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**Notes**
Thermal structure of supra-detachment basins: a case study of the Devonian basins of western Norway

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Abstract: We investigate the peak temperatures of the Devonian Hornelen, Kvamshesten and Solund basins in SW Norway to constrain their thermal history. These basins are the three largest Devonian units exposed in Norway and were formed as supra-detachment basins in the hangingwall of the Nordfjord Sogn Detachment Zone. The peak temperatures of the basins were obtained using a geothermometer based on Raman spectroscopy of carbonaceous material on detrital carbonaceous plant fossils. The data confirm an anchizone to low greenschist-facies metamorphism with temperatures (±30°C) of 284–301°C in the Hornelen and Solund basins and a significantly higher temperature, 345°C in the Kvamshesten basin. The temperature increases toward the detachment fault and cannot be explained by ordinary burial alone. In the Kvamshesten basin this temperature increase is close to 100°C. The new data demonstrate that exhumation of high-grade rocks in the footwall in the Nordfjord Sogn Detachment Zone played an important role in controlling temperatures in the hangingwall. We conclude that the dynamic evolution along large-scale detachments may introduce heat at the base of the hangingwall and thereby control the thermal state of supra-detachment basins formed during extension.

Crustal extensional detachments are remarkable geological features that may produce vast metamorphic discontinuities between the hangingwall and the footwall rocks across high-strain shear zones. Since the 1980s, low-angle normal faults have provided important conceptual and quantitative models of the dynamics and evolution of large-magnitude crustal extension (e.g. Wernicke 1985, 2009; Lister et al. 1986; Jolivet et al. 2010), but important questions remain regarding the thermal evolution of such systems. The classical approach to estimate geotherms above a uniformly stretched lithosphere (i.e. McKenzie 1978) cannot be employed in detachment areas that are characterized by strong localized deformation along shear zones with asymmetric geometries. Common features of metamorphic core complexes in detachment footwalls are rapid exhumation accompanied by quasi-isothermal decompressions (Jolivet et al. 1996; Labrousse et al. 2004). In these conditions, the thermal evolution of the system is likely to be influenced by a temperature contrast between the ‘hot’ footwall and the ‘cold’ hangingwall. Depending on the exhumation rate of the footwall and the sedimentation rate in the hangingwall, this asymmetry would affect the regional geotherms in the supra-detachment basins and their thermal history during burial. Recent studies have reported large variations in temperature across detachment shear zones toward the deeper parts of the footwall (Mulch et al. 2006; Cottle et al. 2011; Gottardi et al. 2011). However, such a temperature gradient in a hangingwall, and more specifically within supra-detachment basins, has not yet been documented.

A well-known example of post-orogenic extension producing a very large detachment is exposed in western Norway. The Nordfjord Sogn Detachment Zone (NSDZ) juxtaposes low-grade Caledonian nappes in the hangingwall against high-grade eclogite-facies rocks across a mylonite zone that is several kilometres thick (Norton 1987; Andersen & Jamtveit 1990; Osmundsen et al. 2000) (Fig. 1). The direct contact between the supra-detachment basins and the detachment mylonites provides an excellent study area to investigate the thermal state of the basins as a function of the distance to the detachment. In this study, we used a geothermometer based on Raman spectroscopy of carbonaceous material (RSCM thermometry; Beyssac et al. 2002) and its extension to low temperature (Lahfid et al. 2010).

Geological setting

The Norwegian Devonian basins differ from other ‘Old Red’ sediments deposited contemporaneously in northern Europe by their supra-detachment setting (i.e. Seranne & Séguret 1987; Osmundsen et al. 2000; Fossen 2010). They are located at the top of the hangingwall of the large-scale extensional NSDZ and other extensional shear zones near Røragen and along the Møre–Trøndelag Fault Complex (McCay et al. 1986; Osmundsen et al. 2005). The detachments were initiated by the late- to post-orogenic extensional collapse in the Early Devonian, and the formation and filling of the basins were coeval with the main movement on the detachments (i.e. Norton 1987; Seranne & Séguret 1987; Seranne et al. 1989; Fossen 2000). The Hornelen, Kvamshesten and Solund basins (north to south) of western Norway are preserved in synclines, bounded to the east by the NSDZ, and by depositional unconformities on the eroded Caledonian nappes in the west and NW (Fig. 1). Sporadically preserved plant and fish fossils constrain their deposition from the Early Devonian (416–391 Ma) for the Solund basin to Middle Devonian (391–372 Ma) for the Kvamshesten and Hornelen basins (Kolderup 1916, 1921, 1927; Hoegh 1945).

