PERGAMON

Journal of Structural Geology 22 (2000) 843–850

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

The World's biggest relay ramp: Hold With Hope, NE Greenland

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Received 8 June 1999; accepted 3 February 2000

Abstract

Fault interaction in the Hold With Hope region of NE Greenland occurs between basin-margin faults that have a separation of about 100 km, with the relay ramp covering an area of about 25 000 km^2. This structure is therefore much larger than previously described relay ramps, showing that interaction between normal faults can occur over large areas and can control deformation across a region. The Western Fault Zone links north and eastwards with the Hochstetters Forland Fault via the Gauss Halvø Fault. These faults that control the relay ramp have kilometre-scale throws, juxtaposing Pre-Caledonian basement against Upper Palaeozoic and Mesozoic cover. The relay ramp initiated during the Devonian, but was at least partially breached at the end of the Devonian or beginning of the Carboniferous. Beds in the relay ramp are tilted towards the footwall, this tilt being similar to the results of recent numerical models of interacting normal faults. The relay ramp is affected by faults that are synthetic to, and that link, the basin-margin faults. These breaching faults suggest that stresses can interact over distances of at least 100 km. This model explains variations in the depth of the Moho across Kong Oscar Fjord. The basin-margin faults may be linked at depth, passing down into a relatively shallow detachment, or into a lower-crustal shear zone. Alternatively, the faults may not be directly connected at depth, but pass down into a zone of distributed ductile deformation.

1. Introduction

A *relay ramp* is an area of tilted bedding between two normal faults with the same dip direction that overstep, but not necessarily overlap, in map-view (Larsen, 1988; Peacock et al., 2000). The footwall is connected with the hanging wall of a fault zone by a relay ramp, which transfers displacement between the overstepping fault segments (Peacock and Sanderson, 1991; Cartwright et al., 1995; Cartwright and Mansfield, 1998). Complex patterns of faulting can occur in a relay ramp to accommodate the tilting of beds (e.g. Griffiths, 1980), and as deformation proceeds the two faults may eventually become linked by connecting faults (Peacock and Sanderson, 1994). Relay ramps are common in extensional basins, where they can be important locations for hydrocarbon migration and entrapment (Larsen, 1988; Morley et al., 1990). For example, the Beryl Embayment is a relay ramp about 20 km across in the North Sea, within which the Beryl and Gryphon oilfields occur (Peacock and Sanderson, 1994, fig. 16a). Relay ramps at the Earth's surface can have a significant effect on drainage, erosion and sedimentation (Morley et al., 1990; Gawthorpe and Hurst, 1993; Jackson and Leeder, 1994).

The region of NE Greenland between 72°N and 74°30′N, between Mesters Vig and Hochstetters Forland, is structurally dominated by a large relay ramp approximately 100 km wide across strike (Fig. 1). The

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PII: S0191-8141(00)00012-2

geometry and development of this structure, here called the *Hold With Hope relay ramp*, is described in this paper. The possible lower-crustal geometries of such a large structure are also discussed. Comparisons are made with the smaller relay ramps described in the literature (e.g. Peacock and Sanderson, 1994) and with recent numerical models of interacting normal faults (Willemse, 1997; Crider and Pollard, 1998). The Hold With Hope structure is much bigger than the relay ramps so far described. For example, the relay ramps in eastern Greenland described by Larsen (1988) are up to about 15 km across, and the relay ramps in the Newark Basin of eastern North America described by Schlische (1992) are up to about 10 km across. The Hold With Hope structure illustrates that interaction can occur between widely separated normal faults, and that this can control regional-scale deformation.

2. Description of the Hold With Hope region

The Hold With Hope region was mapped at a scale of 1:250 000 by Koch and Haller (1965). Koch and Haller show that the region underwent post-Caledonian extension, including Late Cretaceous and Tertiary extension during opening of the North Atlantic. Tertiary basic extrusive and intrusive rocks occur extensively. North-east Greenland, including the Hold With Hope region (Fig. 1), has been used as an analogue for the Mesozoic succession of the NW European margin (e.g. Price and Whitham, 1997; Price et al., 1997).

