Brittle reactivation of ductile precursor structures: the role of incomplete structural transposition at a nuclear waste disposal site, Olkiluoto, Finland

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Abstract

Reactivation of discrete deformation zones that are orientated favourably with respect to the stress field is a well-known phenomenon. What is less clear is the role of other structural features and heterogeneities in localizing deformation. In this paper we describe how brittle deformation structures are localized into zones of incomplete structural transposition inherited from earlier ductile deformation phases. In our example, these zones of incomplete structural transposition are characterised by localised high-strain structures of the latest ductile deformation stage, including short limbs of strongly asymmetric folds and anastomosing networks of minor shear fabrics. When such zones are systematically organized, and orientated favourable with respect to the stress field, they can be very efficient in localizing deformation and forming new fault zones. Applied to the site of the planned geological repository of nuclear waste in Olkiluoto, Finland, the recognized structural inheritance provides tools to understand the geometries, networks and kinematics of the brittle fault zones and the related secondary fracturing which together define the rock mechanical and hydrogeological framework for the repository.

Keywords: Structural inheritance; Fault linkage; Transposition; Nuclear waste disposal; Palaeoproterozoic; Fennoscandian Shield

1. Introduction

This paper addresses the relationship between earlier ductile and later brittle deformation structures within the crystalline Palaeoproterozoic bedrock at the site of the planned geological repository for nuclear waste, Olkiluoto Island, Finland. There are three main trends of brittle faulting, but the role of structural inheritance varies between these main trends. The most significant, km-scale brittle deformation zones of the investigation site are E-W or NE-SW striking, gently to moderately-dipping structures parallel to an earlier migmatitic foliation. The origin of these zones is attributed to reactivation of ductile deformation zones generated during earlier major deformation events (Fig. 1; Engström, 2013; Aaltonen et al., 2016); these structures are only briefly described in this paper. By contrast, there is a group of sub-vertical, N-S striking faults forming a secondary set of brittle deformation zones. These faults, the main focus of this paper, have not been assigned to repository-scale ductile precursor zones controlling their localization even though precursor structures have been observed locally (Pere, 2009; Aaltonen et al., 2016). While the sub-vertical zones have, due to their orientation unfavourable for reactivation and limited extent, a lower significance to the nuclear waste disposal than the gently-dipping zones, they are vital for the long-term safety of the disposal facility as their stability and hydraulic properties y be influenced by possible future changes in the stress state of the bedrock (Mattila and Tammisto, 2012). For this reason, we consider it highly important to improve the prediction capacity of the models over the N-S faults, which may be achieved through development of alternative conceptual models over the structural inheritance within Olkiluoto.

This paper investigates the potential structural inheritance on the localization of the N-S striking, steep brittle structures. We use orientation analysis of ductile structural data, along with a compilation of form line interpretations, to suggest correlations between ductile features and brittle deformation zones. To enhance the objectivity of the interpretation and to challenge the existing structural models (Aaltonen et al., 2016), no distinction is made between the foliations of different generations since structural events overprinting the main foliation-forming stage (D2) rarely generated new foliations but rather transposed the regionally dominant, pervasive S2 fabric (e.g. Aaltonen et al., 2016). Instead, the focus is placed upon recognition of structural patterns and their correlation with both outcrop and regional-scale structural signatures. We will show that, while continuous and regionally significant weakness zones are reactivated in a favourable stress regime and stress field orientation, discontinuous but systematically organized ductile fabrics such as zones of incomplete structural transposition can be equally important in localizing subsequent significant brittle deformation events. In Olkiluoto, this concept provides the so far missing link between the structural pattern formed by the ductile evolution and one main set of brittle deformation zones. At a general level, the results contribute to understanding the coupling between brittle and ductile deformation structures (Ramsay and Huber, 1987; Sylvester, 1988; Twiss and Moores, 1992; Fusseis et al., 2006), which is important for diverse geological applications including mineral exploration, engineering geology and groundwater investigations. The results further highlight the need for development of alternative conceptual models, particularly in cases with sparse and discontinuous datasets.