In contrast to a number of detailed sedimentological and tectonostratigraphic studies (Steel et al. 1977; Osmundsen et al. 1998, 2000; Osmundsen & Andersen 2001), the thermal states of the basins have only been provisionally studied. Palaeomagnetic data suggest a thermochemical resetting of the remanent magnetism after deposition (e.g. Torsvik et al. 1988; Smethurst 1990).
It has also been shown that minor reactivation of the NSDZ partially reset the palaeomagnetic remanence of breccias along the detachment in the Permian and locally in the Late Jurassic or Early Cretaceous (Torsvik et al. 1992; Eide et al. 1997). Braathen et al. (2004) described a complex structure including conglomerates with deformed pebbles in a phyllonitic matrix at the base of the hangingwall of the NSDZ underneath the Kvamshesten basin. Lower greenschist-facies metamorphism accompanied by localized ductile deformation of conglomerates along the detachment was also reported from the Solund basin (Seranne & Seguret 1987). This basin has been interpreted to be the most deeply buried Devonian basin of western Norway.

In addition, the mineralogy of authigenic minerals and fluid inclusion analysis of metamorphic veins found throughout the Hornelen, Kvamshesten and Solund basins document the incipient regional Devonian metamorphism, as described by Svensen et al. (2001). Those workers also suggested that the temperature and burial of the basins increase southward from 250 ± 20 °C at a
depth of 9.1 ± 1.6 km in the Hornelen and Kvamshesten basins to 315 ± 15 °C and a depth of 13.4 ± 0.6 km in the Solund basin. These data are taken to represent the regional metamorphism as a function of the burial of the basins. The new data presented here allow us to discuss the temperature of the basins not only as a function of burial depth, but also in relation to the distance from the NSDZ.

Methods

After sedimentation, the carbonaceous material (CM) trapped in the sedimentary protolith modifies its chemistry (carbonification during diagenesis), and then organizes its internal structure (graphitization) under the effect of gradual heating during metamorphism (Beyssac et al. 2002). RSCM thermometry is based on the quantitative study of the degree of graphitization of CM, which is a reliable indicator of metamorphic temperature. Because of the irreversible character of graphitization, the CM structure is not sensitive to the retrograde overprint during exhumation of rocks and depends only on the maximum temperature reached during metamorphism (Beyssac et al. 2002). Temperature can be determined in the range of 330–650 °C with a calibration-attached accuracy initially estimated to ±50 °C, but re-estimated recently to ±30 °C (Aoya et al. 2010). Relative uncertainties are, however, much smaller, in the range of 10–15 °C (Beyssac et al. 2004; Negro et al. 2006). Recently, Lahfid et al. (2010) have demonstrated that the evolution of the Raman spectra of CM under low-grade metamorphism in the Glarus Alps (Switzerland) is highly correlated with the peak metamorphic temperature in the range of 200–330 °C. The results of that study are currently being expanded and discussed for various tectonic settings, allowing for testing and evaluation of the respective roles of geothermal gradient(s), host rock lithologies or organic precursor as well as improving the temperature constraints. This detailed calibration shows that the correlation between the Raman spectra and temperature is systematic and that the RSCM thermometer may be extended to lower temperatures, in the range of 200–330 °C. For that purpose, the correlation obtained by Lahfid et al. (2010) in Glarus yields an excellent quantitative estimate of temperature. It is important to note that the fitting is different at low temperature compared with the original approach by Beyssac et al. (2002), because the spectra are more complex with at least two more defect bands (Lahfid et al. 2010). Although elaboration of the definitive version of the quantitative calibration is still in progress, we used the qualitative evolution in Glarus based on the RA1 parameter (see Lahfid et al. 2010) as a first approximation to determine temperature values in the low-grade rocks (T < 330 °C). In Table 1 we provide a standard error on T, which is a proxy for the quality of the T data reflecting mostly the within-sample structural heterogeneity. The calibration-attached accuracy at low T is similar to that at high T around ±30 °C.