The Hold With Hope relay ramp is controlled by the Western Fault Zone, the Gauss Halvø Fault and by the Hochstetters Forland Fault. They are N–S-striking, east-dipping normal faults that place Devonian to Tertiary sedimentary rocks in the hanging wall to the east against the crystalline and meta-sedimentary Caledonian basement in the west. Displacements cannot be accurately determined because of lack of stratigraphy in the deformed pre-Caledonian rocks, but minimum estimates of fault throws using the Caledonian peneplane are shown in Fig. 1, and throws must equal or exceed the thickness of the post-Caledonian sequence. Throw on the Western Fault Zone dies out northwards. Larsen and Bengård (1991, fig. 9) show that the Western Fault Zone is segmented northwards, around Ymer Ø, with downthrows of about 3.5 km. The Hochstetters Forland Fault dies out southwards, but its tip is poorly defined and may be under the sea. It is therefore problematic to determine the amount of strike-parallel distance between the tips of these faults. The relay ramp appears, however, to cover an area of about 25 000 km^2 between latitudes 72°N and 74°30′N.

The Western Fault Zone and the Hochstetters Forland Fault are poorly exposed, and are separated by a right-step approximately 100 km wide across strike (Fig. 1). The Gauss Halvø Fault lies between and links the Western Fault Zone with the Hochstetters Forland Fault, so the Hold With Hope structure can be regarded as a composite relay ramp. On the Koch and Haller (1965) maps, these faults are at least 250 km long, which is unusually long for normal fault segments and would indicate a very thick crust (Hayward and Ebinger, 1996). These great lengths are probably only apparent, with the poorly exposed faults being more segmented than shown by Koch and Haller (1965), so the crust would not need to be very thick. Mandler and Jokat (1998) show that the Moho is at a depth of about 48 km in the west of the region.

A Devonian-age basin lies between the northern part of the Western Fault Zone and the Gauss Halvø Fault around Ymer Ø. This basin appears to have been isolated by breaching of the Hold With Hope relay ramp by the Gauss Halvø Fault, probably at the end of the Devonian or the start of Carboniferous. Sinistral transtension may have occurred on the Western Fault Zone during the Devonian (Hartz et al., 1997), indicated by right-stepping en-échelon faults around Ymer Ø (Larsen and Bengård, 1991, fig. 9).

3. Interpretation of the Hold With Hope structure as a relay ramp

Evidence for interaction between the Western Fault Zone and the Hochstetters Forland Fault via the Gauss Halvø Fault, and thus for a relay ramp in the Hold With Hope region, includes:

1. Patterns of stratigraphy (Koch and Haller, 1965) show that displacement on the Western Fault Zone dies out northwards, while displacement on the Hochstetters Forland Fault decreases southwards. For example, the Cretaceous rocks are thrown against the pre-Caledonian rocks near Mesters Vig, while the Devonian is thrown against the pre-Caledonian rocks further north, around Ymer Ø, where the Western Fault Zone becomes highly segmented (Larsen and Bengård, 1991). The isolation of the Devonian basin around Ymer Ø indicates that the relay ramp was at least partially breached by the Gauss Halvø Fault at the end of the Devonian or the beginning of the Carboniferous (Fig. 1).
2. Post-Caledonian beds in the overstep between the Western Fault Zone and the Hochstetters Forland Fault generally dip between 10° and 30° towards the SW. Post-Caledonian beds outside the Hold With Hope relay ramp, however, generally dip a few degrees towards the west (Fig. 1). This indicates south-westwards tilting of beds within the overstep.
3. Faults with displacements of up to several hundred

