GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G48079.1

Manuscript received 29 June 2020
Revised manuscript received 18 August 2020
Manuscript accepted 22 August 2020

A bigger splat: The catastrophic geology of a 1.2-b.y.-old terrestrial megaclast, northwest Scotland

Z. Killingback[1], R.E. Holdsworth[1], R.J. Walker[2], S. Nielsen[1], E. Dempsey[3] and K. Hardman[1,3]
[1]Department of Earth Sciences, Durham University, Durham DH1 3LE, UK
[2]School of Geography, Geology, and the Environment, University of Leicester, Leicester LE1 7RH, UK
[3]Department of Geography, Environment and Earth Sciences, University of Hull, Hull HU6 7RX, UK

ABSTRACT

Rockfalls are relatively little described from the ancient geological record, likely due to their poor preservation potential. At Clachtoll, northwest Scotland, a megaclast (100 m × 60 m × 15 m) of Neoarchean Lewisian gneiss with an estimated mass of 243 kt is associated with basal breccias of the Mesoproterozoic Stoer Group. Foliation in the megablock is misoriented by ~90° about a subvertical axis relative to that in the underlying basement gneisses, and it is cut by fracture networks filled with Stoer Group red sandstone. Bedded clastic fissure fills on top of the megablock preserve way-up criteria consistent with passive deposition during burial. Sediment-filled fractures on the lateral flanks and base show characteristics consistent with forceful injection. Using numerical calculations, we propose that rift-related seismic shaking caused the megablock to fall no more than 15 m onto unconsolidated wet sediment. On impact, overpressure and liquefaction of the water-laden sands below the basement block were sufficient to cause hydrofracturing and upward sediment slurry injection. In addition, asymmetrically distributed structures record internal deformation of the megablock as it slowed and came to rest. The megablock is unrelated to the younger Stac Fada impact event, and represents one of the oldest known terrestrial rockfall features on Earth.

INTRODUCTION

Terrestrial rockfalls are features formed at Earth's surface due to gravity-driven downslope movement of material (e.g., Terzaghi, 1950; Varnes, 1978). Given their association with erosional processes and poor preservation potential, it is unsurprising that they are relatively undescribed from the geological record. Where recognized, large ancient examples of "megaclasts" or "megablocks" of relatively intact bedrock >10 m diameter (Bruno and Ruban, 2017) are mostly associated with marine subduction-accretionary settings (olistostromes; Festa et al., 2016). Examples from onshore and/or near-shore terrestrial settings are relatively uncommon, though some are notably famous (e.g., the "Fallen Stack" of Devonian sandstone in shoreline Jurassic deposits, Moray Firth Basin, Scotland; Pickering, 1984). In this paper, we describe a megaclast of Lewisian gneiss—the Clachtoll megablock (CM)—that was found associated with marginal alluvial-lacustrine clastic deposits from the basal part of the Neoproterozoic Stoer Group in northwest Scotland (Fig. 1A). A diverse set of geological structures is preserved recording the fall of the block onto water-laden unconsolidated sediment, its internal deformation, and incipient fragmentation. The findings have implications for the recognition of localized catastrophic events in the ancient geological record.

GEOLOGICAL SETTING

The Stoer Group is a red, alluvial-fluvial-lacustrine sequence laid down in a continental rift basin (e.g., Stewart, 2002; Kinnaird et al., 2007). The oldest part of the succession, the Clachtoll Formation, has a basal breccia-conglomerate that infills an irregular land surface with paleohills (>150 m high) and steep-sided gullies eroded into the underlying Lewisian gneiss (Fig. 1B; Stewart, 2002). Following deposition, the strata acquired a regional dip of ~15°–20° to the west, possibly due to displacements along the north-south–striking Coigach fault (Fig. 1A; Stewart, 1993). The Mesoproterozoic age of the Stoer Group is based on Ar-Ar ages of authigenic potassium feldspars in hydrothermal veins within the Stac Fada Member (1177 ± 5 Ma; Parnell et al., 2011), which lies ~300 m stratigraphically up section from the Clachtoll Formation base (Stewart, 1993).

