Origin of contrasting Devonian supradetachment basin types in the Scandinavian Caledonides

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ABSTRACT

Supradetachment basins that formed during the Devonian extensional collapse of the Scandinavian Caledonides have been explained as hanging-wall basins formed along the listric breakaway zone of a major detachment fault system. This model involves significant rotation of bedding as the detachment flattens to an approximately horizontal orientation, and explains the large stratigraphic thicknesses of east-dipping layers overlying in tectonic contact the top-to-the-west Nordfjord-Sogn detachment zone (NSDZ). However, it fails to explain one of the basins, the Håsteinen basin, where east-dipping Devonian strata rest unconformably on a metamorphic substrate that forms part of the upper plate of the detachment system. Based on detailed field mapping, we present a model where the Håsteinen forms as a ramp basin that develops on the upper plate above a major west-facing ramp in the NSDZ. We test both of these models by forward modeling using 2DMove (two-dimensional kinematic modeling software). The results show how two different types of supradetachment basins can coexist in a subhorizontal detachment zone in an area that underwent many tens of kilometers of lateral crustal extension.

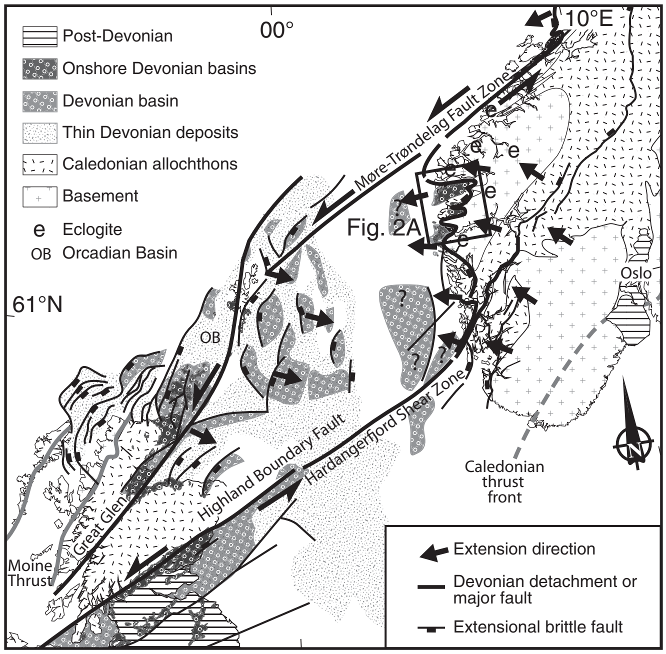

Figure 1. General setting of the Devonian basins and associated detachments and faults in the North Sea region.

INTRODUCTION

Supradetachment basins, i.e., basins that form in the hanging walls of low-angle normal faults, are a special class of basins, the formation and stratigraphic development of which are closely related to tectonic processes. They form in areas of extensional tectonics where extension rates and finite strains are high, such as in the Basin and Range province (Fillmore et al., 1994), the North American Cordillera (McClaughry and Gaylord, 2005), and the Aegean region (van Hinsbergen and Meulenkamp, 2006). Fillmore et al. (1994) distinguished between three detachment-related basin types: footwall basin behind the breakaway fault, classical breakaway basins, and basins formed within the hanging wall due to upper-plate faulting. In addition, ramps in the detachment fault can generate hanging-wall basins where sediments are deposited unconformably onto basement rocks (Osmundsen and Andersen, 2001; Janecke and Blankenau, 2003) or onto prekinematic sediments (Gibbs, 1984; McClay and Scott, 1991; Jackson and Hudec, 2005). Recognizing and correctly interpreting such ramp-generated supradetachment basins are important because they predict the location and size of buried detachment ramps that may be difficult or impossible to observe from subsurface data.

