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Reply to comment by K. Thomson on "The three-dimensional geometry and growth of forced folds above saucer-shaped sills" by D. M. Hansen and J. Cartwright

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We thank Thomson for his discussion of our recent paper (Hansen and Cartwright, 2006), and welcome the opportunity to re-iterate and clarify some of our key interpretations that led us to draw the conclusion that the features in our study area were forced folds overlying saucer-shaped sills. Seismic interpretation relies heavily on human perception, so it is not surprising to find that even with 3D seismic interpretation, there are differences of opinion.

The discussion by Thomson questions the interpretation by Hansen and Cartwright (2006) of a number of domal features imaged by 3D seismic data as forced folds formed above saucer-shaped sills. The domal structures in question have previously been interpreted as small volcanic centres (Thomson, 2005a,b) and it is this interpretation that Thomson sustains in his discussion. Hansen and Cartwright (2006) disagreed with this interpretation for the following reasons: (1) stratal reflections can be mapped across the structures in the sill-to-syn-intrusive interval, (2) the mapped folds are spatially coincident with underlying saucer-shaped sills, and (3) lava flow units within the sill-to-syn-intrusive interval have clearly been deformed during the development of the structures. In his discussion Thomson does not challenge this logic, but lists three criteria that should be met in order to confirm that the structures are intrusion-related forced folds as opposed to small volcanic centres; (1) clear evidence of folding, (2) no evidence of thickening of the potential volcanic sequence across the domal folds, and (3) no evidence of eruptions at the syn-intrusive surface. Thomson argues that these criteria are not met and concludes that the structures are small volcanic centres.

Mapping of internal reflections in the proposed sill-to-syn-intrusive interval of Hansen and Cartwright (2006) is challenging and, as suggested by Thomson, open to debate. Note that Thomson provides an alternative interpretation of Horizons B and C across the proposed Fold B (his Fig. 2) to that provided by Hansen and Cartwright (2006, their Fig. 4). Thomson's alternative correlation illustrates the inherent complexity of detailed stratal correlation in this heavily intruded area. The interpretation of Horizons B and C across the structures provided by Hansen and Cartwright (2006) suggests much less if any thickening of the Horizons B–C interval than indicated by the interpretation of Thomson. However, even if some thickening could be indisputably documented in the Horizons B–C interval across the structures, we argue that this has little bearing on the interpretation of the structures as intrusion-related forced folds. Any primary stratigraphic thickness changes in this interval on the scale indicated by Thomson could simply arise from local faulting, and they would be incorporated into any potential forced fold. The thickening illustrated in Thomson's Fig. 3, is an example of such local thickness variation that in our view, is coincidentally superimposed on the region of later folding. We simply reverse the logic employed by Thomson regarding thickness variations, and ask the question, do any of the cross-sections show stratal thickening that is sufficiently axio-symmetric and outward tapering in form to justify the interpretation of a volcanic centre, as opposed to a forced fold?

Thomson questions whether we are at all justified in our interpretation of the term fold, and presents his Fig. 3 to argue against this interpretation. This profile shows flat-lying NW-dipping reflections within the B–C interval across the structure we termed Fold C. A comparable box-like geometry in which the domal structure is clearly comprised of largely flat-lying reflections, is seen above the proposed Sill 1 (Fold A) of Hansen and Cartwright (2006, their Fig. 7a).

