A reassessment of the proposed 'Lairg Impact Structure' and its potential implications for the deep structure of northern Scotland: a discussion

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The interpretation of the Stac Fada Member of the Stoer Group of NW Scotland as a proximal ejecta blanket of late Mesoproterozoic age (Amor *et al.* 2008) has led to the search for the impact crater from which it originated. One prominent suggestion has been that this crater lies buried beneath east-central Sutherland, broadly centred on the village of Lairg (Fig. 1; Simms 2015). Simms & Ernstson (2019) develop this suggestion by interpreting the well-known negative anomaly that dominates the Bouguer gravity map of northern Scotland to represent the roots of this crater. However, they qualify their interpretation, noting that the geology at the Stac Fada outcrops implies a more distant crater location, and go on to propose hitherto unreported "crustal shortening structures" to explain this discrepancy. In doing so they challenge current understanding of structural evolution in the Moine Thrust Belt and for crustal structure in NW Scotland. The purpose of this discussion is to demonstrate not only that the Simms & Ernstson (2019) proposals are incompatible with the known structural geology of northern Scotland, but that the geology of the Moine Thrust Belt renders the Lairg site to be one of the very few places that can be regarded as a highly unlikely source for the Stac Fada impact rocks. Internal Earth processes, rather than extra-terrestrial interventions, should be sought as explanations for the "Lairg gravity low". A more general aim is to show, through this discussion, that making small changes to tectonic models commonly carry unintended consequences for geological interpretations that can go unrecognised if only illustrated on unscaled sketches.

The Moine Thrust Belt as a crustal dredging machine

As recognised by Simms & Ernstson (2019) amongst many others, any Precambrian structure, whether or not an impact crater, that lies beneath east-central Sutherland, has been buried by the Moine thrust sheet during Scandian tectonism (c. 430-410 Ma; see Thigpen et al. 2013, and references therein). These interpretations require the Moine Thrust, which carries its eponymous thrust sheet, to follow a relatively shallow-dipping trajectory beneath northern Scotland. In this fashion, the Precambrian basement (chiefly the Lewisian complex) that outcrops to the west of the surface trace of the thrust could continue to depth. It is within this ancient metamorphic basement that any crater would need to be preserved. That the Moine Thrust follows such a trajectory (Fig. 2a) relies on (1) the restoration of thrust-stacked rocks within the Moine Thrust Belt, (2) the deduction that the Moine Thrust Sheet was emplaced onto these rocks before they were significantly stacked and that (3) the Moho beneath northern Scotland has not been reset. If these requirements are accepted, then Lewisian rocks preserved in thrust sheets in the Moine Thrust Belt of the Assynt district have been derived directly from the proposed impact site. As Amor et al. (2019) note, they contain no such evidence.

Simms & Ernstson (2019) suggest that structural interpretation in the Moine Thrust Belt is unimportant for their deliberations. Actually, it is critical. The Moine Thrust Belt contains Lewisian rocks, unconformably overlain both by Cambrian and Torridon Supergroup strata, within thrust sheets that were translated to the WNW. The Lewisian thrust sheets never exceed thicknesses of 1 km, and are generally significantly less. In Assynt, the main slices of allochthonous Lewisian basement constitute the Glencoul and Ben More Thrust Sheets (Fig. 1). All workers since their discovery and mapping by Peach et al. (1907; Coward et al. 1980; Elliott & Johnson 1980; Butler & Coward 1984, Butler et al. 2006) restore these thrust sheets of Lewisian basement to several tens km to the ESE of their current location. This is based on offsets of Precambrian structures from their position in the Caledonian foreland. Ramsay (1969) proposed that the Kinlochewe Thrust Sheet, in the southern part of the thrust belt, experienced at least 40 km displacement towards WNW. So, the structural style, of the accretion and translation of thin sheets of basement with its authochthonous cover beneath the over-riding Moine Thrust, is common along the thrust belt.

Displacements of the magnitudes implied by the offset sheets of Lewisian rocks are supported by restorations of the highly imbricated stacks of Cambrian strata which typify much of the northern part of the Moine Thrust Belt. The Foinaven transect (located on Fig. 1) restores to a pre-thrusting width in excess of 50 km (Butler & Coward 1984). A similar value has been estimated for imbricate systems in southern Assynt (located on Fig. 1; Coward 1985). That these imbricate systems only contain Cambro-Ordovician sediments and collectively record substantial lateral displacements, requires that the crust upon which they lay before thrusting, must remain at depth and ESE from the outcrop trace of the thrust belt. It is a demonstration of thin-skinned tectonics not, as Simms & Ernstson (2019) state, an assumption of this tectonic style. Furthermore, it is a requirement of their proposal that the “Lairg gravity low” resides in a structure of Precambrian (and therefore pre-thrusting) age in the crust of northern Scotland. Adopting the foreland crustal thickness of 28km and assuming that the Moho beneath northern Scotland originated in the Precambrian and has not been “reset” since, requires northern Scotland to be underlain by the crustal roots of the Moine Thrust Belt.