Raman spectra were obtained using a Renishaw InVIA Reflex microspectrometer (IMPC Paris). We used a 514 nm Laser Physics argon laser in circular polarization. The laser was focused on the sample by a DMLM Leica microscope with a 100× objective (NA=0.85), and the laser power at the sample surface was set around 1 mW. The Rayleigh diffusion was eliminated by edge filters, and to achieve nearly confocal configuration the entrance slit was closed down to 15 µm. The signal was finally dispersed by a 1800 grooves per mm grating and analysed by a Peltier cooled RENCAM CCD detector. Before each session, the spectrometer was calibrated with silicon standard. Because Raman spectroscopy of CM can be affected by several analytical mismatches, we followed closely the analytical and fitting procedures described by Beyssac et al. (2002, 2003). Measurements were made on polished thin sections and CM was systematically analysed below a transparent adjacent mineral, generally quartz. For each sample 10–20 spectra were recorded in the extended scanning mode (700–2000 cm⁻¹) with acquisition times from 30 to 60 s. Spectra were then processed using the software Peakfit (Beyssac et al. 2003). Raman imaging was performed using the same configuration and the streamline mapping technology as described by Bernard et al. (2008).

Results

Presence of CM

To investigate the temperature conditions in the study area, we sampled from the base to the top across the stratigraphy within the Solund, Kvamshesten and Hornelen basins. Because of the eastward dip of the bedding in the basins, their stratigraphic base is generally several kilometres away from the NSDZ, whereas the highest stratigraphic levels in their eastern parts are at or near the detachment. In spite of careful and extensive sampling, we have been confronted with a systematic absence of CM from most of the fine-grained sand- and siltstones. Indeed, disordered CM was found only as large patches (Fig. 2a) preserved in the lithologies containing macro-fossils of Devonian plants (Fig. 1). This CM is derived from original biological material trapped in the sediment and has been progressively transformed during burial. Presumably, such CM was originally present in most of the silt- and sandstone lithologies of the Devonian basins, and has later been removed by oxidation. Oxidation most probably occurred during the intense fluid circulation that affected the basins after deposition (Svensen et al. 2001; Beinlich et al. 2010). Noticeably, we have observed the local presence of detrital graphite, which can be easily recognized

<table>
<thead>
<tr>
<th>Sample</th>
<th>Origin</th>
<th>Locality (unit)</th>
<th>Number of spectra</th>
<th>RA1Lahfid</th>
<th>ε</th>
<th>R2Beyssac</th>
<th>ε</th>
<th>T(°C)</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Our sampling</td>
<td>Lambholmen (Solund)</td>
<td>19</td>
<td>0.603</td>
<td>0.002</td>
<td>–</td>
<td>–</td>
<td>284</td>
<td>±2.1</td>
</tr>
<tr>
<td>2</td>
<td>P000022*</td>
<td>Skjerdingane (Hornelen)</td>
<td>17</td>
<td>0.612</td>
<td>0.002</td>
<td>–</td>
<td>–</td>
<td>295</td>
<td>±0.5</td>
</tr>
<tr>
<td>3</td>
<td>Our sampling</td>
<td>Lambholmen (Solund)</td>
<td>13</td>
<td>0.615</td>
<td>0.002</td>
<td>–</td>
<td>–</td>
<td>300</td>
<td>±1.9</td>
</tr>
<tr>
<td>4</td>
<td>Our sampling</td>
<td>Lambholmen (Solund)</td>
<td>12</td>
<td>0.616</td>
<td>0.003</td>
<td>–</td>
<td>–</td>
<td>301</td>
<td>±3.6</td>
</tr>
<tr>
<td>5</td>
<td>PTO157.257†</td>
<td>Bleia (Kvemshesten)</td>
<td>13</td>
<td>–</td>
<td>–</td>
<td>0.666</td>
<td>0.004</td>
<td>345</td>
<td>±0.5</td>
</tr>
</tbody>
</table>

The parameters RA1Lahfid (see Lahfid et al. 2010) and R2Beyssac (see Beyssac et al. 2002) are used to estimate temperatures <320 °C and >330 °C respectively. RA1Lahfid, R2Beyssac, and T are expressed in terms of mean values of all the data with a standard error ε (±1σ standard deviation divided by the square root of the number of measurements) within each sample.

*Natural History Collections, University Museum of Oslo.

Table 1. RSCM thermometry results
This detrital graphite was observed either directly as flakes in the mineral matrix (Fig. 2b) or as inclusions within quartz grains (Fig. 2c). In some samples, detrital graphite was found in association with hematite (Fig. 3), which might set precise constraints on redox conditions that prevailed during the rock history. The redox conditions were oxidizing enough to form hematite and to oxidize disordered CM, but not too oxidizing to preserve detrital graphite. Graphite is far less prone to oxidation than disordered CM because it has no chemical radicalization and almost no nano-porosity allowing for fluid permeation (Galy et al. 2008).

