

Geophysical Sciences

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Program of Study

The Department of the Geophysical Sciences offers unique programs of study in the earth, atmospheric, and planetary sciences. Topics include the physics, chemistry, and dynamics of the atmosphere, oceans, and ice sheets; past and present climate change; the origin and history of the Earth, moon, and meteorites; properties of the deep interior of the Earth and the dynamics of crustal movements; and the evolution and geography of life and Earth's surface environments through geologic time. These multidisciplinary topics require an integrated approach founded on mathematics, physics, chemistry, and biology.

Both the B.A. and B.S. programs prepare students for careers that draw upon the earth, atmospheric, and planetary sciences. However, the B.S. degree provides a more focused and intensive program of study for students who intend to pursue graduate work in these disciplines. The B.A. degree also offers thorough study in the geophysical sciences, but it provides a wide opportunity for elective freedom to pursue interdisciplinary interests, such as environmental policy, law, medicine, business, and precollege education.

Program Requirements

The principal distinction between the B.A. and B.S. programs is the number of 20000-level courses required for the concentration and their distribution among subdisciplines.

Program Requirements for the B.A. The B.A. requires a minimum of six geophysical sciences courses beyond the introductory sequence GEOS 13100-13200-13300 (which should be taken first). At least two of these six courses must be from the earth sciences and at least two others must be from atmospheres/oceans. Specific courses are shown in List A that follows. Of the six 20000-level courses, up to two may be from List B.

Program Requirements for the B.S. The B.S. requires a minimum of eight courses beyond GEOS 13100-13200-13300 (which should be taken first). At least four of these eight courses must be drawn from either the earth sciences or atmospheres/oceans (as shown in List A that follows). Because of the interdisciplinary nature of these fields, up to four of the eight courses may be taken from other departments (chemistry, physics, mathematics, biology, and statistics), subject to approval by the departmental adviser. Specific courses are shown in List B that follows.

Summary of Requirements

General Education	CHEM 11101-11201/11102-11202 or equivalent† MATH 13100-13200 or higher†
Concentration	1 CHEM 11301/11302 or equivalent† 3 GEOS 13100-13200-13300 3 PHYS 12100-12200-12300 or higher†

plus the following requirements:

B.A.	B.S.
1 MATH 13300 or higher†, or STAT 22000†, or 24000	2 MATH 13300 or higher†, plus one mathematics or one statistics course. (The remaining course can be selected from mathematics or statistics offerings in List B.)
6 courses in 20000-level geophysical sciences drawn from List A, at least two of which must be in the earth sciences, and at least two of which must be in the atmosphere and ocean sciences	8 courses in 20000-level geophysical sciences. Up to four may be drawn from List B.
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† Credit may be granted by examination.

LIST A (Courses in the geophysical sciences categorized as earth sciences, and atmosphere and ocean sciences.)

Earth Sciences

GEOS 20300. Thermodynamics and Phase Change
 GEOS 21200. Physics of the Earth
 GEOS 21300. Origin and Evolution of the Solar System
 GEOS 21600. Chemistry of the Earth
 GEOS 21700. Introduction to Mineralogy
 GEOS 21800. Introduction to Petrology
 GEOS 21900. Introduction to Structural Geology
 GEOS 22000. Magmatism in the Early Solar System
 GEOS 22100. Sediments and Sedimentary Rock
 GEOS 22200. Principles of Stratigraphy
 GEOS 22300. Introduction to Paleontology
 GEOS 23500. Data Analysis in the Earth Sciences I
 GEOS 23600. Data Analysis in the Earth Sciences II
 GEOS 23800. Biogeochemistry and Global Change
 GEOS 23900. Environmental Chemistry
 GEOS 29700. Reading and Research

Field Courses in Earth Sciences

GEOS 22800. Field Course in Geology and Geophysics
 GEOS 22900. Field Course in Modern Carbonate Environments
 GEOS 23000. Field Course in Structural Geology, Petrology, and
 Stratigraphy
 GEOS 24000. Field Course in Stratigraphy

