

## 26445 - Structural Geology

### Syllabus Information

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**Academic Year:** 2019/20

**Subject:** 26445 - Structural Geology

**Faculty / School:** 100 -

**Degree:** 296 - Degree in Geology

588 - Degree in Geology

**ECTS:** 9.0

**Year:** 588 - Degree in Geology: 2

296 - Degree in Geology: 2

**Semester:** First semester

**Subject Type:** Compulsory

**Module:** ---

## 1.General information

### 1.1.Aims of the course

**The expected results of the course respond to the following general aims**

The general goals of the subject are brought up at three levels:

- (a) Learning of conceptual and methodological aspects through theoretical and practical classes (deductive learning)
- (b) Practical use of techniques for analytical treatment and plotting of structural data.
- (c) Development of research capabilities using empiric methodologies, from field-data collection to final interpretation.

#### **General goals:**

The student should:

- 1) know the different types of tectonic structures: definitions, classifications; as well as geometric, kinematic, and dynamic characteristics at different scales.
- 2) develop observation abilities and collect field data.
- 3) learn the main techniques to represent and analyze tectonic structures.
- 4) know how to apply the concepts and models of Structural Geology to regional scale interpretations.
- 5) be able to work alone and in a group.
- 6) learn to be critical with scientific information, and be able to express clearly his/her scientific results.

### 1.2.Context and importance of this course in the degree

Structural Geology is a fundamental tool to decipher the geology of deformed areas and thus it should be considered an indispensable knowledge for any geologist. On the other hand, Structural Geology deals with geometrical aspects of deformation and thus it is closely related with disciplines like Geological Mapping, Geophysics and Tectonics.

### 1.3.Recommendations to take this course

This branch of the Geology requires the development of a 3-D visualization of the tectonic structures, as well as observation and interpretation abilities both in the lab and in the field. This course in Structural Geology values the comprehension and the reasoning capabilities as much as the rote learning.

## 2.Learning goals

### 2.1.Competences

**After completing the course, the student will be competent in the following skills:**

Recognize, describe and classify the main tectonic structures.

Interpret the genetic mechanism of the studied structures.

Apply the most appropriate geometric, kinematic or dynamic method to study a specific structure or group of structures.

Identify in the field deformational structures and their geometric elements.

Collect structural data in the field. Be able to recognize outcrop and regional scale structures and to draw schemes and geologic cross-sections. Measure linear and planar elements in the field.

Identify deformational structures at hand and thin-section scale.

Have a good command of the main structural techniques related with the representation and analysis of geometric data: stereographic projection, orthographic projection, cross sections, block diagrams, contour maps.

Reconstruct the genetic mechanisms of real structures, as well as their kinematic and dynamic evolution, and in the case of polyphasic deformations, their chronological sequence.

## 2.2.Learning goals

**The student, in order to pass the course, will have to show her/his competence in the following skills:**

Identify the main type of tectonic structures as well as to know their geometric characteristics and genetic mechanisms

Construct geologic maps as well as schemes showing the geometry and relationship of the structures in the field

Measure the attitude of planes and lines using the geologic compass

Represent and read structural elements (planes and lines) by means of orthographic projection, stereographic projection and cross sections

Find and read scientific articles as well as select and understand the most relevant information.

Work alone and in a group, as well as to defend scientific results with reasonable arguments.

## 2.3.Importance of learning goals

Geologic structures provide part of the basis for recognizing and reconstructing the profound changes that have marked the physical evolution of the Earth's outer layers, as observed from the scale of the plates down to the scale of the microscopic. Understanding the nature and extensiveness of deformational structures in the Earth's crust has both scientific value and practical benefit. But, there is a philosophical value as well. Our perceptions of who we are and where we are in time and space are shaped by facts and interpretations regarding the historical development of the crust of the planet on which we live. Knowing fully the extent to which our planet is dynamic, not static, is a reminder of the lively and special environment we inhabit ..... Once the conceptual framework within which structural geologists operate is grasped, the Earth begins to look different. In fact, natural physical processes and natural physical phenomena, whether geologic or not, never quite look the same again (*from Davis and Reynolds, 1996*).

## 3.Assessment (1st and 2nd call)

### 3.1.Assessment tasks (description of tasks, marking system and assessment criteria)

**The student will prove that he/she has achieved the expected learning results by means of the following assessment tasks:**

ASSESSMENT OF STUDENTS THAT ATTEND CLASS REGULARLY

To track the improvement and knowledge of the students, part of the assessment will be carried out during the learning process (continuous assessment) and part at the end of the course (final assessment)

#### 1. Continuous assessment

1) *Question papers/questions for oral answer.* The students will have to answer to question papers or questions for oral answer, alone or in groups, dealing with conceptual and methodological aspects. This activity will be mainly related with the seminar exercises. (Evaluation of skills 1, 5 and 6).