Despite the large number of samples analysed for this study (c. 50), our new temperature data are limited to only the fossil localities. Representative spectra for each sample are depicted in Figure 4 and all measurements are listed in Table 1. Noticeably, the temperature data for each sample show high internal consistency, with small within-sample structural heterogeneity of CM. In sample 5 from Bleia locality in the Kvamshesten basin, the CM is more graphitized and we therefore used the original RSCM calibration by Beyssac et al. (2002).

**Temperature estimates**

Our analyses give temperatures (±30 °C) ranging from 284 to 345 °C in the various localities. These results indicate higher temperature in the Hornelen (295 °C) and Kvamshesten (345 °C) basins compared with the previous estimate of 250°C for these units (Svensen et al. 2001). The new temperatures found in the Solund basin are lower, ranging between 284 and 301°C, compared with the previous estimate of 315°C. The standard errors reported in Table 1 reflect the homogeneity of the measurements of each sample. Therefore, the relative temperature variation between data points is well constrained within a few degrees.

**Discussion**

**Comparison with previous work**

To better compare our results with the previous estimates, we have reproduced the P–T and fluid inclusion isochores diagram (Fig. 5) for the basins from Svensen et al. (2001, p. 67, fig. 9). The new temperatures of our sample localities are shown and compared with the average metamorphic conditions given by that previous study. This diagram (Fig. 5) shows that our new data deviate from the regional metamorphic trend previously determined from the basins. In addition, it is noticed that the estimates of the average metamorphic conditions were based on analyses of veins found throughout the Solund and Hornelen basins, and in the central part of the Kvamshesten basin (see Svensen et al. 2001). Our samples are, in contrast, representative of specific localities in the basins: near the depositional unconformity for samples 1, 3 and 4, and close to the main detachment for samples 2 and 5.

Two hypotheses can be put forward to explain the variation in temperature from the new data presented here.

1. The variation between the previous estimates of the regional metamorphic temperatures and those reported from single localities in our study may suggest a difference in the burial depth at the present erosion level of the basins. Using the result of 345°C found near Bleia (sample 5, Kvamshesten basin), we can infer a local burial depth >16 km for this locality. This estimate is obtained by projecting the temperature on the representative isochore (Kvam/Hor; see Fig. 5). This depth suggests a local burial of at least 6 km.
deeper than the average burial depth of the Kvamshesten basin. Several syndepositional faults have been described in the basin (Osmundsen et al. 1998, 2000), but these cannot explain a differential burial of several kilometres in the area. We therefore exclude this hypothesis.

(2) The fast exhumation of the footwall of the NSDZ provided an additional heat source and thermally overprinted the basins during deposition and burial.

The temperature within the basins may differ internally depending on the distance to the detachment fault. The NSDZ played a dominant role in the exhumation of the high-grade Western Gneiss Region, crustal thinning as well as the formation of the Devonian basins in western Norway. It is reasonable to assume that the juxtaposition of the warmer lower crustal rocks with the upper crust, including the basins, affected their respective thermal evolution. We consequently consider hypothesis 2 as the most appropriate to explain the variation of the data shown in Figure 5. This interpretation is also supported by thermomechanical modelling of the geothermal field around large shear zones (Souche 2008).

The coherence of this preferred hypothesis is also supported by comparing the distances between the studied fossil localities and the detachment. The Lambholmen samples (1, 2, 4) in the northern Solund basin were taken at a low stratigraphic level and c. 8 km from the NSDZ (Fig. 1). Sections with an average regional dip (c. 25°) of the NSDZ (Hacker et al. 2003) suggest a vertical distance of c. 3.5 km above the detachment for this locality (Fig. 6, profile A). Similar reconstructions show that the fossil localities at
The progressive evolution of the NSDZ along the footwall of the detachment can create an asymmetry of the lower crust in the footwall. The progressive evolution of the NSDZ with gradual exhumation and increased thermal conditions of the above sedimentary basins. Rapid deformation within large-scale shear zones may therefore have potential implications for thermal maturation of the above sedimentary basins.

