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Albitization and quartz dissolution in Paleoproterozoic metagranite, central Sweden — Implications for the disposal of spent nuclear fuel in a deep geological repository

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ABSTRACT

Hydrothermal alteration resulting in albitization and quartz dissolution has been identified in Paleoproterozoic metagranites down to −1000 m elevation at Forsmark, Sweden. The alteration features were discovered during investigations to locate a site for the disposal of spent nuclear fuel in a deep geological repository. In general, albitization occurs extensively, but it is also observed locally adjacent to minor intrusive bodies of amphibolite. The altered rocks show a marked decrease in K-feldspar and an increase in quartz relative to the unaltered equivalents, resulting in an epitonalitic composition. Plagioclase is metamorphic in character and generally richer in albite than in the unaltered rocks. It is inferred that albitization was triggered by the input of basic or intermediate melts into the crust during igneous activity close to the peak of regional metamorphism at 1.87–1.86 Ga. The mineralogy of the epitonalites gives rise to an increased thermal conductivity and, thereby, a positive influence for the design and safety of a deep geological repository for spent nuclear fuel. However, the increased frequency of low conductive amphibolite in the albitized volumes, consistent with the proposed mechanism for alteration, gives a negative influence. In sharp contrast to the albitization, a majority of the occurrences of quartz dissolution, which resulted in the formation of episyenite, are located along fracture zones. Quartz dissolution took place between or after 1.8–1.7 Ga, when the bedrock was able to respond to deformation in a brittle manner. Most of the vugs left after the removal of quartz are, to a variable extent, refilled by hydrothermal assemblages, including quartz, albite, K-feldspar, hematite, chlorite and calcite. The geometry and spatial distribution of episyenite argue against an extreme fluid/rock ratio and it is inferred that the fluids had at least a moderate salinity with a temperature in excess of 300 °C. The dissolution process was promoted by the generation of secondary permeability localized in columnar or pipe-like volumes. The close spatial connection to fracture zones provides a basis to avoid bedrock affected by this type of alteration and, thereby, reduce the negative mechanical and hydrogeological aspects for a deep geological repository.

1. Introduction

During the last few decades, granitic rocks have been the major focus in the search for a suitable repository for the disposal of spent nuclear fuel in crystalline bedrock. The occurrence of hydrothermal alteration is widespread in granitic rocks and involves mineralogical and geochemical changes that may significantly influence the physical properties of a rock mass. Consequently, the presence and nature of alteration need to be addressed during a study to locate a deep geological repository.

A detailed characterization of the various types of alteration in Paleoproterozoic, metamorphosed granitic rocks down to −1000 m elevation has formed part of the investigations conducted by the Swedish Nuclear Fuel and Waste Management Company (SKB) at Forsmark, Sweden, in connection with their effort to locate a site for a deep geological repository. The bedrock in the potential repository volume at Forsmark has undergone regional amphibolite-facies metamorphism and is generally fresh. However, three different types of hydrothermal alteration with subordinate volumetric significance have affected this bedrock, in addition to the regional metamorphism. These alterations, in relative order of volumetric importance, have been referred to as oxidation, albitization and quartz dissolution. None of these alterations shows any obvious relationship to metallic mineralization in the Forsmark area. The term “albitization” encompasses the secondary processes, both

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hydrothermal alteration and subsequent metamorphism, that resulted in changes in the An content of igneous oligoclase and, in part, the formation of albite.

The most abundant type of alteration at Forsmark is oxidation. It commonly occurs as a wall–rock alteration along fractures and is characterized by the development of a reddish color due to hematite dissemination within mineral grains, along grain boundaries and in microfractures, rather than by a significant oxidation (Sandström et al., 2010). Associated mineralogical changes include mainly saussuritization of plagioclase, chloritization of biotite and conversion of magnetite into martite. Since it is intimately associated with fracture zones, i.e. brittle deformation zones, which are identified and handled separately in the site evaluation (Stephens et al., 2007), and since this type of alteration inflicts only minor changes in the bedrock physical properties, it has not been judged to be of any major significance for a geological repository, and will not be considered further in this paper. The focus in this paper is on the alterations involving alkali redistribution, referred to as albitization, and quartz dissolution.

Rocks affected by alkali metasomatism, giving rise to the production of epitonalite, are recognized in the field by a whitening of the feldspar in the rock. Quartz dissolution, on the other hand, has resulted in the development of a vuggy, quartz-deficient rock referred to as episyenite in the literature (e.g. Cathelineau, 1986). The quartz dissolution process was also accompanied by pervasive albitization, but there is apparently no spatial, temporal or inferred genetic relationship between the two alteration types at Forsmark.

This paper presents firstly a mineralogical, textural and microstructural description of the unaltered and altered rock equivalents as well as their whole-rock geochemical and petrophysical characteristics. This is followed by a discussion that focuses on how and when these alterations developed, and their possible implications for the construction of a geological repository for spent nuclear fuel at the Forsmark site. Modal, whole-rock geochemical and petrophysical analyses are presented in Supplementary data tables to the paper.

