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The AIRIE Program pioneered Re-Os (rhenium-osmium) technology, and is a global leader in setting protocols for dissecting sample media to determine geologic age. 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 were built for Re-Os analytical work. Collaborating partners span 85 countries and discoveries benefit a large cross-section of the geosciences, from atmosphere to deep earth. We address fundamental scientific questions and use the results to both advance science and enhance discovery in the petroleum and mineral industries. The AIRIE analytical facility is a designated research unit benefitting Colorado State University, reporting to the Vice President of Research. All salaries and the Program's operation are based on external grants and contracts, that is, Colorado State University provides no direct financial support. The AIRIE Program has forged a long-term partnership with research entities in Norway, making Norwegian economic interests the geologic base for fundamental scientific discoveries, for example, Re-Os dating of molybdenite and other sulfides, and the dating of oils in petroleum systems. Our scientific publications are tallied under the Department of Geosciences website, constituting 35-40% of the Department's yearly research output.

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

Metals – Our work has led directly to discovery of ore and sometimes challenges long-standing models for ore formation. AIRIE established the protocols for successful Re-Os ID-TIMS dating of molybdenite, from mineral separation to interpretation of isotopic data. We developed a double Os spike to address young (or low Re) molybdenites, sharing this approach with the geochemistry community. We acquired and characterized a molybdenite reference material (NIST, RM #8599) from the Henderson molybdenum mine in Colorado. We work with other sulfide and oxide minerals such as pyrite, arsenopyrite, chalcopyrite, and magnetite to provide age(s) and fluid source information.

Hydrocarbons – Our work with hydrocarbons includes direct dating of organic material in source rocks, and dating *in situ* and migrated bitumen and oil. In 2016, we published the first Re-Os isochron for a single crude oil. We work with the hydrogenous component in black shales, and for hydrocarbons, we analyze components of the asphaltene and maltene fractions in oils. Re-Os analyses of hydrocarbons are used to model maturation-migration in both conventional and unconventional systems. Our work on sulfides and organic material in shales calibrates Earth's timescale, and determines rates for sedimentologic, bio-evolutionary, and tectonic processes, giving perspective on ancient climates, oceans, global correlation of fauna, and atmospheric evolution. We provided the first absolute age for the rise of atmospheric oxygen (*Nature* 2004, 994 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)

Svetoslav Georgiev, Gang Yang, Rich Markey (Research Associates)

Vineet Goswami and Nicole Hurtig (Post-Docs)

Marisa Boraas-Connor and Jenna DiMarzio (Graduate Students)

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### Refereed Journal Papers:

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

Bussey, S.D., Kakarieka, A., Friedman, R.M., Stein, H.J., Gabites, J.E. (in co-author review) Timing of magmatism and skarn mineralization at the Limon, Guajes and Media Luna Au-Ag-(Cu) skarn deposits at Morelos, Guerrero State, Mexico: for *Economic Geology*.

Hurtig, N.C., Georgiev, S.V., Zimmerman, A., Yang, G., Goswami, V., Hannah, J.L., and Stein, H.J. (in co-author review) Re-Os geochronology in petroleum: NIST RM8505, asphaltene precipitations and uncertainty: for *Journal of Geostandards and Geoanalytical Research*.

Georgiev, S.V., Stein, H.J., Hannah, J.L., Yang, G., Markey, R.J., Dons, C.E., Petersen, J-H., Di Primio, R. (in co-author review) Temporal evolution of the Brynhild petroleum system, Norwegian North Sea: for *Geochimica et Cosmochimica Acta*.

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

Febbo, G.E., Kennedy, L.A., Nelson, J., Savell, M., Campbell, M.E., Creaser, R.A., Friedman, R.M., van Straaten, B.I., and Stein, H.J. (in co-author review) The supergiant Mitchell Au-Cu giant porphyry, northwest BC: effect of syn-mineral structures and alteration on deformation and strain localization: for *Economic Geology*.

Boomeri, M., Moradi, R., Stein, H.J., and Bagheri, S. (in journal review) Geology, Re-Os age,  $^{34}\text{S}$  and  $^{18}\text{O}$  isotopic composition of the Lar Cu-Mo deposit, southeast Iran: *Ore Geology Reviews*.

Hurtig, N.C., Georgiev, S.V., Stein, H.J., and Hannah, J.L. (in journal review) Re-Os in oil – in the company of water: *Geochimica et Cosmochimica Acta*.

Molnár, F., Middleton, A., Stein, H., O'Brien, H., Lahaye, Y., Huhma, H., Pakkanen, L., Johansen, B. (in press) Repeated syn- and post-orogenic gold mineralization events between 1.92 and 1.76

Ga along the Kiistala shear zone in the Central Lapland Greenstone Belt: *Mineralium Deposita*.

Tripathy, G.R., Hannah, J.L., Stein, H.J. (2018) Refining the Jurassic-Cretaceous boundary: Re-Os geochronology and depositional environment of Upper Jurassic shales from the Norwegian Sea: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 503, p. 13-25.

(<https://doi.org/10.1016/j.palaeo.2018.05.005>)

Georgiev, S.V., Zimmerman, A., Yang, G., Goswami, V., Hurtig, N., Stein, H.J., and Hannah, J.L. (2018) Comparison of chemical procedures for Re-isotopic measurements by N-TIMS:

*Chemical Geology*, v. 483, p. 151-161. (<https://doi.org/10.1016/j.chemgeo.2018.03.006>)

Goswami, V., Hannah, J.L., Stein, H.J. (2018) Why terrestrial coals cannot be dated using the Re-Os geochronometer: Evidence from the Finnmark platform, southern Barents Sea and the Fire Clay coal horizon, central Appalachian basin: *International Journal of Coal Geology*, v. 188, p. 121-135.

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