Atmosphere and Ocean Sciences

GEOS 20300. Thermodynamics and Phase Change
 GEOS 23100. Physics and Chemistry of the Atmosphere
 GEOS 23200. Climate Dynamics of the Earth and Other Planets
 GEOS 23300. Physical Oceanography
 GEOS 23400. Chemical Oceanography
 GEOS 23500. Data Analysis in the Earth Sciences I
 GEOS 23600. Data Analysis in the Earth Sciences II
 GEOS 23700. Cumulus Physics
 GEOS 23800. Biogeochemistry and Global Change
 GEOS 23900. Environmental Chemistry
 GEOS 29700. Reading and Research

LIST B (Courses which, with the approval of the departmental adviser, may be substituted in place of geophysical sciences courses in the B.S. concentration. NOTE: Students should consult the catalog listings of other departments for changes and updates to the course numbers listed below.)

Chemistry

CHEM 20100, 20200. Inorganic Chemistry I, II
 CHEM 22000, 22100, 22200 or 22000, 23100, 23200.
 Organic Chemistry
 CHEM 26100, 26200, 26300. Physical Chemistry I, II, III

Physics

PHYS 18500, 18600. Intermediate Mechanics
 PHYS 19700. Thermal Physics
 PHYS 22500, 22700. Intermediate Electricity and Magnetism
 PHYS 22600. Electronics

Biology

BIOS 22234. Chordate Biology
 BIOS 22244. Invertebrate Biology
 BIOS 23240. Biology and Evolution of Plants
 BIOS 23255. Introductory Paleontology
 BIOS 23260. Mammal Evolution
 BIOS 23300. Evolution and Paleobiology
 BIOS 23351. Conservation Biology
 BIOS 23403. Systematic Biology
 BIOS 26099. Quantitative Topics in Biology

Mathematics (One of the following courses can serve as the additional mathematics or statistics course that is required for the B.S. degree. Courses beyond this one can serve as substitutes for geophysical sciences courses.)

MATH 20000, 20100, 20200. Mathematical Methods for Physical
 Sciences I, II, III
 MATH 20300, 20400, 20500. Analysis in R^n I, II, III
 MATH 21100. Basic Numerical Analysis
 MATH 25000. Elementary Linear Algebra
 MATH 27000. Basic Complex Variables
 MATH 27300. Basic Theory of Ordinary Differential Equations
 MATH 27500. Basic Theory of Partial Differential Equations

Statistics

STAT 22000. Statistical Methods and Their Applications

STAT 24000. Probability and Statistics for the Natural Sciences

Grading. Students concentrating in geophysical sciences must receive quality grades in all courses meeting the requirements of the degree program. In order to qualify for the B.A. or B.S. degree, a GPA of 2.0 or higher is needed in required courses, that is, in 20000-level courses in geophysical sciences or in substitutions for geophysical sciences courses.

Honors. The B.A. or B.S. degree with honors is awarded to students who meet the following requirements: (1) minimum GPA of 3.0 in all concentration courses; and (2) completion of a paper based on original research, supervised and approved by a faculty member in geophysical sciences. GEOS 29700 (Reading and Research) can be devoted to the preparation of the required paper.

Field Trips and Field Courses. The department normally sponsors about twelve trips each year that range in length from one day to five weeks. Destinations of trips have included areas as far afield as Newfoundland; the Canadian Rockies; Baja, California; the Caribbean; and Iceland. The longer trips are designed as undergraduate field courses (GEOS 22800, 22900, 23000, and 24000), and the shorter trips are mostly scheduled in connection with undergraduate and graduate lecture courses. However, all students and faculty are welcome to participate, space permitting.

Sample B.S. Program. After satisfying the requirements common to all concentrators in Geophysical Sciences, students can create a B.S. program from a wide range of selections that focuses on a subdiscipline. Sample programs appear below; in consultation with the departmental adviser other programs can be designed. Each program contains nine courses. One course satisfies the mathematics or statistics requirement beyond three quarters of calculus; the remaining eight courses are in geophysical sciences or are approved substitutions for geophysical sciences courses.

