GEOL 30350: Structural Geology

MODULE COORDINATOR: Dr Eoghan Holohan

ADDITIONAL LECTURERS: Dr Conrad Childs
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CREDITS: 5	**MODULE LEVEL**: 3	**SEMESTER**: 2

PRE-REQUISITES/PRIOR LEARNING:

This module is suitable for students who have previously taken at least one general geology course including introductory structural Geology.

OVERVIEW OF MODULE:

Geological structures provide an essential framework for defining the Earth's long-term development, present-day hazards and future economic resources. This module explores how geological structures result from the deformation of rocks. The scope of the module spans ductile deformation characteristic of the deeper Earth through to brittle deformation typifying the development of structures in the shallow Earth and their surface expressions. The module covers the essential theoretical concepts –such as stress, strain, rheology, progressive deformation, failure criteria etc. – underpinning our understanding of the generation and expression of the main geological structures that are observed in the field. Consequently the module places a firm emphasis on the recognition and description of these geological structures in the field, combined with their quantitative analysis in the laboratory.

LEARNING OUTCOMES:

On completion of this module students should be able to:

1. Understand the fundamental concepts of stress and strain in two and three-dimensions and explain their relationships to a range of geological structures.
2. Identify the main ductile or brittle structures and articulate the differing physical conditions required for their development (and hence typical locations of development within the Earth).
3. Quantitatively asses the state of strain in a rock and analyze geometric data from a range of geological structures.
4. Describe geological folds in three dimensions, quantitatively classify them and relate them to one or more folding mechanisms.
5. Understand the relationships of folding to other structures such as cleavage, foliation, and boudinage.
6. Decipher the large-scale structure of complexly folded rocks through analysis of smaller scale observations of minor folds, cleavage bedding intersection, facing on foliation, etc.
7. Analyze the kinematics of ductile, brittle-ductile and brittle shear zones.
8. Articulate the principals of, and differences between, progressive pure and simple shear.
9. Explain how progressive deformation (e.g. pure shear or simple shear) may account for the geometry, orientation and distribution of geological structures.
10. Illustrate the state of stress in rock by using Mohr's circle and explain how this can be used determine the conditions for rock stability or failure.
11. Explain the how failure criteria and failure envelopes relate to the generation of structures such as joints, hydro-fractures, faults and shear zones.
12. Describe the 3D geometry of thrust and normal faults, and explain how such faults act as a geometrically coherent system.
13. Construct and read stereonet projections of structural data.
14. Construct and restore geological cross-sections.

ASSESSMENT:

Continuous Assessment: 50%
(Assessment of practical notebooks)

Examination: 50%
(Two-hour end of semester written examination plus a two-hour practical examination)

LECTURES:

Lecture 1: Structural geology and rock deformation. *(Dr E.P. Holohan)*
Review of laboratory-based studies of rock deformation and recap of fundamental concepts of stress, strain and rheology. Relationship of brittle and ductile deformation to physical conditions of deformation and composition of rocks. Overview of main brittle and ductile structures.

Lecture 2: Strain. *(Dr E.P. Holohan)*
Homogeneous and heterogeneous strain. The 2-D strain ellipse and Ramsay plot. Finite and incremental strain. The 3-D strain ellipsoid and Flinn plot. Relationship of strain ellipse/ellipsoid to stress ellipse/ellipsoid and to observations of geological structures.

Lecture 3: Determination of strain in rocks. *(Dr E.P. Holohan)*
Overview of techniques for 2-D and 3-D strain determination in rocks, such as by measuring eccentricity of initially spherical objects or the geometry of deformed fossils, and using the centre-to centre or Rf/Phi methods for non-spherical objects.

Lecture 4: Fold geometry and classification. *(Dr E.P. Holohan)*
Fundamentals of fold geometry and description. Fold vergence, harmony and parasitic folding. Non-cylindrical folds. Quantitative classification of folds by using orthogonal thickness and dip isogons. Relationship of folds to the 3D strain ellipsoid.

Lecture 5: Foliations. *(Dr E.P. Holohan)*
Nature, geometry and origin of continuous vs non-continuous (disjunctive) foliations. Mechanisms of foliation development including flattening, mechanical rotation, dissolution/precipitation, recrystallization. Relationship of foliations to folding and to the 3D strain ellipsoid.