The Neoarchean Lewisian basement rocks are interbanded, medium-grained, amphibolite-facies, acid, intermediate, and mafic orthogneisses, with a steeply dipping ESE-WNW foliation related to development of the Paleoproterozoic (ca. 2400–1650 Ma) Canisp shear zone (CSZ; Fig. 1A; see Appendix I in the Supplemental Material[1]; Attfield, 1987). Local foliated ultrabasic intrusions described as picrite by Tarney (1973) are also present (Fig. 1B). Gneiss clasts in the clast-supported Clachtoll Formation basal conglomerate-breccia are subrounded to subangular and up to 2 m across, surrounded by a medium- to coarse-grained sandstone matrix.

GEOLOGY OF THE CLACHTOLL MEGABLOCK

The Lewisian gneiss constituting the CM forms an elongate hill up to 18 m high (Figs. 1B and 1C). In a gully on its southeast flank, the megablock overlies 1–2 m of basal breccia-conglomerate of the Clachtoll Formation, which sits unconformably on Lewisian basement (Fig. 2A). The CM is lithologically identical to the gneisses in the underlying autochthonous basement, but it differs in two important ways: (1) The steeply dipping foliation strikes NNE-SSW and lies at 90° to the foliation in the underlying Lewisian gneiss and CSZ (Figs. 1B and 2A); and (2) it is cut by large numbers of millimeter- to decimeter-wide fractures filled with mostly fine- to

[1]Supplemental Material. Appendices: additional maps and sections (I); field photographs (II); solid-collision equations (III); calculation results (IV); and Brazilian Test data (V). Please visit https://doi.org/10.1130/GEOL.S.12935039 to access the supplemental material, and contact editing@geosociety.org with any questions.

CITATION: Killingback, Z., et al., 2020, A bigger splat: The catastrophic geology of a 1.2-b.y.-old terrestrial megaclast, northwest Scotland: Geology, v. 49, p. , https://doi.org/10.1130/G48079.1