Chemistry of Atmosphere and Ocean. GEOS 23100, 23200, 23300, and 23400; CHEM 26100, 26200, and 26300; and MATH 20000 and 20100

Physics of Climate and Circulation. GEOS 23100, 23200, 23300, 23500 (or 23600), and 23700; MATH 20000 and 20100 (or 20200, 21100, and 25000); and PHYS 18500, 18600, and 22500

Paleontology/Stratigraphy. GEOS 21700, 21900, 22100, 22200, 22300, and 23800; STAT 24000; and BIOS 20194 and 20185

Environmental Geology. GEOS 21700, 21800, 22100, 22200, 23800 and 23900; and STAT 24000. For emphasis on chemistry: CHEM 22000, 22100, and 22200. For emphasis on biology: BIOS 20194, 20185, and 23351

Structure/Tectonics. GEOS 20300, 21200, 21300, 21700, 21800, 21900, 22100, and 22200; PHYS 18500; and MATH 20000

Geochemistry. GEOS 20300, 21200, 21300, 21700, and 21800; CHEM 26100, 26200, and 26300; and MATH 20000 and 20100

Geophysics. GEOS 20300, 21200, 21300, 21700, and 23500 (or 23600); PHYS 18500 (or 22500 or 22700); and MATH 20000, 20100, and 20200

	AUTUMN	WINTER	SPRING	SUMMER
<i>First Year</i>	GEOS 13100	GEOS 13200	GEOS 13300	
	General Chemistry	General Chemistry	General Chemistry	
	Calculus	Calculus	Calculus	
<i>Second Year</i>	PHYS 12100	PHYS 12200	PHYS 12300	GEOS 22800 or
	MATH 20000	MATH 20100	MATH 20200	GEOS 24000
<i>Third Year</i>	geophysical sciences elective	geophysical sciences elective	geophysical sciences elective	GEOS 22800 (if not taken in second year)
<i>Fourth Year</i>	geophysical sciences elective	geophysical sciences elective	geophysical sciences elective	

Faculty

A. Anderson, Jr., D. Archer, B. Buffett, G. Eshel, M. Foote, J. Frederick, L. Grossman, D. Heinz, M. Humayun, D. Jablonski, S. Kidwell, M. LaBarbera, D. MacAyeal, N. Nakamura, S. Peacock, R. Pierrehumbert, F. Richter, D. Rowley, J. Smith, R. Srivastava, M. Wadhwa, A. Ziegler

Courses: Geophysical Sciences (GEOS)

13100. Physical Geology. This course is an introduction to plate tectonics, the geologic cycle, and the internal and surface processes that make minerals and rocks and shape the scenery. *D. Rowley. Autumn. L.*

13200. Earth History. *PQ: GEOS 13100 or consent of instructor.* This course covers the paleogeographic, biotic, and climatic development of the Earth. *Winter. L.*

13300. The Atmosphere. (=ENST 13300) *PQ: MATH 13200 or consent of instructor.* This course provides an introduction to the physics, chemistry, and phenomenology of the Earth's atmosphere with an emphasis on the role of the atmosphere as a component of the planet's life support system. Topics include (1) atmospheric composition, evolution, and structure; (2) solar and terrestrial radiation; (3) the role of water in atmospheric processes; (4) winds, the global circulation, and weather systems; and (5) atmospheric chemistry and pollution. We focus on the mechanisms by which human activity can influence the atmosphere and on interactions between atmosphere and biosphere. *J. Frederick, N. Nakamura. Spring.*

13400. Global Warming: Understanding the Forecast. (=ENST 12300, NTSC 12300, PHSC 13400) *PQ: MATH 10600, or placement into 13100 or higher, or consent of instructor required; some knowledge of chemistry or physics helpful.* This course presents the science behind the forecast of global warming to evaluate the likelihood and potential severity of anthropogenic climate change in the coming centuries. It includes an overview of the physics of the greenhouse effect, including comparisons with Venus and Mars; an overview of the carbon cycle in its role as a global thermostat; predictions and reliability of climate model forecasts of the greenhouse world; and an examination of the records of recent and past climates, such as the glacial world and Eocene and Oligocene warm periods. *D. Archer, R. Pierrehumbert. Spring. L.*

