

# GEOLOGY AND GEOPHYSICS

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The Geology and Geophysics program prepares students for the application of scientific principles and methods to the understanding of Earth, the environment, and life on a regional and a planetary scale. Subjects range from the history of Earth and life to present-day environmental processes; integrating the study of Earth's deep interior, tectonic plates, oceans, atmosphere, climate, land surface, natural resources, and biota. The emphasis of the curriculum is on employing basic principles from the core sciences (physics, chemistry, and biology) to further an understanding of Earth's past and present, and addressing issues relating to its future. Students gain a broad background in the natural sciences, and also select a specific track to focus their work on planetary or environmental phenomena of particular interest. The four B.S. tracks emphasize hands-on research experience in fieldwork, in laboratories, or in computer modeling. While some graduates continue on to research, consulting, or industrial careers in Earth, environmental, and planetary sciences, the major's broad scientific training prepares students for a wide variety of other paths, including medicine, law, public policy, and teaching. There is also a B.A. degree, which is most suitable for students who wish to study geoscience as a second major, complementing other majors in, for example, Mathematics, Economics, Physics, Biology, or Engineering, and do so in preparation for a career in law, business, government, or environmental fields.

## PREREQUISITES

With permission of the director of undergraduate studies (DUS), acceleration credits awarded at matriculation for high scores on national or international examinations (such as Advanced Placement subject tests) may be used to satisfy prerequisites, even if the student does not choose to accelerate. Higher-level courses may, with the permission of the DUS, be substituted for prerequisites and for specific required courses. For prerequisites specific for each degree and track, see below under Requirements of the Major.

## REQUIREMENTS OF THE MAJOR

**B.S. degree program** Majors in the B.S. program in Geology and Geophysics choose from four tracks: Atmosphere, Ocean, and Climate; Environmental and Energy Geoscience; Paleontology and Geobiology; and Solid Earth Science. The tracks are suggested pathways to professional careers and major areas of research in geology and geophysics. Students may change tracks during their course of study with guidance from the DUS.

1. The Atmosphere, Ocean, and Climate track provides a comprehensive understanding of the theory, observation, and prediction of the atmosphere-ocean-climate system. Topics range from past climate changes, including the ice ages, to present-day storms and weather, to forecasting climate change and global warming. The prerequisites are CHEM 165 or CHEM 167; PHYS 180, 181 and PHYS 205L, 206L; ENAS 130 or equivalent; and mathematics through differential equations (MATH 120 or ENAS 151, and ENAS 194). The major requirements consist of at least eleven term courses, for ten and one-half course credits, beyond the prerequisites, including either the senior essay or the senior thesis. To begin study of Earth processes, majors take an introductory course in G&G, with any accompanying laboratory, selected from G&G 100; 110 or 115, and 111L; or 125 and 126L. A higher-level course in G&G can be substituted with the permission of the director of undergraduate studies. Six core courses, totaling five and one-half course credits, introduce students to Earth's climate system (G&G 140 and 141L), meteorology (G&G 322), physical oceanography (G&G 335), fluid mechanics (MENG 361), and statistics or linear algebra (S&DS 230 or 238 or MATH 222). Three electives are chosen from topics in the environment and in processes that govern the atmosphere, ocean, and land surface; physics; and statistics. A list of suggested electives is available from the office of the director of undergraduate studies or on the departmental website. At least one elective must be from G&G.
2. The Environmental and Energy Geoscience track provides a scientific understanding of the natural and anthropogenic processes that shape the Earth-atmosphere-biosphere system, including energy and material flows among its components. It emphasizes comparative studies of past and current Earth processes to inform models of humankind's role within the environment's future. The prerequisites are broad and flexible and include CHEM 165 or CHEM 167 and mathematics through multivariate calculus (MATH 120 or ENAS 151). Depending on their area of focus, students may choose a prerequisite in physics (PHYS 170, 171; or 180, 181; or 200, 201), or they may choose cellular biology (BIOL 101 and 102, or MCDB 120) and evolutionary biology (BIOL 103 and 104, or E&EB 122, or G&G 125 and 126L). The major requirements consist of at least eleven term courses, for eleven course credits, beyond the prerequisites, including either the senior essay or the senior thesis. To begin study of the Earth system, majors take two introductory courses in G&G, with any accompanying laboratories, selected from G&G 100; 110 or 115, and 111L; or 140 and 141L (G&G 125 and 126L may count toward this requirement if not selected as the evolutionary biology prerequisite). Higher-level courses in G&G can be substituted with the permission of the director of undergraduate studies. Four core courses are chosen from topics in general resource use and sustainability (G&G 205), Earth's surface processes (G&G 232), the microbiology of surface and near-surface environments (G&G 255), fossil fuels and energy transitions (G&G 274), renewable energies (G&G 275), geochemical principles (G&G 301), structural geology (G&G 312), meteorology (G&G 322), and satellite-based image analysis (G&G 362). Four electives chosen from Geology and Geophysics, Environmental Studies, Ecology and Evolutionary Biology, Engineering, or related fields provide a broad approach to scientific study of the environment. A list of suggested electives is available from the office of the director of undergraduate studies or on the departmental website. Electives may be chosen from the core courses, and at least two must be from G&G.