Here we give an example of supradetachment basin formation in the hanging wall of a major (>50 km displacement) Devonian extensional shear zone in the hinterland of the Scandinavian Caledonides known as the Nordfjord-Sogn detachment zone (NSDZ; Figs. 1 and 2) (Johnston et al., 2007; Fossen, 2010). We focus on similarities and differences between the deeply eroded Håsteinen basin and the neighboring and closely related Hornelen basin, and suggest that they are expressions of two different, albeit related types of supradetachment basins: the breakaway basin that progressively opens as the hanging wall is displaced relative to the footwall (Fig. 3, right part), and a ramp basin where the basin forms in response to a flat-ramp-flat section of the detachment (Fig. 3, left).

GEOLOGIC SETTING

The Caledonian orogeny in the North Atlantic region culminated with the westward subduction of Baltica beneath Laurentia in the Late Silurian to Early Devonian, possibly to as much as ~125 km depth in southwest Norway (Hacker et al., 2010). Here, the cessation of the Caledonian orogeny (Fossen, 2010) is characterized by rapid exhumation of high- to ultrahigh-pressure rocks prior to and during the formation of impressive extensional supradetachment basins that accumulated clastic sequences with large stratigraphic thicknesses (Steel et al., 1985). These Devonian basins in southwest Norway (Fig. 2A) are composed of conglomerates and sandstones eroded from the Caledonian allochthonous units. Fossils have not been found in the Håsteinen basin fill, but Middle Devonian plant and fish fossils have been found in the neighboring Kvamshesten and Hornelen basins (Høeg, 1945).

Sedimentologic aspects of the basins, including the distinct basin-edge fringes of cyclic alluvial-fan conglomerates surrounding axially braided stream-dominated deposits for the Hornelen and Kvamshesten basins, suggest that they are four individual albeit closely connected Devonian supradetachment basins (Hornelen, Håsteinen, Kvamshesten, and Solund basins; Fig. 2A) (Hossack, 1984; Séranne and Séguret, 1987).

THE HORNELEN BASIN

The scoop-shaped Hornelen basin is well studied and exhibits marginal conglomeratic alluvial-fan and fan-delta deposits of debris flow, streamflood, and sheetflood origin surrounding axial sandstones and siltstones deposited in axial river systems that drained to the west. The western contact is a depositional unconformity, but the rest of the basin is in tectonic contact with mylonitic rocks of the top-to-the-west NSDZ (Séranne and Séguret, 1987). The original north and south margins have been affected by post-Devonian brittle faults that closely follow the original marginal faults (Steel et al., 1985; Osmundsen and Andersen, 2001).