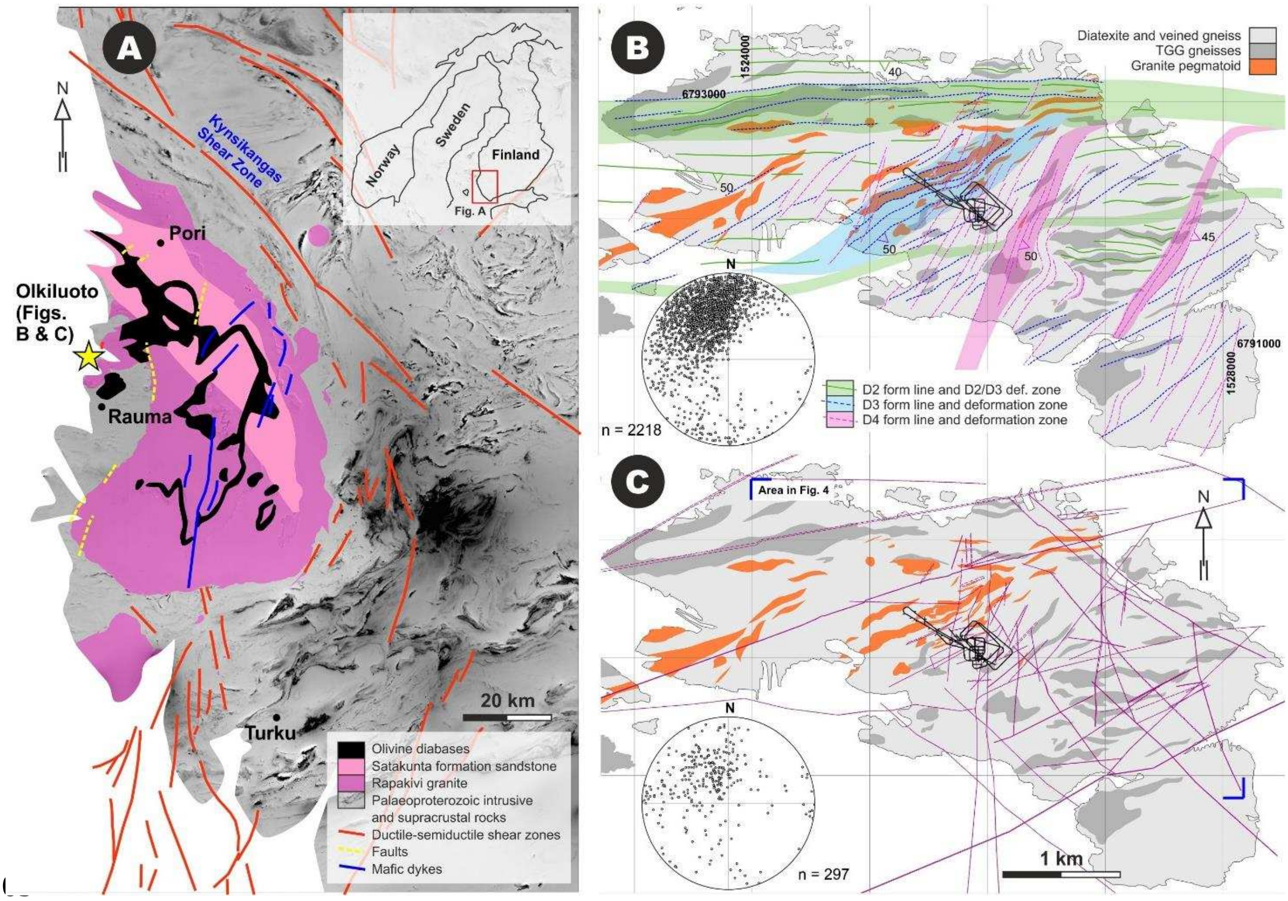

Fig. 1. A: Geological setting of Olkiluoto after Korsman et al. (1997). Aeromagnetic map by Geological Survey of Finland. B: The ductile structural framework of Olkiluoto. The equal-area, lower hemisphere projections show the orientation distribution of all the ductile foliations measured from the ground surface. C: Surface intersections of the modelled Brittle Fault Zones (BFZ). The equal-area, lower hemisphere projections show the orientation all the modelled BFZ surfaces. B and C: Data from Aaltonen et al. (2016). The black line is the

surface projection of the underground investigation facility ONKALO comprising an inclined tunnel and technical facilities at the -420m disposal level.

2. Methods and data

The work has been conducted as part of consulting work for the Radiation and Nuclear Safety Authority in Finland (STUK), with an aim to review the data and models of POSIVA, the company responsible for the disposal of the nuclear waste in Finland, and provide alternative conceptual models to assess the prediction capacity of the structural models. A data-driven approach has been used, utilizing all of POSIVA's data of the structural elements from the ground surface level (Fig. 1b), acquired from natural outcrops and investigation trenches. Geological and geophysical maps and sections and the associated investigation reports from the Olkiluoto Island and the surrounding areas have been reviewed and used in new structural interpretations of both ductile and brittle features. The new ductile structural interpretations, briefly described in this paper, are correlated with the known networks of brittle deformation zones, to arrive at a new conceptual model explaining the generation and localization of the N-S brittle deformation zones.