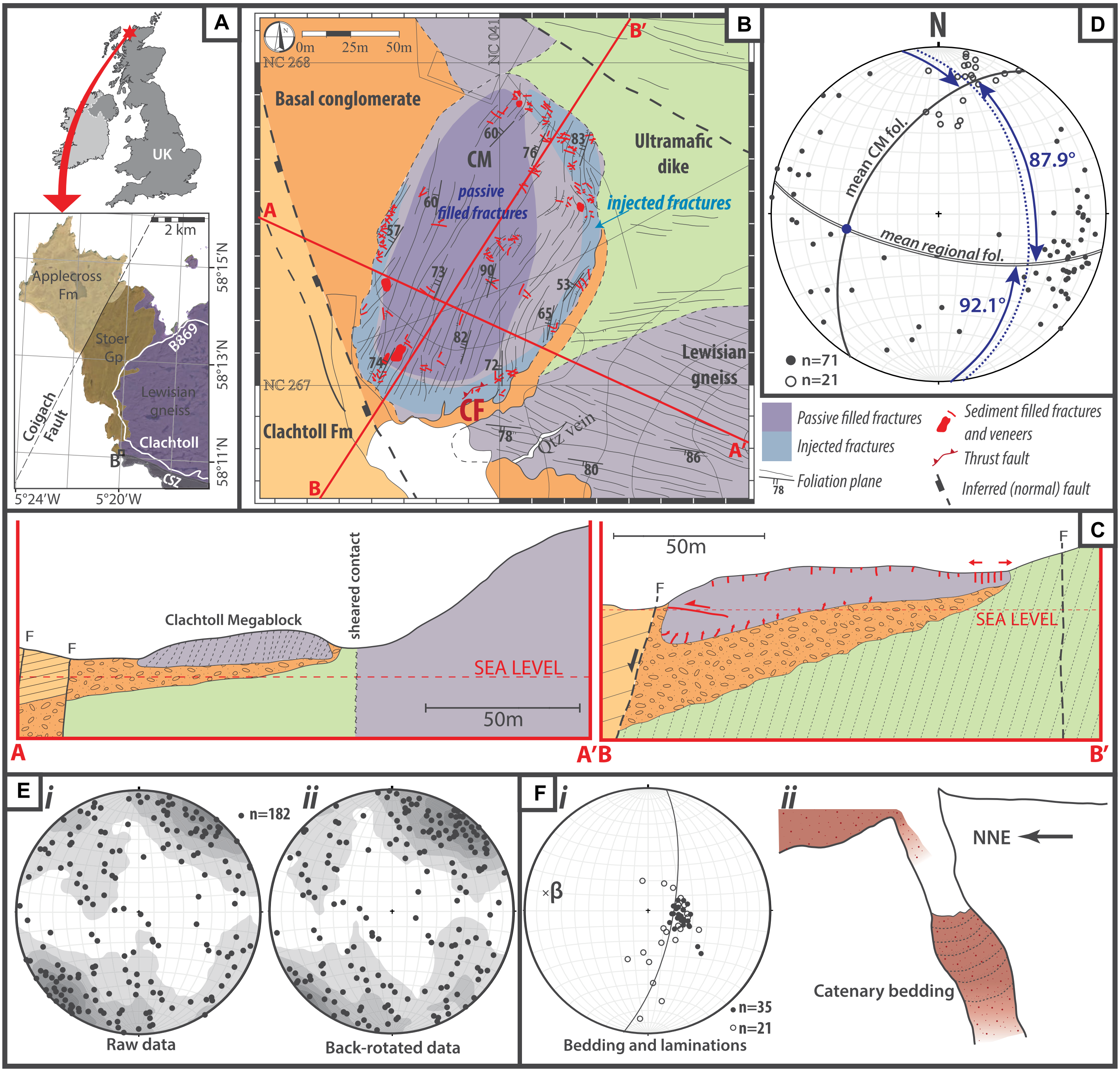

Figure 1. **(A) Location map. CSZ—Canisp shear zone. (B) Geological map of the Clachtoll megablock (CM) in northwest Scotland, showing locations of sediment-filled fractures (after Killingback, 2019). CF—Clachtoll fault; Qtz—quartz. (C) Northwest-southeast and northeast-southwest cross sections through CM; locations are shown in B. F—fault. (D) Lower-hemisphere stereoplot showing misorientation of poles to megablock foliation (solid) relative to regional basement foliation (open). (E) Poles to sediment-filled fractures in the CM (i) at present day and (ii) with postdepositional tilt of Stoer Group removed. (F) Stereoplot of (i) present-day poles to bedding in local Stoer Group sequence (solid) and in group A passive fills (open). Latter set is distributed along partial girdle with gently WNW-plunging beta axis. (ii) Geological sketch to explain curviplanar form of bedding laminations in group A fissure fills.**

medium-grained red sandstone (Figs. 1B and 2–4). The sedimentary fills have been interpreted previously as near-surface fissure fills and injections formed during rifting (Beacom et al., 1999). The age of the sandstone fills has been constrained independently by paleomagnetic analysis (Dulin et al., 2005), which indicated a Stoer Group–age magnetization.

Our detailed mapping shows that the CM has an elliptical shape in plan view, measuring 100 m × 60 m, with its long axis oriented NNE-SSW parallel to the internal basement foliation (Fig. 1B). Its vertical dimension (thickness) is estimated at ~15 m from existing exposures, suggesting a tabular shape in three dimensions (Fig. 1C) and a total volume of ~90,000 m³. Stratum contours constructed on the inferred outcrop trace of the basal surface of the block suggest that it presently dips 25°SW at its southern end, decreasing to 10° at the northern end (see Appendix I).

A few sediment-filled fractures lie parallel to the preexisting foliation in the gneisses (e.g., Fig. 2B); the majority crosscut the