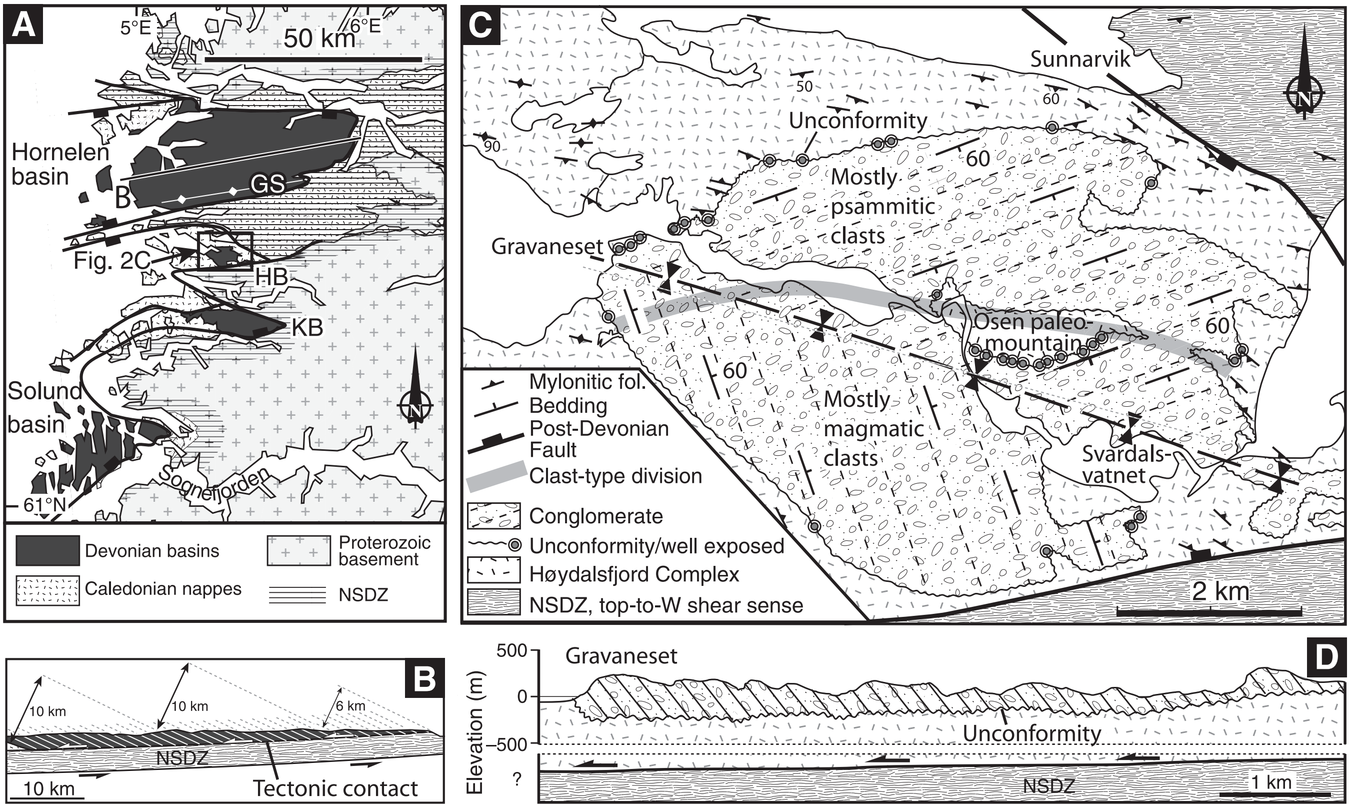

Figure 2. A: Regional map showing Devonian basins and related extensional shear zones. GS—Grøndalen syncline; HB—Håsteinen basin; KB—Kvamshesten basin; NSDZ—Nordfjord-Sogn detachment zone. B: Cross section (1:1) through the Hornelen basin. C: Map of the Håsteinen basin. Trace of bedding and the axial trace of the Osstrupen syncline are shown. D: Cross section through the Håsteinen basin along the axial trace of the Osstrupen syncline. The thickness of the Høydalsfjord Complex is unknown.

Beds in the Hornelen basin dip consistently ~25° to the east, and the basin fill indicates >26 km of compacted stratigraphic thickness (Fig. 2B). However, temperature data indicate that the maximum depth of burial was ~10 km (Séranne and Séguret, 1987). Thus the stacking of sedimentary cycles and their respective depocenters successively overlap eastward. The model that has been used to explain these features is the classical half-graben supradetachment model where the basin fill tectonically overlies a listric fault (Fig. 3, right side) (Hossack, 1984; Séranne and Séguret, 1987). In this model, repeated translation of the hanging wall produced the accommodation space needed to produce a stratigraphic thickness that almost triples the true depth of the basin. While this model explains most aspects of the Hornelen, Kvamshesten, and Solund Devonian basins, a different model is needed to explain the formation of the Håsteinen basin.

