Could peridotite hydration reactions have provided a contributory driving force for Cenozoic uplift and accelerated subsidence along the margins of the North Atlantic and Labrador Sea?

Alasdair Skelton & Martin Jakobsson

Skelton, A. & Jakobsson, M.: Could peridotite hydration reactions have provided a contributory driving force for Cenozoic uplift and accelerated subsidence along the margins of the North Atlantic and Labrador Sea? *Norwegian Journal of Geology,* vol. 87, pp. 241-248,.Trondheim 2007. ISSN 029-196X.

This study evaluates the hypothesis that peridotite hydration reactions (e.g. serpentinisation) at the landward termination of transform fracture zones provide a contributory driving force for coupled uplift and accelerated subsidence along the margins of the North Atlantic and Labrador Sea in the Cenozoic. This evaluation is partly based on the extent and rate of serpentinisation, calculated by Skelton et al. (2005) by using seismic velocity as a proxy for progress of the serpentinisation reactions. The hypothesis is supported by 1) spatial coincidence between most of the uplifted segments of the margin with the landward termination of transform fracture zones, 2) the theoretical capacity of serpentinisation to generate 10^2-10^3 m of uplift at a rate of mm.a^{-1} to cm.a^{-1} which is consistent with observations from the margin, and 3) the potential for landward material flow of a hydrated peridotite inclusion, providing a mechanism for sustaining uplift and its pairing with accelerated subsidence. Also, serpentinisation is more effective than other metamorphic reactions (e.g. granulite to amphibolite, eclogite to amphibolite) as a driving force for uplift. Shortfalls of this model are that 1) extensive peridotite hydration is unlikely at depths exceeding 10-20km and 2) the timing of uplift requires that pulses of extensive peridotite hydration occurred along inactive segments of transform fracture zones. We conclude that the volume expansion caused by peridotite hydration was probably insufficient to account for widespread uplift during the Cenozoic. However, we suggest that the following processes could occur at or near the landward terminations of transform fracture zones: 1) volume expansion caused by extensive peridotite hydration beneath thinned crust at or near the ocean-continent transition and 2) mechanical weakening caused by limited peridotite hydration beneath thicker continental crust. These processes may have important implications for models aimed at explaining Cenozoic uplift and accelerated subsidence.

Alasdair Skelton (e-mail: alasdair.skelton@geo.su.se), Martin Jakobsson, Department of Geology and Geochemistry, Stockholm University, 106 91 Stockholm, Sweden.

Introduction

Hydration of mantle peridotite, primarily by serpentinisation, occurs in active tectonic settings, such as mid-oceanic ridges and transform faults and fracture zones (e.g. Cannat et al. 1992, Michael et al. 2003), subduction zones (e.g. Fryer 1992) and submarine, magma-poor continental rifts (e.g. Nicolas 1985, Boillot et al. 1989, Whitmarsh et al. 2001, Skelton et al. 2005).

In the following sections, we provide a summary of the petrological and physical (density, strength) responses of mantle peridotite to hydration. Wicks (1979), Wicks & O'Hanley (1988) and O' Hanley (1996) provide more detailed discussions to which the interested reader is referred and which are beyond the scope of this paper. Only behaviour, which is essential to the subject of this study, is discussed below.

Petrology

Hydration of mantle peridotite can produce talc and/or anthophyllite at higher T and the serpentine minerals: antigorite, lizardite and chrysotile at lower T (Fig. 1). The type of serpentine mineral which forms is primarily a function of P, T and the activity of H_2O.

Lizardite is the most abundant serpentine mineral, primarily occurring in retrograde serpentinites, typically with brucite and/or magnetite and/or native metals (Wicks & O' Hanley 1988). Lizardite typically contains less than 5 wt. % FeO (Wicks & O' Hanley 1988). Chrysotile is probably the least abundant serpentine mineral. It is primarily associated with shear zones and occurring as vein deposits. Chrysotile typically contains less than 2 wt. % FeO. Occurrences of antigorite (± magnetite) have been reported mainly from prograde serpentinites. However, Wicks (1984) interpreted the formation of antigorite (and talc) directly by retrograde hydration of olivine at higher T from the serpentinised peridotite at Glenurquhart, Scotland. Occurrences of retrograde antigorite have also been interpreted from the Yukon Territories (Wicks & Whitaker 1977, Wicks & Plant 1979) and California (Mittwede et al. 1987, Peacock 1987). These interpretations are consistent with Fig. 1 (see also (e.g.) Evans 1977, Berman et al. 1986).