20300/30300. Thermodynamics and Phase Change. *PQ: MATH 20000-20100-20200, college chemistry and calculus, or consent of instructor. Consent of instructor in advance is required for registration in GEOS 30300.* This course develops the mathematical structure of thermodynamics with emphasis on relations between thermodynamic variables and equations of state. These concepts are then applied to homogeneous and heterogeneous phase equilibrium, culminating in the construction of representative binary and ternary phase diagrams of petrological significance. *D. Heinz. Autumn.*

21200. Physics of the Earth. *PQ: Prior calculus and college-level physics courses, or consent of instructor.* Geophysical evidence bearing on the internal makeup and dynamical behavior of the Earth is considered, including seismology (properties of elastic waves and their interpretation, and internal structure of the Earth); mechanics of rock deformation (elastic properties, creep and flow of rocks, faulting, and earthquakes); gravity (the geoid and isostasy); geomagnetism (magnetic properties of rocks and history and origin of the magnetic field); heat flow (temperature within the Earth, sources of heat, and thermal history of the Earth); and plate tectonics and the maintenance of plate motions. *D. Heinz. Spring. L.*

21300. Origin and Evolution of the Solar System. (=ASTR 21300) *PQ: Consent of instructor. Knowledge of physical chemistry helpful.* Representative topics include abundance and origin of the elements; formation, condensation, and age of the solar system; meteorites and the historical record of the solar system they preserve; comets and asteroids; the planets and their satellites; temperatures and atmospheres of the planets; and the origin of the Earth's lithosphere, hydrosphere, atmosphere, and biosphere. *L. Grossman. Winter. L.*

21600. Chemistry of the Earth. *PQ: GEOS 13100 or consent of the instructor.* This course covers origin of the elements, elemental abundance and distribution, radioactivity and its measurement, geochronology, stable isotopes, and the origin and differentiation of the Earth. *M. Humayun. Autumn.*

21700. Introduction to Mineralogy. *PQ: CHEM 11100-11200-11300 or equivalent.* This course covers structure, chemical composition, stability, and occurrence of major rock-forming minerals. Labs concentrate on mineral identification with the optical microscope. *A. T. Anderson, L. Grossman. Autumn. L.*

21800. Introduction to Petrology. *PQ: GEOS 21700.* We learn how to interpret observable geological associations, structures, textures, and mineralogical and chemical compositions of rocks so as to develop concepts of how they form and evolve. The course theme is the origin of granitic continental crust on the only planet known to have oceans and life. Igneous, sedimentary, and metamorphic rocks; ores; and waste disposal sites are reviewed. *A. T. Anderson. Spring. L.*

21900. Introduction to Structural Geology. *PQ: GEOS 13100.* This course explores the deformation of Earth materials primarily as observed in the crust. We emphasize stress and strain and their relationship to incremental and finite deformation in crustal rocks, as well as techniques for inferring paleostress and strain in deformed crustal rocks. We also look at mesoscale to macroscale structures and basic techniques of field geology in deformed regions. *D. Rowley. Winter.*

22000. Magmatism in the Early Solar System. *PQ: GEOS 21700 or consent of instructor.* This course covers petrographic and mineralogic characteristics of the products of early melting and differentiation of planetesimals as represented by different classes of meteorites; magmatic processes on asteroids, including the physical conditions of asteroidal volcanism; and volcanism on the moon and Mars. *M. Wadhwa. Spring. L.*

22100. Sediments and Sedimentary Rocks. *PQ: GEOS 13100-13200 or equivalent.* This course is an introduction to the composition and genesis of detrital, biogenic, and chemical rocks at the Earth's surface, the diagnosis of major environments of formation, and their application to the analysis of Earth history and Earth resources. *Weekly three-hour lab and two field trips required; consult undergraduate counselor for further information. Spring. L.*