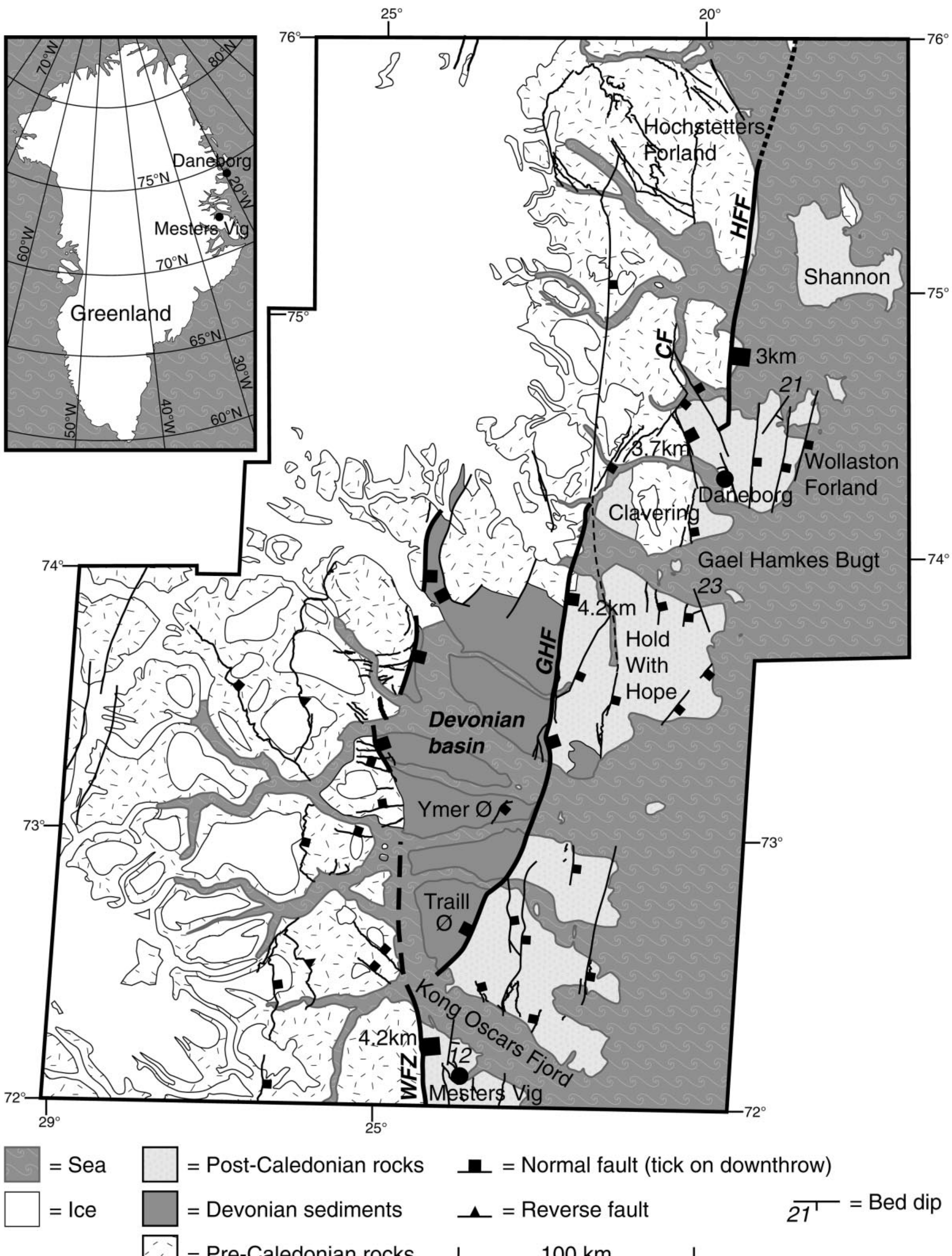

Fig. 1. Simplified geological map of NE Greenland, showing the Hold With Hope region, based on the Koch and Haller (1965) 1:250 000 scale maps. Information from Larsen and Bengård (1991) and from mapping by the Cambridge Arctic Shelf Programme has also been used. Only the faults that show significant displacement of stratigraphy are shown. Quaternary superficial deposits are not shown. Minimum estimates of fault throws using the Caledonian peneplane are shown. CF = Clavering Fault, GHF = Gauss Halvø Fault, HFF = Hochstetters Forland Fault, WFZ = Western Fault Zone. The Western Fault Zone does not extend as far north as shown by Koch and Haller (1965), probably dying out into en échelon oblique-slip faults on Ymer Ø (Larsen and Bengård, 1991).