3. Geological background

The crystalline bedrock of Olkiluoto is part of the 1.9-1.8 Ga Svecofennian crust generated through a complex Palaeoproterozoic tectonic evolution involving a prolonged episode of crustal accretion (e.g. Lahtinen et al, 2005; Hermansson et al., 2008). The earliest major deformation event (>1.86 Ga) in southern and western Finland was mostly non-migmatizing at the presently exposed lithospheric level, and has been attributed to thrust tectonics (Väisänen and Hölttä, 1999). Subsequent major deformation at c. 1.84-1.79 Ga was accompanied by high-grade regional metamorphism (upper amphibolite to granulite facies) including voluminous migmatization (e.g. Ehlers et al., 1993; Skyttä and Mänttäri, 2008). The overall structure is defined by upright, km- to 10-km scale folds and dome-and-basin structures with variably dipping flanks, with some major, steep E-W and SSW-NNE striking anastomosing shear zones (e.g. Ehlers et al., 1993; Väisänen and Skyttä, 2007; Torvela et al., 2013). The subsequent Mesoproterozoic events include the emplacement of the rapakivi granites along pre-existing structures (1.6 Ga; Rämö and Haapala, 2005); the development of the Satakunta graben under NE-SW transtension and the deposition of its sedimentary infill (1.65-1.3 Ga; Kouvo, 1976; Kohonen et al., 1993; Korja and Heikkinen, 1995; Mattila and Viola, 2014); and the emplacement of NE-SW striking 1.27-1.25 Ga and younger N-S striking diabase dykes (Suominen, 1991; Aaltonen et al., 2016).

In order to clarify the structural relationships, the 1.84-1.79 Ga ductile deformation is here divided into three “deformation stages” D2-D4 (Fig. 2), although in reality they may represent a prolonged period of progressive deformation rather than distinct separate phases. Within Olkiluoto, D2 is the most important in terms of its pervasive nature, characterised by gentle to moderate southerly dips of the migmatitic foliation (Fig. 1b; Kukkonen et al., 2010; Aaltonen et al., 2016). At a larger scale, these dips are interpreted to represent the southern limb of an asymmetric N/NW-verging fold (Aaltonen et al., 2016). In Olkiluoto, deeformation during the subsequent D3 stage was more localized andpartitioned into i) two E-W trending, south-dipping major shear zones containing both dextral and reverse movements, and ii) one NE-SW trending D3 zone occurring within the central part of the island, characterised by folds with SE-dipping axial surfaces and axial-surface parallel shear structures (Figs. 1b, 2b; Aaltonen et al., 2016). Overall these D3 deformation zones are sub-parallel to the migmatitic foliation inherited or transposed from the D2 stage. The last ductile deformation stage D4 is characterised by small-scale asymmetric folds, associated with dm- to m-scale axial surface-parallel shear features (Fig. 5; Aaltonen et al., 2016). The zones of most intense D4 deformation define two NNE-SSW trending deformation zones (Fig. 1b). However, only rarely are distinct continuous shear zones parallel to the zone trend observed within these zones (Nordbäck and Engström, 2016).

Overall, the structures exhibit a pattern of overprinting and transposition of structural elements from D2 to D4. This is attributed to progressive counterclockwise rotation of the maximum compressional stress from N-S to ESE-WNW (Fig. 2; Engström, 2013). The crust cooled significantly through this period: deformation stages D2 and D3 were approximately synchronous with intense migmatization, constrained by overlapping ages of 1.86 to 1.82 Ga, whereas D4 at 1.81-1.79 Ga is only associated with localized pegmatite emplacement (Mänttäri et al., 2006; 2007; 2010; Aaltonen et al., 2016).

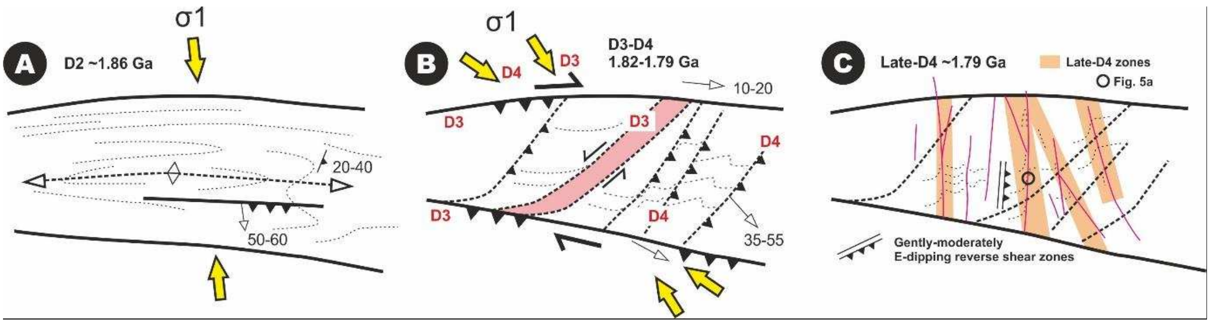

Fig. 2. Schematic representation of the tectonic evolution of the Olkiluoto area. A: D2-stage characterised by N-S compression and development of dominantly E-plunging upright folds. B: D3-D4 -stage characterised by dextral reverse shearing along E-W shear zones, development of NE-SW to NNE-SSW striking, gently to moderately dipping reverse shear zones under NW-SE to WNW-ESE compression (D3 and D4, respectively). C: Development of late-D4 zones of incomplete structural transposition along pre-existing crustal discontinuities, as a progression of the D4-stage, and schematic illustration over their relationship with the approximately N-S striking brittle fault zones (purple).