Based on the P-T diagram shown in Fig. 1, we conclude

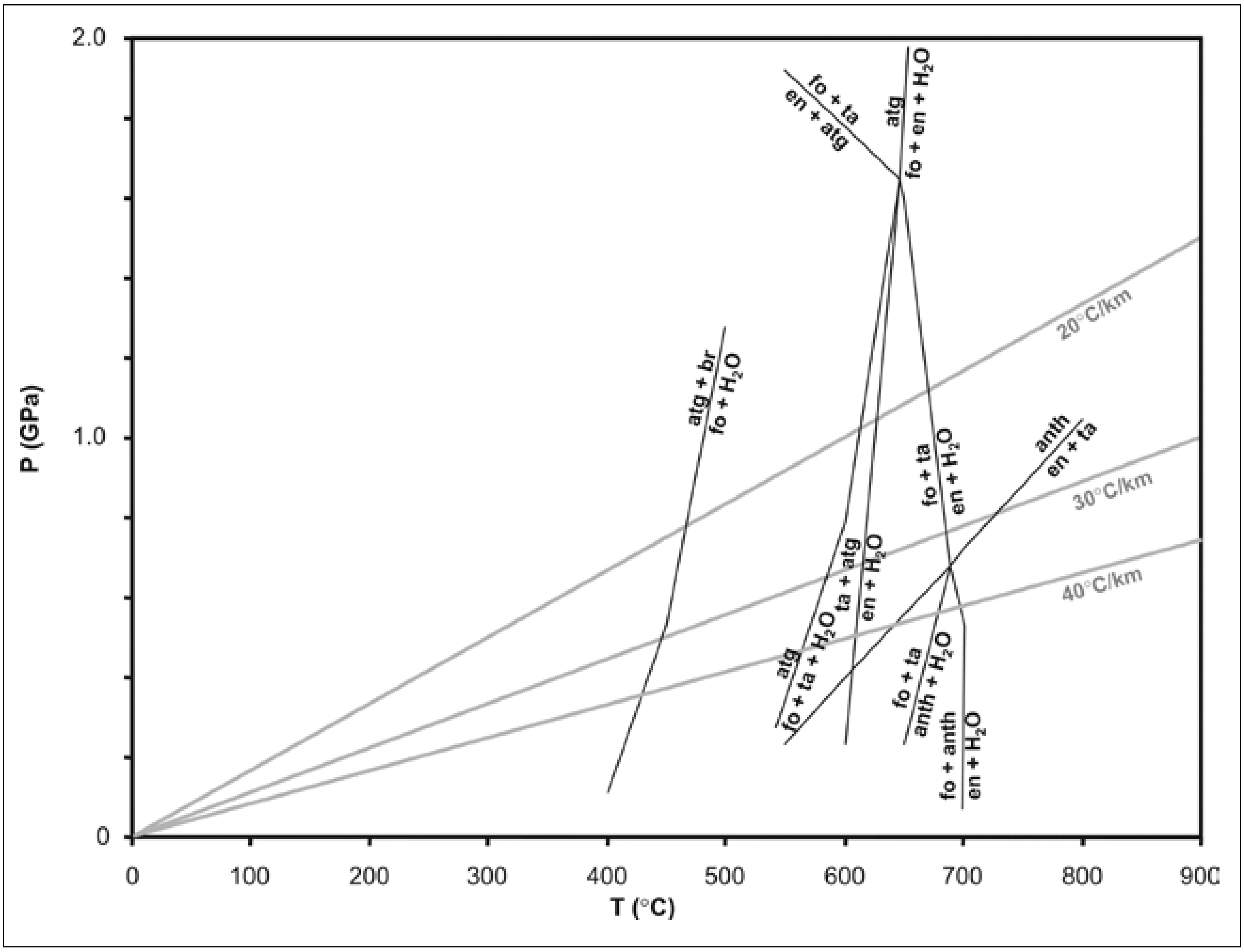

Fig. 1. Plot showing equilibria for peridotite hydration constructed using the computer program THERMOCALC (Holland & Powell, 1998) for the system MgO-SiO_2-H_2O. The 20°, 30° and 40°C.km^{-1} geotherms are also shown. Abbreviations: fo = forsterite, en = enstatite, ta = talc, anth = anthophyllite, atg = antigorite and br = brucite.

that, for a shallow geothermal gradient (20-30°C/km), formation of antigorite can occur at equilibrium, from enstatite below 610-630°C (20-31km) and from olivine (+ talc) below 580-610°C (19-30km). Formation of talc from enstatite, which has been reported from Washington (Frost 1975), Quebec (Laurent 1975), Scotland (Wicks 1984a) and New South Wales (O' Hanley & Offler 1992), can occur below 670-690°C (23-34km). Formation of anthophyllite by higher T hydration of peridotite is only likely if the geothermal gradient exceeds ca. 40°C/km (Fig. 1).

The temperatures (and depths) estimated for hydration of peridotite to antigorite and/or talc are greater than for "normal" serpentinisation by the reaction: olivine = lizardite ± brucite ± magnetite ± native metals (Wicks & O' Hanley 1988). This reaction probably occurs below 300-400°C and at low a(H_2O) (Sanford 1981). However, petrological evidence (e.g. serpentine pseudomorphs after talc rimming enstatite: Wicks 1984) indicates that the volumetric extent of higher T hydration of peridotite (to form antigorite and/or talc) is limited.

Density (ρ)

Hydration of peridotite (ρ ≈ 3.2 g.cm-3) to (1) talc (ρ ≈ 2.8 g.cm-3), (2) antigorite (ρ ≈ 2.7 g.cm-3) ± magnetite (ρ ≈ 5.2 g.cm-3), or (3) lizardite (or chrysotite) (ρ ≈ 2.6 g.cm-3) ± brucite (ρ ≈ 2.4 g.cm-3) ± magnetite, will reduce its density. The respective volume changes (ΔV) are given as functions of reaction progress (ξ) by (modified from Skelton et al. 2005):

peridotite (enstatite) ==> talc:

$$\Delta V\ (\%) \approx 100\cdot\xi\cdot\{1-(2.8/3.2)\} \qquad (1a)$$

peridotite (olivine ± enstatite) ==> antigorite ± magnetite:

$$\Delta V\ (\%) \approx 100\cdot\xi\cdot\{1-(X_{mag}\cdot 5.2/3.2) - [(1-X_{mag})\cdot 2.7/3.2]\} \qquad (1b)$$

Peridotite (olivine ± enstatite) ==> lizardite (or chrysotile) ± brucite ± magnetite:

$$\Delta V\ (\%) \approx 100\cdot\xi\cdot\{1-(X_{mag}\cdot 5.2/3.2) -(X_{brc}\cdot 2.4/3.2) - [(1-X_{mag}-X_{brc})\cdot 2.6/3.2]\} \qquad (1c)$$

where X_{mag} and X_{brc} are the respective weight fractions of magnetite and brucite (which range from 0 to 1).

For complete hydration of peridotite ($\xi = 1$) at low T, producing a "typical" serpentinite, containing lizardite + magnetite, with $X_{mag} < 0.05$, equation 1c yields a volume gain exceeding 15%. For partial hydration ($\xi < 1$), ΔV will be smaller. However, based on petrological studies, Bach et al. (2006) showed that brucite behaves as a reactive intermediary which delays the production of magnetite during serpentinisation. This implies that ΔV will be larger than predicted by equation 1c for small ξ.

