Hydrothermal fractionation of the rare earth elements and the genesis of the Lofdal REE deposit, Namibia

A.E. Williams-Jones[1, a], R. Wollenberg[1], and S. Bodeving[1]

[1] Department of Earth and Planetary Sciences, McGill University, Montreal, QC, Canada
[a] corresponding author: anthony.williams-jones@mcgill.ca

Recommended citation: Williams-Jones, A.E., Wollenberg, R., and Bodeving, S., 2015. Hydrothermal fractionation of the rare earth elements and the genesis of the Lofdal REE deposit, Namibia. In: Simandl, G.J. and Neetz, M., (Eds.), Symposium on Strategic and Critical Materials Proceedings, November 13-14, 2015, Victoria, British Columbia, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015-3, pp. 125-130.

Extended Abstract

The Lofdal rare earth element (REE) deposit in northern Namibia, which is currently being explored by Namibia Rare Earths Inc., is of particular interest because of its unusually high proportion of heavy REE (more than 85%) and because previous research concluded that it was carbonatite-hosted (Wall et al., 2008). This would make the deposit highly unusual because, almost invariably, carbonatite-hosted deposits contain mainly light-REE (Castor, 2008; Moore et al., 2014; and Trofanenko et al., in press). However, as we show below, the Lofdal REE mineralization is not carbonatite-hosted. Instead, it occurs in narrow veinlets in albitite that has been subjected to later carbonate alteration, and thus the host rocks and their REE mineralization are hydrothermal in origin.

The Lofdal deposit, in the Damara Orogen of northern Namibia, is spatially associated with the Lofdal Intrusive suite, a group of alkaline silicate rocks and carbonatites that were emplaced at ~750 Ma during an episode of continental rifting, which preceded the orogeny (de Kock et al., 2000). The suite intrudes Paleoproterozoic schists, gneisses, and amphibolites of the Welwitschia inlier which, together with the Kamenjab and Braklaagte inliers, forms the southern edge of the Archean Congo Craton (Miller, 2008). Several plutons and numerous NW-SE trending dikes follow the regional foliation (Fig. 1). The largest of the plutons is the Main Intrusion (~2 km in diameter), which is composed of an early nepheline syenite facies and a later but subordinate calcio-carbonatite facies. The contact between the two facies is invariably marked by a zone of fenitised nepheline syenite. The dikes form a swarm ~5 km wide that extends ~10 km along strike. They comprise phono-tephrite, phonolite and carbonatite. However, the carbonatite dikes, are largely restricted to within ~1 km of the Main Intrusion. In addition to the carbonatites, many faults follow the regional foliation and are sites where basement gneisses and schists were albitized. Subsequent intense carbonate alteration (both calcite and dolomite) replaced much of the albitite. Weathering of these rocks, which also contain pyrite, produced brown, grey, and red zones that form ridges up to two metres wide and a metre high (Fig. 2). It is these rocks that have been misinterpreted by previous researchers as ferrocarbonatite dikes, and host the REE mineralization.

The Lofdal REE deposit is one of a number of zones in the area with elevated concentrations of REE, but the only one currently deemed to have economic potential. This zone, which is referred to as Area 4 by Namibia Rare Earths Ltd. (Fig. 3), has measured and indicated reserves of 1.65 million tons of ore grading 0.60 wt.% total rare earth oxide with 85.4% heavy REE (Dodd et al., 2014) and is second only to Browns Range, Australia, in having the highest proportion of heavy REE among 50 deposits worldwide currently at an advanced stage of exploration. The heavy REE mineralization occurs as xenotime-(Y), which is mainly concentrated in discontinuous millimetre-wide veinlets that cut albitite and also contain biotite, calcite and, in some cases, pyrite and zircon (Fig. 4). Some of this mineralization is in biotite-rich shear zones in albitite, some is disseminated in albitite, and some is in fluorapatite veinlets, where it occurs at triple junctions of apatite crystals that have incorporated REE at their rims. As mentioned above, the albitites and their REE mineralization have been subjected to carbonate alteration. The intensity of this alteration increases upwards and, at the erosional surface, has largely obliterated the textures of the precursor rocks, creating an impression that the xenotime-(Y) occurs mainly as disseminations in calcite or dolomite. In addition to the heavy REE mineralization, there is also light REE mineralization in the form of monazite-(Ce). This mineralization is concentrated mainly in biotite-calcite±pyrite veinlets that cut amphibolites and mafic dikes immediately outside the confines of the albitized Area 4 fault, although some is seen along the fault beyond the limits of the potentially economic mineralization. The latter also occurs in biotite-calcite±pyrite veinlets, but instead of the veinlets being hosted by albitite, they occur in thin carbonatite dikelets or mafic rocks in the fault zone.

