Advanced Geochemistry

Spring Semester 2015

YOUR PROFESSORS:
Prof. Harold C. Connolly Jr. (drhccjr@me.com)
Prof. Shogo Tachibana (tachi@ep.sci.hokudai.ac.jp)

LECTURE (Day, time, and location): Tuesdays from 13:00 – 14:30. Location: Sci. Bldg. #6 6-204-02.

COURSE GOALS: 1) Understand the philosophy of scientific investigation. 2) Develop a working knowledge and an integrated understanding of Earth Systems Science as applied to Earth and other Solar System bodies. 3) Understand the fundamental geological principles or petrology and geochemistry. 4) Understand how and why human kind explores the Solar System. 5) Appreciate basic concepts of the geochemisty through Meteoritics/Cosmochemistry and the importance of investigating the origin of the Solar System.

JOURNAL ARTICLES: For each class you will be required to read one or more referred journal article. You are required to produce a 1-page (one side only) critical summary of selected readings, which is due each class. As a class (meaning group), we will discuss the assigned papers and you are required to participate in the discussions. Readings listed below may be subject to change.

ATTENDANCE: Attendance to all classes is mandatory. If you have any questions or need help, ask one of your professors.

ACADEMIC HONESTY: Cheating will not be tolerated. Also, please turn off cell phones during class.

EVALUATION AND FINAL GRADE: (1) Summary of assigned journal readings plus participation in discussions = 50% and (2) Final report = 50%.

This syllabus provides a general plan for the course and deviations may be necessary.

Week	Topic
1 (April 7)	Title: **From Meteorites to Asteroids: Exploring the Solar System**. In this lecture we introduce the course, its structure, plus student responsibilities. We will also have an introductory lecture on Exploring the Solar System and the importance of small bodies (e.g., asteroids and comets) in the Cosmic puzzle of Solar System formation.
2 (April 14)	Title: **Meteorites, Asteroids and early Solar System formation: The Basics**. In this lecture we learn about meteorite classification, the importance of chondrites and their components, about what planetary materials can inform about pre- and post-asteroid accretion environments. Required Reading: 1. *Connolly* (2005) From Stars to Dust: Looking into a Circumstellar Disk Through Chondritic Meteorites. Science 307, 75-76. (**Do not summarize**) 2. *Davis* (2010) Early Solar System Chronology, Science 325, 951-952. (**Do not summarize)** 3. *McKeegan et al.* (2011) The oxygen isotopic composition of the Sun inferred from captured Solar Wind. Science 332, 1528-1532. **(Summarize)** Background Readings: *Anders and Grevesse* (1989) Abundances of the elements: Meteoritic and solar, Geochimica et Cosmochimica Acta 53, 197-214. *Bouvier and Wadhwa* (2010) The age of the Solar System redefined by the oldest Pb-Pb age of a meteoritic inclusion, Nature Geoscience 22. *Kita et al.* (2005) Constraints on the Origin of Chondrules and CAIs from Short-lived and Long-lived Radionuclides. In, Chondrites and the Protoplanetary Disk, pp.558-587. *McKeegan and Davis* (2003) Early Solar System Chronology. In, Treatise on Geochemistry, pp. 431-460. *Weisberg et al.* (2006) Systematics and evaluation of meteorite classification. In, Meteorites and the Early Solar System II, pp. 19-52. *Zolensky et al.* (2006) Mineralogy and petrology of comet 81P/Wild 2 nucleus samples. Science 314, 1735-1739.

3 (April 21)	Title: **The Cosmic Significance of Igneous Objects within Chondrites: Their Origin.** In this lecture we discuss the controversy around igneous objects that are the structural components of chondrites. Required Reading: 1. *Connolly* (2005) Refractory Inclusions and chondrules: Insights into a protoplanetary disk and planet formation. Chondrites and the Protoplanetary Disk, 215-224. **(Do not summarize)** 2. *Johnson et al.* (2015) Impact Jetting as the origin of chondrules. Nature 517, 339-341. (**Summarize**) Background Reading: *Shu et al.* (1996) Towards an Astrophysical Theory of Chondrites. Science, 271, 1545-1552. *Connolly and Love* (1997) The formation of chondrules: Petrologic tests of the shock wave model. Science 280, 62-67. *Connolly and Desch* (2004) On the origin of the "kleine Kugelchen" called Chondrules. Chemie de Erde Geochemisty 64, 95-125.
4 (April 28)	Title: **Taxonomy of Asteroids and the Geological Provenance of Meteorites.** In this lecture we discuss how asteroids are classified, their classification, and the relationship of meteorites types to asteroids types. Require Readings: 1. *Burbine* (2008) Identifying ancient asteroids. Science 320, 547-548. **(Do not summarize)** 2. *Sunshine et al.* (2008) Ancient Asteroids Enriched in Refractory Inclusions. Science 320, 514-517. (**Summarize**) Background Readings: *Bus and Binzel* (2002) Phase II of the small main-belt asteroid spectroscopic survey: A feature-based taxonomy. Icarus 158, 146-177. *DeMeo and Carry* (2013) The taxonomic distribution of asteroids from multi-filter all-sky photometrix surveys. Icarus 226, 723-741.