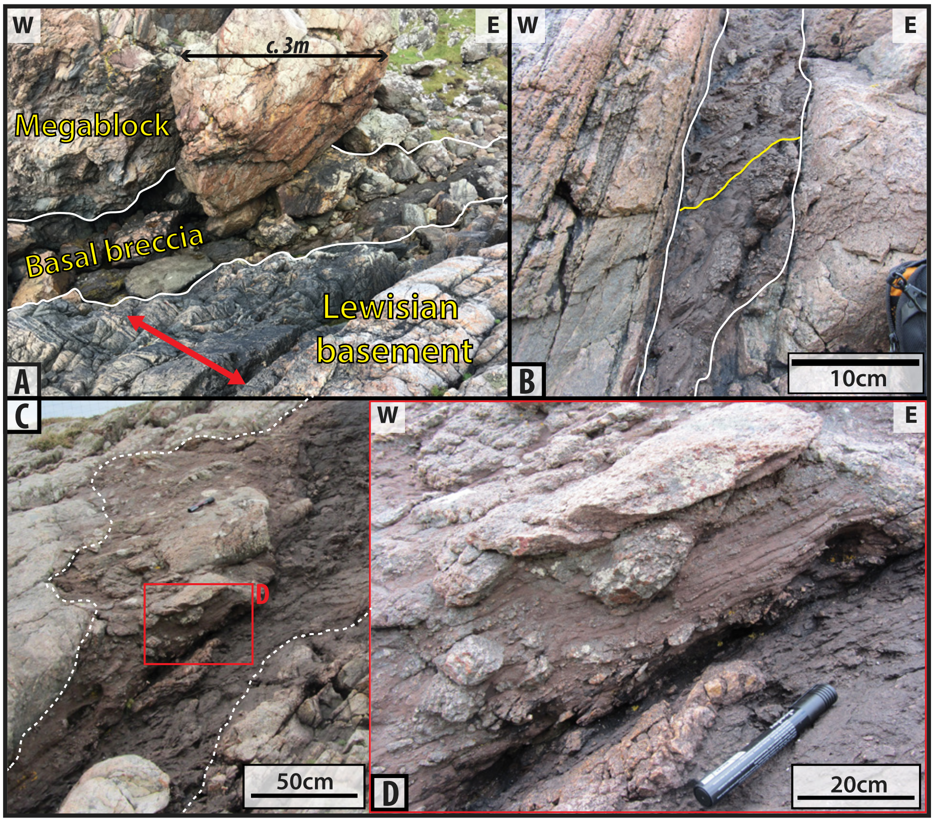

Figure 2. Contact relationships and group A sediment-filled fracture morphologies from the Clachtoll megablock (CM), northwest Scotland. (A) Lewisian megablock overlying basal breccia, which unconformably overlies Lewisian basement gneisses with northwest-southeast foliation (red arrow). View looking north, southeast side of the CM. (B,C) Foliation-parallel (B) and irregular crosscutting (C) group A fills with gently west-dipping bedding laminations consistent with passive filling from above; upper surface of the CM. (D) Close-up of area in red box in C.

preexisting foliation, with steep dips and a dominantly northwest-southeast trend (Fig. 1E, i). This trend is not fundamentally altered by removing the postdepositional tilt of the Stoer Group (Fig. 1E, ii). Offsets of host-rock layers preserve apparent extension-mode opening directions that are dominantly, though not exclusively, subparallel to the long axis of the CM; these are especially prevalent toward the northern end of the block (Figs. 1B and 4A). All sandstone fills have sharp contacts with the host gneisses, and three morphologies are recognized, here termed groups A, B, and C, which show distinct distributions in the CM (Fig. 1B). Group A is composed of irregular fractures filled by bedded, fine to coarse sands, displaying sedimentary structures including lamination and clast imbrication (Figs. 2B and 2C). These fills are only found on the upper part of the CM. Group B is made up of mostly planar, fine- to medium-grained, sand-filled fractures frequently containing matrix-supported clasts of host gneiss (Figs. 3A–3C). Group C consists of irregular zones of intensely fragmented gneiss containing planar to curviplanar clastic fills, forming complex networks with variably sized and oriented pockets of clastic material not clearly confined to individual fractures (Fig. 3D). Groups B and C are restricted to the lateral and lower contacts of the CM (see Appendix II), with the third group being particularly widespread close to the base of the block. The sandstone filling both groups is similar to the matrix of the basal conglomerate, but it is finer grained and lacks sedimentary laminations.

A small, 45°ENE-dipping fault is exposed on the southeast side of the CM, with an apparent left-lateral offset of ~3 m: the "Clachtoll fault" of Beacom et al. (1999). The hanging wall is formed by a group C sandstone breccia that appears to have been crudely folded into a SSW-verging antiform prior to lithification (Fig. 4B). Removal of the westerly postdepositional dip of the Stoer Group reduces the original dip of the Clachtoll fault to <30°, suggesting that it formed as a relatively low-angle, top-to-the-southwest thrust.

DISCUSSION

We propose that two different mechanisms were responsible for the formation and filling of the dilational fractures in the Lewisian gneisses of the CM (Fig. 4C). Group A fills formed by material falling, or being washed into open fissures close to the surface (e.g., Montenat et al., 1991). Bedding in these fills shows orientations that are similar to the regional bedding in the nearby Stoer Group, albeit with a superimposed concave-up, catenary form (Figs. 1F; see Woodcock et al., 2014). Our observations further show that these fissure fills are restricted to the upper part of the CM and are locally continuous with thin veneers of bedded Clachtoll Formation sediment deposited on top of the basement block (Fig. 1B). Rarer examples of centimeter-scale, passively filled fractures are also found in gneisses immediately below the basal Stoer Group unconformity in areas away from the CM (e.g., UK National Grid Reference NC 0402 2700).