2) *Laboratory exercises.* The practical exercises carried out in the lab will be corrected every week. (Evaluation of skill 4).

3) *Field work.* The attendance to the field trips is compulsory. The personal work, expressed in the student's note-book, and the attitude of the student in the field, will be evaluated. (Evaluation of skills 2, 3 and 6).

#### 2. Final assessment

4) *Written exercises.* A theoretical-practical exercise and a practical exercise will be carried out during the period of exams (4-5 hours). The theoretical-practical exercise will be constituted by two parts: a) a test and/or a set of short questions, and b) questions that, in most cases, may be answered by means of drawings. The practical exercise will be closely related with the practical sessions of the course. (Evaluation of skills 1, 2 and 4).

ASSESSMENT OF STUDENTS THAT DO NOT ATTEND CLASS REGULARLY

#### Global assessment

Those students that have not attended the course regularly, as well as those who wish to, may take a global exam:

February exam: It may be an oral (speaking) exam or a written exam. The evaluation may include any activity related to field work.

September exam: It may be an oral (speaking) exam or a written exam. The evaluation may include any activity related to field work.

1) oral exam or a written exam. Duration of the exam: 3-5 hours.

2) a practical exam where the student will have to solve laboratory and field exercises similar to those carried out during the course. Duration of the exam: 3-5 hours.

### Assesment criteria

(a) Assessment of the course for students that attend classes regularly:

As a general rule, to pass the course it will be necessary to:

- 1.- Participate in the laboratory and seminar activities and attend the field trips.
- 2.- Obtain a grade higher than 5 in the theoretical-practical exam.
- 3.- Obtain a grade higher than 5 in the practical exam.

Evaluation of skills:

- Lab work: 5 %
- Seminars: 15 %
- Field work: 5 %
- Practical exercise: 35 %
- Theoretical-practical exercise: 40 %

(b) Assessment of the course for students that do not attend classes regularly:

- Written exam: 50 %
- Practical exam: 50 %

## 4. Methodology, learning tasks, syllabus and resources

### 4.1. Methodological overview

The methodology followed in this course is oriented towards the achievement of the learning objectives. A wide range of teaching and learning tasks are implemented, such as theory and practice sessions, seminars, laboratory sessions, fieldwork and tutorials.

The program of the course is just the framework that should guide the active learning of the students. The students will have class-notes given by the professor as the basis for their learning, but they must extend the information given in class using that coming from technical books and scientific journals. The practical learning will prevail over the theoretical one. The laboratory sessions will be mainly devoted to the analysis of the most common tectonic structures. The fieldwork will focus on the recognition of the studied structures, the determination of their geometries, structural relationships, ages, and the obtained data will be represented on the student's note-book by means of tectonic schemes, cross-sections, etc, and by simple geological maps. It is important to note that the specific terminology used in this course will also be taught in Spanish.

### 4.2. Learning tasks

This course is organized as follows:

- **Theory and practice sessions** (3 ECTS: 30 hours) 3 weekly hours.
- **Seminars** (0,5 ECTS: 5 hours) Oral presentations and discussions. Conceptual, descriptive and genetic aspects of tectonic structures. The most common geometric, kinematic and dynamic methods.
- **Laboratory sessions** (2,5 ECTS: 25 hours). 2.5 weekly hours, 10 sessions in total. How to analyze meso and micro-scale structures. Reconstructing and analyzing the geometry, kinematic and dynamic of tectonic structures.
- **Fieldwork** (3 ECTS: 30 hours). How to work in the field.
- **Tutorials**. Tutorials are considered another academic activity where the student is free to ask any doubt related with the course.

### 4.3. Syllabus

This course will address the following topics:

#### Lectures

##### Section 1: Introduction

- **Topic 1.** Introduction to the course. Structural Geology, Tectonics and Global Tectonics: history, goals and methods. Geometry, kinematics and dynamics in Structural Geology.
- **Topic 2.** Lines and planes in Structural Geology. Orientation of lines and planes. True and apparent dips. Field notes (conventional symbols). Analysis of the orientation of lines and planes. The Stereographic projection.
- **Topic 3.** Stress. Definition of force and units. Definition of stress and units. Simple calculation of stress. Lithostatic stress. Stress due to contact forces. Components of stress. State of stress in a point. Tensor and stress ellipsoid.