Simms & Ernstson (2019) argue that a crater of the size and location they infer from the “Lairg gravity low” is too close to the outcrops of its ejecta blanket on the modern west coast (Fig. 1) given their facies and deformation state. But there are more fundamental problems. The western edge of the Lairg gravity low, as defined by Simms & Ernstson (2019), abuts the eastern edge of the Assynt culmination (note that their fig 5 miss-places the Moine Thrust through the Assynt district, confusing its trace with that of the Sole thrust, up to 10 km further west). A displacement of less than 10 km on the Ben More thrust sheet places its origins on the flanks of their putative crater. A more plausible displacement of 30-40 km restores the Ben More sheet to ground zero. Yet within these Lewisian thrust sheets of Assynt, of impact structures there is not a trace.

Consider the internal structure of the Ben More sheet. It largely comprises gneisses that preserve granulite facies metamorphic assemblages, with complex metaigneous structures cross-cut by mafic dykes that preserve barely deformed primary intrusive relationships and orientations equivalent to the early Mesoproterozoic “Scourie” dyke swarm. Locally these structures are deformed by narrow shear zones and faults that also deform overlying Cambrian strata. So the Ben More Thrust Sheet preserves, in exquisite detail, the geological relationships typical of the “Central Block” of the Lewisian of the foreland (Coward et al. 1980). The striking preservation of geological relationships in allochthonous thrust sheets that can be found in the foreland is undisputed. Beyond being translated in a thrust sheet, the Lewisian rocks have not been deformed in any significant fashion since the early Mesoproterozoic, let alone show any evidence of impact structures or solidified impact melt, prior to Scandian thrusting. The crustal dredging machine of the Moine Thrust Belt found only intact basement without impactites or their structures.

<u>Deep-rooting thrusts beneath northern Scotland?</u>

To overcome the current proximity of the proposed impact site at Lairg and the Stac Fada outcrops on the west coast (Fig. 1), to which we must also add the present-day outcrops of the Ben More Thrust Sheet, Simms & Ernstson (2019) propose a hitherto unrecognized crustal-scale thrust. On this structure they envisage displacements sufficient to telescope the distance between crater and ejecta blanket and, if it is to address the preservation of Lewisian geology, contain the restored position of the Ben More Thrust Sheet. They suggest several tens km lateral displacement on a late thrust, rooting beneath, and carrying, the “Lairg gravity low”.

Obviously, no such structure exists at outcrop so it would need to have been truncated by the Moine Thrust. And to avoid the Ben More Thrust Sheet sampling impact rocks, the Moine Thrust would have to post-date the Ben More and other structures in the Moine Thrust Belt. Although local parts of the Moine Thrust show evidence for these late movements, they do not offer sufficient continuity to have entirely decapitated a crustal-scale thrust sheet (e.g. Butler 2004). Indeed, the trace of the Moine Thrust around Assynt, where it is folded into a broadly antiformal structure, strongly suggests that it pre-dates thrust sheet stacking (including the Ben More sheet) in this area (e.g. Elliott & Johnson 1980, and others since). That emplacement of the Moine Thrust Sheet predates thrust-sheet stacking and imbrication in the rocks of the underlying Moine Thrust Belt is supported by the evolution of fault rocks (from mylonitic to increasingly cataclastic) from east to west across the structures.