**Implications**

The geology along the NSDZ records a setting where sediments were deposited near and partly in contact with a large-scale evolving detachment zone. The temperature in the northeastern margin of the Kvamshesten basin (and also in the Hornelen basin) is c. 100 °C higher than the average temperature of the basins based on the estimates from vein-mineralogy and the authigenic minerals described from the sediments (Svensen et al. 2001). We suggest that a contact metamorphic-like process between the NSDZ, its footwall and the basin can explain this temperature anomaly. If shear heating contributed to the increase in temperature, it is possible that significant temperature anomalies may exist also elsewhere in similar structural settings. Rapid deformation within large shear zones may therefore have potential implications for thermal maturation of the above sedimentary basins.

**Conclusion**

We have presented new peak temperature estimates from the three largest Devonian basins of western Norway. The temperatures are internally consistent from several estimates at each locality, but show a significant regional variation between the basins. The lowest temperatures are found at low stratigraphic levels, near the regional geotherm. Previous estimates of the metamorphic conditions of the Hornelen/Kvamshesten and Solund (Sol) basins. The window shades represent the metamorphic conditions of the same respective units. The temperatures obtained in this study are plotted with the average pressure (av. $P$) of the different units (filled squares). A pressure–depth conversion scale is given on the right side of the diagram assuming overburden of constant rock density of 2600 and 2800 kg m$^{-3}$.

**Heat from the NSDZ?**

The geology along the NSDZ records a setting where sediments were deposited near and partly in contact with a large-scale evolving detachment zone. The temperature in the northeastern margin of the Kvamshesten basin (and also in the Hornelen basin) is c. 100 °C higher than the average temperature of the basins based on the estimates from vein-mineralogy and the authigenic minerals described from the sediments (Svensen et al. 2001). We suggest that a contact metamorphic-like process between the NSDZ, its footwall and the basin can explain this temperature anomaly. If shear heating contributed to the increase in temperature, it is possible that significant temperature anomalies may exist also elsewhere in similar structural settings. Rapid deformation within large shear zones may therefore have potential implications for thermal maturation of the above sedimentary basins.

**Regional geotherm**

The temperatures determined for the three largest Devonian basins of western Norway are important for estimating the regional geotherm. Previous estimates of the metamorphic conditions of the Hornelen/Kvamshesten and Solund (Sol) basins. The window shades represent the metamorphic conditions of the same respective units. The temperatures obtained in this study are plotted with the average pressure (av. $P$) of the different units (filled squares). A pressure–depth conversion scale is given on the right side of the diagram assuming overburden of constant rock density of 2600 and 2800 kg m$^{-3}$.

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**Heat from the NSDZ?**

The progressive evolution of the NSDZ with gradual exhumation of the lower crust in the footwall can create an asymmetry of temperatures in the basin with an increase toward the detachment (Fig. 6). Several studies have discussed the relevance of shear heating during large-magnitude lithospheric deformation (e.g. Brun & Cobbold 1980; Leloup et al. 1999; Burg & Gerya 2005). Additional heat could be generated by deformation in large-scale shear zones, but the relative importance of this process remains mostly unquantified. Migration of fluids may also play a role in the thermal state of the basins by advecting heat. Detachments have long been described as structural pathways for channelling meteoritic water through the crust (McCai 1988; Famin et al. 2004; Gottardi et al. 2011). However, an increase of temperatures in the basins is possible only if the rising fluids were exposed to a significantly warmer host in the shear zone or were migrating from a deeper level in the footwall of the detachment.

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depositional unconformity along the NW margin of the Solund basin. The highest temperatures are found at high stratigraphic levels near the detachment along the eastern and NE margins of the Hornelen and Kvamshesten basins respectively. This is in accordance with previous descriptions pointing to localized ductile shearing of conglomerates adjacent to the detachment fault. To explain the inverse temperature gradient with respect to the stratigraphy in the basin(s) we suggest that the very large and rapidly evolving NSDZ provided an additional heat source in the thermal budget of the basins. These lateral temperature variations cannot be explained by burial alone under a horizontally homogeneous geotherm. Our results illustrate the importance of considering the dynamic evolution of large-magnitude extensional shear zones to access the thermal history of hangingwalls and supra-detachment basins.

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Fig. 6. Cross-sections showing structural position of the fossil-bearing localities above the Nordfjord Sogn Detachment Zone with an average dip of 25°. Topography and bathymetry along the profiles A, B and C (see Fig. 1) obtained from the map database at the Norwegian Geological Survey (http://www.ngu.no). The same legend as in Figure 1 is used for the geological units.

References