The occurrence of the REE mineralization in biotite-calcite veinlets (with or without pyrite) provides clear evidence for a hydrothermal origin. The source of the mineralizing fluids, however, is much less clear. Given the close global spatial association of REE-mineralized rocks to continental rift-related alkaline silicate and carbonatite intrusions, and the observation that such rocks are commonly enriched in REE (e.g., Sørensen,

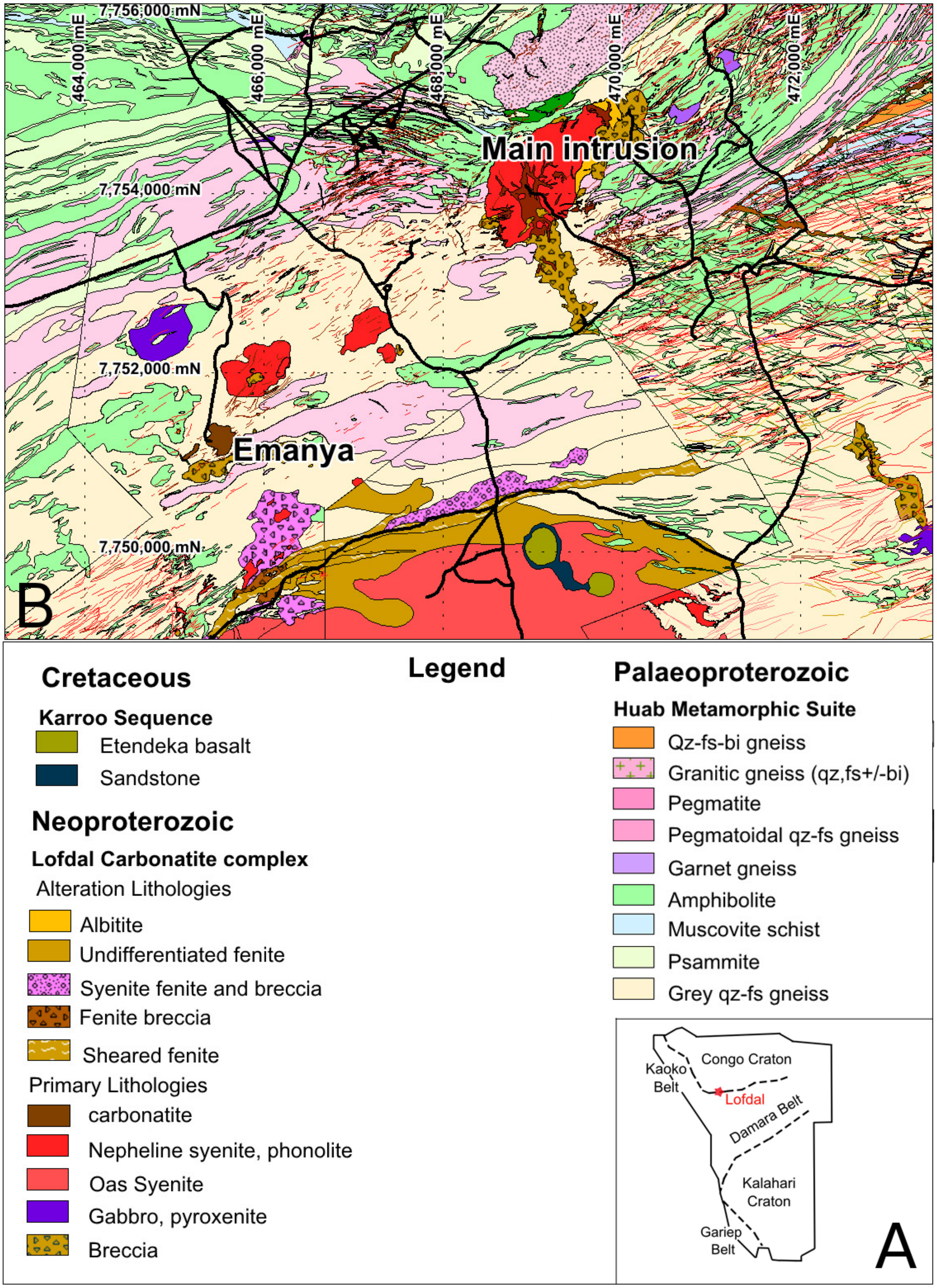

Fig. 1. a) Location of the Lofdal intrusive suite in an outlier of the Congo Craton. **b)** Geological map of the Lofdal field area showing the distribution of alkaline rocks and carbonatites, which intrude upper amphibolite to granulite facies gneisses of the Huab metamorphic complex. The map was prepared by Namibia Rare Earths Inc.

Fig. 2. a) A REE-mineralized fault breccia previously interpreted to be a ferrocarbonatite dike is instead a fault-controlled sodic fenite (albitite) that has been altered to calcite. The red colour reflects the oxidation of pyrite.

Fig. 2. b) A thin, carbonate altered fault breccia surrounded by albitite.

1992; Sheard et al., 2012), it seems likely that magmas generated during Neoproterozoic rifting sourced the Lofdal REE fluids. On the basis of trace element and isotopic data, we consider that these rocks are of mantle origin. Significantly, the data show that they are also cogenetic. Indeed, their geochemistry is best explained by a model in which small degrees of partial melting of a carbonate-metasomatised mantle produced a phono-tephrite parent magma that evolved by fractional crystallization to phonolite and their plutonic equivalent, nepheline syenite, and ultimately calcio-carbonatite. This genesis is particularly evident from chondrite-normalized REE profiles that have the same shape for the three rock types, and a weak trend of increasing La/Lu ratios from