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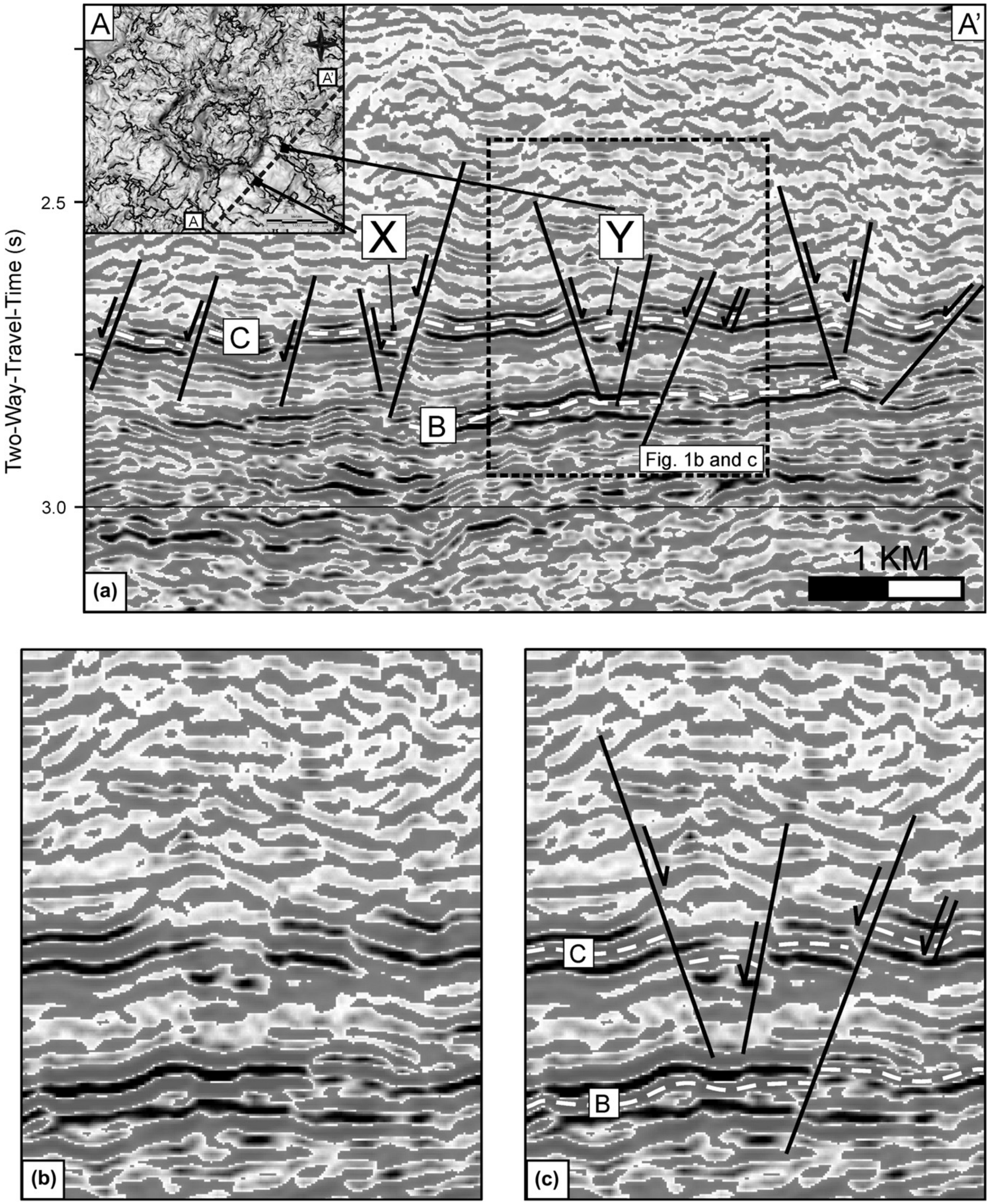

Fig. 1. (a) Seismic section showing the cross-sectional appearance of Horizon C immediately SE of the proposed Fold B of Hansen and Cartwright (2006). Horizon C is clearly offset by small, closely spaced, normal faults with small throws (ranging between 10 and 46 ms twtt at the level of Horizon C) and varying dip directions. X and Y indicate instances of opposite dipping faults that correspond to clearly imaged fault traces that are seen to radiate away from the proposed Fold B on a time-dip map of Horizon C (inset, Fig. 10 of Hansen and Cartwright, 2006) (b) uninterpreted and (c) interpreted enlarged seismic display of subset indicated in (a).

The geometry of forced folds developed above igneous intrusions is directly linked to the thickness distribution across and geometry of the intrusive body. Upward displacement of sediments above an igneous sill that exhibits a constant thickness across most of its lateral extent and is abruptly terminated at its lateral tips would give rise to a box-fold-like structure at the syn-intrusive surface. This geometry is known to develop above laccoliths (Johnson and Pollard, 1973), but may also develop above an intrusion that exhibits a near-constant thickness across its central part and tapers towards its lateral tips if it has a concave upward shape that results in the vertical thickness of the tapering tips to be comparable to that of the central part of the intrusion. We observe a range of fold styles (compare, for example Thomson's Figs. 2 and 3), from box-like to concentric, and suggest that lateral variation in intrusion thickness combined with local strain and thermal effects within the host units are the likely explanation of this variation.