But is a crustal scale thrust, active after the emplacement of the Ben More Sheet but before final motions on the Moine thrust, even plausible? Simms & Ernstson (2019) cite the crustal duplex model of Soper & Barber (1982; and its precursor propositions by Watson & Dunning 1979) to support their late thrust model. However, for Soper & Barber, the Moine Thrust represents the western limit of crust that experienced substantial ductile deformation during the Caledonian orogeny. Certainly, any Proterozoic structures in this crust would have been thoroughly reworked and therefore would not be expected to have retained the original crater shapes. However, while the crustal duplex, in which thrusts cut down to the Moho, may be appropriate elsewhere in the orogen (e.g. Brewer & Smythe 1984), understanding of the structural evolution in the Moine Thrust Belt, published after this model was proposed and fully discussed elsewhere (Butler & Coward 1984; Butler 2010), render this model highly unlikely for mainland Scotland. Simms & Ernstson (2019) are correct to note that thin-skinned thrusting is not the only way that the crust deforms in contraction, either globally or elsewhere within the Caledonian system. However, to achieve significant lateral translations (heaves) on steeply-dipping reverse faults requires those structures to have substantial throws. To achieve lateral translations of several tens km, as postulated by Simms & Ernstson (2019), would uplift almost an entire crustal thickness (Fig. 2b). This thrust would need to lie east of the existing outcrops of the Moine Thrust Belt to avoid appearing at outcrop, and for it later to be decapitated by the Moine Thrust itself. Rather than sketch this schematically (c.f. Simms & Ernstson 2019), we can model the geometry to test its plausibility.

Consider a rotational thrust climbing a crustal ramp (Fig. 2c). Using the general ramp geometries proposed by Fischer & Coward (1982, and many others since), simple trigonometry relates the width of an “exclusion zone” for upper crust preserved after thrusting and lying level with the position in the footwall, to the height and inclination of the ramp. A ramp of 25 km height and at an angle of 35° requires an “exclusion zone” in excess of 43 km wide. So, any preserved Lewisian upper crust, within which a putative crater may lie, cannot be closer than 43km of the trace of the thrust ramp. In our specific case, crustal thrusts cannot bring a crater within 43 km of the trailing edge of the Moine Thrust Belt. Notwithstanding the absence of any outcrop geology to support the notion of large-displacement crustal ramps, had the crustal shortening structures invoked by Simms & Ernstson (2019) existed below the Moine Thrust Sheet, they would have destroyed their proposed crater site.

<u>“Lairg gravity low” is an unlikely late Meosproterozoic impact crater</u>

Collectively, the geological evidence argues strongly against the crust beneath the village of Lairg containing a Mesoproterozoic impact crater. Indeed, other studies argue that the Stac Fada rocks were derived from a broadly NW direction (e.g. Amor et al. 2019). So what is the geological explanation of the negative Bouguer gravity anomaly in central Sutherland? Butler & Coward (1984) argue that there are slightly thickened Moine Rocks here, preserved in the excavated footwall ramp from which the Lewisian sheets of the Moine Thrust Belt were derived. Leslie et al. (2010) developed this proposal to model the gravity anomaly, adding a buried late Caledonian granite. This explanation satisfies both gravity data and our discussions above. It is interesting to note that the Lairg area would certainly contain the roots of the Borrolan igneous complex (Fig. 1), now translated into the Moine Thrust Belt of southern Assynt (e.g. Elliott & Johnson 1980; Coward 1985). While the site is a highly unlikely location for the crater from which the Stac Fada ejecta blanket was sourced, we do concur with Simms & Ernstson (2019) that further investigations of crustal structure in northern Scotland, and indeed elsewhere in the British Isles, is sorely needed.

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Figures

Fig. 1 Simplified geological map of northern Scotland, with locations discussed in the text, together with the location of the contested “Lairg impact crater”. X-Y is the location of the section line for Fig. 2a.

Fig. 2 a) Scaled crustal cross-section through northern Scotland (X-Y on Fig. 1). b) Geometry of a crustal scale thrust, as envisaged and schematically illustrated by Simms & Ernstson (2019) but here drawn to scale to illustrate the separation of upper crustal rocks across an elevated crustal section. c) The geometric model from which the width of an “exclusion zone” can be calculated – within which a putative impact crater would be lost by deformation, erosion or decapitation by (hypothetical) late motion on the Moine Thrust. Collectively these diagrams illustrate the implausibility that the “Lairg gravity low” represents a Precambrian impact crater.