metres or even kilometres occur between the Western Fault Zone and the Hochstetters Forland Fault, apparently linking these basin-margin faults. The largest and most important of these breaching faults appears to be the Gauss Halvø Fault, which forms a relay ramp with the Western Fault Zone in the south-west and with the Hochstetters Forland Fault in the north-east (Fig. 1). The Hold With Hope structure may therefore be regarded as a composite relay ramp. Although the faults within the relay ramp are dominantly synthetic to the basin-margin faults (e.g. Kelly et al., 1998, fig. 2), an antithetic (west-dipping) fault does occur near the northern end of the Western Fault Zone (Fig. 1; Larsen and Bengård, 1991). For example, the Hochstetters Forland Fault transfers displacement onto the Clavering Fault. Many faults in the Hold With Hope relay ramp mostly strike a few degrees clockwise of the Western Fault Zone and the Hochstetters Forland Fault, indicating linkage and stress refraction between the basin-margin faults. These are typical *breaching faults* (e.g. Peacock et al., 2000) that cause *hard-linkage* (e.g. Huggins et al., 1995) between the faults that control the relay ramp.

The Hold With Hope relay ramp, and the relay ramps in east Greenland described by Larsen (1988), have hanging wall beds that dip towards the footwall (c.f. Peacock and Sanderson, 1991, 1994; Huggins et al., 1995). In the model of Barnett et al. (1987), an isolated normal fault has hanging wall down-folding and footwall uplift (*transverse displacement-gradient folds*; e.g. Schlische, 1995; Faulds and Varga, 1998; Janecke et al., 1998, fig. 8g), with displacement on the fault decreasing to zero at the tips. Such folding could be exaggerated where two normal faults interact, in accordance with the numerical modelling of Willemse et al. (1996). It is possible that the south-westerly dip (i.e. with a component towards the footwall) of beds in the Hold With Hope structure is caused by the interaction between the hanging wall syncline of the Western Fault Zone and the footwall anticline of the Hochstetters Forland Fault, especially where these faults connect with the Gauss Halvø Fault.

The dip direction of faults within relay ramps appears to be partly related to the orientation of beds in a relay ramp, bed tilting in one direction being accommodated by faults dipping in the other direction. Mandl (1987, figs. 2–5) shows such an arrangement of faults dipping in the opposite direction to the tilting direction of beds. Bed tilting within the Hold With Hope structure has a component towards the footwall and is mostly accommodated by faults (> 50 m displacement) that are synthetic to the overstepping basin-margin faults. In contrast, the relay ramps described by Peacock and Sanderson (1999) show bed tilting towards the hanging wall that is accommodated by faults that are antithetic to the main overstepping faults. Faults in the Hold With Hope structure with millimetre- to metre-scale displacements have a much wider range of orientations (Fig. 2) and include faults that are antithetic to the Western Fault Zone and the Hochstetters Forland Fault. This wide range of orientations is typical of minor faults in relay ramps (e.g. Griffiths, 1980; Peacock and Shepherd, 1997).

4. The evolution of very large relay ramps

One hundred kilometres is a large distance across which interaction can occur between two normal faults. Nelson et al. (1992, figs. 6 and 8b) speculate, however, that interaction can occur between rift systems over distances as large as 1000 km. The geometry of the Hold With Hope relay ramp indicates that it evolved rather differently than the smaller relay ramps described by Peacock and Sanderson (1994, figs. 3 and 12). The Hold With Hope relay ramp is characterised by basin-margin faults with kilometres of displacement, beds that have a component of dip towards the footwall, and by synthetic minor faults within the relay ramp. To completely breach such a large relay ramp there would need to be tens of kilometres of dis-