Thomson interprets a radiating spoke pattern imaged on Horizon C above our proposed Fold B, and to a lesser extent above our proposed Fold C (Thomson's Fig. 4) as lava flows originating from his interpreted volcanic centres. In contrast, Hansen and Cartwright (2006) interpreted these features as polygonal faults forming a radial pattern across the crest of the proposed Fold B. This interpretation is further supported by Fig. 1 in which a seismic section that crosses several of the radiating features clearly demonstrates that the discontinuities seen on the time-dip map and the edge-like features imaged by Thomson are linked to offsets of Horizon C by small normal faults with offsets of a few tens of metres (10–46 ms twtt). These small faults can be observed over the greater part of the study area, and exhibit the classical random strike orientations of polygonal fault systems (Cartwright and Lonergan, 1996). Whilst we do not think that lava flows are present at the level of Horizon C across the crest of our proposed Fold B or C we emphasise that a lava flow unit is present in the area surrounding Folds B and C at the stratigraphic level of Horizon B, demonstrating a clear spatial and temporal association between intrusive and extrusive volcanism in the area.

The domal structures are all developed immediately overlying high amplitude concave upwards reflections and correctly interpreting the origin of these is of crucial importance to establishing the origin of the domal structures. Hansen and Cartwright (2006) interpreted them as saucer-shaped igneous sills based on their clear similarity with saucer-shaped sills that are widely recognised on 3D data from the NE Atlantic (e.g. Hansen et al., 2004), including the study area (Thomson, 2005b). Thomson (2005a,b) originally interpreted these features as ring faults confining areas of chaotic basaltic morphology. However, we note that Thomson has since changed his interpretation and now concurs with an interpretation of these features as sills, which strongly adds to the argument of Hansen and Cartwright (2006). Thomson does not explain how a volcanic centre could be directly underlain at such shallow depth by a major sill, although from simple depth considerations the sills could not be considered as magma chambers for the putative volcanic cones.

Thomson makes an excellent point that the inflation of such thick sill bodies should lead to the development of inward dipping reverse faults around the sill margins. We suspect that such structures exist around the peripheries of the sills, tipping out upwards close to the inflection points at the margins of the domal folds within the B–C interval. The challenges of stratal correlation in this study area alluded to earlier, however, prevent a robust interpretation of reverse offsets, so this issue remains unresolved. The schematic kinematic model (Fig. 14 of Hansen and Cartwright, 2006) challenged by Thomson does indeed show normal faulting within the fold crests. We omitted to explain this in detail, but noted that the extensional faulting of the crest occurs simply to accommodate the outer arc stretching of the forced fold, and this in no way precludes the theoretically predicted reverse faulting on the flanks. Both fault styles could develop synchronously.

In conclusion, we have addressed each of the issues raised by Thomson and have found no reason to alter our original interpretation. The domal structures resemble intrusion-related forced folds imaged by 3D seismic data throughout the North Atlantic Igneous Province (e.g. Trude et al., 2003). We suggest that it is more difficult to reconcile the resemblance between the seismic expression of these features with classical cross-sections of volcanic centres (cf. Press and Siever, 1994; Walker, 2000). Our interpretation relies on the identification of two separate features, namely the saucer-shaped sills, and the immediately overlying domal folds. Neither of these elements by themselves is particularly contentious from a seismic interpretation viewpoint: there are many published examples to act as comparators. It seems a straightforward matter, therefore to judge each in turn, and having done so, it is hard to escape the conclusion that the sills and folds are causally related.

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Dorthe Møller Hansen*,[1]
Joe Cartwright
3DLab, School of Earth,
Ocean and Planetary Sciences, Cardiff University,
Main Building, Park Place,
Cardiff CF10 3YE, Wales, UK
*Corresponding author. Tel.: +44 161 275 7679.
E-mail address: dorthe.hansen@manchester.ac.uk
(D.M. Hansen)
[1]Present address: North Africa Research Group,
School of Earth, Atmospheric and Environmental Sciences,
University of Manchester,
Williamson Building,
Oxford Road,
Manchester M13 9PL, UK.

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