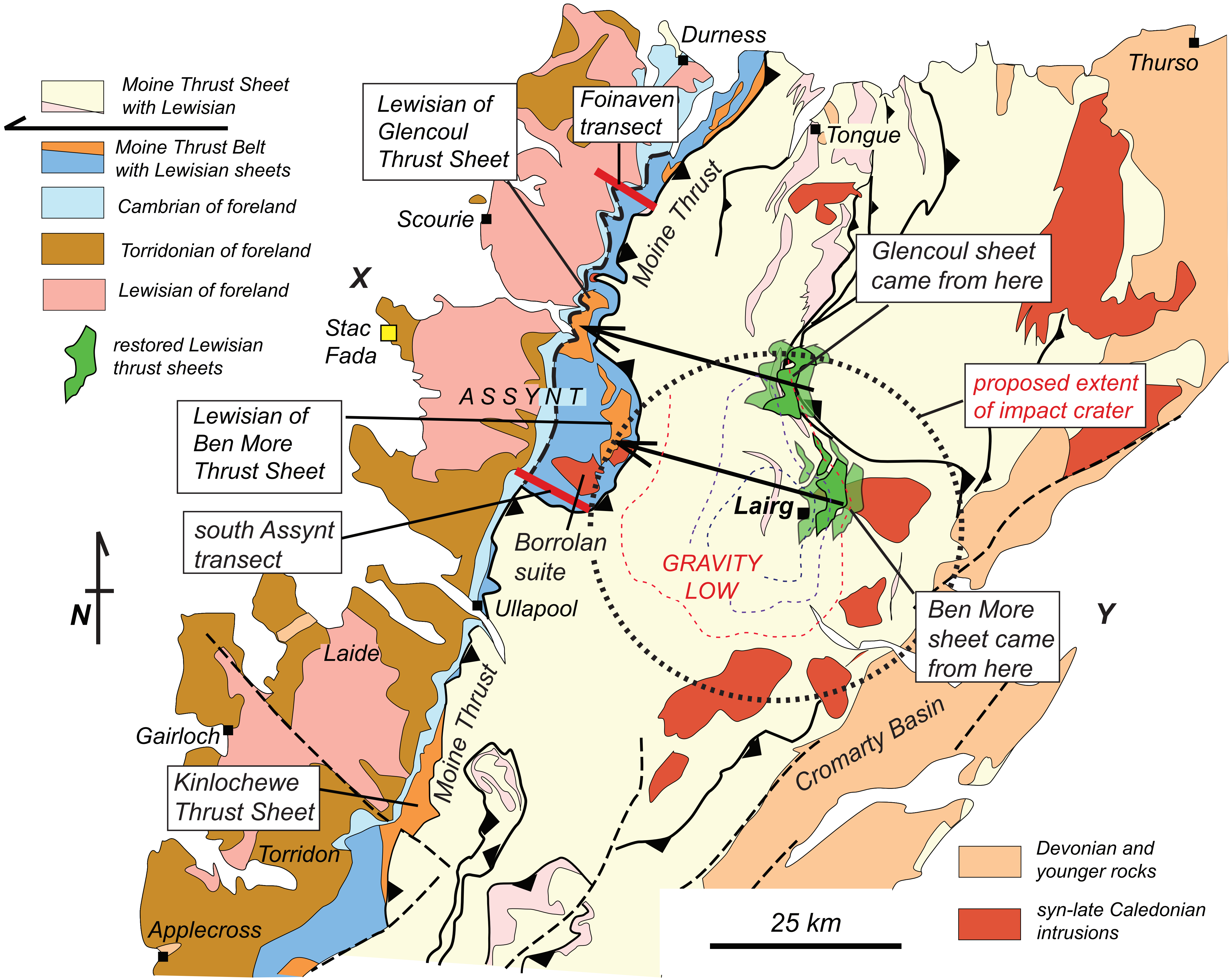
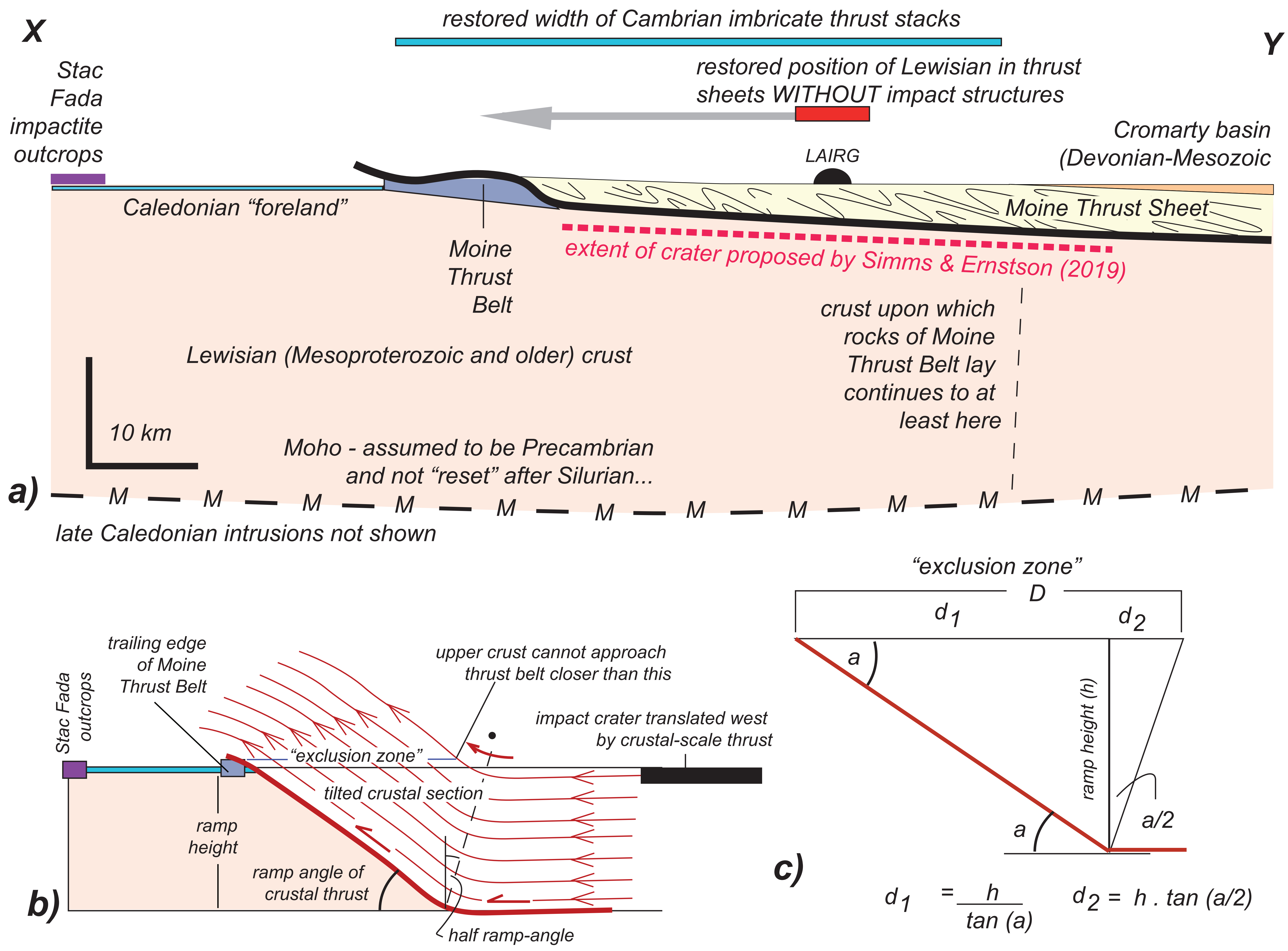