Types of state of stress. Resolving the state of stress on a plane. Mohr stress diagram. Mean stress, deviatoric and differential stress. Stress field and stress trajectories.

## Section 2: Ductile structures

- **Topic 4.** Strain. Definition and types of deformation. Classification of internal deformation: continuous/discontinuous, fragile/ductile, and homogeneous/inhomogeneous. Vector, trajectory and displacement field. Finite, infinitesimal and progressive deformation. Measuring and representing deformation: rigid body deformation (translation, rotation) and non-rigid-body deformation (longitudinal strain, shear strain and dilation). The strain ellipsoid: types of strain ellipsoids. Flinn's diagram. Special terms in strain (coaxial, non-coaxial; rotational, non-rotational; pure and simple shear). Progressive deformation and the length of deformed lines. Zonation of the finite strain ellipse. The fundamental strain equations. The Mohr strain diagram.
- **Topic 5.** Ductile deformation processes. Ductile deformation. Cataclasis/Cataclastic flow. Crystal plasticity (dislocation migration, mechanical twinning). Diffusional mass transfer (volume-diffusion creep, grain boundary diffusion creep, superplastic creep; pressure solution. Deformation microstructures (recovery, dynamic and static recrystallization), neomineralization. Deformation mechanisms and physical conditions during deformation (deformation maps).
- **Topic 6.** Rheology and mechanical behavior of rocks. Definition. Strain rate. Laboratory deformational experiments (compressional and extensional tests). Duration of deformational experiments (long and short term deformational experiments). Short duration lab experiments: elastic and plastic behavior, yield stress/strength, rupture strength; strain/work hardening, strain softening, ultimate strength. Long duration lab experiments: creep (primary, secondary, tertiary). Rheological relationships (linear and non-linear rheologies): Elastic behavior, viscous (viscoelastic, elastico-viscous, general behavior), ideal plastic behavior and elastic-plastic. Factors that influence the mechanical behavior of rocks: lithology, temperature, confining pressure, time, the magnitude of stress, strain rate, pore fluid pressure (effective stress). Classification of rocks according to their rheological behavior (brittle and ductile, competent and incompetent). Rheological behavior and depth: structural levels.
- **Topic 7.** Rock fabrics. Introduction: concept of fabric. Classification of fabrics (primary, secondary; isotropic, anisotropic; mesoscopic, microscopic; crystallographic; penetrative, non-penetrative; dimensional. Types of dimensional fabrics (planar, linear, double fabric). Tectonites (L, S, S-L, S-C). Cleavage. Types of cleavage: disjunctive (space, stylonitic, rough cleavage, crenulation cleavage); continuous cleavage (slaty, phyllitic cleavage, and schistosity); gneissic structure. Genetic mechanism of cleavage. Tectonic meaning of cleavage (cleavage fans, axial plane cleavage, cleavage refraction). Lineations. Most common lineations: intersection, crenulation, stretching and mineral lineations. Some linear structures: mullions and boudinage.
- **Topic 8.** Folds. Definition and tectonic environment. Scientific and economic interest. Geometrical and physical elements (parts of a fold: hinge point, line, zone; flanks, core, inflection points-lines, curvature, axial surface, etc). Elements of a folded surface (crest point-line, trough point-line, culminations and depressions, etc). Size of an isolated fold/train of folds (wavelength-amplitude). Fold description: shape, tightness, size and attitude. Fold classifications according to: a) relative age of the rocks, b) direction of the concavity/convexity, c) fold shape (Hudleston, 1973), d) form of the fold, geometry of the axial surface, e) symmetry (vergence), f) fold attitude (Fleuty diagram), g) fold tightness, h) changes of wavelength and/or amplitude. Ramsay's classification; Ramsay's diagram. Fold termination. Large scale folding (anticlinorium, synclinorium, fold belts, ...). Superposed folding. Fold interference pattern. Folding style.
- **Topic 9.** Folding mechanisms and kinematic models. Active and passive folding. Three mechanisms and five kinematic models of folding at meso-macroscopic scale: Flexure (flexural-slip, flexural flow and volume-loss folding); fold shape modification by superimposed homogeneous strain; flow (simple shear transverse to bedding; shear folding. 1) Flexural-mechanism: bending and buckling. Internal strain in flexural folding: Longitudinal strain in the hinge zone and shear strain in the flanks. Flexural flow folds. Volume loss folds. 2) Flattening-mechanism: homogeneous and inhomogeneous. Cleavage associated to flattening. Combination of flexure and flattening. 3) Flowage-mechanism. Types of deformation by flow. Shear folding. Tectonic environment and folding. Donath and Parker (1964): genetic classification. Some special types of folding: kink folds and drag folds.

