

## **The origin of early Archean barite deposits on the Kaapvaal and Pilbara cratons**

Desiree Roerdink, Paul Mason, Mark van Zuijen, Dylan Wilmeth and Liadh Keogh

### **References for Figure 5**

Ledevin, M., Arndt, N., Chauvel, C., Jaillard, E. and Simionovici, A. (2019) The sedimentary origin of black and white banded cherts of the Buck Reef, Barberton, South Africa. *Geosciences*. 9(10), 424.

Van den Boorn, S.H.J.M., Van Bergen, M.J., Vroon, P.Z., De Vries, S.T. and Nijman, W. (2010) Silicon isotope and trace element constraints on the origin of ~ 3.5 Ga cherts: implications for Early Archaean marine environments. *Geochimica et Cosmochimica Acta* 74, 1077-1103.

Hofmann, A., Bolhar, R., Orberger, B. and Foucher, F. (2013) Cherts of the Barberton Greenstone Belt, South Africa: Petrology and trace-element geochemistry of 3.5 to 3.3 Ga old silicified volcaniclastic sediments. *South African Journal of Geology*, 116, 297-322.

### **References for Figure 6**

Van den Boorn, S.H.J.M., Van Bergen, M.J., Vroon, P.Z., De Vries, S.T. and Nijman, W. (2010) Silicon isotope and trace element constraints on the origin of ~ 3.5 Ga cherts: implications for Early Archaean marine environments. *Geochimica et Cosmochimica Acta* 74, 1077-1103.

### **References for Figure 7**

Roerdink, D.L., Ronen, Y., Strauss, H. and Mason, P.R.D. (2022) Emergence of felsic crust and subaerial weathering recorded in Palaeoarchaean barite. *Nature Geoscience* 15, 227-232.

### **References for Figure 8**

Agangi, A., Hofmann, A., Eickmann, B., Marin-Carbonne, J. and Reddy, S.M. (2016) An atmospheric source of S in Mesoarchaean structurally-controlled gold mineralisation of the Barberton Greenstone Belt. *Precambrian Res.* 285, 10-20.

Aoyama, S. and Ueno, Y. (2018) Multiple sulfur isotope constraints on microbial sulfate reduction below an Archean seafloor hydrothermal system. *Geobiology* 16, 107-120.

Bao, H., Rumble III, D. and Lowe, D.R. (2007) The five stable isotope compositions of Fig Tree barites: Implications on sulfur cycle in ca. 3.2 Ga oceans. *Geochim. Cosmochim. Acta* 71, 4868-4879.

Baumgartner, R.J., Caruso, S., Fiorentini, M.L., Van Kranendonk, M.J., Martin, L., Jeon, H., Pagès, A. and Wacey, D. (2020) Sulfidization of 3.48 billion-year-old stromatolites of the Dresser Formation, Pilbara Craton: Constraints from in-situ sulfur isotope analysis of pyrite. *Chem. Geol.* 538, 119488.

Bekker, A., Holland, H., Wang, P.-L., Rumble, D., Stein, H., Hannah, J., Coetzee, L. and Beukes, N. (2004) Dating the rise of atmospheric oxygen. *Nature* 427, 117-120.

Bekker, A., Barley, M.E., Fiorentini, M.L., Rouxel, O.J., Rumble, D. and Beresford, S.W. (2009) Atmospheric Sulfur in Archean Komatiite-Hosted Nickel Deposits. *Science* 326, 1086-1089.

Bottomley, D.J., Veizer, J., Nielsen, H. and Moczydlowska, M. (1992) Isotopic composition of disseminated sulfur in Precambrian sedimentary rocks. *Geochim. Cosmochim. Acta* 56, 3311-3322.

Busigny, V., Marin-Carbonne, J., Muller, E., Cartigny, P., Rollion-Bard, C., Assayag, N. and Philippot, P. (2017) Iron and sulfur isotope constraints on redox conditions associated with the 3.2Ga barite

deposits of the Mapepe Formation (Barberton Greenstone Belt, South Africa). *Geochim. Cosmochim. Acta* 210, 247-266.

Cameron, E.M. (1982) Sulphate and sulphate reduction in early Precambrian oceans. *Nature* 296, 145-148.

