Tectonophysics 653 (2015) 68–94

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Review of the deterministic modelling of deformation zones and fracture domains at the site proposed for a spent nuclear fuel repository, Sweden, and consequences of structural anisotropy

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ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form 13 January 2015
Accepted 27 March 2015
Available online 20 April 2015

Keywords:
3-D model
Structural anisotropy
Stress state
Hydraulic transmissivity
Spent nuclear fuel

ABSTRACT

This paper presents a review of the data sets and methodologies used to construct deterministic models for the spatial distribution of deformation zones and intervening fracture domains in 3-D space at Forsmark, Fennoscandian Shield, Sweden. These models formed part of the investigations to characterize this site, recently proposed as a repository for the storage of spent nuclear fuel in Sweden. The pronounced spatial variability in the distribution of bedrock structures, formed under ductile (lower amphibolite- or greenschist-facies) and subsequently brittle conditions, was controlled by two factors; firstly, the multiphase reactivation, around and after 1.8 Ga, of older ductile structures with a strong anisotropy formed under higher-temperature conditions at 1.87–1.86 Ga; and, secondly, by the release of rock stresses in connection with loading and unloading cycles, after 1.6 Ga. The spatial variability in bedrock structures is accompanied by a significant heterogeneity in the hydraulic flow properties, the most transmissive fractures being sub-horizontal or gently dipping. Although the bedrock structures at Forsmark are ancient features, the present-day aperture of fractures and their hydraulic tranmissivity are inferred to be influenced by the current stress state. It is apparent that the aperture of fractures can change throughout geological time as the stress field evolves. For this reason, the assessment of the long-term (up to 100,000 years) safety of a site for the storage of spent nuclear fuel in crystalline bedrock requires an evaluation of all fractures at the site, not only the currently open fractures that are connected and conductive to groundwater flow. This study also highlights the need for an integration of structural data from the ground surface and boreholes with magnetic field and seismic reflection data with high spatial resolution, during the characterization of structures at a possible site for the storage of spent nuclear fuel in crystalline bedrock.

1. Introduction

Since the 1980´s, the storage of spent nuclear fuel in Sweden has been envisaged as a deep geological repository in crystalline bedrock. The method for storage proposed by the Swedish Nuclear Fuel and Waste Management Company (SKB), referred to as KBS-3 (SKB 2011), is based on several protective barriers. It is planned that the spent nuclear fuel is encapsulated in copper canisters with cast iron inserts containing the spent nuclear fuel rods and placed in deposition holes in crystalline bedrock at a depth of approximately 400–700 m. The depositional tunnels will subsequently be back-filled with bentonite and sealed with concrete plugs. Rock caverns, transport and main tunnels will also be back-filled and a top sealing put in place after the disposal is completed.

Regional surveys in the Swedish part of the Fennoscandian Shield (Fig. 1A), including feasibility studies in eight municipalities (Fig. 1B), have been carried out to locate suitable storage localities for more detailed site investigations. These studies followed and accompanied methodological work at various type locations, including experiments at two underground laboratories (Fig. 1B). Geological considerations, in combination with infrastructural and public acceptance aspects, provided the basis for the choice of two areas for more detailed site investigation (SKB, 2000), Forsmark and Laxemar-Simpevarp in southeastern Sweden (Fig. 1A), in order to provide necessary information for the design as well as for the safety and environmental impact assessment of a possible repository.