3. The Paleontology and Geobiology track focuses on the fossil record of life and evolution, geochemical imprints of life, and interactions between life and Earth. Topics range from morphology, function, relationships, and biogeography of the fossils themselves, through the contexts of fossil finds in terms of stratigraphy, sediment geochemistry, paleoecology, paleoclimate, and geomorphology, to analysis of the larger causes of paleontological, geobiological, and evolutionary patterns. Integrative approaches are emphasized that link fossil evidence with the physical and chemical evolution of Earth. The prerequisites are college-level biology (BIOL 101–104; or MCDB 120 and E&EB 122); CHEM 165 or CHEM 167; and mathematics through multivariate calculus (MATH 120 or ENAS 151). The major requirements consist of at least thirteen term courses, for twelve course credits, beyond the prerequisites, including either the senior essay or the senior thesis. Students take G&G 100; G&G 110 or 115, and 111L, to gain geological and environmental context, and they are introduced to the fossil record and evolution in G&G 125 and 126L; higher-level courses in G&G can be substituted with the permission of the director of undergraduate studies. Four core courses give majors a comprehensive background in sedimentary rocks and rock correlation (G&G 232 or equivalent), the study of evolution (G&G 250 or equivalent), microbiology in past and present environments (G&G 255 or equivalent), Earth's carbon cycle (G&G 308 or equivalent), and statistical data analysis as applied to the life sciences (S&DS 101 or equivalent). Four electives selected from Geology and Geophysics, Ecology and Evolutionary Biology, Molecular, Cellular, and Developmental Biology, and related fields offer students flexibility in pursuing their specific interests. A list of suggested electives is available from the office of the DUS or on the departmental website. At least one elective must be from G&G.
4. The Solid Earth Science track emphasizes an integrated geological, geochemical, and geophysical approach to the study of processes operating within Earth and their manifestation on the surface. It includes the structure, dynamics, and kinetics of Earth's interior and their impacts on our environment both in the long term (e.g., the evolution of the land surface) and in the short term (e.g., the causes for natural disasters such as earthquakes, tsunamis, and volcanic eruptions). Students acquire a fundamental understanding of the solid Earth system, both as it exists today and as it has evolved over geologic time scales. The prerequisites are CHEM 165 or CHEM 167; physics (PHYS 170, 171; or 180, 181; or 200, 201); and mathematics through multivariate calculus (MATH 120 or ENAS 151). The major requirements consist of at least eleven courses, for eleven course credits, beyond the prerequisites, including either the senior essay or the senior thesis. To begin study of the Earth system, majors take two introductory courses in G&G, with any accompanying laboratories, selected from G&G 100; 110 or 115, and 111L; 125 and 126L; or 140 and 141L. Higher-level courses in G&G can be substituted with the permission of the director of undergraduate studies. The core of the track consists of four courses chosen from topics in mountain building and global tectonics (G&G 212), rocks and minerals (G&G 220), sedimentary rocks and processes (G&G 232 or equivalent), geochemical principles (G&G 301), and structural geology (G&G 312). Students also select four electives in geology, geochemistry, geophysics, or related topics. A list of suggested electives is available from the office of the director of undergraduate studies or on the departmental website. Electives may be chosen from core courses, and at least two must be from G&G.