phono-tephrite through phonolite to calcio-carbonatite (La, with a much larger charge/radius ratio than Lu, is the more incompatible element and thus is predicted to be most enriched in the most fractionated magma, i.e., the calcio-carbonatite magma); the calcio-carbonatites are the most enriched in the REE of the three rock-types. However, all three rock types are preferentially enriched in the light REE and thus any fluid exsolved from them would be expected to be light REE-enriched. By contrast, the Lofdal REE deposit, as noted above, is extremely rich in the heavy REE. The alternative would be to call upon a magma that is not represented by the igneous rock-types observed at surface, but this just transfers the problem. Furthermore, to our knowledge, no igneous rocks on the planet contain heavy REE in proportions even approaching those at Lofdal. It therefore seems more reasonable to attribute the source of the REE to a magma corresponding to one of the three igneous rock-types referred to above. As the calcio-carbonatites contain the highest proportions of the REE and their chondrite-normalized REE profiles have the same shapes as the other two rock-types, we consider that the calcio-carbonatite magma is the most plausible source for the REE-bearing fluids. Normally, such a choice would be unreasonable, as most carbonatites display strong depletions in the heavy REE. In marked contrast, the Lofdal calcio-carbonatites have chondrite-normalized REE profiles that are effectively flat from gadolinium to lutetium, and therefore the corresponding magmas could have contributed significant heavy REE to an orthomagmatic mineralizing fluid (Fig. 5). Assuming that a calcio-carbonatite magma was the source of the mineralizing fluid, it therefore follows that the reason for the hyper-enrichment of the potential ores must lie in the hydrothermal process that gave rise to the deposit.

