schist, a gneiss and a migmatite.
c) What is the pressure at the base of the crust at a depth of 30 km. Note that crustal density is about 2700 kg/m^3, g =9.8 m/s^2, SI units of pressure are Pa and 1 kilobar (kb) = 100 MPa.
d) How can you distinguish metamorphic rocks from igneous and sedimentary rocks in the field?
e) What is the difference between dynamic metamorphism and regional orogenic metamorphism?

a) *(2 points) Sum of all changes (minerals, grainsize and grain shape) that occur when the PT environmental conditions are changed. Processes are mineral transformations, reactions, recrystallization and deformation.*
b) *(2 points) Schist, metamorphic rock with continuous foliation; gneiss.partly foliated structure; migmatite mixed rock with igneous layers (produced by melting) and foliated layers of residue from melting.*
c) *(2 point) P=g x density x depth   9.8 x 2700x 103 x 30x 103=793.8 MPa =7.9 kb about 8kb*
d) *(2 points) Metamorphic rocks have foliations and porphyroblasts, clasts. Sedmentary rocks have bedding, sedimentary structures, clastic grains; igneoud rocks have interlocking grains and usually no banding or foliation.*
e) *(2 points)Dynamic..recrystallization reaction and deformation in local high strain zone. Regional..reaction and deformation and heating in mountain range.*

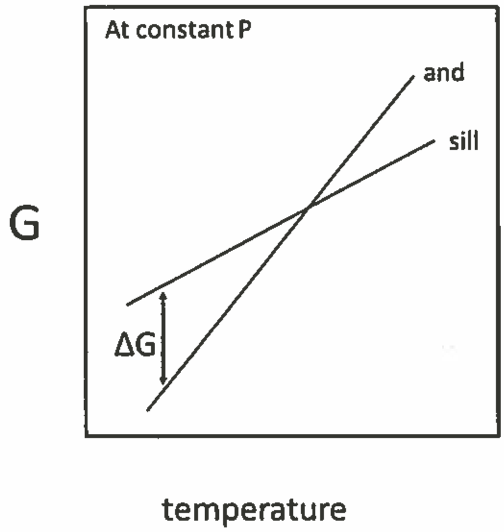
8. Some rocks in a metamorphic belt contain the following minerals: jadeite = $NaAlSi_2O_6$, quartz = SiO_2 , Andalusite Al_2SiO_5, Silliminite Al_2SiO_5, and albite $NaAlSi_3O_8$

a) How many chemical components are needed to describe these rocks and minerals?

b) What chemical reactions and polymorphic reactions can occur in this system?

c) Define the phase rule and use this rule to determine how many minerals will be present in this system in a divariant mineral assemblage and an invariant assemblage in this chemical system.

d) The diagram shows a plot of the Gibbs free energy for sillimanite and andalusite, with increasing temperature, at constant pressure. Which mineral will be stable at high temperatures?

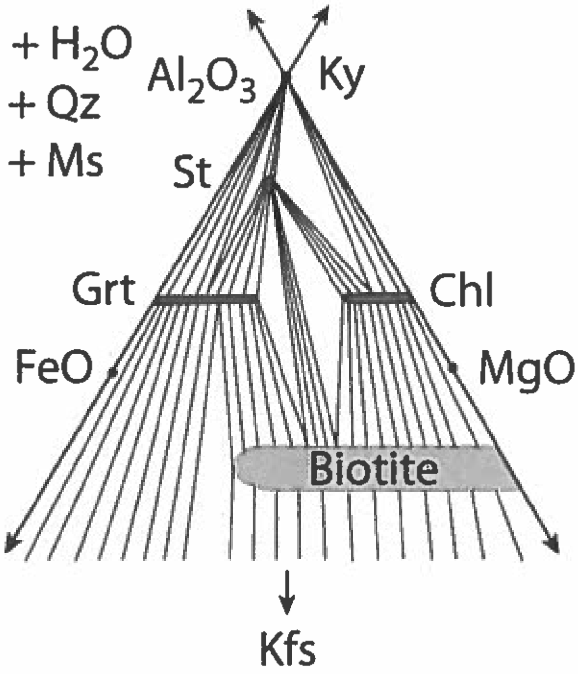


e) What thermodynamic parameter controls the slope of the Gibbs free energy versus temperature plot in the figure above.