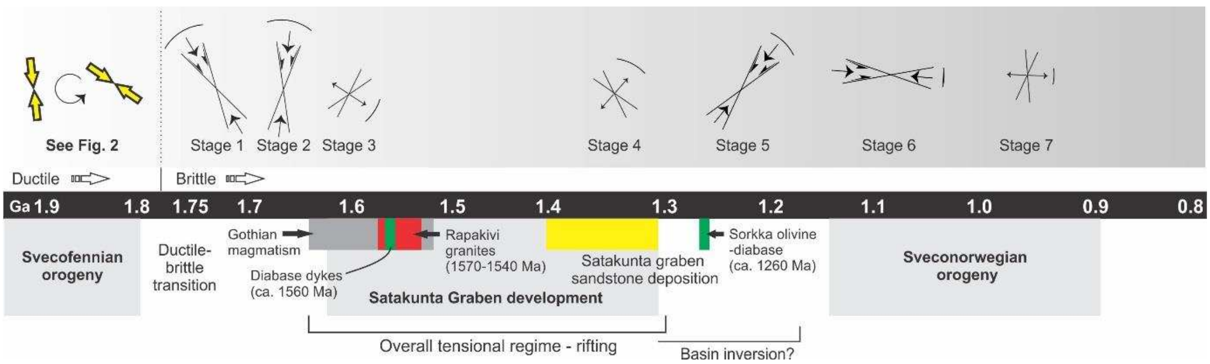

Fig. 3. Summary of major crustal events from 1.9 to 0.8 Ga (bottom) and conceptual model over the brittle evolution of southwestern Finland (top; modified after Mattila and Viola, 2014). The filled yellow arrows refer to the palaeostress configurations of the ductile evolution pre-dating the brittle deformation.

The subsequent brittle deformation zones define three coherent groups with respect to their orientations (Fig. 1c): 1) gently SE-dipping; 2) approximately E-W striking, gently to moderately SSE or SSW dipping; and 3) sub-vertical to vertical, N-S to NNW-SSE striking (Fig. 1c; Aaltonen et al., 2016). Zones of Group 1 and 2, the dominant brittle structures of the area, were probably formed at a late stage of D4, and are controlled by the inherited gentle to moderate S2 foliations and foliation-parallel high-grade deformation zones dipping towards S-SE (Engström, 2013; Mattila and Viola, 2014; Aaltonen et al., 2016). These major brittle deformation zones (Fig. 1c) and their ductile precursor foliations probably also controlled the emplacement of sub-horizontal diabase dykes (Kukkonen et al., 2010). Group 3 zones, typically 0.5-2 km in length, cross-cut the host rock features. The few observed ductile precursors for Group 3 faults are localized mylonites characterised by abundant mica and low-temperature deformation microstructures (Pere, 2009). The age of these N-S faults that are the main topic of this paper is uncertain, but the brittle deformation within the Olkiluoto area spanned the period between c. 1.8-1.0 Ga, during which seven distinct palaeostress states have been recognized from inversion of fault-slip data (Fig. 3; Mattila and Viola, 2014). Using the model of Mattila and Viola (2014), the brittle episodes at c. 1.75 Ga and 1.7 Ga have the best potential to produce the Group 3, steep, approximately N-S striking strike-slip faults.

4. Structural interpretations

Figures 2c and 4 show a new structural interpretation including structural form lines and the youngest inferred ductile deformation zones in Olkiluoto area. The main difference from the existing POSIVA interpretation is the presence of discontinuous swarms of N-S trending foliations representing the latest stage of ductile deformation, (late/post-D4 in POSIVA terminology) forming narrow N-S to NNW-SSE trending zones acting as suitable zones of weakness for the generation of the brittle N-S faults. Furthermore, the WSW-ENE to SW-NE structures (D2-3 by POSIVA) are less distinct and more anastomosing in nature, locally displaying open, large-scale asymmetric S-shaped folds.