Recent experimental data and thermodynamic modelling have shown convincingly that, in most geological settings, the

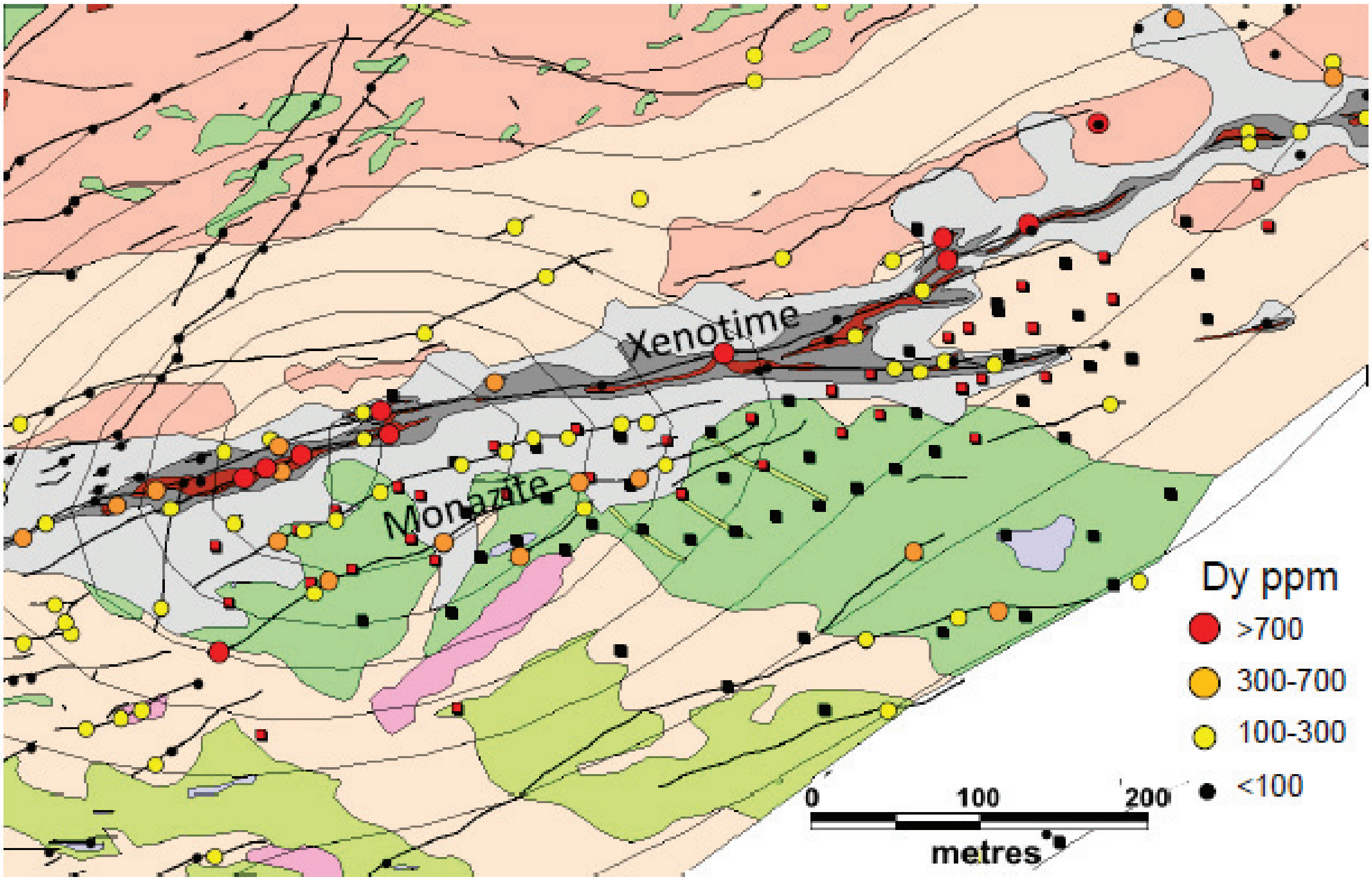

Fig. 3. Distribution of dysprosium in surface samples of the potential ore zone on the Lofdal property. The dark grey denotes a zone of intensely fenitised Huab gneisses adjacent to a fault; the surrounding light grey area is a zone of weaker fenitization. The other lithological units are: amphibolite (green); calc-silicate gneiss (apple green); granitic gneiss (light pink); quartzofeldspathic gneiss (tan) and pegmatite (pink).

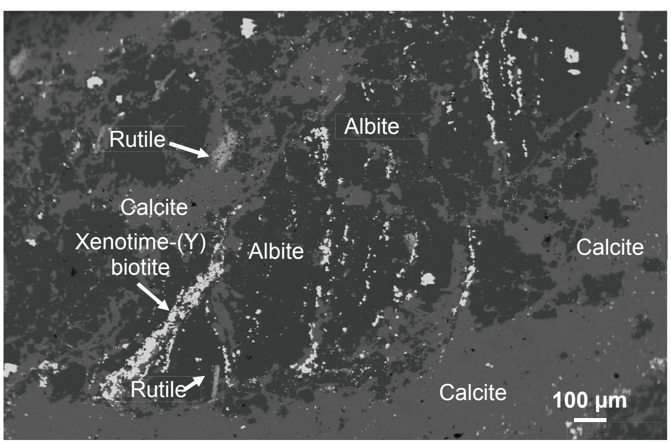

Fig. 4. Albitite cut by xenotime-(Y)-biotite veins and, in turn, replaced by calcite.

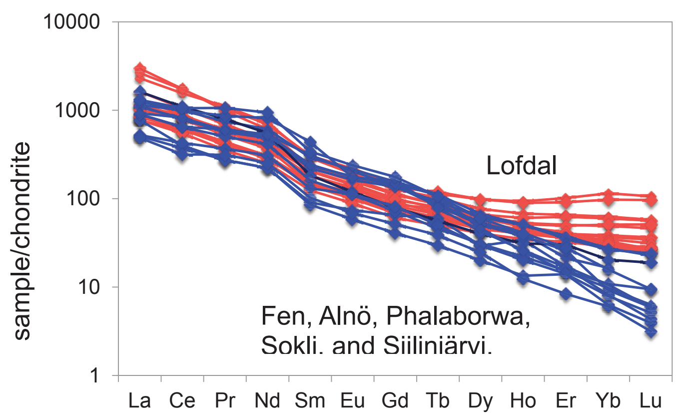

Fig. 5. Chondrite-normalised REE profiles for Lofdal calcio-carbonatites compared with those of other carbonatites.

REE are transported mainly as chloride complexes (Migdisov et al., 2009; Williams-Jones et al., 2012; and Migdisov and Williams-Jones 2014). Furthermore, the experimental data show that chloride complexes of the light REE are considerably more stable than those of the heavy REE, and that this difference in stability increases with increasing temperature. Thus, hydrothermal fluids in which the REE are transported as chloride complexes have the capacity to strongly fractionate the REE by preferentially mobilizing the light REE to locations that are considerably more distal from their source than those in which the heavy REE are concentrated. The main factors controlling the deposition of REE minerals are decreasing temperature, increasing pH, and the activities of the transporting and depositional ligands (Williams-Jones et al., 2012; and Migdisov and Williams-Jones 2014).