## Section 3: Brittle structures

- **Topic 10.** Rock mechanics/rock fracturing. The fundamental fracture modes (modes I, II, and III). Introduction to rock mechanics (tensile and compressive strength tests); Mohr diagram and envelope of failure. Constructing an envelope of failure: tensile strength tests, tensile and compressive strength tests transitional tensile behavior, parabolic failure envelopes). Griffith's law of fracture criterion. Compressive strength tests-Coulomb's fracture criterion. Application of the Murrell and Coulomb fracture equations. Compressive tests raising confining pressure; von Mises' fracture criterion. Grand failure envelope. Effective stress: the influence of pore fluid pressure. Testing prefractured rocks (Failure envelope for frictional sliding, coefficient of sliding friction, ..., Byerlee's law). Classification of fractures and physical discontinuities. Brittle fractures and the Mohr circle.
- **Topic 11.** Joints and shear fractures. Definition. Geometry: form of the joint surface. Classification of joints

considering: a) general characteristics (joint set, joint system); b) angular relationship between joints (Hancock, 1985); c) characteristics of the opening. Joint-face ornamentation: plumose markings (origin, hackles, ribs, fringes, ...). Joint spacing; spacing/bed thickness. Some criteria to determine the relative chronology. Recording joint data. Dynamic interpretation of joints and shear fractures: joints, shear fractures and the Mohr circle.

- **Topic 12.** Stylolites surfaces and extension veins. Definition of stylolitic surface and stylolite. Geometry of stylolites and stylolitic surfaces; normal and oblique stylolites; bedding and transverse stylolites. Slickolites. Genesis of stylolitic surfaces: pressure solution mechanism. Stylolitic surfaces/stylolites and the stress tensor. Definition and characteristics of extension veins. Criteria to determine the extension direction (tension vein texture; syntaxial and antitaxial crystal fiber veins). Tension gashes and shearing; tension gashes and folding. Extension veins and the stress tensor. Relationship between stylolites and extension veins: dynamic implications.
- **Topic 13.** Faults. Definition of fault, fault zone and ductile shear zone. Classification based on: a) the fault surface geometry-attitude; b) hanging wall movement (rotational, non-rotational). Geometric elements of faults (tip point-line; blind fault, exposed fault, fault scarp, .., cut-off point-line, ..)The slip of a fault and fault separation. Net slip: components (heave, throw). Classification of faults considering the slip components ( dip-slip, strike-slip, oblique-slip, scissor-like or rotational). Naming oblique-slip faults. Criteria to identify the direction and sense of displacement of a fault (from the fault surface: striations, slickolites, grooves, crystal fiber lineations, .... ; cartographic criteria: orthographic and stereographic projections; structures related to the fault kinematics: drag folds, ...). Extensional and contractional faults. Fault systems (branch point/line). Horsts and duplexes. Conjugate faults; synthetic and antithetic faults. Kinematics of crossing conjugate fault sets. Anderson's theory of faulting: relation between conjugate faults and the principal stress axes. Fault reactivation and inversion tectonics. Fault rocks: brittle ( breccias, cataclasites, pseudotachylites) and "ductile" ( mylonitic) fault rocks.
- **Topic 14.** Thrusts and reverse faults. Definition and general characteristics. Geometric elements and types of thrusts (thrust-sheet, backthrust, nappes, ...). Thin and thick-skinned tectonics. Map view (klippe, tectonic window, breached window). Geometric characteristics of staircase-like thrusts. Types of ramps (frontal, oblique, lateral). Associated folding: fault-bend folds; fault-propagation folds, trishear folding; detachment folds; break-thrust folds). Thrust systems; terminology (foreland, hinterland, duplex roof-floor, antiformal stack, imbricate fans, ....). Relay zones and transfer faults. Thrust kinematics: criteria to determine the transport direction and the age of the structure. Syntectonic or growth deposits/synsedimentary or growth structures. Geometry of syntectonic deposits (onlap, offlap, thinning-thickening, syntectonic unconformity, progressive unconformity; Riba, 1976). Thrust sequence (break-back, forward-breaking, out of sequence). Palinspastic restoration and shortening calculation. Tectonic environment for thrust faulting.
- **Topic 15.** Normal faults. Definition and general characteristics. Geometric elements. Meso-macro-scale structures associated to normal faults: roll-over anticlines, fault-bend folds, drag folds, extensional duplexes, release faults, transfer faults, ... . Regional-scale normal-fault systems (Graben, horst, half-graben, detachment fault, synthetic/antithetic faults, ...); pseudo-rollover/compensation graben, imbricate listric fan. Basic kinematic models of normal faults. Normal fault sequences. Determining stretching caused by normal faults. Tectonic environment.
- **Topic 16.** Strike-slip faults. Definition and general characteristics. Strike-slip shear zones and associated structures (e.g. Riedel shears, P and R' shears among others). Bends and step-overs in strike-slip fault zones; geometry and terminology. Pull-apart basins and pop-ups. Strike-slip duplexes (flower structures). Tectonic environment for strike-slip faulting (... , tear faults, transform faults, escape tectonics, ...). Modelling of shear zones (Tchalenko, 1970).