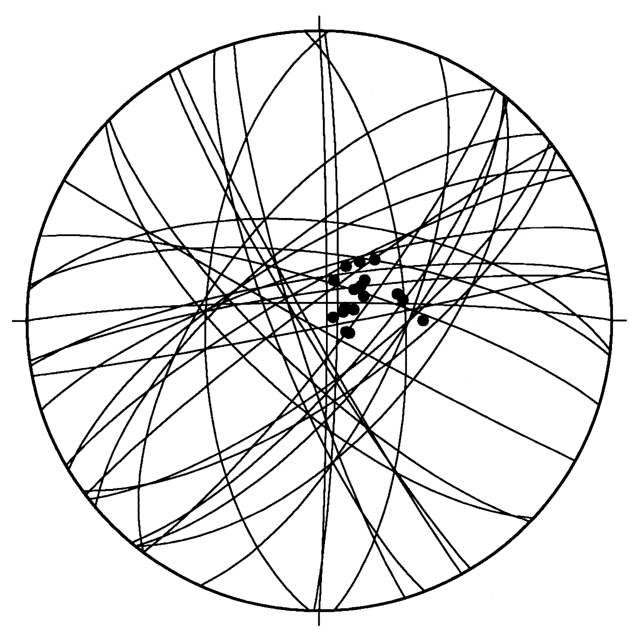

Fig. 2. Equal area stereogram with < 1 m displacement (great circles) and of poles to beds (circles) at Gulelvdal, Hold With Hope. The small faults show a much wider range of orientations than the regional-scale faults (Fig. 1), which appears to be common in relay ramps (e.g. Griffiths, 1980). The overall extension direction is, however, approximately east–west.

placement on the basin-margin faults, which seems unlikely on normal faults, as this would involve complete displacement of the lithosphere. The development of very large relay ramps, such as the Hold With Hope structure, may be arrested before breaching. It is probable that the smaller faults within the Hold With Hope ramp have more advanced relay ramps. An example occurs on Clavering Ø between the Clavering Fault and the Gauss Halvø Fault (Fig. 1).

There appears to have been a decrease in the spacing of the minor faults within the Hold With Hope structure as it evolved. From the Carboniferous to the Middle Jurassic, deformation involved fault blocks 10–50 km wide across strike, Late Jurassic to Cretaceous extension occurred on blocks 1–10 km wide, while Tertiary extension was even more distributed. This decrease in fault spacing through time may be related to the progressive break-down of the relay ramp, and to the progressive thinning of the crust. This illustrates how the mechanics of deformation may change as a large relay ramp evolves.

5. Possible three-dimensional geometry of the Hold With Hope relay ramp

Three models for the continuation of the Hold With Hope relay ramp into the lower crust are illustrated in Fig. 3. In the first model, the basin-margin faults are listric, linking downwards into a relatively shallow sub-horizontal detachment (Fig. 3a). Such a model was proposed for the smaller relay ramps further south along the east Greenland coast by Larsen (1988).

In the second model (Fig. 3b), the basin-margin faults pass downwards into one or more dipping shear zones, in the way suggested by Wernicke and Burchfiel (1982). If the basin-margin faults link downwards into a single shear zone, the shear zone may have a lateral ramp (Peacock et al., 1998, fig. 1). Evidence for this model comes from Hartz and Andresen (1995), who show that the Western Fault Zone passes downwards into an east-dipping extensional shear zone. This shear zone, the Fjord Zone Fault of Larsen and Bengård