For hydration of peridotite at higher T, producing talc rims, surrounding enstatite (Wicks 1984), ξ is unlikely to exceed 0.1 (10% talc) and equation 1a yields a volume gain of ca. 1%.

Strength

Hydration of peridotite not only causes volume expansion but also mechanical weakening. For example, serpentinite has a low coefficient of internal friction (lizardite ~ 0.35, antigorite ~ 0.34: Escartin et al. 1997) compared with peridotite (0.73: Shimada et al. 1983). Escartin et al. (1997) showed that the relative weakness of serpentinite relates to the low fracture energy of the [001] cleavage in lizardite and antigorite, based on optical microscopy and TEM on experimental run products. They showed this to be valid, both above and below the brittle-ductile transition, which is at 0.2 - 0.4GPa for T < 450-500ºC (Escartin et al. 1997, Brodie & Rutter 1985, Murrell & Ismail 1976, Raleigh & Paterson 1965). Localised deformation in the brittle regime and distributed deformation in the ductile regime are accommodated in serpentinite by intragranular and grain boundary shear micro-cracks, oriented parallel to the [001] cleavage. Because of this micro-structural behaviour, a serpentinised body can behave as a weak inclusion (Koyi & Skelton 2001, Skelton et al. 2005), capable of vertical and/or lateral viscous flow in response to deformation and/or volume expansion.

Escartin et al. (2001) showed that this change in rheological properties occurs at a serpentine content of 10-15% or less. Thus slightly serpentinised peridotites are as weak as completely serpentinised peridotite. Here, we speculate that even hydration of peridotite at higher T, which probably produces only small amounts (< 10%) of talc, will cause significant mechanical weakening. This speculation is based on similarities between the micro-structural properties of serpentine and talc (coefficient of internal friction ~ 0.2: Moore & Lockner, 2003).

In summary, for a shallow geothermal gradient (20-30°C/km), hydration of peridotite can cause (1) production of small amounts of talc (rimming enstatite) at T < 670-690°C (23-34km), (2) replacement by antigorite ± magnetite at T < 580-630°C (19-31km) and/or (3) complete or partial replacement by lizardite (or chrysotile) ± brucite ± magnetite at T < 300-400°C (10-20km). This causes a volume expansion, which exceeds 15% for complete replacement of peridotite by lizardite ± magnetite at low T, but is only about 1% for the production of small amounts of talc (rimming enstatite) at high T. Partial or complete hydration of peridotite, at low T producing lizardite (or chrysotile) or at higher T producing talc or antigorite is expected to cause significant mechanical weakening.

This paper aims to provide a quantitative assessment of the potential for these physical responses to peridotite hydration providing a contributory driving force for tectonic processes. This has been argued for mantle exhumation at the ocean-continent transition, west of Iberia (e.g. Skelton & Valley 2002, Skelton et al. 2005). We focus on Cenozoic uplift around the North Atlantic which has been inferred from geological and topographical data, but for which the driving mechanism remains uncertain (Japsen et al. 2005, Japsen & Chalmers 2000). We compare the potential contribution of peridotite hydration to tectonic uplift with other metamorphic reactions.

Cenozoic uplift

Cenozoic uplift along the margins of the North Atlantic and the Labrador Sea has been interpreted based on geomorphological studies (Doré 1992, Riis 1996, Lidmar-Bergström 2000), velocity studies (Bulat & Stoker 1987, Japsen 1998), vitrinite reflectance studies (Jaspen et al. 2005), apatite fission-track studies (Rohrman et al. 1995, Hansen 2000, Green et al. 2002, Jaspen et al. 2005), sediment-supply and structural studies (Andersen et al. 2000, Chalmers, 2000, Clausen et al. 2000, Evans et al. 2000). Multiple phases of uplift occurred during the Cenozoic (Japsen & Chalmers 2002, Doré et al. 2002, Japsen et al. 2005), with vertical movements of the order of ~1 km (Japsen et al. 2005). Most regions of onshore uplift/erosion are paired with an offshore region of accelerated subsidence/deposition (Fig. 2). The driving force for these episodes of uplift and accelerated subsidence during the Cenozoic remains uncertain. Both plume activity and post-glacial isostatic rebound have been proposed (Japsen & Chalmers 2000). In the 'plume model', uplift is a consequence of the coupling of underplating and/or asthenospheric diapirism with faster erosion (caused by a wetter climate and/or glacial activity). The main problem with these models is that more recent uplift postdates North Atlantic breakup, but predates the onset of glaciation (Rohrman & van der Beek 1996). In the following section, we examine the spatial distribution, extent, rate and mechanical consequences of peridotite hydration and provide a quantitative assessment of its potential as a contributory driving force for uplift around the North Atlantic and Labrador Sea in the Cenozoic.

