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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 belong to the Program. 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 analytical results to advance fundamental science and 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 salaries and the Program's operation rely on external grants and contracts; that is, Colorado State University provides no 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, dating of oils and bitumens, and most recently, reconstruction of whole petroleum systems in absolute time. Our scientific publications and contributions are tallied under the Department of Geosciences' website, and constitute 35-40% of that 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. We discovered the unique phenomenon of parent-daughter (^{187}Re - ^{187}Os) decoupling in molybdenite prompting new approaches for acquiring mineral separates. 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 (mill) in Colorado. We work with other sulfide and oxide minerals such as pyrite, marcasite, arsenopyrite, chalcopyrite, pyrrhotite 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 asphaltene and maltene components 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 date for the rise of atmospheric oxygen (*Nature* 2004, 1002 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)

Jenna DiMarzio and Marisa Boraas-Connor (Recent Graduate Students)

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### Refereed Journal Papers:

Scarlett, A.G., Holman, A.I., Summons, R.G., Georgiev, S.V., Stein, H.J., and Grice, K. (in co-author review) Multi spectroscopic, elemental and Re-Os characterization of southern Australian asphaltites: *Geochimica et Cosmochimica Acta*.

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*.

Hall, W.S., Stein, H.J., Kylander-Clark, A.R.C., Knight, C., Enders, M.S., and Hitzman, M.W. (in co-author review) Re-Os sulfide and U-Th-Pb xenotime geochronology of sedimentary rock-hosted Cu-Ag deposits, Kalahari Copperbelt, Botswana: *Economic Geology*.

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*.

Stewart, P.W., Stein, H.J., and Roa, K. (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*.

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. (submitted) The supergiant Mitchell Au-Cu giant porphyry, northwest BC: effect of syn-mineral structures and alteration on deformation and strain localization: *Economic Geology*.

Kouhestani, H., Mokhtari, M.A.A., Chang, Z., Stein H., and Johnson, C. (in review) Timing and genesis of ore formation in the Qarachilar Cu-Mo-Au deposit, Tethyan metallogenic belt, NW

- Iran: Evidence from geology, fluid inclusions, O-S isotopes and Re-Os geochronology: *Ore Geology Reviews*.
- Boomeri, M., Moradi, R., Stein, H.J., and Bagheri, S. (in 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 revision) Controlling factors on Re-Os systematics in petroleum during water-oil interaction: the effects of oil chemistry, water-oil ratio and interaction time: *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: *Ore Geology Reviews*.
- 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>)
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