## Seminars

- Topic 17. The nature of shear zones and types of shear zones.
- Topic 18. Salt structures. Diapirs.
- Topic 19. Gravitational structures.
- Topic 20. Impact structures. Meteorites.
- Topic 21. Superposed folding.
- Topic 22. Tectonic structures in plutons.
- Topic 23. Non tectonic structures in Structural Geology

## Laboratory sessions

- Session 1. Geologic cross sections (I) constructed from geologic maps with folds, normal faults and unconformities.
- Session 2. Geologic cross sections (II) constructed from geologic maps with folds, thrust faults and angular unconformities.
- Session 3. Geologic cross section. Recumbent fold. Geologic history of different geologic Session cross-sections.
- Session 4. Stereographic projection (I). Lines and planes. Poles to planes. True and apparent dips. Pitch of a line.

Intersection between planes.

- Session 5. Stereographic projection (II). Angles between lines and planes. Projection of lines onto planes. Fitting lines and planes to small and large circles. Tilting and rotations.
- Session 6. A) Tectonic fabrics: Identifying linear and planar elements. Relationship with the strain ellipsoid. B) Orthographic projection: True and apparent dips. Three points problem.
- Session 7. Density diagrams. Using a density diagram to calculate a fold axis. Determining the paleo-orientation of a fold situated below an angular unconformity.
- Session 8. 3D methods (I). Contour maps. Stress analysis using Mohr circle in 2D (homework)
- Session 9. Computer programs: using computer programs to plot lines and planes as well as to determine their geometric relationships. Density diagrams.
- Session 10. Riedel experiment: shear zones in semi brittle rocks.

## Fieldwork

- Field Trip 1
  - Locality: Vadiello (Huesca); Mesozoic and Cenozoic.
  - Date: see the academic calendar approved by the Departamento de Ciencias de la Tierra
  - Activities: Collecting field data along a structural traverse in the External Sierras. Study of brittle tectonic structures. Tecto-sedimentary relationships. Construction of a geological cross section.
- Field Trip 2
  - Locality: Isuela - Pico del Águila (Huesca); Mesozoic - Cenozoic.
  - Date: see the academic calendar approved by the Departamento de Ciencias de la Tierra
  - Activities: Construction of a regional scale cross-section. Study of brittle tectonic structures. Syntectonic structures.
- Field trip 3
  - Locality: Aliaga (Teruel); Cretaceous and Tertiary.
  - Date: see the academic calendar approved by the Departamento de Ciencias de la Tierra
  - Activities: Study of polyphasic deformation. Geometric and kinematic reconstruction of superposed folding. Tecto-sedimentary relationships.
- Field trip 4
  - Locality: Montalbán-Molinos (Teruel); Mesozoic and Cenozoic.
  - Date: see the academic calendar approved by the Departamento de Ciencias de la Tierra
  - Activities: Construction of a regional cross section of a thrust system and associated folds. Study of brittle structures (faults, stylolites, extension veins): Field schemes, measuring of linear and planar elements, timing of deformation.
- Field trip 5
  - Locality: Cerveruela - Puerto de Paniza (Zaragoza); Paleozoic.
  - Date: see the academic calendar approved by the Departamento de Ciencias de la Tierra
  - Activities: Study of ductile and brittle tectonic structures.

## 4.4.Course planning and calendar

Further information concerning the timetable, classroom, office hours, assessment dates and other details regarding this course will be provided on the first day of class or please refer to the Faculty of Sciences and Earth Sciences Department websites (<https://ciencias.unizar.es>, <https://cienciatierra.unizar.es>) and Moodle.

## 4.5.Bibliography and recommended resources

[http://biblos.unizar.es/br/br\\_citas.php?codigo=26445&year=2019](http://biblos.unizar.es/br/br_citas.php?codigo=26445&year=2019)