**B.A. degree program** The B.A. degree in Geology and Natural Resources requires fewer upper-level courses than the B.S. degree. It may be more appropriate for students who wish to major in two separate Yale programs, who study geoscience in preparation for a career in law, business, government, or environmental fields, or who decide to pursue a science major only after the first year. The prerequisites include mathematics (MATH 115), biology (BIOL 101 and 102, or MCDB 120, or G&G 255), and a lecture course in chemistry. The major requirements consist of at least nine term courses beyond the prerequisites. These include two courses in G&G numbered 100–150, with any accompanying laboratories; courses in natural resources (G&G 205) and geochemical processes (G&G 220 or 232 or 280 or 301); and five additional courses at the 200 level or higher in Geology and Geophysics or related fields, approved by the DUS and including either the senior essay or the senior thesis. Course selections can be guided by any of the B.S. tracks described above.

**Credit/D/Fail** Geology and Geophysics majors may not employ the Credit/D/Fail option for prerequisites or for courses in the major.

#### SENIOR REQUIREMENT

Seniors in both degree programs must prepare either a senior essay based on one term of library, laboratory, or field research (G&G 492) or, with the consent of the faculty, a two-term senior thesis (G&G 490, 491), which involves innovative field, laboratory, or theoretical research. Students electing to do a senior thesis must first select a topic and obtain the consent of a faculty member to act as an adviser. They must then petition the faculty through the DUS for approval of the thesis proposal. The petition should be submitted by the end of the junior year. If the two-term senior thesis is elected, G&G 491 may count as an elective toward the major. A copy of each senior thesis or senior essay is made available on the departmental website.

#### ADVISING

Qualified juniors and seniors are encouraged to enroll in graduate courses, with permission of the instructor and of the directors of graduate and undergraduate studies. Descriptions of graduate courses are available at the office of the director of undergraduate studies.

**Practical experience** In addition to prerequisites and required courses in Geology and Geophysics, candidates for the B.A. and B.S. degrees are strongly encouraged to gain practical experience in the Earth sciences. This can be done in two ways: (1) by attending a summer field course at another academic institution, or (2) by participating in summer research opportunities offered by the Department of Geology and Geophysics, by other academic institutions, or by certain government agencies and private industries. Consult the DUS or see the departmental website for further information.

**Combined B.S./M.S. degree program** Exceptionally able and well-prepared students may complete a course of study leading to the simultaneous award of the B.S. and M.S. degrees after eight terms of enrollment. See “Simultaneous Award of the Bachelor’s and

Master's Degrees" under section K, Special Arrangements, in the Academic Regulations. Interested students should consult the director of undergraduate studies prior to the sixth term of enrollment for specific requirements in Geology and Geophysics.

**Physics and Geosciences major** The Department of Geology and Geophysics also offers a combined major with the Department of Physics. For more information, see under Physics and Geosciences.

## REQUIREMENTS OF THE MAJOR

**Prerequisites** *B.A.* – MATH 115; BIOL 101 and 102, or MCDB 120, or G&G 255; a lecture course in chem; *B.S.* – *All tracks* – CHEM 165 or CHEM 167; MATH 120 or ENAS 151; *Atmosphere, Ocean, and Climate track* – ENAS 130 or equivalent; ENAS 194; PHYS 180, 181, 205L, 206L; *Environmental and Energy Geoscience track* – physics (PHYS 170, 171, or 180, 181, or 200, 201) or biology (BIOL 101 and 102, or MCDB 120; and BIOL 103 and 104, or E&EB 122, or G&G 125 and 126L); *Paleontology and Geobiology track* – BIOL 101–104, or MCDB 120 and E&EB 122; *Solid Earth Science track* – PHYS 170, 171, or 180, 181, or 200, 201