2. Geological setting and tectonothermal evolution

Forsmark is situated inside one of planet Earth's ancient continental nuclei, the Fennoscandian Shield (Fig. 1a), within a steeply dipping, ductile deformation belt along part of the coastal area in central Sweden. This broad belt strikes WNW–ESE and is several tens of kilometers wide (Fig. 1b).

A calc-alkaline suite of predominantly medium-grained, intrusive rocks dominates the bedrock in the Forsmark area (Figs. 2 and 3). The rocks in this suite range in composition from granite, granodiorite and tonalite to diorite, quartz diorite and gabbro; ultrabasic rock (pyroxenite) is also present (Stephens et al., 2005, 2008). These rocks crystallized at 1.89–1.87 Ga (Hermansson et al., 2008a) and intruded into supracrustal rocks dominated by acid volcanic rock with magnetite mineralization (Figs. 2 and 3). All these rocks were affected by penetrative, yet variably intense ductile strain with the development of a grain-shape fabric under amphibolite-facies metamorphic conditions at 1.87–1.86 Ga (Hermansson et al., 2007, 2008a). The fabric development was followed by folding on different scales. Field evidence for a dextral strike–slip component of movement prior to the folding has locally been observed (Stephens et al., 2008).

Basic or intermediate dykes and minor lensoid bodies, all in the form of amphibolite, as well as dykes and more irregular, minor intrusive bodies of fine- to medium-grained and variably metamorphosed granite, granodiorite and tonalite intruded between 1.87 and 1.85 Ga, during the waning stages of the major tectonothermal event (Hermansson et al., 2007, 2008a; Stephens et al., 2008). Different generations of pegmatite and pegmatitic granite in the form of concordant sheets, variably discordant dykes and more irregular

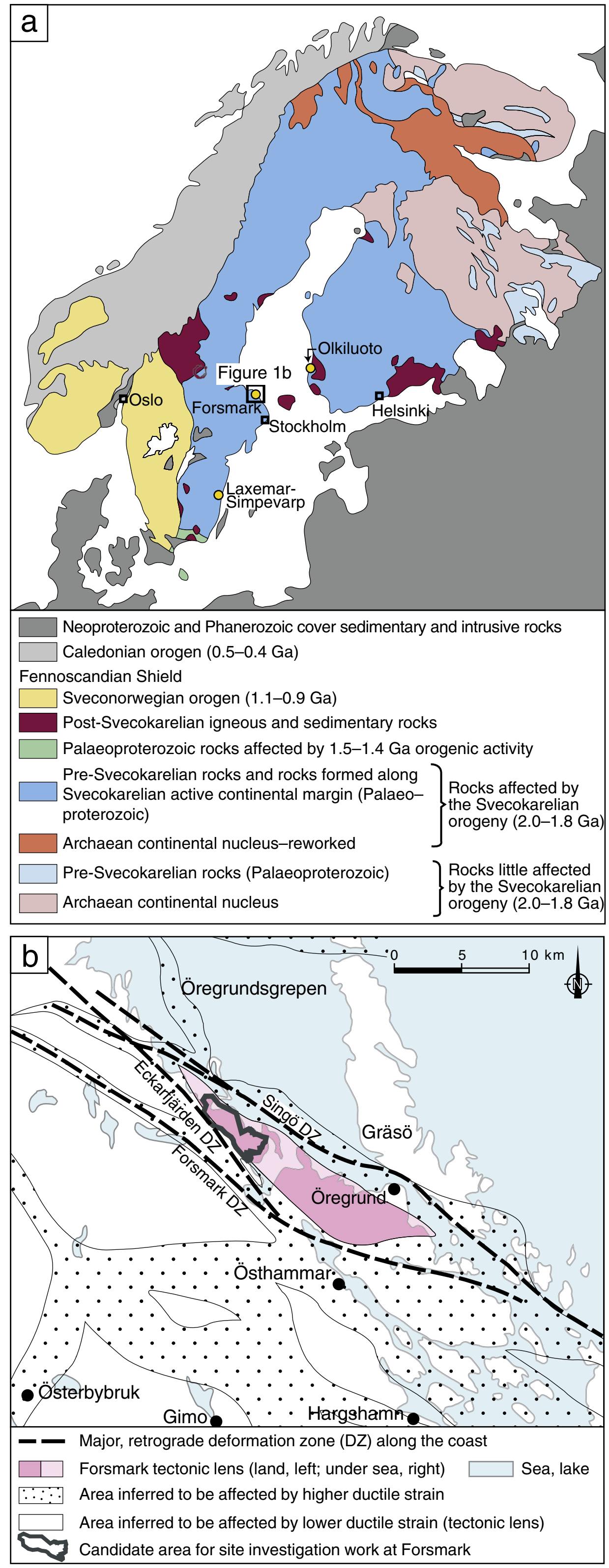

Fig. 1. (a) Major tectonic units in the northern part of Europe. b) Forsmark tectonic lens and outline of areas affected by strong ductile deformation in the area close to Forsmark. Map in (a) is modified after Koistinen et al. (2001). Map in (b) is modified after Stephens et al. (2007).

minor intrusive bodies are also commonly present (Stephens et al., 2008). All these rocks are subordinate in character and only a few larger occurrences are shown in Figs. 2 and 3.