GEOL 30240: Igneous Petrology

MODULE COORDINATOR: Prof. Frank McDermott

ADDITIONAL LECTURERS: Assoc. Prof. Julian Menuge

CREDITS: 5	**MODULE LEVEL:** 3	**SEMESTER:** I

PRE-REQUISITES/PRIOR LEARNING:

Students should be familiar with the use of a petrological microscope and have taken an introductory level course in mineralogy such as GEOL 20120 Investigating Minerals or equivalent offered by home institution.

OVERVIEW OF MODULE:

The module begins with an introduction to magma sources and the variability of igneous rocks compositions. This is followed by a discussion of the processes involved in generating and modifying magmas, including partial melting, fractional crystallization, assimilation, mixing and mingling. Techniques used for chemical and isotopic analysis are introduced and the utility of trace elements and radiogenic isotopes in igneous petrology is explained. Magma sources and petrogenetic processes are then discussed in a plate tectonic context. Practical classes amplify the concepts raised in the lectures using graphical plotting and calculations and use thin section petrography to make links between texture and magmatic processes, especially crystallization.

Lectures and online material in the second part of the module explore the petrogenesis of igneous rocks in the framework of plate tectonics, using understanding of magmatic processes, geochemical and isotopic data covered in the first part of the module. It covers the formation of magmas and igneous rocks at mid-ocean ridges, destructive margins, oceanic intraplate settings and at continental rifts. The classification, magma genesis and emplacement of granites are discussed. Practicals, including thin section petrography, rock classification, interpretation of phase diagrams and radiogenic isotope plotting are used to illustrate some of the variety of igneous rocks in these different plate tectonic settings and as evidence demonstrating the generation, evolution and crystallization of magmas.

LEARNING OUTCOMES:

On completion of this module students should be able to:

1. Explain how igneous rocks can be classified;
2. Describe the range of processes that lead to the formation of igneous rocks;
3. Explain how geochemical and radiogenic isotope data are acquired and their uses in constraining the sources, evolution and crystallization of magmas;
4. Interpret igneous rock textures and mineral assemblages in thin sections and relate thin section observations to inferences drawn from phase diagrams;
5. Critically evaluate the evidence for the petrogenesis of igneous rocks in a variety of plate tectonic settings.

ASSESSMENT:

Continuous Assessment: 20%
(Assessment of practical notebook)

Examination: 40%
(Mid term examination on theory & practical work of first half of course)

Examination: 40%
(End of Semester examination on theory & practical work of second half of course)

LECTURES:

Lecture 1: The composition of Earth's mantle and crust *(Prof. P.F. McDermott)*
Earth's internal structure based on compositional and physical properties. Variation in mineralogy as a function of pressure/depth. Mineralogy of the upper mantle. Peridotites and Pyroxenites. Mantle depletion and enrichment. Composition of the upper and lower continental crust. Discussion of nature of the evidence. The oceanic crust, ophiolites and basalt-seawater interactions.

Lecture 2: Classification and nomenclature of igneous rocks *(Prof. P.F. McDermott)*
The basic terminology of igneous petrology. Mineral modes. Hand specimen and thin section description of igneous rocks. The IUGS mineralogical based classification and nomenclature scheme for phaneritic and aphanitic igneous rocks. Classification of quartz-bearing plutonic rocks in the IUGS scheme. Brief introduction to feldspathoid-bearing plutonic rocks. Classification of gabbros and other plagioclase-rich rocks. Classification of ultramafic rocks. Classification of volcanics and pyroclastic rock nomenclature.

Lecture 3: Partial Melting *(Prof. P.F. McDermott)*
Partial melting. Pressure and temperature gradients in the Earth. Mechanisms of partial melting of Earth's mantle. Aluminous phases as a function of depth in the mantle. Decompression melting and MORB. Role of mantle temperature in determining melt fraction during decompression melting. Decompression melting and MORB. Dehydration melting. Stability fields of amphibole and phlogopite in mantle. Melting by temperature increases. Batch partial melting and trace element fractionation.

Lecture 4: Fractional Crystallisation *(Prof. P.F. McDermott)*
Discussion of liquid only, liquid-gas and liquid-crystal-gas magmatic systems. Example from Makaopuhi lava lake (Hawaii) of fractional crystallization in action. Mechanisms of crystal-liquid separation. Review of relevant phase diagrams for olivine and plagioclase and a simple ternary system. Normal and reverse zoning in plagioclase. Open and closed systems. Simultaneous assimilation and fractional crystallization. Cumulates. Simple Rayleigh models for fractional crystallization applied to trace element ratios.

Lecture 5: Igneous Textures *(Prof. P.F. McDermott)*
Primary and secondary textures in igneous rocks. Terminology to describe crystal face development, crystal shapes and orientations. Crystal-glass relationships and reactions in volcanics. Ophitic and corona overgrowth textures. Skeletal, sieve and cumulophyric textures. Discussion of different twinning patterns in feldspars. Formation of myrmekite and graphic textures. Granophyres. Sub-solidus unmixing reactions. Perthite and anti-perthite. Exsolution in inverted pigeonite. Hydration and other sub-solidus reactions to form secondary minerals in igneous rocks. Introduction to cumulus rock terminology and description in advance of practical.

