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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 is 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 salaries and the Program's operation rely on external grants and contracts; CSU and the Geosciences Department provide no financial support. Starting in 2000, the AIRIE Program 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 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, chalcopyrite, pyrrhotite and magnetite to provide age(s) and fluid source information, not only for ore deposits, but for metamorphic processes defining 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 provided the first radiometric age for the rise of atmospheric oxygen, with citations beyond the geoscience literature (*Nature* 2004, 1265 citations; *EPSL* 2004, 223 citations).

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AIRIE PROGRAM, COLORADO STATE UNIVERSITY: RE-OS PUBLICATIONS

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### Refereed Journal Papers:

Pollard, P.J., Jongens, R., Stein, H.J., Fanning, M., and Smillie, R. (2021) Rapid formation of porphyry and skarn copper-gold mineralization in a post-subduction environment: Re-Os and U-Pb geochronology of the Ok Tedi mine, Papua New Guinea: *Economic Geology*, v. XXX, no. X, p. XX-XX. (<https://doi.org/10.5382/econgeo.4799>, [26 p.](#))

Hall, W.S., Stein, H.J., Kylander-Clark, A.R.C., Hitzman, M.W., Kuiper, Y.D., Knight, C., and Enders, M.S. (2021) Diagenetic and epigenetic mineralizing events in the Kalahari Copperbelt, Botswana: evidence from Re-Os sulfide dating and U-Th-Pb xenotime geochronology: *Economic Geology*, v. XXX, no. X, p. XX-XX. (<https://doi.org/10.5382/econgeo.4809>, [19 p.](#))

Georgiev, S.V., Stein, H.J., Hannah, J.L., Pedersen, J.-H., and di Primio, R. (2021) Timing and origin of multiple petroleum charges within the Solveig oil field, Norwegian North Sea: a Re-Os isotopic study: *AAPG Bulletin*, v. 105, no. 1, p. 109-134. (<https://doi.org/10.1306/02272019219>)

Georgiev, S.V., Stein, H.J., Yang, G., Hannah, J.L., Böttcher, M.E., Grice, K., Holman, A.I., Turgeon, S., Simonsen, S., and Cloquet, C. (2021) Late Permian-Early Triassic environmental changes recorded by multi-isotope (Re-Os-N-Hg) data and trace metal distribution from the Hovea-3 section, Western Australia: *Gondwana Research*, v. 88, p. 353-372. (<https://doi.org/10.1016/j.gr.2020.07.007>)

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Hurtig, N.C., Georgiev, S.V., Zimmerman, A., Yang, G., Goswami, V., Hannah, J.L., and Stein, H.J. (2020) Re-Os geochronology for the NIST RM8505 crude oil: The importance of analytical protocol and uncertainty: *Chemical Geology*, v. 539, 119381, 17 p. (<https://doi.org/10.1016/j.chemgeo.2019.119381>)

Georgiev, S.V., Stein, H.J., Hannah, J.L., Yang, G., Markey, R.J., Dons, C.E., Pedersen, J.H., di Primio, R. (2019) Comprehensive evolution of a petroleum system in absolute time: the example of Brynhild, Norwegian North Sea: *Chemical Geology*, v. 522, p. 260-282. (<https://doi.org/10.1016/j.chemgeo.2019.05.025>)

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