THE HÅSTEINEN BASIN AND THE NEED FOR A NEW MODEL

The Håsteinen basin was poorly known until substantial mapping and analysis were carried out (Vetti, 2008). Vetti (2008) showed that the basin fill is highly dominated by upper-plate–derived clast-supported polymictic conglomerates that were deposited by mass flows in a proximal alluvial-fan environment. A change from magmatic clasts in the southern part to metasedimentary clasts in the northern part (Fig. 2C) suggests that at least two different source areas and fan systems were present. The preserved cumulative bedding-normal stratigraphic thickness is 11 km. The basin and its substrate are folded into an upright open chevron-style syncline (the Osstrupen syncline; Fig. 2C) with an ~50° east-southeast–plunging fold hinge and a subvertical axial plane, and bedding dips ~60° on both limbs. The origin of this and similar folds appears to be related to the generally transtensional deformation of this region (Krabbendam and Dewey, 1998). A lowermost greenschist crenulation cleavage in sandy beds in the Håsteinen basin (Vetti, 2008) suggests that the folding was going on at the time of maximum basin burial. Unfolding the strata gives a consistent eastward dip of 35°, i.e., somewhat steeper but otherwise very similar to the Hornelen basin. In map view, two steep post-Devonian normal faults now separate the basin and its substrate from the NSDZ (Fig. 2C). These faults postdate the basin formation and are not considered further here.

The main difference between the two basins lies in their basal contact relations: sedimentary strata in the Hornelen basin are in tectonic contact with the NSDZ, while Håsteinen strata overlie, with a well-preserved and rugged primary depositional unconformity, its substrate (Vetti, 2008). The Håsteinen substrate consists of meta-psammitic to meta-pelitic rocks that were intruded by gabbro in an oceanic backarc setting prior to the Scandian continent-continent collision. This complex, known as the Høydalsfjord Complex, forms part of the upper plate of the NSDZ (Fig. 2C). Therefore, the listric-fault model, which explains well the geometric relations of the Hornelen basin, and in general also the neighboring Kvamshesten and Solund basins (Osmundsen and Andersen, 2001), fails to explain the Håsteinen basin.

A new model is therefore called for; we here present a ramp-basin model where the basin fill is deposited unconformably on the upper plate of the detachment system above a west-dipping ramp in the subjacent detachment zone. The basin forms on top of the hanging-wall block of an active detachment without being in direct contact with the detachment itself. Note that this ramp model calls for a listric Hornelen-style breakaway fault east of the currently preserved Håsteinen basin fill, a fault removed by erosion. The model is illustrated in Figure 3 (left part) and is explored in the following.

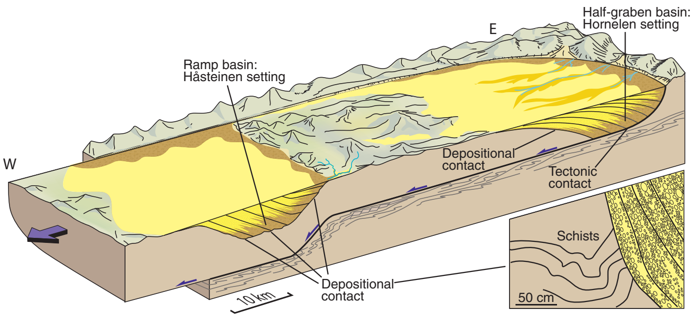

Figure 3. The two supradetachment basin types discussed in this paper. The ramp-basin model is the one suggested for the Håsteinen basin. Sketch of unconformity (lower right) is based on picture displayed in the GSA Data Repository[1].

MODELING THE TWO SUPRADETACHMENT BASIN TYPES

Geometric Constraints

The listric-fault and ramp-basin models were explored simultaneously in a single section by means of the modeling software 2DMove (http://www.mve.com/software/2dmove), as shown in Figure 4. We do not know the exact geometry of the Devonian extensional detachment system, and we primarily base the model on bedding geometry with respect to the substrate and estimates of burial depths. In detail, the easternmost fault was, for simplicity, modeled as a straight fault with 25° dip that abruptly flattened to define a horizontal detachment. The eastern detachment level was set at 10 km depth to match the Hornelen basin (Séranne and Séguret, 1987; Svensen et al., 2001). However, it may have been less, which would make the upper plate thinner.