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http://dx.doi.org/10.1016/j.tecto.2015.03.027
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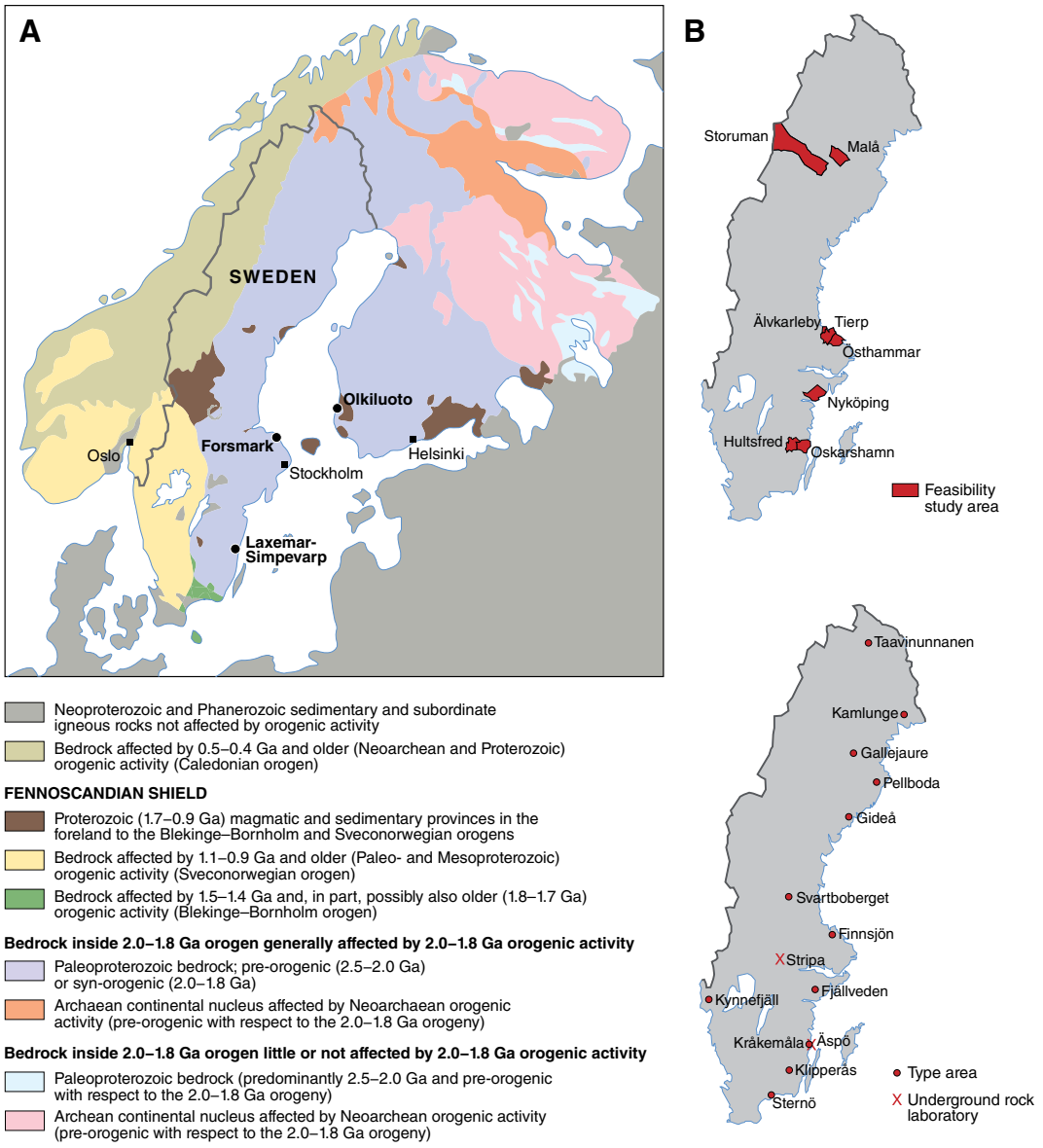

Fig. 1. (A) Location of Forsmark and Laxemar-Simpevarp in the context of the major tectonic units in the northern part of Europe (modified after Koistinen et al., 2001). Olkiluoto in south-western Finland, where detailed studies of a potential repository site for spent nuclear fuel are currently in progress, is also shown. (B) Location of type areas and underground rock laboratories, where methodology work has been completed, and the eight municipalities where feasibility studies have been carried out in Sweden.

Requirements and preferences for the bedrock conditions applicable to a KBS-3 repository at a depth of approximately 400−700 m were identified by SKB prior to the start of the detailed site investigations (Andersson et al. 2000). The stipulated requirements relate to economic ore potential and the need to avoid future human activities at the site; positioning of the repository and canisters in relation to interpreted deformation zones and the capability of the protective barriers to sustain, for example, damage caused by large earthquakes; rock strength and rock stresses and their relationship to the constructability of the site; groundwater flow and its implications for the erosion of the bentonite buffer due to unacceptably high groundwater flow rates along water-conducting fractures during different climate conditions; salt content and the absence of dissolved oxygen in the groundwater so as to avoid corrosion of the copper canisters. More than 30 years of studies (see review in Milnes et al., 2008) followed by a safety assessment culminated with the submission of an application to the governmental regulatory authorities by SKB to build a repository at approximately 470 m depth (−470 m elevation) at Forsmark (Fig. 1A; SKB, 2011).

The process of detailed site investigation generated, amongst other information, a wealth of geological and geophysical data in 3-D space. These data provided a basis for geological modelling work that was both deterministic in character, where outcomes are determined through known relationships among attributes and events without any room for random variation, and stochastic, where outcomes were based on statistical distributions inferred among attributes and events of random nature, so-called discrete fracture network modelling (SKB, 2008, 2009). This paper provides a review of the data used in the deterministic modelling of geological structures at Forsmark, the results of the analysis of these data as a forerunner to the modelling work, the methodology adopted to construct the models and the resulting models. Most of this information has not previously been published in peer-reviewed journals, but are available for public scrutiny in open-file reports on SKB's website (http:/www.skb.se/publications).

On account of the quantity of data available and the extent of the analytical and modelling work completed, reference to relevant open-file reports is deemed necessary and is carried out throughout this paper.