Groups B and C fills are only found in the CM. They are interpreted to be wet sediment injections (or injectites; Hurst et al., 2011; Siddoway et al., 2019), based on their homogeneous texture, lack of laminations, and the widespread development of tapered fracture geometries and jigsaw breccias. Beacom et al. (1999) argued that the group A infills formed earlier and were locally remobilized and injected shortly after deposition due to active deformation associated with movement along the Clachtoll fault (Fig. 4B). This is now considered unlikely given the mapped contact relationships of the CM, the misoriented nature of the basement gneiss foliation within it, and the clear spatial association between the lateral margins and basal contact of this block and the development of the group B and C injectites (e.g., Figs. 1B, 2, and 3). Furthermore, the observed continuity of the group A fissure fills with sediments that unconformably overlie the megablock suggests that they filled during burial of the megablock following emplacement; i.e., they are later relative to syn-emplacement groups B and C fills.

Given the newly discovered contact relationships, we propose that early in the deposition of the Clachtoll Formation, the CM collapsed from a local topographic high onto recently deposited breccia-conglomerate below. Soft-sediment deformation features consistent with seismic shaking are widespread in basal parts of the Stoer Group sedimentary sequence (Stewart, 1993, 2002), making it possible that the fall of the CM was triggered by an earthquake related to the nearby Coigach fault (Fig. 1A). Alternatively, it may have occurred due to freeze-thaw processes if the earliest period of Stoer Group deposition was influenced by glaciation, as suggested by Davison and Hambrey (1996). Since the CM demonstrably formed during early deposition of the Clachtoll Formation, it is clearly unrelated to the Stac Fada impactite event (e.g., Simms, 2015; Amor et al., 2019), which lies 300 m higher in the stratigraphic succession.

The vertical impact of the CM caused localized overpressure and injection of the fluid-laden sandstone matrix into fractures at the base and

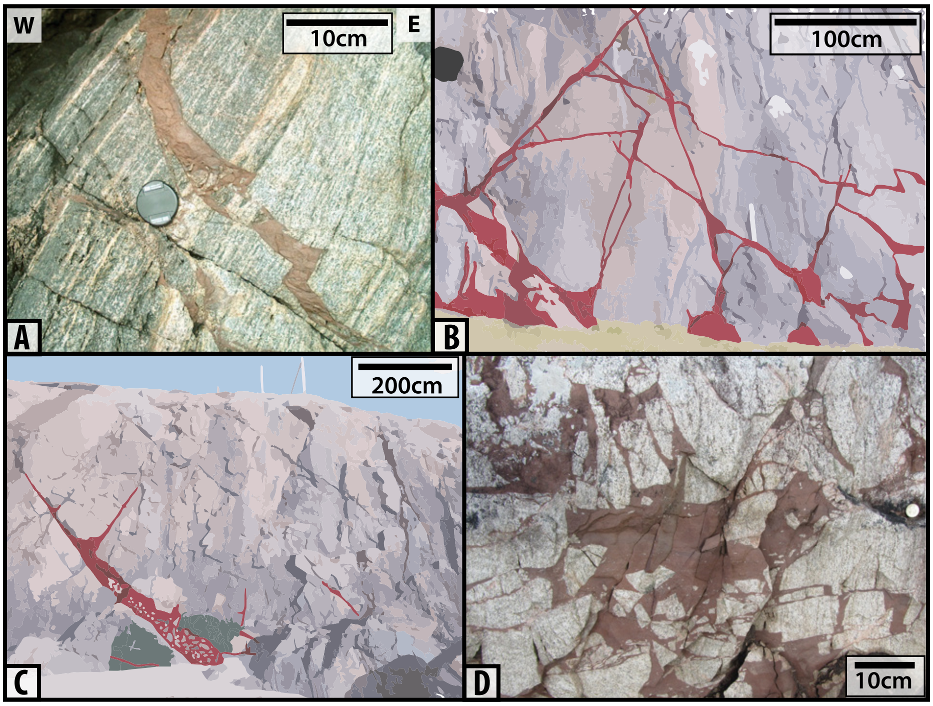

Figure 3. (A–C) Typical group B sandstone fills interpreted to represent injectites from (A) southeast and (B,C) west flanks of the Clachtoll megablock (CM; northwest Scotland). In B and C interpreted images, note the upward narrowing of fracture fills. (D) Typical group C morphology from the lower southeast flank of the CM with tapered fracture shapes, jigsaw brecciation, and finer-grained, homogeneous fill.