4.1. Relationships between the ductile deformation and the sub-vertical brittle deformation zones

At regional scales, N-S trending structures are pronounced within Olkiluoto and its surroundings, contrasting with most parts of southern Finland characterised by approximately E-W structural trends (Fig. 1a). The large-scale N-S structural features occurring west of the major arcuate Kynsikangas shear zone comprise foliation patterns mapped from the surrounding areas (Paulamäki, 2007), distinct shear zones, Rapakivi granite contacts, and mafic dykes cutting the Rapakivi intrusions and their host rocks.

The observations of N-S striking ductile foliation and corresponding N-S striking deformation zones in Olkiluoto area are few compared to the dominant SE-dipping population (Figs. 1a, 4). Therefore, although N-S features are present, they do not obviously correlate with and explain the presence of the approximately N-S oriented brittle structures. The formation of the N-S fault zones could, theoretically, be explained without ductile precursors by the Andersonian fault model or solely as type I tension veins formed during the brittle deformation Stage 1 to Stage 2 (Fig . 3), depending on the maximum principal stress orientation. However, as this is likely not the case, it is important to investigate whether the fault zones could have been localized by more obscure ductile precursors.

Examination of data reveals that N-S fabrics do exist at various scales: NNW-SSE to N-S striking km-scale features are recognised from geological observation (Fig. 1a, Paulamäki, 2007) and site-scale discontinuities truncating the dominant ENE-WSW trends within the geophysical datasets and stereographic projections (Figs. 1b, 4b). At outcrop-scale, the sub-vertical approximately N-S trending faults often characterised by termination by fault splaying locally show ductile deflection of the foliation into the faults, and the presence of retrograde mylonitic precursors (Figs. 5a,b). These zones have subsequently been reactivated under brittle regime, including emplacement of several generations of quartz veins and displacements. Structures previously not attributed contributing to structural inheritance comprise approximately N-S striking short limbs of asymmetric D4-folds which are associated with development of en échelon type arrays of fractures: the individual, approximately N-S striking dominant fracture orientations have a clockwise vergence with respect to the more NNW-SSE trends of the late-D4 zones (Fig. 5d). Moreover, the above fractures, together with other north-southerly but more variably oriented fractures, define anastomosing fracture networks which are comparable to i) the map-scale pattern of the c. N-S fault zones (Figs. 1c and 4b), ii) with splaying of the brittle fault zones BFZ045 and BFZ100 (Figs. 5b,c), and iii) the detailed site investigations at -420 m level within the subsurface of the Olkiluoto Island (Fig. 5c; Aaltonen et al., 2016). One further mode of inheritance is N-S fracturing and emplacement of younger dykes truncating the main generation of migmatitic leucosomes displayed parallel to the axial surfaces of D4 folds (Fig. 5e).