Cameron, E.M. and Hattori, K. (1987) Archean sulphur cycle: Evidence from sulphate minerals and isotopically fractionated sulphides in superior province, Canada. *Chemical Geology: Isotope Geoscience section* 65, 341-358.

Chen, M., Campbell, I.H., Ávila, J.N., Tian, W., Hayman, P.C., Cas, R.A.F., Ireland, T.R. (2022) Atmospheric and hydrothermal sulfur isotope signatures recorded in Neoarchean deep marine sedimentary pyrites from the Yilgarn Craton, Western Australia. *Geochim. Cosmochim. Acta* 322, 170-193.

Deb, M., Hoefs, J. and Bauman, A. (1991) Isotopic composition of two Precambrian stratiform barite deposits from the Indian shield. *Geochim. Cosmochim. Acta* 55, 303-308.

Diekrup, D., Hannington, M.D., Strauss, H. and Ginley, S.J. (2018) Decoupling of Neoarchean sulfur sources recorded in Algoma-type banded iron formation. *Earth Planet. Sci. Lett.* 489, 1-7.

Domagal-Goldman, S.D., Kasting, J.F., Johnston, D.T. and Farquhar, J. (2008) Organic haze, glaciations and multiple sulfur isotopes in the Mid-Archean Era. *Earth Planet. Sci. Lett.* 269, 29-40.

Eickmann, B., Hofmann, A., Wille, M., Bui, T.H., Wing, B.A. and Schoenberg, R. (2018) Isotopic evidence for oxygenated Mesoarchaean shallow oceans. *Nat. Geosci.* 11, 133-138.

Farquhar, J., Bao, H. and Thiemens, M. (2000) Atmospheric Influence of Earth's Earliest Sulfur Cycle. *Science* 289, 756-758.

Farquhar, J., Cliff, J., Zerkle, A.L., Kamysny, A., Poulton, S.W., Claire, M., Adams, D. and Harms, B. (2013) Pathways for Neoarchean pyrite formation constrained by mass-independent sulfur isotopes. *Proceedings of the National Academy of Sciences* 110, 17638-17643.

Farquhar, J., Peters, M., Johnston, D.T., Strauss, H., Masterson, A., Wiechert, U. and Kaufman, A.J. (2007) Isotopic evidence for Mesoarchaean anoxia and changing atmospheric sulphur chemistry. *Nature* 449, 706-709.

Galić, A., Mason, P.R., Mogollón, J.M., Wolthers, M., Vroon, P.Z. and Whitehouse, M.J. (2017) Pyrite in a sulfate-poor Paleoarchean basin was derived predominantly from elemental sulfur: Evidence from 3.2 Ga sediments in the Barberton Greenstone Belt, Kaapvaal Craton. *Chem. Geol.* 449, 135-146.

Golding, S.D., Duck, L.J., Young, E., Baublys, K.A., Glikson, M. and Kamber, B.S. (2011) Earliest Seafloor Hydrothermal Systems on Earth: Comparison with Modern Analogues, in: Golding, S.D., Glikson, M. (Eds.), Earliest Life on Earth: Habitats, Environments and Methods of Detection. Springer Netherlands, pp. 15-49.

Guo, Q., Strauss, H., Kaufman, A.J., Schroder, S., Gutzmer, J., Wing, B., Baker, M.A., Bekker, A., Jin, Q., Kim, S.-T. and Farquhar, J. (2009) Reconstructing Earth's surface oxidation across the Archean-Proterozoic transition. *Geology* 37, 399-402.

Guy, B., Ono, S., Gutzmer, J., Kaufman, A., Lin, Y., Fogel, M. and Beukes, N. (2012) A multiple sulfur and organic carbon isotope record from non-conglomeratic sedimentary rocks of the Mesoarchean Witwatersrand Supergroup, South Africa. *Precambrian Res.* 216, 208-231.

Hattori, K. and Cameron, E.M. (1986) Archaean magmatic sulphate. *Nature* 319, 45-47.

Hou, K., Li, Y. and Wan, D. (2007) Constraints on the Archean atmospheric oxygen and sulfur cycle from mass-independent sulfur records from Anshan-Benxi BIFs, Liaoning Province, China. *Science in China Series D: Earth Sciences* 50, 1471-1478.