**Number of courses** *B.A.* – at least 9 courses beyond prereqs for letter grades (incl senior req); *B.S.* – *Atmosphere, Ocean, and Climate track* – at least 11 courses, for 10½ credits, beyond prereqs for letter grades (incl senior req); *Environmental and Energy Geoscience and Solid Earth Science tracks* – at least 11 courses beyond prereqs for letter grades (incl senior req); *Paleontology and Geobiology track* – at least 13 courses, for 12 credits, beyond prereqs for letter grades (incl senior req)

**Specific courses required** *B.A.* – G&G 205; 1 from G&G 220, or 232, or 280, or 301; *B.S.* – *Atmosphere, Ocean, and Climate track* – G&G 140, 141L, 322, 335; MENG 361; S&DS 230 or 238 or MATH 222; *Environmental and Energy Geoscience track* – 4 from G&G 205, 232, 255, 274, 275, 301, 312, 322, 362; *Paleontology and Geobiology track* – G&G 100 or 115, and 111L, G&G 125, 126L, 4 from 232, 250, 255, 308, S&DS 101 or equivalents; *Solid Earth Science track* – 4 from G&G 212, 220, 232 or equivalent, 301, 312

**Distribution of courses** *B.A.* – 2 intro courses in G&G, with labs, as specified; 5 addtl courses at 200 level or higher in G&G or related fields; *B.S.* – *Atmosphere, Ocean, and Climate track* – 1 intro course in G&G, with lab, as specified; 3 electives as specified; *Environmental and Energy Geoscience and Solid Earth Science tracks* – 2 intro courses in G&G, with labs, as specified; 4 electives as specified; *Paleontology and Geobiology track* – 4 electives as specified

**Substitution permitted** *All programs* – with DUS permission, higher-level courses for prereqs or required courses

**Senior requirement** *All programs* – senior essay (G&G 492) or, with permission of faculty, two-term senior thesis (G&G 490, 491)

## FACULTY OF THE DEPARTMENT OF GEOLOGY AND GEOPHYSICS

**Professors** Jay Ague (*Chair*), David Bercovici, Ruth Blake, Mark Brandon, Derek Briggs, David Evans, Alexey Fedorov, Debra Fischer, Jacques Gauthier, Shun-ichiro Karato, Jun Korenaga, Maureen Long, Jeffrey Park, Peter Raymond, Danny Rye, James Saiers, Ronald Smith, Mary-Louise Timmermans (*DUS*), John Wettlaufer

**Associate Professors** Kanani Lee, Trude Storelvmo

**Assistant Professors** Bhart-Anjun Bhullar, Pincelli Hull, Noah Planavsky, Alan Rooney

**Lecturers** Marilyn Fox, Michael Oristaglio, Frank Robinson, Lawrence Schwartz, Ellen Thomas

## Courses

\* **G&G 010a / EVST 010a, Earth, Resources, Energy, and the Environment** Mary-Louise Timmermans

Humankind's interactions with, and place within, the natural world. Plate tectonics and natural disasters, biological evolution and mass extinction, human evolution, population growth and ecology, industrial resources, groundwater and pollution, fossil fuels and energy transitions, the carbon cycle and greenhouse gases, paleoclimates, current global warming, alternative energies, and a planetary perspective on the Earth as a singular oasis in space. Enrollment limited to freshmen. Preregistration required; see under Freshman Seminar Program. SC

**G&G 100a, Natural Disasters** David Bercovici and Maureen Long

Natural events and their impact on humanity and the built environment. Earthquakes, volcanoes, tsunamis, landslides, coastal flooding, tornadoes, hurricanes, and meteoritic impacts. Hazard mitigation strategies. Consequences of global warming. SC

\* **G&G 105b / APHY 100b / ENAS 100b / EVST 100b / PHYS 100b, Energy Technology and Society** Daniel Prober, Michael Oristaglio, and Julie Paquette