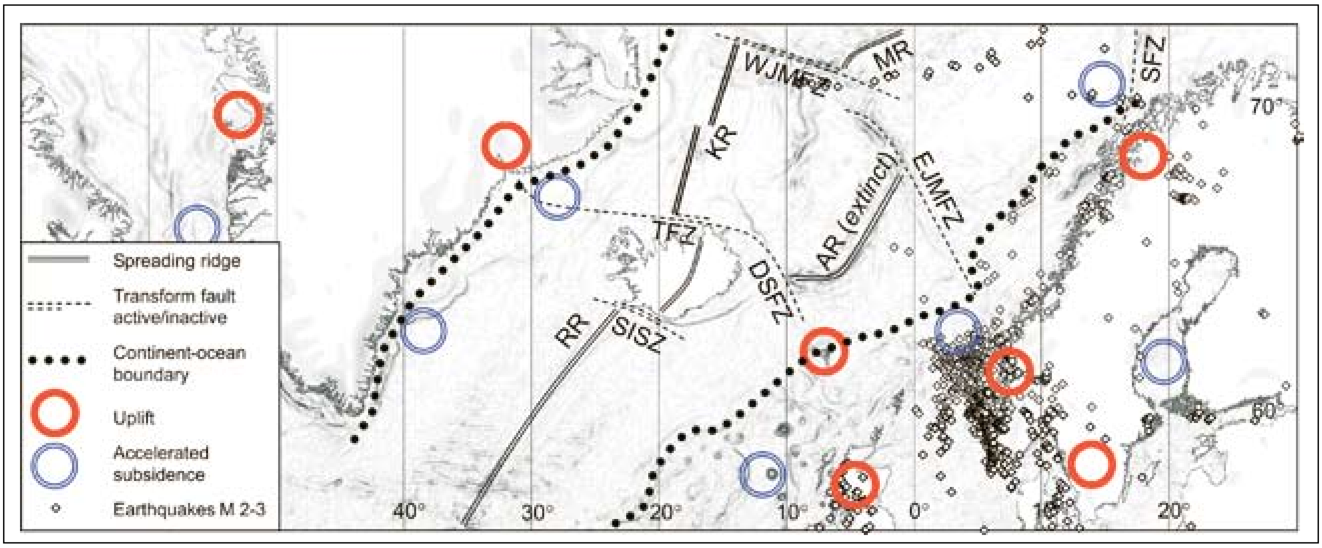

Fig. 2. Map showing 1) the slope of the gravity anomaly, constructed using the On-Line Gravity Map Construction Tool by A. Shettino, which uses version 9.1 of the gravity anomaly grid of Sandwell & Smith (1997), 2) epicenters of M 2 – 3 earthquakes reported in the USGS/NIEC PDE-W database from 1973 to 2005 (http://neic.usgs.gov/neis/epic/) and 3) the locations of late Cenozoic uplift and accelerated subsidence, after Japsen & Chalmers (2000). Major tectonic features are seen as increased slope of the gravity anomaly. Abbreviations: SFZ, Svalbard Fracture Zone; EJMFZ, East Jan Mayen Fracture Zones; WJMFZ, West Jan Mayen Fracture Zones; SISZ, South Iceland Seismic Zone; TFZ, Tjörnes Fracture Zone; DSFZ, Denmark Strait Fracture Zone. Uplift of the northeast margin of Greenland is reported by Johnson and Gallaghar (2000). The uplifted region is near the landward termination of the WJMFZ, which is not shown.

Peridotite hydration

Peridotite hydration occurs along mid-oceanic ridges, transform fracture zones, subduction zones and non-volcanic (or magma poor) continental margins (where mantle rocks are exhumed at the ocean-continent transition, e.g. Whitmarsh et al. 2001), because seawater can access the uppermost mantle in each of these tectonic settings. Much of the North Atlantic ocean-continent transition is masked by magmatic rocks linked to the break-up process (Skogseid et al. 1992, Saunders et al. 1997, Eldholm et al. 2000, Berndt et al. 2001). It is thus unlikely that mantle rocks are exhumed at either ocean-continent transition (cf. Whitmarsh et al. 2001) and significant peridotite hydration along this margin is therefore likely to be restricted to where the margin is intersected by transform fracture zones. Vertical movements both along and extending beyond the active segments of transform fracture zones are evident from ocean bathymetry. Peive (2006) cites several examples from the Central Atlantic. Here we examine the East Jan Mayer Fracture Zone (EJMFZ). North of the EJMFZ, seafloor spreading is centered on the Mohns Ridge (MR). South of the EJMFZ, seafloor spreading is currently centered on the Kolbeinsey Ridge (KR). Scott et al. (2005) proposed that seafloor spreading has transferred from the now extinct Aegir Ridge (AR) to the KR, by its stepwise northwards propagation. They argue that this caused the progressive separation of the Jan Mayen microcontinent from the East Greenland margin. Fig. 3 shows the bathymetry of the EJMFZ. Vertical topography, similar to that reported by Peive (2006), extends from the KR/MR to the ocean-continent boundary. Peive (2006) attributes this topography to vertical movements caused by several contributory factors, which include tectonic effects, thermal effects, friction heating, melt migration, erosion/uplift and serpentinisation. Seawater access and consequent peridotite hydration occurring along transform fracture zones and extending beyond their active segments requires that fault-related structural damage generates a preferential (high permeability) pathway along which seawater can access and penetrate the uppermost mantle. Because peridotite hydration reactions are generally exothermic they can be self-propagating, powering their own hydrothermal cell, sustaining seawater access and continued hydration. However, seawater access may also be restricted by fault sealing mechanisms, e.g. magmatism, gouging vein mineralization and/or volume expansion. Fig. 2 shows a spatial correlation between regions of late Cenozoic uplift and the landward terminations of major transform fracture zones in the North Atlantic. This provides supporting (but inconclusive) evidence for the hypothesis that peridotite hydration is a contributory driving force for uplift.

Skelton et al. (2005) used seismic velocity as a proxy to calculate the extent, rate and duration of serpentinisation at the non-volcanic (or magma-poor) continental margin beneath the Iberia Abyssal Plain. Here, mantle rocks are exhumed within the ocean-continent transition and have therefore been accessible for seawater. Samples for this study were collected by scientific drilling during Leg 173 of the Ocean Drilling Program. Skelton et al. (2005) used a chromatographic model, which considers