Jamieson, J., Wing, B., Farquhar, J. and Hannington, M. (2013) Neoarchaean seawater sulphate concentrations from sulphur isotopes in massive sulphide ore. *Nat. Geosci.* 6, 61-64.

Kakegawa, T. and Ohmoto, H. (1999) Sulfur isotope evidence for the origin of 3.4 to 3.1 Ga pyrite at the Princeton gold mine, Barberton Greenstone Belt, South Africa. *Precambrian Res.* 96, 209-224.

Kamber, B.S. and Whitehouse, M.J. (2007) Micro-scale sulphur isotope evidence for sulphur cycling in the late Archean shallow ocean. *Geobiology* 5, 5-17.

Kurzweil, F., Claire, M., Thomazo, C., Peters, M., Hannington, M. and Strauss, H. (2013) Atmospheric sulfur rearrangement 2.7 billion years ago: Evidence for oxygenic photosynthesis. *Earth Planet. Sci. Lett.* 366, 17-26.

Lewis, J.A., Hoffmann, J.E., Schwarzenbach, E.M., Strauss, H., Liesegang, M., Rosing, M.T. (2021) Sulfur isotope evidence for surface-derived sulfur in Eoarchean TTGs. *Earth. Planet. Sci. Lett.* 576, 117218.

Liu, L., Ireland, T. and Holden, P. (2020) In-situ quadruple sulfur isotopic compositions of pyrites in the ca. 3.2–2.72 Ga metasedimentary rocks from the Pilbara Craton, Western Australia. *Chem. Geol.* 557, 119837.

Marin-Carbonne, J., Remusat, L., Sforna, M.C., Thomazo, C., Cartigny, P. and Philippot, P. (2018) Sulfur isotope's signal of nanopyrites enclosed in 2.7 Ga stromatolitic organic remains reveal microbial sulfate reduction. *Geobiology* 16, 121-138.

Marin-Carbonne, J., Busigny, V., Miot, J., Rollion-Bard, C., Muller, E., Drabon, N., Jacob, D., Pont, S., Robyr, M. and Bontognali, T.R. (2020) In Situ Fe and S isotope analyses in pyrite from the 3.2 Ga Mendon Formation (Barberton Greenstone Belt, South Africa): Evidence for early microbial iron reduction. *Geobiology* 18, 306-325.

Mojzsis, S.J., Coath, C.D., Greenwood, J.P., McKeegan, K.D. and Harrison, T.M. (2003) Mass-independent isotope effects in Archean (2.5 to 3.8 Ga) sedimentary sulfides determined by ion microprobe analysis. *Geochim. Cosmochim. Acta* 67, 1635-1658.

Monster, J., Appel, P.W.U., Thode, H.G., Schidlowski, M., Carmichael, C.M. and Bridgwater, D. (1979) Sulfur isotope studies in early Archaean sediments from Isua, West Greenland: Implications for the antiquity of bacterial sulfate reduction. *Geochim. Cosmochim. Acta* 43, 405-413.

Montinaro, A., Strauss, H., Mason, P.R.D., Roerdink, D., Münker, C., Schwarz-Schampera, U., Arndt, N.T., Farquhar, J., Beukes, N.J., Gutzmer, J. and Peters, M. (2015) Paleoarchean sulfur cycling:

Multiple sulfur isotope constraints from the Barberton Greenstone Belt, South Africa. Precambrian Res. 267, 311-322.

Muller, E., Philippot, P., Rollion-Bard, C. and Cartigny, P. (2016) Multiple sulfur-isotope signatures in Archean sulfates and their implications for the chemistry and dynamics of the early atmosphere. Proceedings of the National Academy of Sciences xx.

Muller, É., Philippot, P., Rollion-Bard, C., Cartigny, P., Assayag, N., Marin-Carbonne, J., Mohan, M.R. and Sarma, D.S. (2017) Primary sulfur isotope signatures preserved in high-grade Archean barite deposits of the Sargur Group, Dharwar Craton, India. Precambrian Res. 295, 38-47.

Nabhan, S., Marin-Carbonne, J., Mason, P.R. and Heubeck, C. (2020) In situ S-isotope compositions of sulfate and sulfide from the 3.2 Ga Moodies Group, South Africa: A record of oxidative sulfur cycling. Geobiology.