A model for the genesis of the Lofdal REE deposit must explain both the albitization and the occurrence of the REE in biotite-calcite veinlets, mainly as xenotime-(Y) but in places as monazite-(Ce). An important feature of carbonatite magmas is that they exsolve carbo-hydrothermal fluids, which are responsible for fenititisation of the host rocks. Indeed, the Lofdal carbonatites that intruded the nepheline syenites in the Main Intrusion are surrounded by haloes of fenitised nepheline syenite. Depending on the temperature, fenites may be sodic or potassic and, in the case of felsic host rocks, the fenitisation may involve albitization or K-feldspathization (Kresten, 1988; Williams-Jones and Palmer, 2002; Le Bas, 2008). Commonly but not universally, the sodic fenitisation is early and occurs at higher temperature than the potassic fenitisation; the same is true of sodic and potassic alteration in porphyry systems (Le Bas, 2008; Sillitoe, 2010).

In view of the above, we propose that albitization at Lofdal, which was focussed along faults, was produced by early high-temperature carbo-hydrothermal fluids exsolved from a carbonatite magma emplaced below these structures, and that the biotite-calcite veins and biotite-filled shear zones, which host the REE mineralization and cut the albitites, formed from the same fluids as temperature decreased. Late carbonate alteration was the product of relatively cold orthomagmatic carbo-hydrothermal fluids. According to this model, REE mineral deposition was due in large part to the decrease in temperature. This, however, does not explain the REE fractionation, namely why the core of the deposit is so rich in heavy REE and the distal parts in light REE. For this, we turn to pH. As was noted earlier, REE-mineral deposition is favoured by increasing pH, and as was also noted, the heavy REE mineralization (xenotime-(Y)) is hosted exclusively by albitite, whereas the light REE mineralization (monazite-(Ce)) is hosted by carbonatite dikes, amphibolites and mafic dikes, which have much higher capacity to buffer pH than albitite. We therefore propose that in the albitites, where the capacity to buffer pH was very low, the fluids transported the light REE above the present erosional surface, precipitating only the less mobile heavy REE, whereas in rocks with much higher pH buffer capacity, both light and heavy REE were deposited in the proportions in which they were present in the fluid, thereby ensuring light-REE dominated mineralization (Fig. 6).

In summary, contrary to previously reported research, the heavy REE mineralization at Lofdal, Namibia, is not hosted by carbonatites but by albitites developed along faults. However, the source of fluids responsible for albitization and REE mineralization was a carbonatite magma. We propose a model in which early carbo-hydrothermal fluids albitized quartzofeldspathic gneisses and, on cooling, deposited xenotime-(Y)-bearing biotite-calcite±pyrite veins. The poor pH buffering capacity of the albitite ensured that that only the heavy REE deposited. Outside the the main faults or along strike from the main REE mineralization, where the fluids encountered carbonatites, amphibolites and mafic dikes, the higher pH buffering capacity of these rocks caused the fluids to deposit both light and heavy REE (monazite-(Ce)) in the proportions that they were originally present. This model likely explains the genesis of other heavy REE deposits where hydrothermal processes were predominant.

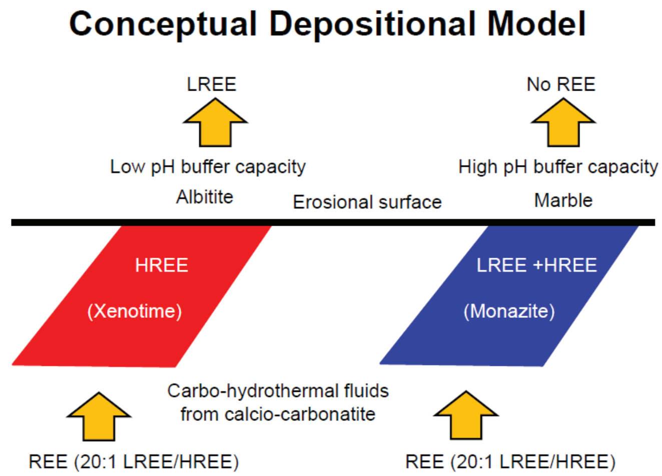

Fig. 6. Conceptual model for the formation of the Lofdal HREE deposit from carbonatite-derived carbo-hydrothermal fluids.