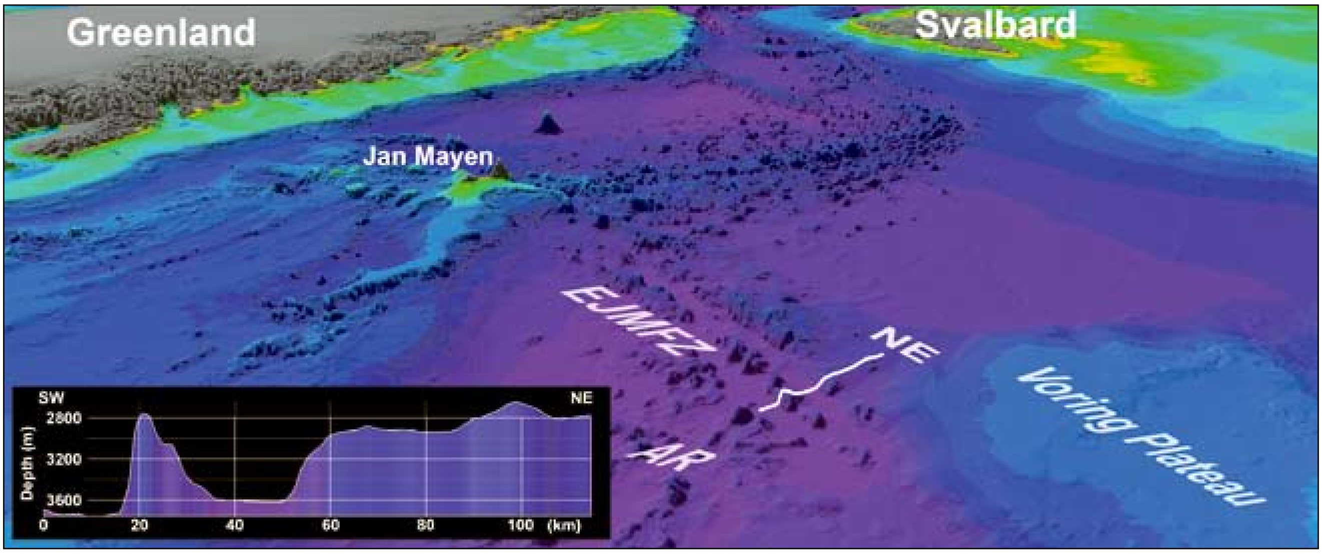

Figure 3. Bathymetry of the Norwegian-Greenland Sea portraying the morphology the East Jan Mayen Fracture Zone (EJMFZ). The inactive Aegir Ridge is denoted "AR". The NE-SW profile shown in the inset is highlighted on the figure. The bathymetry is based on the new version 2.0 of the International Bathymetric Chart of the Arctic Ocean (IBCAO) grid model (Jakobsson et al. in prep, Jakobsson et al. 2000) where multibeam data have been included over the Aegir Ridge and the EJMFZ from Jung and Vogt (1997).

both advection and kinetic dispersion of a reaction front (after Bickle 1992), to estimate the depth of propagation of the serpentinisation front from the seismic proxy data. They calculated a depth of 2197 ± 89 m. It should be noted that because of kinetic dispersion, partial serpentinisation and/or other peridotite hydration reactions continue beyond the serpentinisation front (to a depth of 6-7 km). Given that for serpentinites from the Iberia Abyssal Plain, $X_{mag} \approx 0.04$ (Skelton et al. 2005), the calculated penetration depth for the serpentinisation front of 2197 ± 89 m could cause a maximum uplift of 341 ± 14 m (ΔV =15.5% for X_{brc} = 0: equation (1c)). This assumes that the volume expansion due to serpentinisation is entirely translated into vertical motion. Although this is possible, expansion induced lateral flow cannot be excluded. There is no basis for assuming that the extent of serpentinisation will be similar at the landward termination of a transform fault beneath a volcanic margin, particularly because we do not know which factor (e.g. temperature, pressure, permeability) ultimately limits the downward propagation of a possible peridotite hydration front. Its quantification requires velocity-depth profiles for the uplifted segments of the North Atlantic margin which are of similar resolution to those available for the Iberia margin and some independent confirmation that velocity anomalies relate to peridotite hydration and not to some other process.

Skelton et al. (2005) estimated the minimum duration of serpentinisation along the Iberia margin by comparison with experimentally determined rates of reaction and diffusion. Given their estimate of 10^4 to 10^5 years for T = 225°C, the time-averaged propagation velocity of the serpentinisation front was 2.1 – 23 $cm.a^{-1}$. This could cause a time-averaged uplift rate of 0.3 – 3.6 $cm.a^{-1}$ (ΔV =15.5%) or 1 km of uplift in 0.03 – 0.31 Ma. These calculations similarly assume that volume expansion due to serpentinisation is entirely translated into vertical motion.

Finally, mechanical weakening caused by peridotite hydration might render a hydrated peridotite inclusion capable of vertical and/or lateral material flow in response to tectonic forces (cf. Koyi and Skelton 2001, Skelton et al. 2005). Landward material flow of a hydrated peridotite inclusion could (1) explain pairing of uplift regions onshore with regions of accelerated subsidence offshore and (2) sustain coupling between uplift triggered by peridotite hydration, tectonically-enhanced fluid access (e.g. Graham et al. 1997), continued peridotite hydration and erosion/uplift related to isostatic re-equilibration. This mechanism could be verified by velocity-depth profiling of paired uplifted and subsided regions along the margins of the North Atlantic.

In conclusion, the 'peridotite hydration model' whereby peridotite hydration reactions at the landward termination of transform faults provide a contributory driving force for uplift and subsidence in the Cenozoic is supported by the following: (1) uplifted segments of the margin generally coincide with the landward termination of transform fracture zones, which are (a) possible pathways for seawater access and consequent peridotite hydration and (b) loci of vertical motion; (2) the inferred extent and rate of uplift are similar to those predicted by the 'peridotite hydration model'; and (3) landward 'flow' of a hydrated peridotite body might provide a mechanism for the pairing of uplifted regions with regions of accelerated subsidence. It is also of interest that no metamorphic reactions, which can occur in the lower crust, have a similar potential for inducing uplift. Conversion of eclogite to amphibolite causes a maximum volume expansion (ΔV) of 10-15%, but the volume of eclogite in the lower crust is likely to be small. Granulites may be more abundant, but the volume expansion on conversion of granulite to amphibolite is small.