The technology and use of energy. Impacts on the environment, climate, security, and economy. Application of scientific reasoning and quantitative analysis. Intended for non-science majors with strong backgrounds in math and science. Enrollment limited to 24. For application instructions, visit the course site on Canvas @ Yale. QR, SC

[ **G&G 110, Dynamic Earth** ]

**G&G 111La, Dynamic Earth Laboratory and Field Methods** Danny Rye

Practical exercises in the laboratory and in the field to complement G&G 110 or 115. Identification of minerals and rocks; construction of geologic maps and cross sections to determine Earth-system processes and histories. Includes a field trip to the northern Appalachians during the October recess. After or concurrently with G&G 110, or after G&G 115. SC ½ Course cr

**\* G&G 125b / E&EB 125b, History of Life** Derek Briggs and Pincelli Hull

Examination of fossil and geologic evidence pertaining to the origin, evolution, and history of life on Earth. Emphasis on major events in the history of life, on what the fossil record reveals about the evolutionary process, on the diversity of ancient and living organisms, and on the evolutionary impact of Earth's changing environment. SC

**G&G 126Lb, Laboratory for the History of Life** Derek Briggs and Pincelli Hull

A survey of the diversification of life using suites of fossils and related modern organisms drawn from critical evolutionary stages.

Emphasis on direct observation and description of specimens, the solution of problems posed by the instructor, and the generation and testing of hypotheses by the students. To be taken concurrently with or following G&G 125. SC ½ Course cr

**G&G 140a / EVST 201a, Atmosphere, Ocean, and Environmental Change** Ronald Smith

Physical processes that control Earth's atmosphere, ocean, and climate. Quantitative methods for constructing energy and water budgets. Topics include clouds, rain, severe storms, regional climate, the ozone layer, air pollution, ocean currents and productivity, the seasons, El Niño, the history of Earth's climate, global warming, energy, and water resources. Must be taken concurrently with EVST 202L. QR, SC

**\* G&G 141La / EVST 202La, Laboratory for Atmosphere, Ocean, and Environmental Change** Ronald Smith

Laboratory and field exercises to accompany EVST 201. Must be taken concurrently with EVST 201. SC ½ Course cr

**\* G&G 207b, The Science of Water** Kanani Lee

A study of water in its physical, chemical, biological, astronomical, geological, and environmental aspects. Topics include water's role in food and energy production, conservation and pollution, magnetic field generation, plate tectonics and volcanism, climate, and security. SC

**\* G&G 212b, Global Tectonics** David Evans

The architecture of continents and oceans; detailed geology of lithospheric plate margins and mountain chains. Examples of plate-interaction histories from the ancient geological record emphasize the interdisciplinary approaches used to determine interlinked Earth-system processes involving the mantle, crust, hydrosphere, atmosphere, and biosphere. The course features a field trip during spring break. Prerequisite: one course in G&G (preferably 100, 110, or 115), or permission of instructor. Enrollment limited to 15. SC

**[ G&G 215, Global Warming: The Carbon Cycle ]****\* G&G 216a, Global Warming: Climate Physics** Trude Storelvmo

Lectures on the basics of global warming and presentations and discussions of some of the classic papers that combined have led to our current understanding of global warming. The knowns and the unknowns of global warming; the paper trail of cutting-edge climate science through time, from the late 1800s to the present. Recommended preparation: basic calculus and physics. SC

**G&G 220b, Petrology and Mineralogy** Danny Rye

Comprehensive study of the structures, chemistry, and physical properties of minerals. Interpretation of mineral associations and textures in terms of processes acting in the formation of igneous and metamorphic rocks. Study of the interplay between plate tectonics and the genesis of igneous and metamorphic rocks. After one year of college-level chemistry; G&G 110 recommended. SC