22200. Principles of Stratigraphy. *PQ: GEOS 13100-13200 or equivalent required; GEOS 22100 and/or 23300 recommended.* This course offers an introduction to the principles and methods of stratigraphy, including facies analysis, physical and biostratigraphic correlation, development and calibration of the geologic time scale, and controversy concerning the completeness of the stratigraphic record, origin of sedimentary cycles, and interactions between global sea level, tectonics, and sediment supply. *S. Kidwell. Autumn. L.*

22300. Introductory Paleontology. (=BIOS 23255, EVOL 32300) *PQ: GEOS 13100-13200, or PHSC 10900-11000, or completion of the general education requirement for the biological sciences, or consent of instructor.* The focus of the course is on the nature of the fossil record, the information it provides on patterns and processes of evolution through geologic time, and how it can be used to solve geological and biological problems. Lectures cover the principles of paleontology (e.g., fossilization, classification, morphologic analysis and interpretation, biostratigraphy, paleoecology, macroevolution); labs are systematic, introducing major groups of fossil invertebrates. *M. Foote. Spring. L.*

22500/33200. Global Tectonics. *PQ: GEOS 13100 or consent of instructor.* We review the spatial and temporal development of tectonic and plate tectonic activity of the globe. We focus on the style of activity at

compressive, extensional, and shear margins, as well as on the types of basin evolution associated with each. *This course is offered in alternate years. D. Rowley. Winter.*

22800. Field Course in Geology and Geophysics. *PQ: Consent of instructor.* This is a summer field camp with emphasis on rocks, structure, stratigraphy, geodesy, and rates of erosion and deposition. The department provides field vehicles and camping equipment. *This course is offered in alternate years. A. T. Anderson. Summer.*

22900. Field Course in Modern Carbonate Environments. *PQ: Consent of instructor.* On a weeklong field trip (during spring break) we visit San Salvador in the Bahamas to examine modern coral reefs, as well as their geological antecedents. *Discussion section required. This course is offered in alternate years. Staff, M. LaBarbera. Spring.*

23000. Field Course in Structural Geology, Petrology, and Stratigraphy. *PQ: GEOS 13100-13200 and consent of instructor.* On a weeklong field trip (during spring break), we visit classic locations to examine a wide variety of geological environments and processes, including active tectonics, ancient and modern sedimentary environments, and geomorphology. *This course is offered in alternate years. Winter, Spring.*

23100. Physics and Chemistry of the Atmosphere. *PQ: CHEM 12100-12200-12300, PHYS 13100-13200-13300, or consent of instructor.* This course introduces atmospheric thermodynamics and cloud microphysics. *R. Srivastava. Autumn.*

23200. Climate Dynamics of the Earth and Other Planets. *PQ: Prior course in physics (preferably PHYS 13300 or 14300) and knowledge of ordinary differential equations, or consent of instructor.* This course serves as an introduction to the basic physical principles that determine the climate of the Earth and similar planets. The emphasis is on atmospheric phenomena, but elementary aspects of glaciology and oceanography are also brought in as needed. Problem sets are supplemented by data labs involving computer analysis of extensive collections of Earth climate data. Topics covered include survey of major issues in planetary climates and their evolution, properties of solar and infrared radiation, radiation balance, thermodynamics, grey-gas radiation models, one-dimensional radiative-convective models, runaway greenhouse effect, theories of the seasonal cycle, and of the pole-equator temperature gradient, and the Milanković theory of the ice ages. *R. Pierrehumbert. Winter. L.*

23300. Physical Oceanography. *PQ: GEOS 23200 or consent of instructor.* This course provides a conceptual understanding of the dynamics of ocean circulation and a background in physical oceanography for students interested in further study of climate dynamics, chemical oceanography, marine biology, and paleontology. Topics include geometry of map projections, hypsometry of ocean basins and the geoid, temperature and salinity structure, watermasses, geostrophy and geostrophic adjustment, Ekman layers, coastal upwelling, Sverdrup balance, vorticity balance and western intensification, and waves and tides. Macintosh computers and oceanographic databases are used for lab exercises. *G. Eshel, D. MacAyeal. Spring. L.*