The Håsteinen basin is folded into the Osstrupen syncline (Fig. 2C), and the cross section along the axial trace of this syncline shows bedding dips of ~50° (Fig. 2D). The effect of this folding needs to be accounted for, and we do so with reference to the Grøndalen syncline in the southeast part of the Hornelen basin (GS in Fig. 2A). Bedding in the Hornelen basin dips ~25° to the east where unaffected by folding, and 38° within the east-west–trending Grøndalen syncline (Steel et al., 1985), whose fold axis plunges 38° to the east. Hence, this folding event involved steepening of bedding by ~13° as viewed along the vertical axial plane (east-west section).

This effect of folding on bedding is thought to be similar for the Håsteinen basin. A cross section along the axial trace of the Osstrupen syncline shows bedding dips of ~50° (Fig. 2D). The relations from the nearby Grøndalen syncline motivate the assumption that the Håsteinen beds steepened during the folding from a prefolding dip of ~35°. We therefore constructed a ramp geometry that produces beds dipping 35° to the east (Fig. 4). In particular, the ramp underneath the Håsteinen basin was modeled as a 40° dipping fault segment linking the upper flat Hornelen detachment to a lower detachment that was given a gentle (5°) westward dip. This gentle westward dip prevented isostatic readjustments from giving the upper detachment an eastward dip. The ramp was, for practical reasons, made angular rather than curved. The ramp height was set to 10 km so that a 10 km deep Håsteinen basin would open immediately west of the ramp.

The 2DMove modeling (Fig. 4) involves a repetitive four-stage sequence: (1) extension of the upper plate so that the two basins form or lengthen, (2) isostatic compensation involving uplift of the lower plate due to the thinning of the upper plate in the basin area, (3) deposition of horizontal sediments with a depositional contact against the ramp in the east, and (4) subsidence due to sedimentary loading of the upper and lower plate. All of these four steps are incorporated in each of Figures 4B–4D, and were repeated until a horizontal extension of ~30 km was obtained—sufficient to test the model.

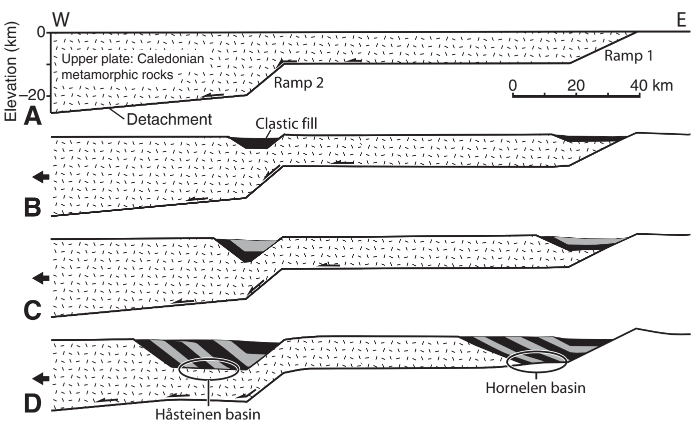

Figure 4. 2DMove forward modeling of the two supradetachment basin types discussed in the text.

Modeling Results

The forward modeling of the Hornelen basin is shown in Figure 4 (right-hand part), where the geometry of the basin is reproduced by means of a listric fault that transforms into a subhorizontal detachment at 10 km depth. Footwall uplift is included in the model, which helps maintain a positive relief in the footwall. Accommodation space is continually produced as the fault slips, generating a laterally growing basin consisting of east-dipping strata in fault contact with the NSDZ.

A Håsteinen-type basin develops above the ramp (Ramp 2 in Fig. 4), expanding as the upper plate moves westward in response to horizontal extension. The subhorizontal beds that are deposited in the ramp basin have a primary contact against the rotated upper plate in the ramp. It is conditional that the beds are deposited against a fully rotated upper plate. If the basin had overstepped the crest of the ramp, the angle between bedding and the substrate at the unconformity would become too low.