Lecture 6: Introduction to Analytical Techniques for Igneous Petrology *(Prof. P.F. McDermott)*
Introduction to the main analytical methods for geochemical analysis of igneous rocks. XRF, ICP-OES, ICP-MS, TIMS, Electron microprobe and ion probes. Laser ablation analysis for geochronology and mineral analysis. Discussion of detection limits, analytical precision and accuracy of analyses. Inspection of data tables from published literature to discuss nature of the data, how it was generated and its use in igneous petrology.

Lecture 7: Isotope Geology *(Prof. P.F. McDermott)*
Explanation of isotopes with focus on radiogenic isotope systems. Basics of radioactive decay, half-lives and decay constants. Review of basic assumptions in radiometric dating. Rb-Sr, Sm-Nd, U-Pb, K-Ar and Ar-Ar. General principles. Concept of closure ages. Whole-rock and mineral isochrons. Significance of initial Sr and Nd isotope ratios in igneous rocks. U-Pb and Ar-Ar dating using laser ablation systems. Argon loss and excess. Plateau ages.

Lecture 8: Magma chamber processes and layered intrusions *(Prof. P.F. McDermott)*
Introduction to layered basic intrusions with brief description and comparison of examples ranging from the Precambrian Bushveld to the Eocene Skaergaard. Focus on Skaergaard example. Discussion of modal, phase and cryptic layering. Discussion of possible causes of layering using simple phase diagrams. Focus next on the Bushveld Complex. Role of liquid immiscibility. Focus next on Rum. Harrisitic olivine. Grain boundaries and textural equilibrium in cumulate rocks in the Rum intrusion.

Lecture 9: Assimilation, magma mixing and mingling *(Prof. P.F. McDermott)*
General discussion of magma differentiation processes. Simple closed-system fractional crystallization processes versus more realistic open-systems that involve simultaneous crystallization and assimilation. Discussion of energy budgets of magmatic systems. Magma mixing and magma mingling. Hybrid magmas. De Paolo's original AFC model. Not thermally constrained. Discussion of more recent energy constrained systems. MASH processes. Identification of crustal assimilation using isotope tracers.

Lecture 10: Mantle melting in plate tectonic context *(Prof. P.F. McDermott)*
MORB. Recap of various triggers for mantle melting. Discussion of dry and wet peridotite solidi curves. Decompression melting. Melting by volatile fluxing. Basic anatomy of a subduction zone. Stability of hydrous minerals in the subducting slab and the mantle wedge. Relative constancty of depth to top of slab beneath volcanic fronts. Pressure-dependent stability of amphibole. Melting at intra-plate settings. Ocean Island basalts and mantle plumes.

Lecture 11: Mid-ocean ridge magmatism *(Assoc. Prof. J.F. Menuge)*
Introduction to the global mid ocean ridge system. Iceland and the mid-Atlantic Ridge. Age of oceanic crust at mid-ocean ridges. Crustal section at a mid-ocean ridge. Chemical features of MORB. Normal and enriched MORB. Trace element patterns. Formation of partial melts beneath mid ocean ridges. McKenzie model. Sr and Nd isotope ratios in MORBs. Fast and slow spreading ridges. Chemical variations with depth within the oceanic crust. Distinguishing between the effects of mantle temperature and mantle composition.

Lecture 12: Island Arc magmatism *(Assoc. Prof. J.F. Menuge)*
Review of subduction zones globally. Distinction between island arcs and continental margin settings. Characteristics of island arc magmas. Compositional range of island arc rocks on an alkalis-silica diagram. Distinction between tholeiitic and calc-alkaline trends. Alkaline magmas and the reasons for variations in the potassium content of primary magmas. Effect of fractional crystallization on a range of geochemical parameters. Incompatible trace element patterns in arc basalts. Melt producing in subduction zones. Rates of magma production.

Lecture 13: Continental Destructive margins *(Assoc. Prof. J.F. Menuge)*
Characteristics of the Andean arc and comparison between Andean and island arc volcanism; plutonic rocks and the preponderance of intermediate to acid compositions; slab melting as a possible source of magmatism; evidence for magma chambers in continental arcs; arc flare-ups and their causes; normative and I-S-A classification schemes for granitoids; field, experimental, chemical and isotopic evidence for the origin of I, S and A-type granitoids.