**G&G 232b, Earth Surface Processes** Mark Brandon and Noah Planavsky

Introduction to sedimentary rocks as paleoenvironmental archives. Reconstruction of depositional environments and paleoclimatic conditions using geochemical and sedimentological tools. Topics include sedimentology, stratigraphy, basin analysis, diagenesis, and sedimentary geochemistry. Prerequisite: G&G 100, 110, or 115, or permission of instructor. SC

**[ G&G 235, Geomorphology and Surface Processes ]****\* G&G 240b, Forensic Geoscience** Maureen Long

Approaches and technologies developed for geoscience that have been adapted and applied in criminal, environmental, historical, and archaeological investigations. Methods related to seismology, geophysics, geomorphology, geochemistry, and radiometric dating. Case studies include nuclear treaty verification, detection of unexploded ordnance and clandestine graves, military history, soil and groundwater contamination, archaeological controversies, art and antiquities fraud, and narcotics provenance. SC

**G&G 247b / AMTH 247b / MATH 247b, Partial Differential Equations** Staff

Introduction to partial differential equations, wave equation, Laplace's equation, heat equation, method of characteristics, calculus of variations, series and transform methods, and numerical methods. Prerequisites: MATH 222 or 225, MATH 246, and ENAS 194, or equivalents. QR

**G&G 255b / EVST 265b, Environmental Geomicrobiology** Ruth Blake

Microbial diversity in natural geologic habitats and the role of microorganisms in major biogeochemical cycles. Introduction to prokaryote physiology and metabolic diversity; enrichment culture and molecular methods in geomicrobiology. Prerequisite: college-level chemistry. SC

**\* G&G 261a / EVST 261a / F&ES 261a, Minerals and Human Health** Ruth Blake

Study of the interrelationships between Earth materials and processes and personal and public health. The transposition from the environment of the chemical elements essential for life. After one year of college-level chemistry or with permission of instructor; G&G 110 recommended. SC

\* **G&G 274a, Fossil Fuels and Energy Transitions** Michael Oristaglio

The origins, geologic settings, exploration, distribution, and extraction of fossil fuels as finite Earth resources. Energy use today; transitions to future renewable resources. Topical issues include peak oil, deep-water exploration, carbon sequestration, and shale gas. Prerequisites: high school chemistry, mathematics, and Earth science. Recommended preparation: G&G 110 or 205. SC

\* **G&G 275b, Renewable Energy** Ronald Smith

Introduction to renewable energy, including physical principles, existing and emerging technologies, and interaction with the environment. Energy demand; transmission and storage; generation by hydroelectric, wind, solar, biofuel, and geothermal sources, as well as waves and tidal generation. Includes field trips to conventional, hydroelectric, and wind power facilities in Connecticut. Prerequisites: high school physics, chemistry, and mathematics; college-level science, engineering, and mathematics recommended. SC

[ **G&G 280, Organic Geochemistry** ]

[ **G&G 290, Earthquakes and Volcanoes** ]

\* **G&G 301b, Introduction to Geochemistry** Ruth Blake and Danny Rye

Basic principles of geochemistry and their use in geological science. Thermodynamics of aqueous and igneous systems. Element fractionation and isotope geochemistry. Biogeochemical cycles, geochronology, cosmochemistry. After CHEM 161, 165, or 167 (or CHEM 115 or 118), and MATH 115; G&G 220 recommended. QR, SC

**G&G 305Lb, Practical Paleontology** Marilyn Fox

Principles of preparation, conservation, and collection management; the value of collections; basic and best practices for the responsible use of collections and data. Designed for students who plan to incorporate paleontological specimens and data in their studies, or who are considering a career as either a museum-based researcher or curator or a user of museum collections. ½ Course cr

**G&G 310a, Isotope Geochemistry** Alan Rooney and Noah Planavsky

Fundamental principles of stable and radiogenic isotope geochemistry. Emphasis on applications to specific geologic problems, including petrogenesis, geochronology, geothermometry, surface processes, hydrology, and biogeochemistry. Prerequisites: CHEM 115, MATH 120, and PHYS 171 or equivalents, or with permission of instructor. QR, SC RP