23400. Chemical Oceanography. *PQ: Consent of instructor.* This course introduces the geochemistry of the oceans with an emphasis on topics relevant to global change, past and future. The role of the ocean in the global carbon cycle is discussed, along with the interplay between ocean circulation, biology, and physical chemistry and its impact on the distributions of nutrients, carbon, and oxygen in the ocean. Also covered are sediment geochemistry and what sediments can tell us about oceans and climates of the past. *D. Archer. Autumn.*

23500. Introduction to Data Analysis in the Earth Sciences I. *PQ: Knowledge of calculus, differential equations, and linear algebra; or consent of instructor.* This course, which was formerly titled Introduction to Inverse Methods, is an introduction to linear algebra, least-square analysis, constrained minimization, and variational methods commonly used for analysis of data in the physical sciences. This class is taught in a tutorial style with emphasis on lab participation. Topics include eigenvalue/eigenvector analysis, singular-value decomposition, variational methods with least-squares metrics, and Lagrange multipliers, as well as the role that these methods play in analysis of noisy data in both overdetermined and underdetermined data analysis problems. Lab applications address simple problems in geophysics, geochemistry and fluid dynamics. *D. MacAyeal. Winter. L.*

23600. Data Analysis in the Earth Sciences: Application to Spatio-Temporal Data II. *PQ: GEOS 23500 or consent of instructor.* This course extends material presented in GEOS 23500 and covers new material in probability, distributions, sampling, and time-series analysis. The bulk of the course is devoted to geophysical applications (including oceanography, atmospheric and climate dynamics, geochemistry, and solid-earth geophysics). Topics covered include EOF (i.e., empirical orthogonal function) analysis, higher-dimensional (auto)correlation analysis, canonical correlation, SVD (i.e., singular value decomposition) in its various incarnations, Monte Carlo methods applied to spatiotemporal data, filtering and interpolation, least squares and optimization, control and regularization, and linear models of time-series analysis (e.g., AR, MA, ARMA, ARIMA). *Work in departmental computing lab required. G. Eshel. Spring. L.*

23700. Cumulus Physics. *PQ: GEOS 23100 or 23200, or consent of instructor.* This course introduces microphysical processes attendant on the formation of rain and snow and introduces cloud dynamics, especially the dynamics of convective clouds. *R. Srivastava. Spring.*

23800. Global Biogeochemical Cycles. *PQ: CHEM 11100-11200 or consent of instructor.* This survey course covers the geochemistry of the surface of the Earth, with emphasis on biological and geological processes, their assembly into self-regulating systems, and their potential sensitivity to anthropogenic or other perturbations. Budgets and cycles of carbon, nitrogen, oxygen, phosphorous, sulfur, and silicon are discussed, as well as fundamentals of the processes of weathering, sediment diagenesis, and isotopic fractionation. What is known about Earth biogeochemistry through geologic time is also presented. *This course is offered in alternate years. D. Archer. Autumn.*

23900. Environmental Chemistry. (=CHEM 21000, ENST 23900) *PQ: CHEM 11101-11201 or equivalent, and prior calculus course.* The focus of this course is the fundamental science underlying issues of local and regional scale pollution. In particular, the lifetimes of important pollutants in the air, water, and soils are examined by considering the roles played by photochemistry, surface chemistry, biological processes, and dispersal into the surrounding environment. Specific topics include urban air quality, water quality, long-lived organic toxins, heavy metals, and indoor air pollution. Control measures are also considered. *S. Peacock. Spring. L.*

24000. Field Course in Stratigraphy. (=EVOL 33100) *PQ: GEOS 13100-13200 or equivalent.* This is a one-month excursion to the northwestern United States and/or eastern Canada to examine the tectonic and stratigraphic evolution of the margin of North America from the Cambrian period to the present. The purpose of the course is to acquaint students with sedimentary and volcanic rocks deposited in a variety of environments and to examine the tectonic and stratigraphic evolution of a complicated region. The trip takes place from late August to early September, with field vehicles and camping equipment provided. *This course is offered in alternate years. Summer, Autumn.*