Ohmoto, H., Watanabe, Y., Ikemi, H., Poulson, S.R. and Taylor, B.E. (2006) Sulphur isotope evidence for an oxic Archaean atmosphere. Nature 442, 908-911.

Ono, S., Beukes, N.J. and Rumble, D. (2009a) Origin of two distinct multiple-sulfur isotope compositions of pyrite in the 2.5 Ga Klein Naute Formation, Griqualand West Basin, South Africa. Precambrian Res. 169, 48-57.

Ono, S., Beukes, N.J., Rumble, D. and Fogel, M.L. (2006) Early evolution of atmospheric oxygen from multiple-sulfur and carbon isotope records of the 2.9 Ga Mozaan Group of the Pongola Supergroup, Southern Africa. S. Afr. J. Geol. 109, 97-108.

Ono, S., Eigenbrode, J.L., Pavlov, A.A., Kharecha, P., Rumble Iii, D., Kasting, J.F. and Freeman, K.H. (2003) New insights into Archean sulfur cycle from mass-independent sulfur isotope records from the Hamersley Basin, Australia. Earth Planet. Sci. Lett. 213, 15-30.

Ono, S., Kaufman, A.J., Farquhar, J., Sumner, D.Y. and Beukes, N.J. (2009b) Lithofacies control on multiple-sulfur isotope records and Neoarchean sulfur cycles. Precambrian Res. 169, 58-67.

Papineau, D. and Mojzsis, S.J. (2006) Mass-independent fractionation of sulfur isotopes in sulfides from the pre-3770 Ma Isua Supracrustal Belt, West Greenland. Geobiology 4, 227-238.

Papineau, D., Mojzsis, S.J. and Schmitt, A.K. (2007) Multiple sulfur isotopes from Paleoproterozoic Huronian interglacial sediments and the rise of atmospheric oxygen. Earth Planet. Sci. Lett. 255, 188-212.

Paris, G., Adkins, J., Sessions, A.L., Webb, S. and Fischer, W. (2014) Neoarchean carbonate-associated sulfate records positive  $\Delta^{33}\text{S}$  anomalies. Science 346, 739-741.

Paris, G., Fischer, W.W., Johnson, J.E., Webb, S.M., Present, T.M., Sessions, A.L. and Adkins, J.F. (2020) Deposition of sulfate aerosols with positive  $\Delta^{33}\text{S}$  in the Neoarchean. Geochim. Cosmochim. Acta.

Partridge, M.A., Golding, S.D., Baublys, K.A. and Young, E. (2008) Pyrite paragenesis and multiple sulfur isotope distribution in late Archean and early Paleoproterozoic Hamersley Basin sediments. Earth Planet. Sci. Lett. 272, 41-49.

Philippot, P., Ávila, J.N., Killingsworth, B.A., Tessalina, S., Baton, F., Caquineau, T., Muller, E., Pecoits, E., Cartigny, P. and Lalonde, S.V. (2018) Globally asynchronous sulphur isotope signals require re-definition of the Great Oxidation Event. *Nature communications* 9, 1-10.

Philippot, P., van Zuilen, M. and Rollion-Bard, C. (2012) Variations in atmospheric sulphur chemistry on early Earth linked to volcanic activity. *Nature Geosci* 5, 668-674.

Ripley, E.M. and Nicol, D.L. (1981) Sulfur isotopic studies of Archean slate and graywacke from northern Minnesota: evidence for the existence of sulfate reducing bacteria. *Geochim. Cosmochim. Acta* 45, 839-846.

Roerdink, D.L., Mason, P.R., Whitehouse, M.J. and Reimer, T. (2013) High-resolution quadruple sulfur isotope analyses of 3.2 Ga pyrite from the Barberton Greenstone Belt in South Africa reveal distinct environmental controls on sulfide isotopic arrays. *Geochim. Cosmochim. Acta* 117, 203-215.

Roerdink, D.L., Mason, P.R.D., Farquhar, J. and Reimer, T. (2012) Multiple sulfur isotopes in Paleoarchean barites identify an important role for microbial sulfate reduction in the early marine environment. *Earth Planet. Sci. Lett.* 331-332, 177-186.