**G&G 312b, Structural Geology** Mark Brandon

An introduction to the origin and structure of the lithosphere and continental and oceanic crust. Topics include what controls the solid versus fluid behavior of rocks during deformation, and what controls the character and motion of tectonic plates. Laboratory exercises and field trips. QR, SC

**G&G 319a, Introduction to the Physics and Chemistry of Earth Materials** Shun-ichiro Karato

Basic principles that control the physical and chemical properties of Earth materials. Thermodynamics, equation of state, phase transformations, elastic properties and phase diagrams. After CHEM 161, 165, or 167 (or CHEM 115), MATH 120, and PHYS 181, or equivalents. QR, SC

**G&G 322b, Physics of Weather and Climate** Trude Storelvmo

The climatic system; survey of atmospheric behavior and climatic change; meteorological measurements and analysis; formulation of physical principles governing weather and climate with selected applications to small- and large-scale phenomena. After PHYS 181 and MATH 120 or equivalents. QR, SC

**G&G 323b, Climate Dynamics** Alexey Fedorov

An introduction to climate dynamics. Special emphasis on phenomena controlled by large-scale interactions between the ocean and atmosphere, from El Niño to decadal climate variability. Topics include conceptual models of climate, general circulation of the atmosphere, ocean wind-driven and thermohaline circulation, abrupt climate changes, climate models by means of GCMs, and climate predictability. After PHYS 181, MATH 120 or equivalent, and one course in meteorology or physical oceanography; or with permission of instructor. QR, SC

**G&G 325a, Vertebrate Paleontology** Jacques Gauthier

Phylogeny and evolution of the major clades of vertebrates from Cambrian to recent, as inferred mainly from the fossilized remains of the musculoskeletal system (cranial, axial, and appendicular skeletons). Special attention to the evolution of vertebrate feeding, locomotor, and sensory systems. Prerequisite: E&EB 225, or with permission of instructor. SC 1½ Course cr

**G&G 326a, Introduction to Earth and Planetary Physics** Kanani Lee

An introduction to the structure and dynamics of Earth and other planets in the context of cosmic evolution. Review of basic physical principles and their applications to geophysics and planetary physics. Star formation and nucleosynthesis; planetary accretion and the birth of the solar system; heat flow, plate tectonics, and mantle dynamics; seismology and geodesy; core dynamics, geomagnetism, and planetary magnetism. Prerequisites: PHYS 181b and MATH 120a or b, or equivalents. QR, SC

\* **G&G 331a / EVST 311a, Environmental Communication for Public Engagement & Policy** Paul Lussier

Analysis, assessment, and application of narrative strategies to the communication of climate and energy science toward public policy engagement and action. Emerging interdisciplinary theory and research in narratology, sociology, and psychology, as well as cultural, education, and media sciences. SO

**G&G 335a, Physical Oceanography** Alexey Fedorov

An introduction to ocean dynamics and physical processes controlling large-scale ocean circulation, the Gulf Stream, wind-driven waves, tsunamis, tides, coastal upwelling, and other phenomena. Modern observational, theoretical, and numerical techniques used to study the ocean. The ocean's role in climate and global climate change. After PHYS 181 and MATH 120 or equivalents, or with permission of instructor. QR, SC

**\* G&G 336a / ANTH 336a / ARCG 336a, Geoarchaeology** Ellery Frahm

A survey of the numerous ways in which theories, approaches, techniques, and data from the earth and environmental sciences are used to address archaeological research questions. A range of interfaces between archaeology and the geological sciences are considered. Topics include stratigraphy, geomorphology, site formation processes, climate reconstruction, site location, and dating techniques. Prior introductory coursework in archaeology or geology (or instructor permission) suggested. SC, SO

**G&G 342a / PHYS 342a, Introduction to Earth and Environmental Physics** John Wettlaufer

A broad introduction to the processes that affect the past, present, and future features of the Earth. Examples include climate and climate change and anthropogenic activities underlying them, planetary history, and their relation to our understanding of Earth's present dynamics and thermodynamics. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261, or permission of instructor. Recommended preparation: familiarity with basic calculus and differential equations. QR, SC

