Colorado State University
AIRIE Program, Geosciences
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New at AIRIE – We are now analyzing Hg (mercury) using our state-of-the-art DMA (Digital Mercury Analyzer). Hg concentration data are available for almost any media through our AIRIE-Hg program.

The AIRIE Program pioneered Re-Os (rhenium-osmium) protocols for working with resource-related geologic media in crustal rocks (e.g., sulfides, shales and oils). Since 1995, AIRIE has produced state-of-the-art Re-Os geochronology and Os isotopic tracer studies, framed by geologic observation at all scales. Two multi-collector Triton mass spectrometers built for Re-Os analytical work and two wet-chemistry labs were funded by the Program. Collaborating partners span 90 countries and discoveries benefit an expanding cross-section of the sciences, from atmosphere to deep earth, geology-biology-chemistry. We address fundamental scientific questions and use creative approaches and interpretations to stimulate new and progressive thinking. This is how we advance science to enhance discovery in the petroleum and mineral industries. The AIRIE Program is a designated research unit benefitting Colorado State University, and reporting to the CSU Vice President of Research. All AIRIE salaries and the Program's operation rely on external grants and contracts; CSU and the Geosciences Department provide no base financial support. Starting in 2000, AIRIE forged a long-term partnership with research entities in Norway, making Norwegian economic interests the geologic base for fundamental scientific discoveries. These include Re-Os dating of molybdenite and other sulfides, dating of oils and bitumens, and most recently, reconstruction of whole petroleum systems in absolute time.

Re-Os isotope geochemistry enlightens our understanding of how
metallic and hydrocarbon resources are created, interrelated, and where they are located.

Metallic Resources – Our work has led directly to discovery of ore and has challenged several long-standing models for ore formation. AIRIE established now globally employed protocols for Re-Os ID-TIMS dating of molybdenite (*Terra Nova* 2001, 753 citations). We discovered the unique phenomenon of parent-daughter (^{187}Re-^{187}Os) decoupling in molybdenite prompting us to develop new approaches for acquiring mineral separates. We were the first to develop a double Os spike to address young (or low Re) molybdenites and to measure and correct for common Os isotope fractionation. We acquired and characterized a molybdenite reference material (NIST, RM #8599) from the Henderson molybdenum mine (mill) in Colorado to share with the geoscience community. We pioneered Re-Os dating of other sulfide and oxide minerals, for example, arsenopyrite, pyrite, marcasite, bismuthinite, chalcopyrite, pyrrhotite and magnetite providing ages and information of fluid sources, not only for ore deposits, but also for fundamental processes shaping planet Earth.

Hydrocarbon Resources – Our work with hydrocarbons includes Re-Os dating of organic material extracted from shales. Re-Os dating of both *in situ* and *migrated* bitumen and oil also permits tracking interactions between Earth fluids and hydrocarbons using the Os isotopic tracer ratio. In 2016, we published the first Re-Os isochron for a single crude oil based on its asphaltene and maltene components. Re-Os analyses of hydrocarbons are useful in modeling maturation-migration in both conventional and unconventional systems. Our work on sulfides and organic material in shales calibrates Earth's timescale permitting global correlations, and determines rates for sedimentologic, bio-evolutionary, and tectonic processes, giving perspective on ancient climates, oceans, correlation of fauna, and atmospheric evolution. We determined the first radiometric age for the rise of atmospheric oxygen (GOE, Great Oxidation Event), with citations reaching beyond the geoscience literature (*Nature* 2004, 1406 citations; *Earth and Planetary Science Letters* 2004, 251 citations).

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AIRIE PROGRAM, COLORADO STATE UNIVERSITY: RE-OS PUBLICATIONS

Holly Stein (Founding Director, Senior Research Scientist and Professor)
Judith Hannah (Professor)
Aaron Zimmerman (Lab Manager and Research Associate)
Gang Yang (Senior Research Associate)
Svetoslav Georgiev (Research Scientist Affiliate)
Vineet Goswami (Research Scientist Affiliate)
Juni Park (Ph.D. Student)

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Refereed Journal Papers:

Bobos, I., Stein, H., Deng, X.-D., Sudo, M., and Noronha, F. (in co-author review) U-Pb LA-ICP-MS and Re-Os dating of wolframite and molybdenite capturing high T tungsten mineralization and $^{40}Ar/^{39}Ar$ dating of mica defining cooling history, Borralha W deposit, northern Portugal: for *Mineralium Deposita*.

Goswami, V., Stein, H.J., and Hannah, J.L. (in co-author review) Re-Os-Hg geochemistry of Fish Clay, black nodular cherts, and chalks across the Cretaceous-Paleogene (K-Pg) boundary at Stevns Klint, Denmark: for *Palaeogeography, Palaeoclimatology, Palaeoecology.*

Stewart, P.W., Stein, H.J., Roa, K., and Gabites, J. (in co-author review) U-Pb, $^{40}Ar/^{39}Ar$, and Re-Os geochronologic constraints on the genesis of the Fruita del Norte epithermal gold-silver deposit, southeast Ecuador: for *Economic Geology*.

Boni, M., Stein, H., Balassone, G., Yang, G., and Mondillo, N. (in co-author revision) Wulfenite ($PbMoO_4$) in the oxidation zones of the Alpine Zn-(Pb) of the Alpine Zn-(Pb) deposits: first results of Re-Os isotopic analyses: for *Mineralium Deposita*.

Runyon, S.E., Barrier, J., Chapman, J., Brown, T.R., Stein, H., and Autenrieth, K. (in co-author revision) Central alkalic group Au system, Rattlesnake Hills Alkaline Complex, Wyoming: U-Pb and Re-Os geochronology and magmatic evolution: for *Mineralium Deposita*.

Burisch, M., Bussey, S.D., Landon, N., Nasi, C., Kakarieka, A., Gerdes, A., Albert, R., Stein, H.J., Gabites, J.A., Friedman, R.M., and Meinert, L. (submitted, in review) Timing of magmatism and skarn formation at the Limon, Guajes and Media Luna Au ± Cu skarn deposits at Morelos, Guerrero State, Mexico: *Economic Geology*.

Goswami, V., Hannah, J.L., Stein, H.J., Ahlberg, P., Maletz, J., Lundberg, F., Ebbestad, J.O.R., and Cloquet, C. (submitted, in review) Evolution of Baltic shales from late Cambrian to Middle Ordovician: Insights from Re-Os geochronology and geochemistry of Tøyen and Alum shales, Sweden: *Global and Planetary Change.*

Jones, S.M., Cloutier, J., Prave, A.R., Raub, T.D., Stueeken, E.E., Stein, H.J., and Boyce, A.J. (in revision) Fluid flow, alteration and Cu-Ag mineralization associated with the White Pine deposit, Michigan: *Economic Geology*.

Park, J., Stein, H.J., Georgiev, S.V., and Hannah, J.L. (accepted) Degradation of mercury (Hg) signals on incipient weathering: core versus outcrop geochemistry of Upper Permian shales, East Greenland and Mid-Norwegian shelf: *Chemical Geology*.

Zimmerman, A., Yang, G., Stein, H., and Hannah, J. (accepted) Addressing molybdenite ^{187}Re parent-^{187}Os daughter intra-crystalline decoupling in light of recent in-situ micro-scale observations: *Geostandards and Geoanalytical Research*.

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