However, for the 'peridotite hydration model' to provide an effective contributory driving force for Cenozoic uplift, hydration must occur at sub-crustal depths, beneath (or close to) the margin. Extensive serpentinisation, by the reaction: olivine = lizardite ± brucite ± magnetite ± native metals (Wicks & O' Hanley 1988) probably only occurs below 300-400°C (10-20km). Fig. 1 shows that, for a shallow geothermal gradient (20-30°C/km), less extensive peridotite hydration, producing antigorite and/or talc can occur at 580-690°C (19-34km). Thus, peridotite hydration beneath normal continental crust will be limited in extent and the associated volume expansion will be minimal. However, beneath the ocean-continent transition, extensive peridotite hydration is feasible at the landward termination of transform fracture zones, wherever the crust is thinned to less than 10-20km. On the other hand, mechanical weakening is feasible beneath considerably thicker crust (cf. Escartin et al. 2001). Fig. 1 is constructed for the system $MgO-SiO_2-H_2O$. However, consideration of additional components (e.g. FeO, Al_2O_3) has only minor influence on the P-T stability of the reaction curves (O'Hanley, 1996). We conclude that extensive peridotite hydration by serpentinisation is only feasible beneath thinned crust at the ocean-continent transition or if fluid flux rates are sufficient to induce advective cooling. The latter requires fluid flux rates exceeding 10^{-9} $m^3.m^{-2}s^{-1}$ (Bickle & McKenzie 1987), which is more than an order-of-magnitude faster than the fluid flux rate of $0.35\text{-}3.5 \times 10^{-10}$ $m^3.m^{-2}s^{-1}$ calculated by Skelton et al. (2005) for serpentinisation beneath the Iberia Abyssal Plain.

Furthermore, the 'peridotite hydration model' must also explain the timing of multiple phases of uplift, reported to have occurring in the Palaeogene and Neogene, along the margins of both the North Atlantic (Faleide et al. 2002, Lidmar-Bergström & Näslund 2002) and the Labrador Sea (Japsen et al. 2005). Because the active parts of the major transform fracture zones were only near the margins of the North Atlantic in the early Palaeogene, the 'peridotite hydration model' requires extensive fluid access along the inactive segments of major transform fracture zones. This is not consistent with studies showing spatial and temporal coupling of fluid flow and active deformation (e.g. Skelton et al. 2002). Infiltration must occur in a "pulsating" manner to explain discrete phases of uplift. This may be reasonable given the discrepancy between calculated durations for metamorphic fluid flow event(s) ($<10^4$ years: Skelton et al. 1997, 2000) and the probable duration of metamorphic events ($>10^6$ years).

Conclusions

In conclusion, the 'peridotite hydration model', whereby peridotite hydration at the landward termination of transform fracture zones is a contributory driving force for uplift and subsidence in the Cenozoic is favored by 1) a general spatial coincidence of uplifted segments of the margin with the landward termination of transform fracture zones, 2) the theoretical capacity of serpentinisation to generate the inferred extent (10^2-10^3m) and rate of uplift ($mm.a^{-1}$-$cm.a^{-1}$), 3) the potential for landward 'material flow' of a hydrated peridotite inclusion, which could explain pairing of uplifted regions with regions of accelerated subsidence. Also, peridotite hydration is considered more effective than other metamorphic reactions (e.g. granulite to amphibolite, eclogite to amphibolite) as a driving force for uplift. The main disadvantages of the 'peridotite hydration model' are that 1) extensive peridotite hydration (by serpentinisation) is unlikely below normal continental crust and 2) timing constraints require that "pulsed" peridotite hydration events occurred along the inactive segments of transform fracture zones. We conclude that volume expansion caused by peridotite hydration was restricted to regions of thinned crust at ocean-continent transitions and therefore its extent was insufficient to account for widespread uplift during the Cenozoic. However, mechanical weakening caused by limited peridotite hydration, even at sub-crustal depths at the landward termination of transform fracture zones may have important tectonic implications in models which attempt to explain uplift and subsidence in the Cenozoic.

Acknowledgements: Odleiv Olesen, Peter Jaspen, Karna Lidmar-Bergström and Johan Bonow are thanked for constructive discussions. Stockholm University, the Royal Swedish Academy of Science and the Swedish Research Council are acknowledged for financial support. Mike R. Drury and Peter Robinson are thanked for thoughtful and constructive reviews.

References

Bach, W., Paulick, H., Garrido, C. J., Ildefonse, B., Meurer, W. P., & Humphris, S. E. 2006: Unraveling the sequence of serpentinization reactions: petrography, mineral chemistry, and petrophysics of serpentinites from MAR 15°N (ODP Leg 209, Site 1274). *Geophysical Research Letters 33,* doi:10.1029/2006GL025681.

Berman, R.G., Engi, M., Greenwood, H.J. & Brown, T.H. 1986: Derivation of internally-consistent thermodynamic data by the technique of mathematical programming: a review with application to the system $MgO-SiO_2-H_2O$. *Journal of Petrology 27*, 1331-1364.

Berndt, C., Planke, S., Alvestad, E., Tsikalas, F. & Rasmussen, T. 2001: Seismic volcanostratigraphy of the Norwegian Margin: constraints on tectonomagmatic break-up processes. *Journal of the Geological Society, London 158*, 413-426.

Bickle, M. J. & McKenzie, D. 1987: The transport of heat and matter by fluids during metamorphism. *Contributions to Mineralogy and Petrology 95*, 384-392.

Bickle, M. J. 1992: Transport mechanisms by fluid flow in metamorphic rocks: oxygen and strontium decoupling in the Trois Seigneurs

Massif – a consequence of kinetic dispersion? *American Journal of Science 292,* 289-316.

Boillot, G., Feraud, G., Recq, M. & Girardeau, J. 1989: Undercrusting by serpentinite beneath rifted margins. *Nature 341*, 523-525.

Brodie, K. H. & Rutter, E. H. 1985: On the relation between deformation and metamorphism, with special reference to the behaviour of basic rocks. *In* Thompson, A. & Rubie, D. (eds): *Kinematics, Textures and Deformation, Advances in Physical Geochemistry 4*, 138-179.

Bulat, J., Stoker, S.J., 1987: Uplift determination from interval velocity studies, UK, southern North Sea. *In* Brooks, J. & Glennie, K.W. (eds.): *Petroleum Geology of North West Europe,* 293–305. Graham and Trotman, London.