Once deposited, the initially subhorizontal Devonian layers are passively transported downward and westward, remaining fixed to the rotating ramp section of the upper plate. The transport down the ramp, which is here modeled by vertical shear, results in rotation of the beds to an eastward dip of ~35° as the upper plate back-rotates to a subhorizontal or gently west-dipping detachment. Other shear angles would alter these angular relationships somewhat, but give qualitatively similar results. As extension proceeds, more beds are added to the east-dipping succession, and the >11 km of stratigraphic thickness accumulates.

While the exact dip, depth, and geometry of the ramp are uncertain, the simple model presented here demonstrates not only how the Hornelen basin can be modeled as a breakaway basin, but more importantly how a ramp-generated basin can produce the geometric relations that characterize the Håsteinen basin.

DISCUSSION

The ramp model presented here is the only one that we have found capable of explaining the geometric and depositional relations of the Håsteinen basin. Geometrically it requires the upper plate between the (now eroded away) breakaway basin and the ramp basin to be exposed to erosion during basin formation, which requires that portion of the detachment to be close to horizontal. Phyllosilicate minerals in the Early

[1]GSA Data Repository item 2012163, supplemental Figures DR1–DR7, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Devonian NSDZ may have given the zone sufficiently weak properties for low-angle slip, and rotation of the zone to a subhorizontal orientation may be linked to the regional rotation and exhumation of its footwall (Western Gneiss Region) during the Devonian extensional history (Fossen, 1992).

A source area is needed for the conglomeratic clast material in the Håsteinen basin. A paleotopographic relief of ~500 m has been mapped out in this basin (Vetti, 2008), suggesting a mountainous upper plate that could have represented a local source for the conglomeratic fans. However, lateral influx was probably more important, and explains the aforementioned difference in clast material between the northern and southern parts of the Håsteinen basin (Fig. 2C).

The ramp model implies an ~35° bending of the upper-plate substrate (Høydalsfjord Complex) and then a similar unfolding during sedimentation, akin to classic fault-bend folds associated with ramps in fold-and-thrust belts. The type and density of structures expected to form during bending depend on the curvature and the deformation mechanisms involved. For a gentle ramp curvature and flexural slip along micaceous layers, the amount of brittle fracture may be small. Fractures are common in the Høydalsfjord Complex, but their relation to this particular bending event is uncertain.

The ramp model presented here is relevant to other regions where extensional detachments form ramp-flat geometries. Supradetachment ramp basins have been reported from the Apennines (Brogi, 2011), the Eocene–Miocene extensional detachment basins in Idaho and Montana, United States (Janecke and Blankenau, 2003), and the Basin and Range region of the United States and northwest Mexico (Dorsey and Martin-Barajas, 1999). Fundamental aspects of the Håsteinen ramp-basin model also pertain to smaller-scale structures found on passive margins—e.g., the Matelles basin in Gulf of Lion, France (Benedicto et al., 1999), and the Angolan passive margin, West Africa (Jackson and Hudec, 2005). In these cases, detachments develop in evaporite or shale layers, and ramps are then generated due to an underlying fault-controlled topography (Benedicto et al., 1999) or salt diapirism (Jackson and Hudec, 2005).

Few supradetachment ramp basins have their basal parts exposed, hence interpretations rely on models or seismic data of limited resolution. In general, angular relations such as those described and modeled here (i.e., dipping beds on top of a subhorizontal unconformity that represents a rotated onlap surface) should be searched for. Geometrically such ramp basins may mimic a downlapping sequence, but have fundamentally different tectonic and depositional implications: the vertical basin depth is related to the height of the underlying ramp, and the horizontal length of the basin is directly related to the amount of displacement and extension on the detachment since the creation of the ramp. In general, we suggest that modeling of the kind shown here should be applied more frequently to basins located above nonplanar detachment faults in order to better interpret the geometric relations in unexposed parts of supradetachment ramp basins.

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