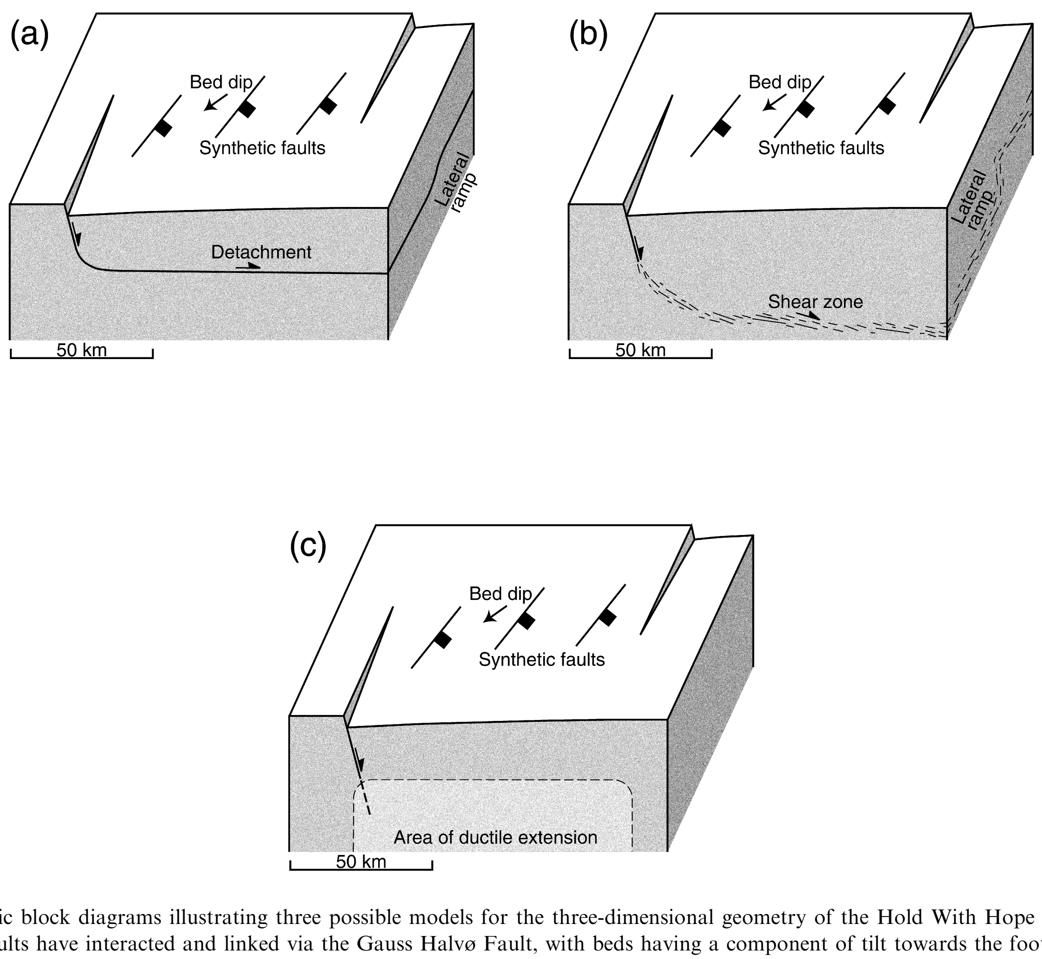

Fig. 3. Schematic block diagrams illustrating three possible models for the three-dimensional geometry of the Hold With Hope relay ramp. The basin-margin faults have interacted and linked via the Gauss Halvø Fault, with beds having a component of tilt towards the footwall, accommodated by synthetic normal faults. (a) The basin-margin faults connect downwards into a relatively shallow detachment (e.g. Larsen, 1988). (b) The basin-margin faults connect downwards into a more steeply dipping shear zone, possibly with a lateral ramp where the faults connect at depth (Peacock et al., 1998, fig. 1). (c) The basin-margin faults are not directly connected, but pass downwards into a distributed zone of extension (McKenzie, 1978).

(1991), is an extensionally reactivated Caledonian thrust that crops out further west.

In the third model (Fig. 3c), the basin-margin faults are not directly connected, but extend downwards into a zone of distributed extension. McKenzie (1978) suggests that normal faults commonly connect downwards into such zones of distributed deformation.

The crust thins from up to 48 km in the west, to only about 22 km beneath the post-Caledonian rocks of Jameson Land (Mandler and Jokat, 1998). This crustal thinning was caused by the post-Caledonian extension. Schlindwein and Jokat (1999, figs. 14 and 15) show that the thinning of the Moho shifts eastwards to the north of Kong Oscar Fjord, and speculate that this is accommodated by a non-exposed NW–SE-trending fault along Kong Oscar Fjord. Either of the three models for the lower-crustal geometry of the Hold With Hope relay ramp (Fig. 3) may, however, cause the change in geometry of the Moho reported by Schlindwein and Jokat (1999). Post-Devonian extension and crustal thinning would have been concentrated east of the Hochstetters Forland Fault, the Gauss Halvø Fault and the Western Fault Zone.