Moine Thrust Sheet with Lewisian
Moine Thrust Belt with Lewisian sheets
Cambrian of foreland
Torridonian of foreland
Lewisian of foreland
restored Lewisian thrust sheets
Durness
Thurso
Tongue
Scourie
Lewisian of Glencoul Thrust Sheet
Foinaven transect
Moine Thrust
Glencoul sheet came from here
X
Stac Fada
ASSYNT
proposed extent of impact crater
Lewisian of Ben More Thrust Sheet
south Assynt transect
Borrolan suite
Lairg
GRAVITY LOW
N
Ullapool
Ben More sheet came from here
Y
Laide
Gairloch
Moine Thrust
Cromarty Basin
Kinlochewe Thrust Sheet
Torridon
Applecross
25 km
Devonian and younger rocks
syn-late Caledonian intrusions

Fig 2



X
Y
restored width of Cambrian imbricate thrust stacks
Stac Fada impactite outcrops
restored position of Lewisian in thrust sheets WITHOUT impact structures
Cromarty basin (Devonian-Mesozoic
LAIRG
Caledonian “foreland”
Moine Thrust Sheet
Moine Thrust Belt
extent of crater proposed by Simms & Ernstson (2019)
crust upon which rocks of Moine Thrust Belt lay continues to at least here
Lewisian (Mesoproterozoic and older) crust
10 km
Moho - assumed to be Precambrian and not “reset” after Silurian...
a)
M M M M M M M M M M M M M
late Caledonian intrusions not shown
“exclusion zone”
D
d1
d2
a
ramp height (h)
a
a/2
c)
d1 = h / tan (a)
d2 = h . tan (a/2)
trailing edge of Moine Thrust Belt
upper crust cannot approach thrust belt closer than this
Stac Fada outcrops
impact crater translated west by crustal-scale thrust
“exclusion zone”
tilted crustal section
ramp height
ramp angle of crustal thrust
half ramp-angle
b)