5 (May 12)	Title: **The Ground Truth: Sample Return Missions**. In this lecture we learn about the relationship of Sample Return Missions to meteorites and how data from both constrain hypotheses on Solar System formation and evolution. Required Reading: 1. *Krot* (2011) Bringing Part of an Asteroids Back Home. Science 333, 1098-1099. (**Do not summarize**). 2. *Yurimoto et al.* (2011) Oxygen isotopic compositions of asteroidal materials returned from Itokawa by the Hayabusa mission. Science 333, 1116-1118. (**Summarize**). 3. *Nakamura et al.* (2008) Chondrulelike objects in short-period comet 81P/Wild 2. Science 321, 1664-1667. (**Do not summarize)** Background Readings: *Nakamura et al.* (2011) Itokawa dust particles: A direct link between S-Type asteroids and ordinary chondrites. Science 333, 1113-1116. *Nakamura et al.* (2012) Space environment of an asteroid preserved on micrograins returned by the Hayabusa spacecraft. Proceedings of the National Academy of Sciences 109, E624-629.
6 (May 19)	Title: **Sample Return Missions: The Dynamical Evolution of Asteroids and Future Missions.** In this lecture we discuss how the analyses of asteroids grains returned by Hayabusa can be used to generate and constrain hypothesis on the evolution of Itokawa. We also discuss future Sample Return Missions and the collaboration of scientists from two missions. Required Reading: 1. *Connolly et al*. (2015) Towards understanding the dynamical evolution of asteroid 25143 Itokawa: Constraints from Sample Analysis. Earth, Planet and Space 67. **(Summarize)** Background Reading: *Tachibana et al.* (2014) Hayabusa2: Scientific importance of samples returned from C-type near-Earth asteroid (162173) 1999 JU_3. Geochemical Journal 48, 571-587. *Lauretta et al.* (2014) The OSIRIS-REx target asteroid (101955) Bennu: Constraints on its physical, geological, and dynamical nature from astronomical observations. Meteoritics and Planetary Science 49, 1-16.

7 (June 2)	Title: **Dust in the Galaxy.** In this lecture we learn about dust present in the Galaxy and its relationship to Solar System materials. Required Reading: 1. *Russell* (2004) Stars in stones. Nature 428, 903-904. (**Do not Summarize)** 2. *Nagashima et al*. (2004) Stardust silicates from primitive meteorites. Nature 428, 921–924. **(Summarize)** Background Reading: *Messenger et al*. (2005) Supernova olivine from cometary dust. Science 309, 737-741. *Westphal et al*. (2014) Evidence for interstellar origin of seven dust particles collected by the Stardust spacecraft. Science 345, 786-791. *Takigawa et al*. (2014) Morphology and crystal structures of solar and presolar Al_2O_3 in unequilibrated ordinary chondrites. Geochim. Cosmochim. Acta 124, doi:10.1088/0004-637X/750/2/149. *Henning* (2010) Cosmic silicates. Annu. Rev. Astron. Astrophys. 48, 21–46.
8 (June 9)	Title: **Chemical Reactions in Molecular Cloud and Protoplanetary Disk.** In this lecture we discuss chemical reactions responsible for chemical evolution of molecular clouds and protoplanetary disks. Required Reading: 1. *Shock* (2002) Astrobiology: Seeds of life? Nature 416, 380-381. (**Do not summarize)** 2. *Muñoz Caro et al*. (2002) Amino acids from ultraviolet irradiation of interstellar ice analogues. Nature 416, 403-406. **(Summarize)** Background Reading: *Bernstein et al*. (1999) UV Irradiation of Polycyclic Aromatic Hydrocarbons in Ices: Production of Alcohols, Quinones, and Ethers. Science 83, 1135-1138. *Watanabe and Kouchi* (2002) Efficient Formation of Formaldehyde and Methanol by the Addition of Hydrogen Atoms to CO in H_2O-CO Ice at 10 K. Astrophys. J. Letters 571, L173-L176. *Brucato and Nuth* (2010) Laboratory studies of simple dust analogs in astrophysical environments. In, Protoplanetary Dust. pp 128-160. *Tachibana et al*. (2011) Kinetic condensation and evaporation of metallic iron and implications for metallic iron dust formation. Astrophys. J. 736, doi:10.1088/0004-637X/736/1/16. *Takigawa et al*. (2015) Evaporation and condensation kinetics of corundum: The origin of the 13-μm feature of oxygen-rich AGB stars. Astrophys. J. Suppl., in press.