Lecture 6: Lineations and L/S fabrics *(Dr E.P. Holohan)*
Nature and origin of structural and mineral lineations. Generation of L/S fabrics and relationships to folds and the 3D strain ellipsoid.

Lecture 7: Folding of Rocks - Mechanisms and Controls. *(Dr E.P. Holohan)*
Folding mechanisms, including buckle, flexural slip, flexural flow folding, as well as shear, chevron and kink folding. Consider also associated small-scale structures, including fractures, lineations and foliations. Controls from pressure, temperature, viscosity/competence contrast, layer thickness and layer spacing.

Lecture 8: Boudinage. *(Dr E.P. Holohan)*
Nature and origin of cylindrical and chocolate tablet boudinage. Controls on boudin geometry from layer thickness and viscosity contrast. Relationship to folds and 3D strain ellipsoid.

Lecture 9: Fold interference. *(Dr E.P. Holohan)*
Geometrical classification of 3-D fold interference patterns arising from the superimposition of shear folds on pre-existing fold forms. Recognition and analysis of related outcrop and map patterns.

Lecture 10: Orientation and mapping within complexly folded areas. *(Dr E.P. Holohan)*.
The use of cleavage/bedding, fold facing, vergence and facing on cleavage in the analysis of folded regions. Importance of way-up indicators. Impact of fold interference on fold facing and on parasitic folds. Use of facing directions, parasitic folds and folded lineations to unravel complex deformation.

Lecture 11: Progressive deformation 1 –Pure shear. *(Dr E.P. Holohan).*
The 2D finite and infinitesimal strain ellipses and their relationships in progressive pure shear.

Lecture 12: Progressive deformation 2 –Pure shear. *(Dr E.P. Holohan)*
Implications of progressive pure shear for the nature, distribution and evolution of ductile structures, including non-cylindrical folds, cleavage/foliations, lineations, crenulation cleavage and boudins.

Lecture 13: Progressive deformation 3 – Simple shear. *(Dr C.J. Childs)*
The 2D finite and infinitesimal strain ellipses and their relationships in progressive simple shear. Implications of progressive simple shear for the nature, distribution and evolution of structures formed in ductile and brittle-ductile shear zones.

Lecture 14: Kinematic indicators in ductile shear zones. *(Dr C.J. Childs)*
Development of shear sense indicators, such as fabric rotation, S/C fabrics , sheath folds, porphyroblast rotation, porphyroclast tails, and sheared porphyroclasts, and their relationships to progressive simple shear.

Lecture 15: Geological analysis of a ductile shear zone. *(Dr C.J. Childs)*
The case study of the Needle Falls shear zone, Canada, illustrating typical structural observations of ductile shear sense, together with and kinematically-consistent late-stage brittle shear overprint.

Lecture 16: Transpression. *(Dr C.J. Childs)*
Review of principal structures formed in transpression and transtension, e.g. positive and negative flower structures. Overview of Sanderson and Marchini's (1984) kinematic model for transpression.

Lecture 17: The fracturing of rocks. *(Dr E.P. Holohan)*
A closer look at brittle rock failure. Principal, normal and shear stresses, and their relationships to rock fracture and the strain ellipse. The Mohr diagram for stress and the derivation of failure envelopes. Coulomb Failure criterion, Byerlee's law, Griffith failure criterion. Link to von Mises's ductile failure criterion.

Lecture 18: Geometry and growth of thrust fault systems. *(Dr E.P. Holohan)*
Internal geometry of thrust sheets. Review of ramp-flat geometries, duplexes, antiformal stacks and imbricate systems. Side wall ramps and tear faults. The scaling properties and mechanical development of thrusts.

Lecture 19: Geometry and growth of normal fault systems. *(Dr E.P. Holohan)*
Geometric and kinematic coherence of normal fault systems. Scaling properties and growth models of normal faults. Kinematic analysis of faults by using displacement back-stripping methods.