0.5 albite → jad

a) *(2 points) 3 components SiO, AlO and NaO*
b) *(2 points) Albite = quartz + jadeite, quartz to coesite and andalusite-kyanite-sillimanite*
c) *(2 points) F (degrees of freedom)= (chemical components+2) – phase number. If C=3 then divariant is F=2 so 3 phases. Invariant F=0, so 5 phases.*
d) *(2 points) The phase with lowest gibbs free energy will be stable so sillimanite.*
e) *(2 points) Entropy is the slope dG/dT*

9. The figure below shows an AFM diagram for the staurolite metamorphic zone from NE Scotland. This zone occurs in a sequence of garnet zone, staurolite zone, kyanite zone and sillimanite zone.

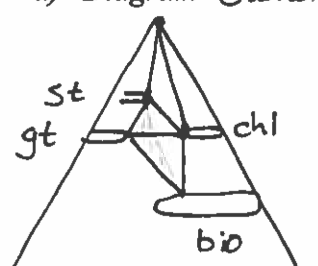


(2 points per section)

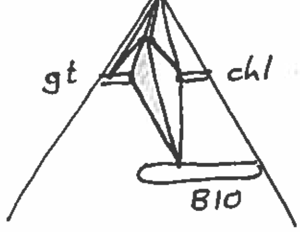
Staurolite zone

a) Why are the minerals like biotite plotted as a band of compositions?
b) Why does garnet (G) plot on the Fe rich side of the diagram and chlorite (Chl) on the Mg-rich side of the diagram?
c) Make a list of the all of the mineral assemblages containing staurolite (St) that can occur in this zone.
d) Draw AFM diagrams for the garnet zone and the kyanite zone. The reactions at each isograd are: at the strauolite "in" isograd, staurolite + biotite = garnet + chlorite + water; and at the kyanite "in"isograd, staurolite + chlorite = kyanite + biotite + water.
e) If a rock has a mineral assemblage of staurolite, garnet, biotite in the staurolite zone, what will be the mineral assemblage in the garnet and kyanite metamorphic zones?

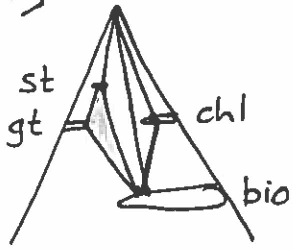
a) Biotite is a solida solution with variable Fe/Mg ratio.
b) Fe fits better into garnet structure and Mg better into chl structure.
c) 3 phases : St-chl-bio, st-ky-chl;st-gt-bio; st-gt-ky.2 phases st-gt, st-ky. St-bio, st-chl.
d) Diagram Garnet zone