flanks of the overlying basement block (Fig. 4C, i). This form of soft-sediment deformation process has not previously been documented or included in existing classification schemes (e.g., see van Loon, 2009). The presence of northwest-southeast–striking sandstone injectites (extension) in the northern (i.e., rear) end of the block, and the development of contractional folding and the Clachtoll fault—which likely formed as a thrust—at the southern end (front) of the CM suggest that impact was additionally associated with a southwest-directed horizontal displacement and internal deformation (Fig. 4C, ii). The lack of any clearly defined basal detachment or deformation zone in the conglomerate below the CM suggests that any such translation was likely no more than a few meters. The CM was then buried by further sedimentation, which passively infilled the group A fractures in upper surfaces of the block, which in turn likely opened during impact (Fig. 4C, iii). The similarity in the orientations of the bedding laminations in these fractures and those of the overlying Clachtoll Formation (Fig. 1F) demonstrates that the formation of the CM and misorientation of its foliation occurred very early in the depositional history of the Stoer Group. That misorientation of the basement foliation in the CM requires a vertical axis rotation of ~90°, pivoting the block during collapse. However, while the model accounts for the distribution of the different types of sandstone fills around the margins of the CM, is the impact and overpressure mechanism proposed mechanically feasible?

To explore this issue, we assumed a simplified vertical fall scenario to consider the pressure surge generated upon impact, and the fall distance, h, required to induce hydrofracturing in the gneiss block. In the underlying medium (poorly consolidated, fluid-saturated breccia-conglomerate), impact-generated compressional waves would result in a dynamic transient overpressure P in the fluid (water); in the overlying block, corresponding vertical (σ_{zz}) and horizontal stress (σ_{xx}, σ_{yy}) would be generated by the matching boundary deflection. We derived an original solution for the pressure and stress surge generated upon impact for two types of media with different properties (see Appendix III). These are given by:

$$P = 2\zeta v_1 = \sigma_{zz}, \tag{1}$$

and

$$\sigma_{xx} = \sigma_{yy} = (\lambda / \lambda + 2\mu)\sigma_{zz}, \tag{2}$$

where $\zeta = \frac{1}{2}\left(\frac{1}{\sqrt{\rho K}} + \frac{Vp}{\lambda + 2\mu}\right)^{-1}$ is the harmonic mean of the elastic impedances of the block and the underlying material; l and m are the Lamé and shear elastic moduli, respectively; V_p is the compressional wave velocity in the gneiss block; and r and K are the density and incompressibility of the water saturating the conglomerate, respectively. Field observations suggest that injectites form due to tensile fracturing, which would occur when the pressure surge P exceeds or equals the cumulated value of the tensile strength T and the transient horizontal compressive stress s_{xx} generated on impact, i.e., $P = T + \sigma_{xx}$. This equates to:

$$v_i = \frac{1}{2\zeta\left(1 - \frac{\lambda}{\lambda + 2\mu}\right)}. \tag{3}$$

Finally, the free-fall equation $v_{i=\sqrt{2gh}}$, where g *is* gravity, allows determination of the height h from v_i.

To derive values of height and impact velocity with the above formulae, we used the parameters given in Appendix IV, Table IV.1 (in the Supplemental Material). A range of values compatible with Lewisian gneiss and fluid-laden sediment was considered for λ, μ, V_p, ρ, and K. Brazilian tests on samples of Lewisian gneiss from the block (Appendix V) suggest a range of tensile strengths, i.e., $6 < T < 12$ MPa. An impact velocity of $7 < v_i < 14.8$ m/s, corresponding to a fall height range of $2.5 < h < 11.2$ m, would therefore be sufficient to cause tensile fracture. Given that the basal Clachtoll Formation is locally associated with a paleotopography of at least 150 m (Stewart, 2002), a fall of <15 m from a cliff-like escarpment seems geologically plausible. It is not currently possible to further determine the detailed kinematics of emplacement, although the relatively intact nature of the misoriented basement and modest calculated fall heights seem to rule out a large-scale toppling process for a megablock of such large dimensions.