Lecture 20: Fault rocks and fault zones. *(Dr E.P. Holohan/C.JChilds/T. Manzocchi)*
Geometry of fault zones and nature of kinematic indicators. Nature and origin of fault rocks. Geometric models for fault zone development. Effects of fault zone structure and fault rock properties on fluid flow.

Lecture 21: Joints, veins and hydrofractures. *(Dr E.P. Holohan/C.JChilds/T. Manzocchi)*
Mechanics of the formation of joints, veins and their relationships to folding and regional uplift. Controls on joint spacing in layered rocks. Use of veins in kinematic analysis. Characteristics and mechanical principals of natural or man-made hydraulic fracturing.

Lecture 22: Structures related to igneous activity *(Dr E.P. Holohan)*
Overview of forms and mechanisms of igneous emplacement. Ductile structures related to igneous emplacement in mid/lower crust. Brittle structures, such as sills, dykes, ring faults and cone sheets, related to high level emplacement. Influences of physical conditions, rock properties and stress regime.

Lecture 23: Course Summary/ Discussion 1 *(Dr E.P. Holohan)*
Lecture summarizing key concepts and main learning outcomes of the course.

Lecture 24: Course Summary/Discussion 2 *(Dr E.P. Holohan/C.JChilds/T. Manzocchi)*
Open-format question and answer session for students to fill in any gaps in their understanding of the main learning outcomes of the course.

PRACTICAL CLASSES:

Practical 1: **Practical strain measurement in rocks and regions.** *(Dr E.P. Holohan)*
Use of strain markers such as deformed fossils, ooids and reduction spots to estimate the finite 3D strain state in rock samples. Use of GPS data to estimate the incremental 2D strain pattern of a tectonically active region.

Practical 2: Folds. *(Dr E.P. Holohan)*
Classify folds in rocks by using the dip isogon method. Construct a cross-section through folds from map data.

Practical 3: Foliations and Lineations (*Dr E.P. Holohan)*
Describe and classify a variety of foliated and lineated rocks in hand specimen. Plot folded lineation data by using a stereonet to explore how different types of folds affect the final geometry of a pre-existing lineation.

Practical 4: Non-cylindrical folding *(Dr E.P. Holohan)*
Map and stereonet exercises analyzing the geometry of non-cylindrical folds.

Practical 5: Analysis of Folding and Fold Superposition. (*Dr E.P. Holohan)*
Examine the strain distribution in folds generated by differing folding mechanisms and by fold superposition. Explain how strain variation, and consider implications for geological structures in outcrop and in map view.

Practical 6: Analysis of Pure Shear. (*Dr E.P. Holohan)*
Use a strain matrix to deform a square with differently oriented material lines (passive markers). Explain line behaviour in terms of infinitesimal and finite strain ellipses. Deduce implications for deforming rock layers.

Practical 7: Heterogeneous Strain. *(Dr C.J. Childs)*
Examine the concept of heterogeneous strain by creating an idealized shear zone (analogue model) in the laboratory.

Practical 8: Transpression/Transtension. *(Dr C.J. Childs)*
Investigate 2D deformation associated with either volume loss or volume gain (transpression and transtension, respectively) and apply this idealised type of deformation to natural shear zones.

Practical 9: Restoration and balancing of cross-sections (*Dr E.P. Holohan)*
Line balancing of thrusting and the development of kinematic models for thrust systems. Restoration and validation of cross-sections from the Jura Mountains and Rockies Mountains (the Lewis Thrust).

Practical 10: Fault Growth (*Dr E.P. Holohan)*
Analyse growth of faults under the Timor Sea by using seismic reflection data. Examine fault displacement rates and relationship to fault size. Test alternative fault growth models.

Practical 11: Fault rocks *(Dr E.P. Holohan/C.JChilds/T. Manzocchi)*
Hand specimen and thin section analysis of faults rocks in sandstone and shale sequences. Sandstone cataclasites, shaley gouge and granulation seams. Identification of kinematic indicators.

Practical 12: Troubleshooting Workshop *(Dr E.P. Holohan/C.JChilds/T. Manzocchi)*
Open-format question and answer session for students to fill in any gaps in their understanding of the main learning outcomes of the theoretical or practical components of the course.