Roerdink, D.L., Mason, P.R.D., Whitehouse, M.J. and Brouwer, F.M. (2016) Reworking of atmospheric sulfur in a Paleoarchean hydrothermal system at Londozi, Barberton Greenstone Belt, Swaziland. *Precambrian Res.* 280, 195-204.

Saitoh, M., Nabhan, S., Thomazo, C., Olivier, N., Moyen, J.-F., Ueno, Y., Marin-Carbonne, J. (2020) Multiple Sulfur Isotope Records of the 3.22 Ga Moodies Group, Barberton Greenstone Belt. *Geosciences* 10, 145.

Shen, Y., Buick, R. and Canfield, D.E. (2001) Isotopic evidence for microbial sulphate reduction in the early Archaean era. *Nature* 410, 77-81.

Shen, Y., Farquhar, J., Masterson, A., Kaufman, A.J. and Buick, R. (2009) Evaluating the role of microbial sulfate reduction in the early Archean using quadruple isotope systematics. *Earth Planet. Sci. Lett.* 279, 383-391.

Siedenberg, K., Strauss, H. and Hoffmann, E.J. (2016) Multiple sulfur isotope signature of early Archean oceanic crust, Isua (SW-Greenland). *Precambrian Res.* 283, 1-12.

Strauss, H. (1986) Carbon and sulfur isotopes in Precambrian sediments from the Canadian Shield. *Geochim. Cosmochim. Acta* 50, 2653-2662.

Thomassot, E., O'Neil, J., Francis, D., Cartigny, P. and Wing, B.A. (2015) Atmospheric record in the Hadean Eon from multiple sulfur isotope measurements in Nuvvuagittuq Greenstone Belt (Nunavik, Quebec). *Proceedings of the National Academy of Sciences* 112, 707-712.

Thomazo, C., Ader, M., Farquhar, J. and Philippot, P. (2009) Methanotrophs regulated atmospheric sulfur isotope anomalies during the Mesoarchean (Tumbiana Formation, Western Australia). *Earth Planet. Sci. Lett.* 279, 65-75.

Thomazo, C., Nisbet, E.G., Grassineau, N.V., Peters, M. and Strauss, H. (2013) Multiple sulfur and carbon isotope composition of sediments from the Belingwe Greenstone Belt (Zimbabwe): A biogenic methane regulation on mass independent fractionation of sulfur during the Neoarchean? *Geochim. Cosmochim. Acta* 121, 120-138.

Ueno, Y., Ono, S., Rumble, D. and Maruyama, S. (2008) Quadruple sulfur isotope analysis of ca. 3.5 Ga Dresser Formation: New evidence for microbial sulfate reduction in the early Archean. *Geochim. Cosmochim. Acta* 72, 5675-5691.

Wacey, D., McLoughlin, N., Whitehouse, M.J. and Kilburn, M.R. (2010) Two coexisting sulfur metabolisms in a ca. 3400 Ma sandstone. *Geology* 38, 1115-1118.

Wacey, D., Noffke, N., Cliff, J., Barley, M.E. and Farquhar, J. (2015) Micro-scale quadruple sulfur isotope analysis of pyrite from the ~3480 Ma Dresser Formation: New insights into sulfur cycling on the early Earth. *Precambrian Res.* 258, 24-35.

Whitehouse, M.J., Kamber, B.S., Fedo, C.M. and Lepland, A. (2005) Integrated Pb- and S-isotope investigation of sulphide minerals from the early Archaean of southwest Greenland. *Chem. Geol.* 222, 112-131.

Williford, K.H., Van Kranendonk, M.J., Ushikubo, T., Kozdon, R. and Valley, J.W. (2011) Constraining atmospheric oxygen and seawater sulfate concentrations during Paleoproterozoic glaciation: In situ sulfur three-isotope microanalysis of pyrite from the Turee Creek Group, Western Australia. *Geochim. Cosmochim. Acta* 75, 5686-5705.

Zerkle, A.L., Claire, M.W., Domagal-Goldman, S.D., Farquhar, J. and Poulton, S.W. (2012) A bistable organic-rich atmosphere on the Neoarchaean Earth. *Nature Geosci* 5, 359-363.

Zhelezinskaia, I., Kaufman, A.J., Farquhar, J. and Cliff, J. (2014) Large sulfur isotope fractionations associated with Neoarchean microbial sulfate reduction. *Science* 346, 742-744.