References cited

Castor, S.B., 2008a. Rare earth deposits of North America. Resource Geology, 58, 337-347.

Castor, S.B., 2008b. The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California. The Canadian Mineralogist 46, 779-806.

de Kock, G.S., Eglington, B., Armstrong, R.A., Harmer, R.E., Walraven, F., 2000. U-Pb and Pb-Pb ages of the Naauwpoort rhyolite, Kawakeup leptite and Okongava Diorite: implications for the onset of rifting and of orogenesis in the Damara belt, Namibia. Communications of the Geological Survey of Namibia, 12, 89-97.

Dodd, D.S., Siegfried, P.R., Hall, M.R., Hannon, P., Roy, W.D., 2014. Preliminary economic assessment of the Lofdal Rare Earths Project Namibia. http://www.namibiarareearths.com/upload/5.November_14_2014_NREI_Files_43-101_PEA_Report_for_Heavy_Rare_Earth_Mine_at_Lofdal.pdf> accessed October 1, 2015.

Kresten, P., 1988. The chemistry of fenitization: Examples from Fen, Norway. Chemical Geology, 68, 329-349.

Le Bas, M.J., 2008. Fenites associated with carbonatites. The Canadian Mineralogist, 46, 915-932.

Migdisov, A.A., and Williams-Jones, A.E., 2014. Hydrothermal transport and deposition of the rare earth elements by fluorine-bearing aqueous liquids. Mineralium Deposita 49, 987-997.

Migdisov, A.A., Williams-Jones, A.E., Wagner, T., 2009. An experimental study of the solubility and speciation of the rare earth elements (III) in fluoride- and chloride-bearing aqueous solutions at temperatures up to 300ºC. Geochimica et Cosmochimica Acta 73, 7087-7109.

Miller, R.McG., 2008. The Geology of Namibia. Ministry of Mines and Energy, Geological Survey, Windhoek, Volumes 1-3.

Moore, M., Chakhmouradian, A.R., Mariano, A.N., and Sidhu, R., 2014. Evolution of rare earth mineralization in the Bear Lodge carbonatite, Wyoming: Mineralogical and isotopic evidence. Ore Geology Reviews, 64, 499-521.

Sheard, E. R., Williams-Jones, A. E., Heiligmann, M., Penderson, C., and Trueman, D. L., 2012. Controls on the concentration of zirconium, niobium, and the rare earth elements in the Thor Lake

rare metal deposit, Northwest Territories, Canada. Economic Geology, 107, 81–104.
Sillitoe, R.H., 2010. Porphyry copper systems. Economic Geology, 105, 3-41.
Sørensen, H., 1992. Agpaiitic nepheline syenites: A potential source of rare elements. Applied Geochemistry, 7, 417-427.
Trofanenko, J., Williams-Jones, A.E., Simandl, G.J. Migdisov, A.A., in press. The nature and origin of the REE mineralization in the Wicheeda carbonatite, British Columbia, Canada. Economic Geology.
Wall, F., Niku-Paavola, V.N., Storey, C., Müller, A., and Jeffries, T., 2008. Xenotime-(y) from carbonatite dykes at Lofdal, Namibia: Unusually low LREE:HREE ratio in carbonatite, and the first dating of xenotime overgrowths on zircon. The Canadian Mineralogist, 46, 861-877.
Williams-Jones, A.E., and Palmer, D., 2002.The evolution of aqueous–carbonic fluids in the Amba Dongar carbonatite, India: implications for fenitisation. Chemical Geology, 185, 283-301.
Williams-Jones, A.E., Migdisov, A.A., and Samson, I.M., 2012. Hydrothermal mobilization of the rare earth elements – a tale of “Ceria” and “Yttria”. Elements, 8, 355-360.