9 (June 16)	Title: **Water in Planets, Comets and Asteroids.** In this lecture we learn about water and its possible origin in planets and small bodies within the Solar System. Required Reading: 1. *Taylor et al*. (2015) Rosetta begins its Comet Tale. Science 347, 387. (**Do not summarize)** 2. *Altwegg et al*. (2015) 67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio. Science 347, DOI: 10.1126/science.1261952 (**Summarize**). Background Reading: *Campins et al*. (2010) Water ice and organics on the surface of the asteroid 24 Themis. Nature 464, 1320-1321. *Smyth and Jacobsen* (2006) Nominally Anhydrous Minerals and Earth's Deep Water Cycle. In, Earth's Deep Water Cycle, pp. 1-11. *Yurimoto et al*. (2014) Isotopic compositions of asteroidal liquid water. Geochem. J. 48, 549-560. *Piani et al*. (2015) Micron-scale D/H heterogeneity in chondrite matrices: A signature of the pristine solar system water? Earth Planet. Sci. Lett. 415, 154–164.
10 (June 23)	Title: **Extraterrestrial Organic Matter.** In this lecture we learn about the diversity of extraterrestrial organic materials and their origins. Required Reading: 1. *Sandford et al*. (2006) Organics captured from comet 81P/Wild 2 by the Stardust spacecraft. Science 314, 1720-1724 (**Summarize**). 2. *Herd et al*. (2011) Origin and evolution of prebiotic organic matter as inferred from the Tagish Lake meteorite. Science 332, 1304-1307. (**Do not summarize)** Background Reading: *Duprat et al*. (2010) Extreme deuterium excesses in ultracarbonaceous micrometeorites from central Antarctic snow. Science 328, 742-745. *Glavin and Dworkin* (2009) Enrichment of the amino acid L-isovaline by aqueous alteration on CI and CM meteorite parent bodies. Proc. Natl. Acad. Sci. USA 106, 5487-5492.

11 (July 14)	Title: **Planetary Accretion, Differentiation and Planet Formation.** In this lecture we discuss the formation of planetesimal, planetary differentiation, heat sources for early differentiating bodies, the formation of planets. Required Readings: 1. Meier (2012) Earth's titanium twin. Nature Geoscience 5, 240-241. **(Do not summarize)** 2. *Zhang et al.* (2012) The Proto-Earth as a Significant Source of Lunar Material. Nature Geoscience 5, 451-455. (**Summarize**) Background Reading: *Halliday* (2003) The origin and earliest history of the Earth. In, Treatise on Geochemistry, pp. 509-557. *Scott* (2006) Meteorite Evidence for the Accretion and Collisional Evolution of Asteroids. In, Meteorites and the Early Solar System II, pp. 697-709. *Halliday* (2012) The Origin and Earliest History of the Earth. Science 338, 1040-1041. *Warren* (2011) Stable-isotopic anomalies and the accretionary assemblage of the Earth and Mars: A subordinate role for carbonaceous chondrites. Earth and Planetary Science Letters 311, 93-100.
12 (July 21)	Title: **Potential Habitable Worlds in Icy Bodies.** In this lecture we discuss the presence of liquid water in Solar System bodies, especially in icy satellites. Required Reading: 1. *Gaidos et al*. (1999) Life in ice-covered oceans. Science 284, 1631-1633. **(Do not summarize)** 2. *Tobie* (2015) Planetary science: Enceladus' hot springs. Nature 519, 162-163. **(Do not summarize)** 3. *Hsu et al*. (2015) Ongoing hydrothermal activities within Enceladus. Nature 519, 207–210. (**Summarize**) Background Reading: *Postberg et al*. (2011) A salt-water reservoir as the source of a compositionally stratified plume on Enceladus. Nature 474, 620–622. *Saur et al*. (2015) The search for a subsurface ocean in Ganymede with Hubble Space Telescope observations of its auroral ovals. J. Geophys. Res. Space Physics 120, doi:10.1002/2014JA020778.

13 (July 28)	Title: **Cosmochemistry and Solar System Exploration: Summary.** In this lecture we summarize the course: the importance of geochemistry/cosmochemistry to understand the origin and evolution of the Solar System.