Cannat M, Bideau D, & Bougault H. 1992: Serpentinized peridotites and gabbros in the Mid-Atlantic Ridge axial valley at 15°37'N and 16°52'N. *Earth and Planetary Science Letters 109*, 87-106.

Chalmers J A. 2000: Offshore evidence for Neogene uplift in central West Greenland. *Global and Planetary Change 24*, 311–318.

Clausen O R, Nielsen O B, Huuse M, & Michelsen O. 2000: Geological indications for Palaeogene uplift in the eastern North Sea Basin. *Global and Planetary Change 724*, 175–187.

Doré A G. 1992: The base Tertiary surface of southern Norway and the northern North Sea. *Norsk Geologisk Tidsskrift 72*, 259–265.

Doré, A. G., Cartwright, J. A., Stoker, M. S., Turner, J. P. & White, N. 2002: Exhumation of the North Atlantic margin: introduction and background. In Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner J.P. & White N. (eds.): *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration, Geological Society of London, Special Publications 196*, 1–12.

Eldholm, O., Gladczenko, T. P., Skogseid, J. & Planke, S. 2000: Atlantic volcanic margins: a comparative study. *Geological Society of London, Special Publication 167*, 411-428.

Escartin, J., Hirth, G. & Evans, B. 1997: Nondilatant brittle deformation of serpentinites: Implications for Mohr-Coulomb theory and the strength of faults. *Journal of Geophysical Research 102*, 2897-2913.

Escartin, J., Hirth, G. & Evans, B. 2001: Strength of slightly serpentinized peridotites: implications for the tectonics of oceanic lithosphere. *Geology 29*, 1023-1026.

Evans, B.W., 1977: Metamorphism of Alpine peridotites and serpentinites. *Annual Reviews of Earth and Planetary Science 5*, 397-448.

Evans, D., McGiveron, S., McNeill, A. E., Harrison, Z. H., Østmo, S. R. & Wild, J. B. L. 2000: Plio-Pleistocene deposits on the mid-Norwegian margin and their implications for late Cenozoic uplift of the Norwegian mainland. *Global and Planetary Change 24*, 233–237.

Frost, B.R., 1975: Contact metamorphism of serpentinite, chloritic blackwall and rodingite at Paddy-Go-Easy Pass, Central Cascades, Washington. *Journal of Petrology 16*, 272-312.

Fryer, P. 1992: A synthesis of leg 125 drilling of serpentine seamounts on the Mariana and Izu-Bonin forearcs. *In Proceedings of the Ocean Drilling Program Scientific Results, 125.* College Station, TX (Ocean Drilling Program).

Faleide, J. I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R., Jordt, H., Fanavoll, S. & Bjerke, M. D. 2002: Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. *In* A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds.): *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration, Geological Society of London, Special Publications 196,* 235–269.

Graham C. M., Skelton, A. D. L., Bickle, M. & Cole, C. 1997: Lithological, structural and deformational controls on fluid flow during regional metamorphism. *In* Holness, M. (ed.): *Deformation-enhanced Fluid Transport in the Earth's Crust and Mantle,* 196-226. Chapman & Hall, London.

Green, P. F., Duddy, I. R. & Hegarty, K. A. 2002: Quantifying exhumation from apatite fission-track analysis and vitrinite reflectance data: precision, accuracy and latest results from the Atlantic margin of NW Europe. *In* A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds.): *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration, Geological Society of London, Special Publications 196*, 331–354.

Hansen, K. 2000: Tracking thermal history in East Greenland: an overview. *Global and Planetary Change 24*, 303-309.

Holland, T. & Powell, R. 1998: An internally consistent thermodynamic dataset for phases of petrological interest. *Journal of Metamorphic Geology 16*, 309-343.

Jakobsson, M., Cherkis, N., Woodward, J., Coakley, B., & Macnab, R., 2000: A new grid of Arctic bathymetry: A significant resource for scientists and mapmakers. *EOS Transactions, American Geophysical Union 81*, 9, p. 89, 93, 96.

Japsen, P. 1998: Regional velocity–depth anomalies, North Sea Chalk: a record of overpressure and Neogene uplift and erosion. *AAPG Bulletin 82,* 2031–2074.

Japsen, P. & Chalmers, J. A. 2000: Neogene uplift and tectonics around the North Atlantic: overview. *Global and Planetary Change 24*, 165–173.

Japsen, P., Green, P. L. & Chalmers, J. A. 2005: Separation of Palaeogene and Neogene uplift on Nuussuag, West Greenland. *Journal of the Geological Society, London 162*, 299-314.

Johnson, C. & Gallagher, K. 2000: A preliminary Mesozoic and Cenozoic denudation history of the North East Greenland onshore margin. *Global and Planetary Change 24,* 261-274.

Jung, W-Y., & Vogt, P.R., 1997: A gravity and magnetic anomaly study of the extinct Aegir Ridge, Norwegian Sea. *Journal of Geophysical Research 102,* 5065-5089.

Koyi, H. & Skelton, A.D.L. 2001: Initiation of detachment faults: insights from centrifuge modelling. *Journal of Structural Geology 23*, 11 79-1185.

Laurent, R. 1975: Petrology of the alpine-type serpentinites of Asbestos and Thetford Mines, Québec. *Schweizerische Mineralogische und Petrographische Mitteilungen Bulletin 5*, 431-455.

Lidmar-Bergström, K. & Näslund, J. O. 2002: Landforms and uplift in Scandinavia. *In* A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds.): *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration, Geological Society of London, Special Publications 196,* 103–116.

Michael, P. J., Langmuir, C. H., Dick, J. B. H., Snow, J. E., Goldstein, S. L., Graham, D. W., Lehnert, K., Kurras, G., Jokat, W., Mühe, R. & Edmonds, H. N. 2003: Magmatic and amagmatic seafloor generation at the ultraslow-spreading Gakkel ridge, Arctic Ocean. *Nature 423,* 956-961.