24500. Atmosphere and Ocean in Motion. *PQ: GEOS 13300 or equivalent and calculus.* The motion of the atmosphere and ocean not only affects daily weather conditions but is also critical in maintaining the habitable climate of our planet. This course teaches: (1) observed patterns of large-scale circulation of the atmosphere and ocean; (2) physical principles that drive the observed circulation; (3) transport of heat, angular momentum, and other quantities; and (4) climate variability and predictability. The lectures are supplemented by problem sets and a computer lab project. *N. Nakamura. Autumn.*

29700. Reading and Research in the Geophysical Sciences. *PQ: Consent of instructor and departmental counselor. Open by arrangement to selected students, both concentrators and qualified nonconcentrators; students are required to submit the College Reading and Research Course Form. Normally taken for either P/N or P/F grading. Summer, Autumn, Winter, Spring.*

30700. Advanced General Petrology. *PQ: Advanced standing. Prior college-level chemistry and physics courses, and consent of instructor.* We study density, viscosity, rheology, and surface tension and their roles in volcanic and magmatic processes including convection and rock deformation. Crystal settling, bubble coalescence, neutral buoyancy, and eruption dynamics comparing observations with theoretical models are also explored. *A. T. Anderson. Spring.*

30800. Radiogenic Isotope Geochemistry. *PQ: Consent of instructor.* This course covers the principles and applications of radiogenic isotopes in geochemistry and cosmochemistry. Topics include principles of radioactive decay; origin of the elements; use of radioactive elements in geochronology; chemical fractionation; long-lived radionuclides; short-lived radionuclides; extinct radionuclides; radioactive heat production in planets; use of radiogenic isotopes as tracers; mantle geochemistry of Sr, Nd, Os, and Pb systems; and core-mantle interaction. *This course is offered in alternate years. M. Humayun. Winter.*

31000. Cosmochemistry. *PQ: Consent of instructor.* This course covers chemical, mineralogical, and petrographic classifications of meteorites. Topics include abundance of the elements, origin of the elements and stellar evolution, the interstellar medium and formation of the solar nebula, condensation of the solar system, chemical fractionations in meteorites and planets, age of the solar system, extinct radionuclides in meteorites, and isotopic heterogeneity of the solar nebula. Emphasis is placed on current topics at the frontiers of research. Part of the course takes the form of seminars prepared by the students. *L. Grossman. Autumn.*

31100. Geochemistry. *PQ: Consent of instructor.* This course covers the principles and applications of stable isotopes, noble gases, and trace elements; and chemical composition, origin, and differentiation of the Earth. *This course is offered in alternate years. M. Humayun. Winter.*

31200. Mineral Physics. *PQ: GEOS 20300/30300 and 21700. Knowledge of calculus and physical chemistry.* This course examines the theory behind those properties of minerals relevant to the study of Earth's deep interior. Topics include elasticity, electrical and thermal conductivity, anharmonicity, lattice defects, solid state diffusion, and creep. *D. Heinz. Winter. Not offered 2003-04; will be offered 2004-05.*

31900. Topics in Paleobiology. *PQ: Consent of instructor.* In this seminar we investigate paleobiological and historical geological topics of current interest to students and faculty. Previous subjects include benthic paleoecology, the Pleistocene, and arthropod paleobiology. *Autumn.*

33700. Present and Paleoclimatology. *PQ: Consent of instructor.* This course reviews the Earth's present atmospheric and oceanic circulation and examines the possibilities of reconstructing climates of the geologic past. *Autumn.*

36800. Radar Meteorology. *PQ: Consent of instructor.* This course covers principles of pulsed microwave radar (coherent and incoherent), scattering and extinction of electromagnetic waves by hydrometeors, effects of polarization on extinction and scattering, theory of the Doppler spectrum, and use of radar for meteorological observations. *R. Srivastava. Winter.*