St ky



Kyanite Zone



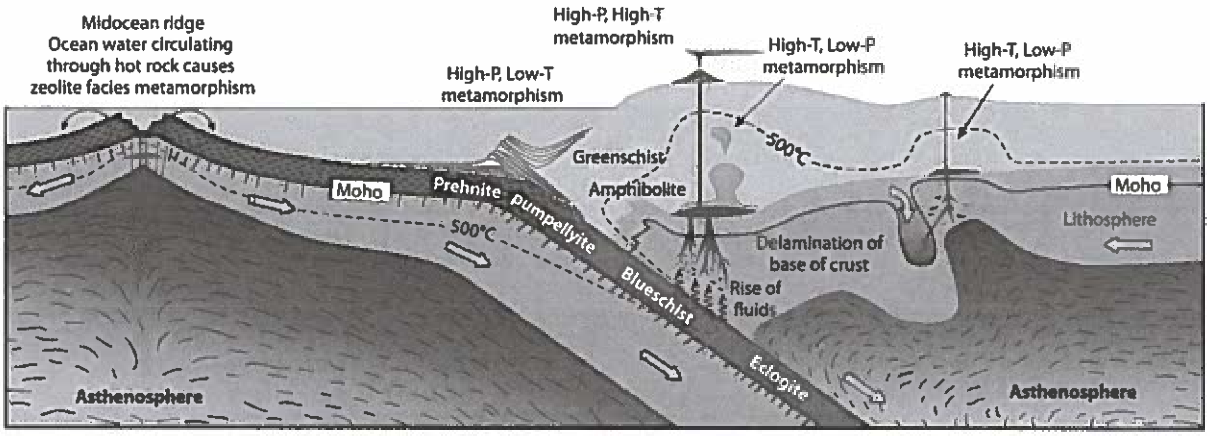
e) From diagram

St Gt chl ⟵ St Gt Bio ⟶ St Gt Bio

or

Gt Chl Bio

10. The figure below shows the pressure and temperature produced in different plate tectonic environments.



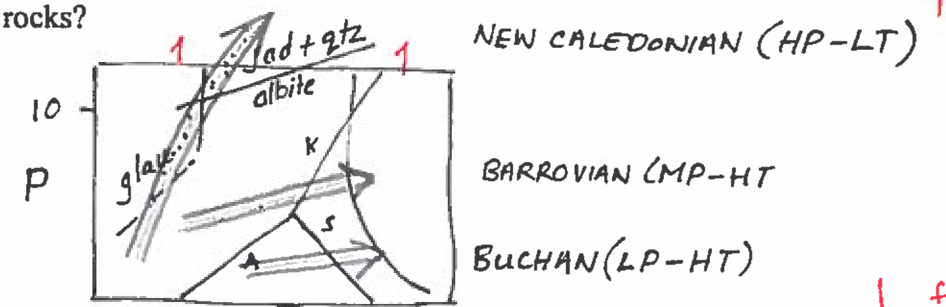
a) Draw a sketch PT diagram showing: the stability fields of the Al_2SiO_5 polymorph minerals, the amphibole glaucophane, the pyroxene omphacite and the three main types of metamorphic field gradient.

b) What are the plate tectonic environments where the different metamorphic field gradients can be formed?

c) Draw a sketch diagram showing the relationship between the PT paths, the geotherms, and the metamorphic field gradient, expected for a simple history of crustal shortening.

d) What metamorphic rocks are found in the Alps and what is the tectonic history indicated by these rocks?

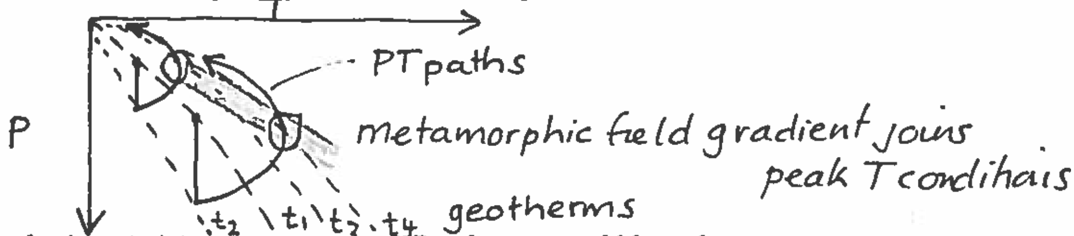
3 *a) Diagram*



2 *b) HP-LT (new Caledonia) gradient is formed in subduction zones, MP-HT (Barrovian is formed in continental collision, or thickening; LP-MT (Buchan) is found in rift zones, volcanic arcs or in zones of delamination at base of crust.*

1 for 1
1.5 for 2
2 for 3

3 *c) Diagram*



2 *d) Series of UHP rocks (coesite) in upper nappe, HP eclogites and blueschists in oceanic nappe and lower pressure rocks in lower nappes. This subduction related metamorphism occurs before nappe stacking and crustal shortening. The nappe stack is overprinted by barrovian field gradient with ky and sill isograds. This is related to thermal relaxation and erosion after collision.*