Mittwede, S., Idegard, M. & Sharp, W.E. 1987: Major chemical characteristics of the Hemmett Grove meta-igneous suite, northwestern South California. *Southeastern Geology 28,* 49-63.

Moore, D. E. & Lockner, D. A. 2003: Friction of 2:1 sheet silicates; how crystal structure influences shear strength. *Geological Society of America, Abstracts with Programs 35*, 634.

Murrell, S. A. F. & Ismail, I. A. H. 1976: The effect of decomposition of hydrous minerals on the mechanical properties of rocks at high pressures and temperatures. *Tectonophysics 31*, 207-258.

Nicolas, A. 1985: Novel type of crust produced during continental rifting. *Nature 315*, 112-115.

O'Hanley, D. 1996: Serpentinites: records of tectonic and petrological history. *Oxford Monographs on Geology and Geophysics 34,* 277 pp.

O'Hanley, D. & Offler, R. 1992: Characterization of multiple serpentinization, Woodsreef, New South Wales. *Canadian Mineralogist 30*, 1113-1126.

Peacock, S.M. 1987: Serpentinization and infiltration metasomatism of the Trinity peridotite, Klamath province, northern California: implications for subduction zones. *Contributions to Mineralogy and Petrology 95*, 55-70.

Peive, A.A. 2006: Vertical tectonic movements of the crust in transform fracture zones of the Central Atlantic. *Geotectonics 40*, 25-36.

Raleigh, C. B. & Paterson, M. B. 1965: Experimental deformation of serpentinite and its tectonic implications. *Journal of Geophysical Research 70*, 3965-3985.

Riis, F. 1996: Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. *Global and Planetary Change 12*, 331–357.

Rohrman, M. & van der Beek, P. 1996: Cenozoic postrift domal uplift of North Atlantic margins: an asthenospheric diapirism model. *Geology 24*, 901–904.

Rohrman, M., van der Beek, P., Andriessen, P. & Cloetingh, S. 1995: Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. *Tectonics 14*, 704–718.

Sandwell, D. T. & Smith, W. H. F. 1997: Marine gravity anomaly from Geosat and ERS 1 satellite altimetry. *Journal of Geophysical Research 102,* B5, 10039-10054.

Sanford, R.F. 1981: Mineralogical and chemical effects of hydration reactions and applications to serpentinization. *American Mineralogist 66,* 290-297.

Saunders, A. D., Fitton, J. G., Kerr, A. C., Norry, M. J. & Kent, R. W. 1997: The North Atlantic Igneous Province. *In* Mahoney, J. J. & Coffin, M. F. (eds.): *Large igneous provinces: continental, oceanic and planetary flood volcanism, Washington, American Geophysical Union, Geophysical Monograph 100*, 45–94.

Scott, R.A., Ramsey, L.A., Jones, S.M., Sinclair, S. & Pickles, C.S. 2005: Development of the Jan Mayen microcontinent by linked propagation and retreat of spreading ridges. *In* B. Wandas et al. (eds.): *Onshore-Offshore Relationships on the North Atlantic Margin, Norwegian Petroleum Society Special Publication 12*, 69-82.

Shimada, M., Akio, C. & Yukutake, H. 1983: Fracture strength of dry silicate rocks at high confining pressures and activity of acoustic emission. *Tectonophysics 96*, 159-172.

Skelton, A.D.L., Bickle, M.J. & Graham, C.M., 1997: Fluid-Flux and Reaction Rate from Advective-Diffusive Carbonation of Mafic Sill Margins in the Dalradian, S.W. Scottish Highlands. *Earth and Planetary Science Letters 146*, 527-539.

Skelton, A.D.L., Valley, J.V., Graham, C.M., Bickle, M.J. & Fallick, A.E., 2000: The Correlation of Reaction and Isotope Fronts and the Mechanism of Metamorphic Fluid Flow. *Contributions to Mineralogy and Petrology 138*, 364-375.

Skelton, A.D.L. & Valley, J.W., 2002: The relative timing of serpentinisation and mantle exhumation at the ocean-continent transition, Iberia: constraints from oxygen isotopes. *Earth and Planetary Science Letters 178*, 327-338.

Skelton, A.D.L., Annersten, H. & Valley, J.V., 2002: $\delta^{18}O$ and Yttrium Zoning in Garnet: Time Markers for Fluid Flow? *Journal of Metamorphic Geology 20*, 457-466.

Skelton, A. D. L., Whitmarsh, R., Arghe, F., Crill, P. & Koyi, H. 2005: Constraining the rate and extent of mantle serpentinization from seismic and petrological data: implications for chemosynthesis and tectonic processes. *Geofluids 5*, 153-164.

Skogseid, J., Pedersen, T., Eldholm, O. & Larsen, B. T. 1992: Tectonism and magmatism during NE Atlantic continental break-up: the Vøring Margin. *Geological Society of London, Special Publication 68*, 305-320.

Whitmarsh, R. B., Manatschal, G. & Minshull, T. A. 2001: Evolution of magma-poor continental margins from rifting to seafloor spreading. *Nature 413*, 150-154.

Wicks, F.J. 1979: Mineralogy, crystal chemistry and crystallography of chrysotile. In Ledoux, R.L. (ed.): *Mineralogical techniques of asbestos determination, Mineralogical Association of Canada Short Course Handbook 4*, 35-78.

Wicks, F.J. 1984: Deformation histories as recorded by serpentinites. I. Deformation prior to serpentinization. *Canadian Mineralogist 22*, 185-195

Wicks, F.J. & Whitaker, E.J.W. 1977: Serpentine textures and serpentinization. *Canadian Mineralogist 15*, 459-488.

Wicks, F.J. & Plant, G. 1979: Electron microprobe and X-ray microbeam studies of serpentine textures. *Canadian Mineralogist 17*, 785-830.

Wicks, F.J. & O'Hanley D. 1988: Serpentines: structures and petrology. *In* Bailey, S.W. (ed.): *Hydrous phyllosilicates exclusive of micas, Mineralogical Society of America Reviews in Mineralogy 19*, 91-168.