6. Implications for previous models

The beds in the Hold With Hope relay ramp have a component of dip towards the west (i.e. towards the footwall) and a component of dip towards the south (Fig. 2). The large relay ramps described by Larsen (1988) also have a component of dip towards the footwall, suggesting that the Hold With Hope relay ramp does not have a unique geometry. In contrast, beds in the much smaller relay ramps described by Peacock and Sanderson (1991, 1994) and by Huggins et al. (1995) typically have a component of dip towards the hanging wall. The smaller relay ramps described by Peacock and Sanderson (1994) and by Huggins et al. (1995) are from several different locations and settings, so also do not have unique geometries. This suggests that the behaviour of relay ramps is partly scale-dependant. Scale-dependence is understandable because, when relay ramps have widths of kilometres or tens of kilometres, they would affect the entire thickness of the Earth's crust.

Numerical modelling of the development of normal faults and relay ramps (Willemse, 1997; Crider and Pollard, 1998) use boundary element methods to show that the relay ramp surface has a component of dip toward the footwall (Willemse, 1997, fig. 13a; Crider and Pollard, 1998, fig. 9b), which is different from the field examples they are designed to represent, where the relay ramp surface has a component of dip towards the hanging wall (Willemse, 1997, figs. 13b and c; Crider and Pollard, 1998, fig. 9a). Thus far, published numerical models for the evolution of relay ramps have investigated only purely elastic deformation and do not account for more complex inelastic deformation that may cause the surface to dip towards the hanging wall. More sophisticated numerical models are needed to obtain a greater understanding of more evolved relay ramps. The existing numerical models appear similar to, and therefore may be applicable to, the Hold With Hope relay ramp. It is possible that the similarities between models and the Hold With Hope relay ramp may be coincidental, especially as such large structures depart from the homogeneous, isotropic, semi-infinite elastic body used in numerical models (J. Crider, personal communication).

7. Conclusions

1. The Hold With Hope relay ramp covers about 25 000 km^2, which is much larger than the relay ramps that have been described previously. This shows that interaction can occur between normal faults with a separation of about 100 km, and that this interaction can control the deformation at a regional scale. The Western Fault Zone and the Hochstetters Forland Fault overstep by about 100 km in the Hold With Hope region, linking via the Gauss Halvø Fault. These basin-margin faults have kilometres of displacement, faulting the pre-Caledonian basement against Upper Palaeozoic to Tertiary cover rocks. The Hold With Hope relay ramp probably initiated during the Devonian, but was at least partially breached by the Gauss Halvø Fault at the end of the Devonian or beginning of the Carboniferous, leaving an isolated Devonian basin around Ymer Ø. Deformation within the relay ramp consists of tilting of beds such that they have a component of dip towards the footwall, and a set of dominantly synthetic (east-dipping) normal faults.
2. Three possible models are suggested for the continuation of the Hold With Hope relay ramp into the lower crust (Fig. 3): (a) the basin-margin faults are listric, connecting downwards into a relatively shallow detachment; (b) the basin-margin faults connect downwards into a more steeply dipping shear zone, possibly with a lateral ramp; (c) the basin-margin faults are not directly connected, but pass downwards into a distributed zone of extension.
3. The component of bed dip towards the footwall and the dominance of synthetic faults in the Hold With Hope relay ramp are not typical of previously described smaller relay ramps (e.g. Peacock and Sanderson, 1994; Huggins et al., 1995). Smaller relay ramps are usually dominated by a component of bed dip towards the hanging wall and by anti-

thetic faults. This indicates that scale influences relay ramp geometry and development. Existing numerical models of relay ramps are probably only applicable to those that show limited interaction of normal faults, but may also be applicable to the large Hold With Hope relay ramp.

Acknowledgements

The Cambridge Arctic Shelf Program is thanked for funding the fieldwork and for providing logistic support. DCPP was funded by a NERC ROPA award to Rob Knipe. Juliet Crider, Roy Schlische and Manuel Willemse are thanked for their useful comments. This paper benefited greatly from comments by James Evans, Susanne Janecke and an anonymous reviewer.

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