Colorado State University
AIRIE Program, Geosciences
322 Natural Resources Building
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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 successful Re-Os ID-TIMS dating of molybdenite. 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 to provide age(s) and fluid source information, not only for ore deposits, but for metamorphic processes defining long-term terrane evolution.

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 far beyond the geoscience literature (*Nature* 2004, 1350 citations; *Earth and Planetary Science Letters* 2004, 238 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)
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Refereed Journal Papers:

Goswami, V., Hannah, J.L., Stein, H.J., Ahlberg, P., Maletz, J., Lundberg, F. (in co-author review) Geochemistry and Re-Os geochronology of Tøyen and Alum shales from Sweden: for *Palaeogeography, Palaeoclimatology, Palaeoecology*.

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. (ready to submit, November 2021) Wulfenite in the oxidation zone of the Alpine Zn-(Pb) deposits revisited using Re-Os isotope geochemistry: for *Economic Geology*.

Jones, S.M., Cloutier, J., Prave, A.R., Raub, T.D., Stueeken, E.E., Stein, H.J., and Boyce, A.J. (ready to submit, November 2021) Fluid flow, alteration and Cu-Ag mineralization associated with the White Pine deposit, Michigan: *Economic Geology*.

Runyon, S.E., Barrier, J., Chapman, J., Brown, T.R., Stein, H., and Autenrieth, K. (ready to submit, November 2021) Central alkalic group Au system, Rattlesnake Hills Alkaline Complex, Wyoming: U-Pb and Re-Os geochronology and magmatic evolution: *Economic Geology*.

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