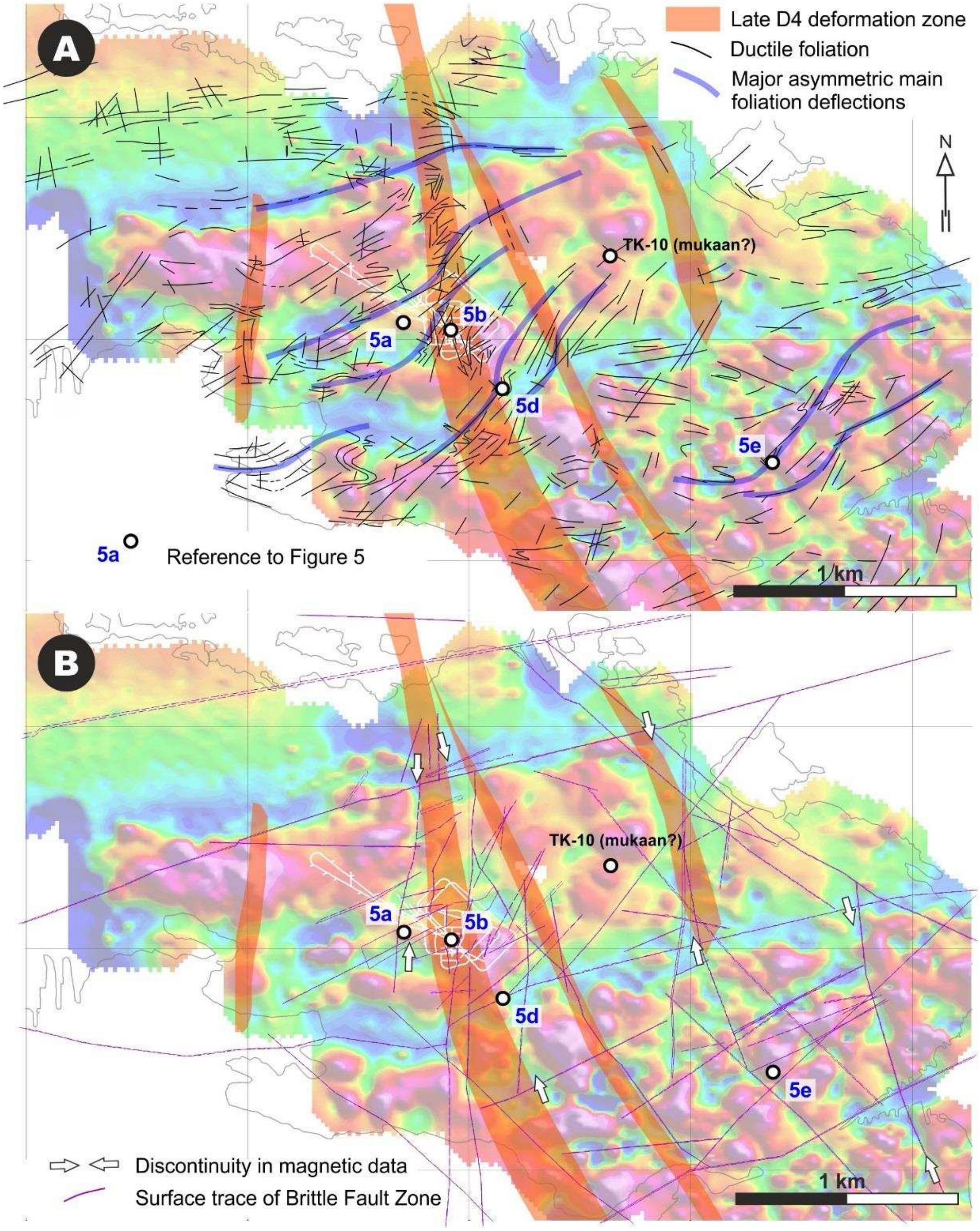

Fig. 4. A: A revised structural interpretation with foliation form lines and late-D4 deformation zones. The interpretation is based on a total of 2218 foliation measurements from the ground surface (Fig. 1b), complemented by 132 foliation strike readings with no dip data. The ground magnetic map is from Posiva, white line is the surface projection of ONKALO (see Fig. 1 caption). B: Correlation of the late-D4 deformation zones and the brittle fault zone intersections at ground surface level. The white arrows exemplify the locations of N-S

to NNW-SSE discontinuities that contributed to development of the late-D4 zones and subsequent brittle fault zones.