**G&G 350b, Petrology of Mountain Belts** Jay Ague

The fundamental principles governing the formation of metamorphic and igneous rocks during mountain building. Topics include processes of heat and mass transfer in orogenic belts, generation of igneous rocks in continental and subduction settings, ultrahigh pressure and ultrahigh temperature metamorphism, spatial and temporal patterns of petrologic processes throughout geologic time, and pressure-temperature-time paths of metamorphic and igneous rocks. Prerequisites: G&G 220 or equivalent, MATH 120, and CHEM 161, 165, or 167 (or CHEM 115, 118); or with permission of instructor. SC RP

**\* G&G 362b / ARCG 362b / EVST 362b, Observing Earth from Space** Ronald Smith

A practical introduction to satellite image analysis of Earth's surface. Topics include the spectrum of electromagnetic radiation, satellite-borne radiometers, data transmission and storage, computer image analysis, the merging of satellite imagery with GIS and applications to weather and climate, oceanography, surficial geology, ecology and epidemiology, forestry, agriculture, archaeology, and watershed management. Prerequisites: college-level physics or chemistry, two courses in geology and natural science of the environment or equivalents, and computer literacy. QR, SC

**[ G&G 370, Regional Perspectives on Global Geoscience ]****G&G 421b, Geophysical Fluid Dynamics** Mary-Louise Timmermans

Examination of the equations governing rotating stratified flows with application to planetary atmospheres and oceans. Mathematical models are used to illustrate the dynamical principles of geophysical fluid phenomena such as waves, boundary layers, flow stability, turbulence, and large-scale flows. Concepts are investigated through laboratory experiments in a rotating water tank. Prerequisite: a course in fluid mechanics (MENG 361 or equivalent) or permission of the instructor. QR, SC

**G&G 428a / AMTH 428a / E&EB 428a / PHYS 428a, Science of Complex Systems** Jun Korenaga

Introduction to the quantitative analysis of systems with many degrees of freedom. Fundamental components in the science of complex systems, including how to simulate complex systems, how to analyze model behaviors, and how to validate models using observations. Topics include cellular automata, bifurcation theory, deterministic chaos, self-organized criticality, renormalization, and inverse theory. Prerequisite: PHYS 301, MATH 247, or equivalent. QR, SC

**G&G 450b, Deformation of Earth Materials** Shun-ichiro Karato

Basic physics and chemistry of Earth materials, with emphasis on kinetic and transport properties. Geochemical and geophysical processes in Earth's crust and mantle and their influence on the dynamics and evolution of this planet. Topics include plastic flow, diffusion, electrical conductivity, and chemical reaction. Prerequisites: CHEM 115, MATH 120, and PHYS 181, or equivalents. QR, SC

**[ G&G 456, Introduction to Seismology ]****\* G&G 487a or b, Individual Study in Geology and Geophysics** Mary-Louise Timmermans

Individual study for qualified undergraduates under faculty supervision. To register for this course, each student must submit a written plan of study, approved by the adviser, to the director of undergraduate studies. May be taken more than once for credit. ½ Course cr

**\* G&G 488a and G&G 489b, Research in Geology and Geophysics** Mary-Louise Timmermans

Individual study for qualified juniors and seniors under faculty supervision. To register for this course, each student must submit a written plan of study, approved by the adviser, to the director of undergraduate studies.

**\* G&G 490a and G&G 491b, Research and Senior Thesis** Mary-Louise Timmermans

Two terms of independent library, laboratory, field, or modeling-based research under faculty supervision. To register for this course, each student must submit a written plan of study, approved by a faculty adviser, to the director of undergraduate studies by the end of the junior year. The plan requires approval of the full G&G faculty.

\* **G&G 492a or b, The Senior Essay** Mary-Louise Timmermans

One term of independent library, laboratory, field, or modeling-based research under faculty supervision. To register for this course, each student must submit a written plan of study, approved by a faculty adviser, to the director of undergraduate studies at the beginning of the term in which the essay is to be written.