Lecture 14: Oceanic Intraplate and LIP Magmatism *(Assoc. Prof. J.F. Menuge)*
Global distribution of oceanic intraplate volcanoes; normative compositions of basalts; chemical and isotopic compositions of oceanic intraplate basalts; conditions required to generate the spectrum of oceanic intraplate basalts; global distribution of large igneous provinces (LIPs): continental flood basalts and oceanic plateau basalts and picrites, their compositions and possible plate tectonic settings; Columbia River basalts and the Ontong Java plateau as examples; relationships between LIPs and oceanic intraplate volcanism; evidence for mantle heat anomalies and mantle plumes; alternative possible causes of magmatism.

Lecture 15: Continental Rift Alkaline Magmatism *(Assoc. Prof. J.F. Menuge)*
Definition of alkaline and peralkaline magmas; the East African Rift – history of development and magmatism of the western and eastern branches; extreme variability of magma composition - sodic and potassic volcanism; cross-section of the eastern rift; active vs passive rifting; trace element and radiogenic isotope data; fractional crystallization; the role of mantle plumes in generating magmas in the eastern and western branches of the rift; how the continental crust and mantle lithosphere complicate interpretation of magma origin.

PRACTICAL CLASSES

Practical 1: Classification and nomenclature of phaneritic igneous rocks *(Prof. P.F. McDermott)*
The IUGS classification scheme. Review of how to normalise and plot data on triangular graphs. Classify and assign names to four rocks for which modal mineralogy is given. Estimate the modal mineralogy of the Leinster granite and Ardara tonalite from thin sections and plot normalised modal mineralogy on the IUGS classification diagram. Fully labelled sketch of thin sections of the Ardara tonalite.

Practical 2: Partial melting and fractional crystallisation calculations *(Prof. P.F. McDermott)*
Practice using batch partial melting equation and Rayleigh fractional crystallization to test some hypotheses about magma generation from a specified source rock and subsequent fractional crystallization. Calculation of bulk partition coefficients. Interpretation of whole-rock geochemical data.

Practical 3: Intrusive rock textures *(Prof. P.F. McDermott)*
Use of petrological microscope to examine thin sections of a granite and a gabbro. Emphasis on primary igneous textures and how these can be distinguished from secondary features in these plutonic rocks.

Practical 4: Skaergaard petrography *(Prof. P.F. McDermott)*.
Use of petrological microscope to examine thin sections of a picrite and a ferrogabbro from the Skaergaard Intrusion. Determination of plagioclase composition using extinction angle tests. Determination of olivine composition using maximum interference colour. Emphasis on cumulate textures and textural equilibration.

Practical 5: Volcanic rock textures *(Prof. P.F. McDermott)*
Use of petrological microscope to examine thin sections of an olivine basaltic andesite from Mexico and a trachyte from Drachenfels, Germany.

Practical 6: Radiogenic isotope ratios in oceanic basalts: probing the mantle *(Assoc. Prof. J.F. Menuge)*.
Plotting of radiogenic isotope data from mid-ocean ridge and ocean island basalts and use of the plots to constrain mantle isotopic and chemical variation and its causes, and to understand mantle evolution through time.

Practical 7: Calc-alkaline volcanics of Mexico: petrography and petrology *(Assoc. Prof. J.F. Menuge)*.
Examination of Cenozoic lavas from Mexico in thin section; textural interpretation to constrain the crystallization history of supra-subduction zone magmas; the problem of using petrography to name volcanic rocks.

Practical 8: Pan-African granites of Dur al Gussa, Libya: petrography and petrology
(Assoc. Prof. J.F. Menuge)
Examination of Pan-African granitic rocks in thin section; use of petrography in naming granitic rocks and to constrain their petrogenesis.

Practical 9: Tahiti ocean island basalt (OIB) igneous activity *(Assoc. Prof. J.F. Menuge)*
Contrasting textures in thin section of volcanic and plutonic rocks from a typical ocean island basalt province; the distinction between tholeiitic and alkali-olivine basaltic rocks in thin section.

Practical 10: Petrography of Si-undersaturated continental alkaline rocks *(Assoc. Prof. J.F. Menuge)*
Introduction to feldspathoid minerals and to their recognition in thin section (nepheline, leucite, nosean) in thin section; description and naming of feldspathoid-bearing rocks in thin section and interpretation of their crystallization history.

ONLINE EXERCISES:

Exercise 1: Mid-ocean ridge magmatism *(Assoc. Prof. J.F. Menuge)*
Evaluation of recent research on mid-ocean ridges basalts using online resources provided.

Exercise 2: Island arc magmatism *(Assoc. Prof. J.F. Menuge)*
Evaluation of recent research on island arc magmatism.

Exercise 3: Continental destructive margin magmatism *(Assoc. Prof. J.F. Menuge)*
Evaluation of recent research on continental destructive margin magmatism.

Exercise 4: Oceanic intraplate and LIP magmatism *(Assoc. Prof. J.F. Menuge)*
Evaluation of recent research on oceanic intraplate magmatism and large igneous provinces.

Exercise 5: Movement of granitic magma and eruption of rhyolites *(Assoc. Prof. J.F. Menuge)*
Evaluation of recent research on granitic magma movement and its relationship to rhyolite eruption.