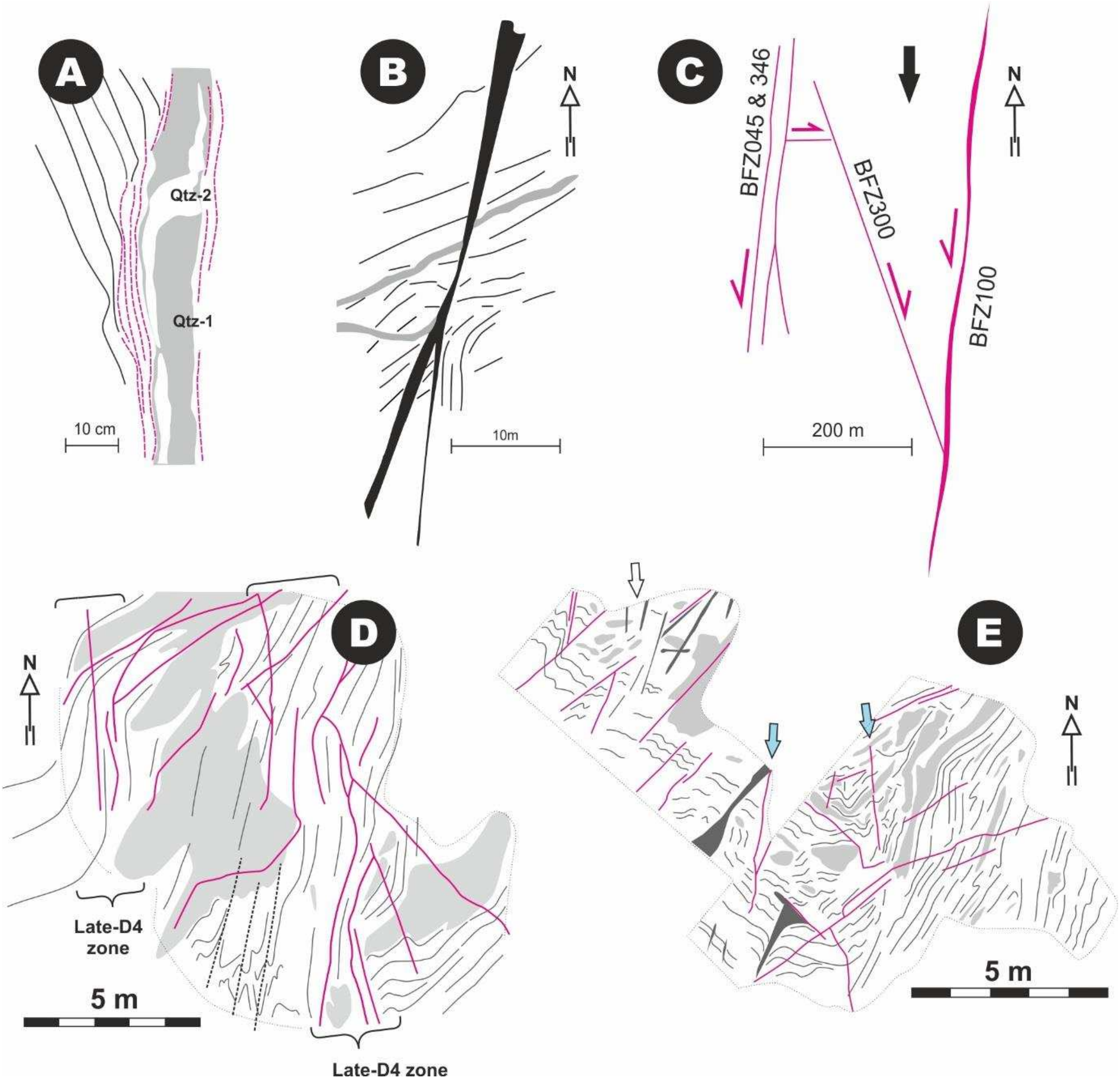

Fig. 5. A: Deflection of the host-rock foliation (black lines) into the shear zone precursor (magenta lines) of the brittle fault zone BFZ-045. Redrawn after Mattila (2009). B: Main foliation (black lines) deflection associated with the brittle fault zone BFZ-100 (black polygons) and the older ductile shear zones (grey polygons; redrawn after Mattila et al., (2007 [TK-11]). C: Geometric and kinematic summary of the network of approximately N-S striking brittle deformation zones at disposal level in Olkiluoto, including the dominant sinistral and the secondary dextral zones (BFZ-300). Sketch map from -420 m level after Aaltonen et al., 2016. D: Development of N-S striking fracture arrays along the short limbs of D4 folds. Black and purple lines represent ductile and

brittle fabrics, black dotted lines are fold axial surface traces and the grey polygons are migmatitic schlieren or pods. E: An open D4 fold showing generation of N-S fracturing into the fold core (blue arrows), and a younger generation of dykes (dark grey polygons) cutting the main generation of migmatitic leucosomes (white arrow). Symbology as in Fig. D. D and E are redrawn after Engström, 2013.