CONCLUSIONS

Geological observations and numerical calculations suggest that early in the depositional history of the Stoer Group, an ~90,000 m^3, 243 kt block of basement gneiss fell onto unconsolidated wet sediment. Impact following a vertical decent of <15 m would be sufficient to overpressure and liquify the rapidly compacted, water-laden sand matrix in the basal breccia conglomerates, leading to hydrofracturing and upward sediment slurry injection into the immediately overlying fractured basement block. On impact, the block also deformed internally due to a subordinate component of southwest-directed horizontal translation. It was then passively buried by continued sedimentation. Our findings show that terrestrial rockfall megablocks—features that are widely recognized on both Earth and other planets in the present day (see Ruban et al., 2019, 2020)—also exist in the ancient geological record at least as far back as the Mesoproterozoic.

ACKNOWLEDGMENTS

We thank Paul Ryan, Jonas Ruh, and an anonymous reviewer for constructive reviews. Killingback was funded by a Charles Waites scholarship (Durham University).

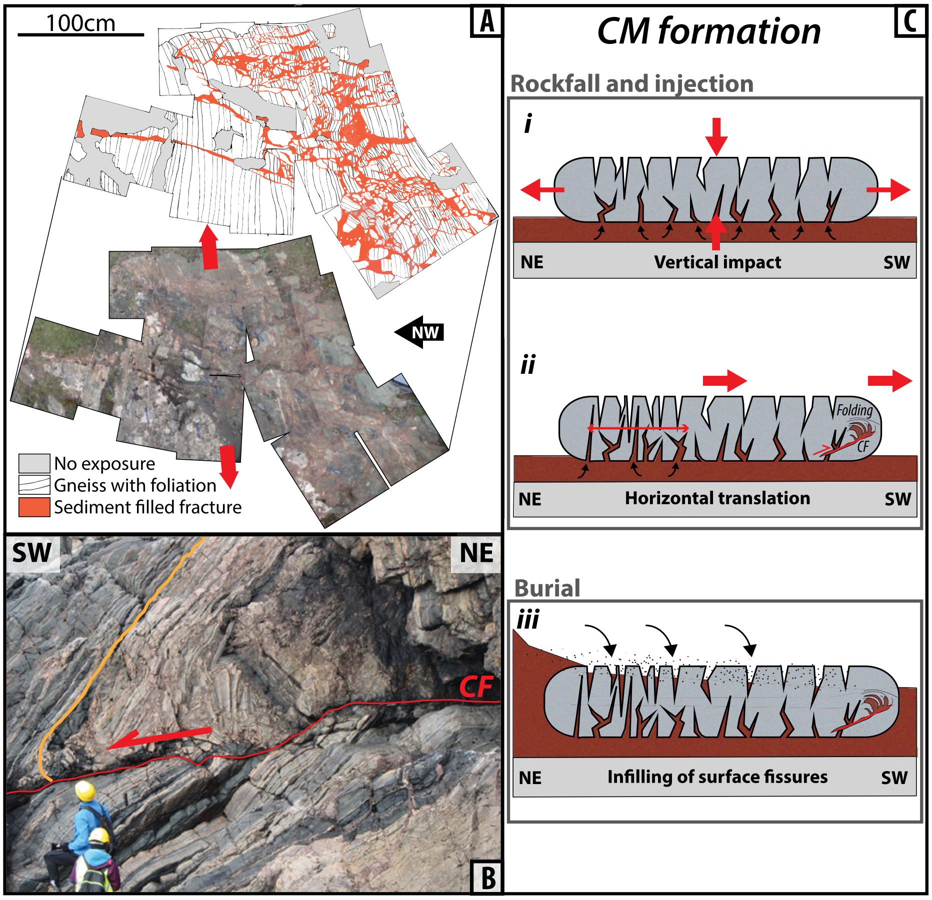

Figure 4. (A) Montage of subvertical northwest-southeast sandstone-filled fractures at the northern end of the Clachtoll megablock (CM; northwest Scotland). (B) Sinistral top-to-the-southwest Clachtoll fault (red line labelled CF) of Beacom et al. (1999) with southwest-verging hanging-wall antiform folding sandstone breccia (see Fig. 1B for location). (C) Simplified sequential model (i–iii) to account for formation of the CM.

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Printed in USA