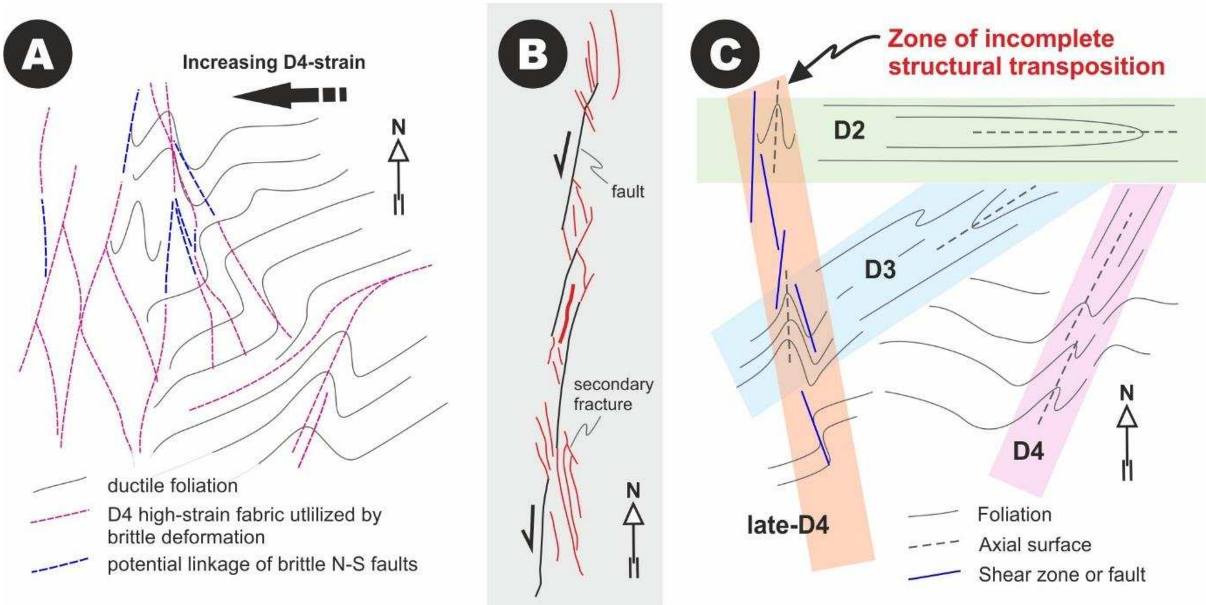

Fig. 6: A conceptual model explaining the origin of the N-S faults in Olkiluoto. A: Development of (late-) D4 high strain fabrics along the short limbs of F4 folds and formation of anastomosing shear zone networks. B: Conceptual model of fracture linkage from en échelon set of joints (after Joussineau et al., 2007). C: Structural zones with either complete or high degree of transposition (D2-4), characterised by structural elements parallel to the zone orientation, and the introduced zone of incomplete structural transposition (late-D4), characterised by structural elements at oblique angles to, but preferential occurrence within the zone.

Based on the above observations, we suggest that the sub-vertical N-S faults were formed as a result of strain localisation during the late-D4 event, progressing from the generation of asymmetric folds (Figs. 5d, 6a) to an anastomosing network of thin discrete retrograde shear (and fracture) zones (Fig. 5a,b). Nucleation of the shear zones utilized suitably oriented late-D4 structural elements (see above) and was pronounced within the pre-existing N-S to NNW-SSE trending site-scale weakness zones (Fig. 4b). Subsequent formation of the brittle faults involved semi-brittle to brittle reactivation of the thin precursor shear zone networks, and likely also linkage of individual shorter fault segments into more continuous faults by e.g. generation of linking secondary fracturing (Fig. 6b). Based on the available palaeostress constraints, favourable palaeostress orientations to form N-S brittle faults, including the more rarely observed conjugate dextral zones, prevailed during 1.75-1.70 Ga and around 0.9 Ga (Fig. 2; Mattila and Viola, 2014).

The proposed linkage of discontinuous and at least partially ductile structures into continuous brittle zones is similar to the better-known process of fault growth by linkage of individual sub-parallel (en echelon) joints or anisotropy planes by generation of splays, secondary fractures or wing cracks during strike-slip deformation (e.g. Joussineau et al., 2007; Crider, 2015). Alternatively, the fault segments could be linked by slip along intersected E-W fault segments, but their inferred younger relative age with respect to the N-S faults (Nordbäck, 2018) does not support this. The presence of approximately N-S trending deformation zones with dominantly sinistral and locally opposing dextral shear senses provides a tool to understand the networks of brittle deformation zones which are essential for the geological disposal of the nuclear waste. Moreover, correlation with palaeostress constraints will allow understanding the kinematic nature of the faults and the related secondary fracture networks defining the fractured damage zone (e.g. Riedel, 1929; Faulkner et al. 2003; Mattila and Viola, 2014; Peacock et al., 2017). However, the degree and mode of linkage of N-S fault segments is presently relatively uncertain and hence needs to be considered a major target of future investigations during the progressive excavation of the disposal facility.

The key outcome of this work is the recognition of the zones of incomplete structural transposition (Fig. 6c) that contributed markedly to the localisation of subsequent N-S brittle faults. These zones are characterised by approximately zone-parallel but discontinuous highest-strain ductile (precursor) structural elements, whereas the average orientation of the continuous D4 elements, previously used as a reference to the N-S brittle faults (Aaltonen et al., 2016), occurs at an oblique angle to these late-D zones and do not provide adequate explanation for the structural inheritance. The mode of transposition is hence different from the ductile D2-4 zones where the foliation trends and at least the axial surfaces within these zones characteristically display complete transposition towards parallelism with the zone margins (Fig. 6c). For the above reasons, we deduce that the less-frequent, localised high-strain D4 structures were more suitably orientated and therefore more important in localising the subsequent brittle deformation than the overall anisotropy generated by the dominant D4 fabric.

Our hypothesis of strong control of zones of incomplete structural transposition to formation of later deformation zones may be applicable at various scales, and may help to explain strain localization in other areas where obvious precursor structures are not present or are unfavourably orientated to the prevailing stress field. Additional field observations as well as numerical and analogue modelling studies are now needed to further test and develop this hypothesis.

5. Conclusions

- New analysis of a set of discontinuous, outcrop-scale ductile structures revealed a previously unrecognized link between ductile precursors and a set of large-scale N-S striking brittle fault zones in Olkiluoto
- These ductile zones of incomplete structural transposition are suggested to have controlled the orientation of the later, longer N-S striking brittle faults, through progressive linkage of the discontinuous segments.

6. Acknowledgements

The authors acknowledge POSIVA for the permission to use the data and STUK for the permission to publish the outcome of the work conducted during the consulting work, and Frederick W. Vollmer for the use of Orient software for the stereographic projections. The comments by Dr. Eiichi Ishii and Dr. Paul Evins helped to improve the paper and are well appreciated.

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