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Anomalous terrain at Dove Crags ‘cirqueform’ and Gasgale Gill asymmetric valley, English Lake District, attributed to large-scale RSF of pre-LGM origins

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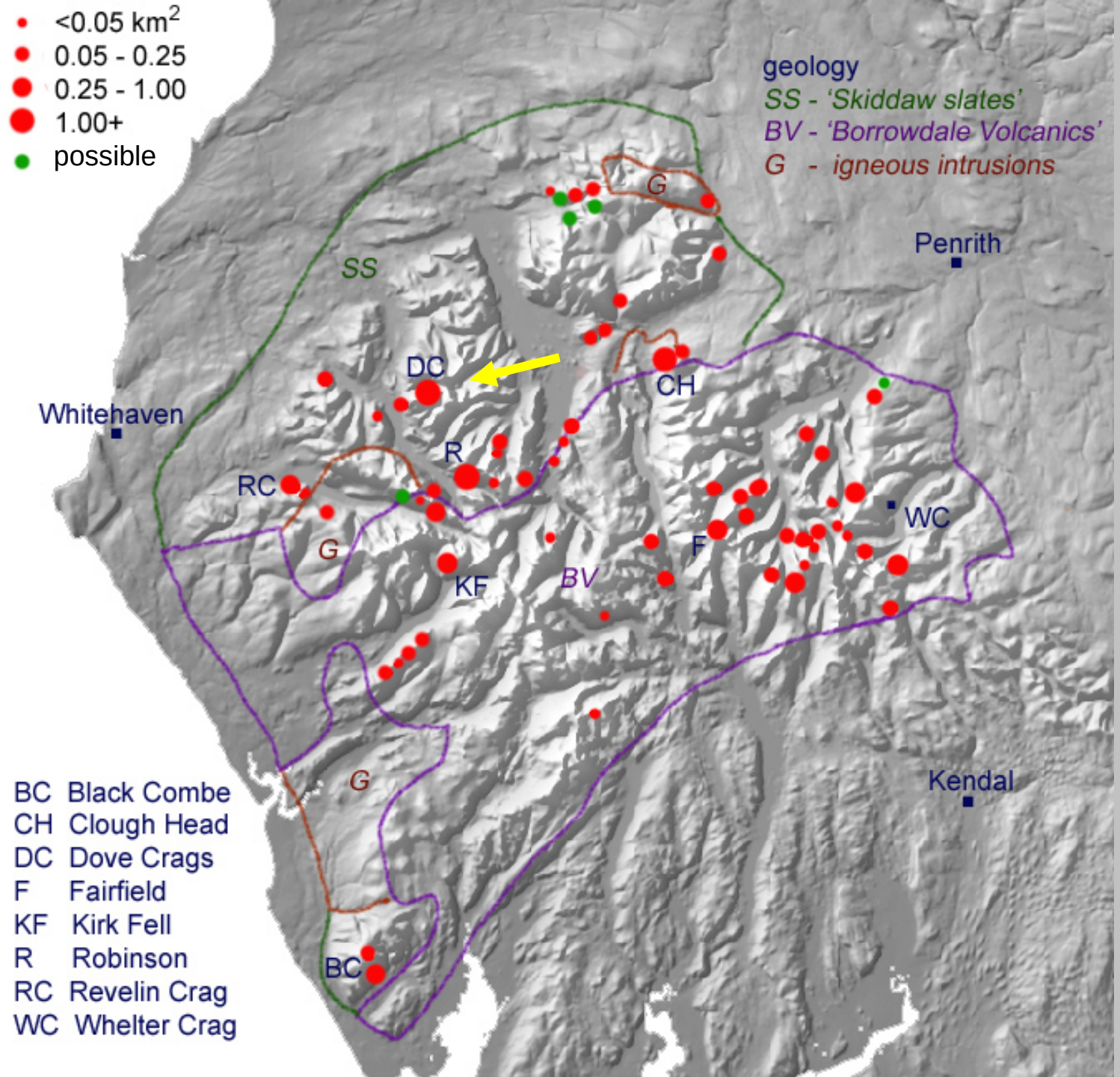
slides are grouped thematically, not by order of appearance in the text

Supporting Information ppt

SI-02 - 04 Lake District RSF distribution, site locations; Northwestern Fells locus; Dove Crags RSF causes*
SI-05 - 09 Gasgale Gill valley
SI-10 - 21 Dove Crags cirque and slipmass; moraines
SI-22 - 24 Hause Crag scar and slipmass
SI-25 - 30 Liza Beck cutbank sections, springs, dry channels
SI-31 - 35 reconstruction – pre-RSF Gasgale valley, Grasmoor plateau, Whiteside ridge
SI-36 - 39 the vicinity – Coledale Hause; Hope Gill; cirque pattern and seeding*
SI-40 - 45 comparator sites (Lake District) : Clough Head / Cotley / Robinson / Revelin Crag / Fairfield / Kirk Fell / Whelter Crags
SI-46 (Snowdonia) : Pen yr Helgi-du
SI-47 - 50 (Highlands / Sweden) : Cobbler / Streap, Karkevagge / Sgurr an Fhuarail / Tullich Hill
SI-51 - 52 alternative interpretations – cirque floor rebound* (B an Fhidhleir); parafluvial RSF* (B Buidhe Arnisdale)
SI-53 - 54 general diagrams - RSF typology; Lakes RSF:geology; non-exploitation of RSF cavities by glaciers
SI-55 - 58 - measures of RSF depth; cataclinal slopes; zone of crush : Beinn Fhada; Norway drill logs
SI-59 - 60 Gasgale Gill diagrams - volume calculations – long sections
SI-61 - 62 - sequence of events : spatial / temporal
SI-63 comparator reconstruction - Clough Head

* text slides – additional discussion material



Dove Crags - Gasgale Gill location *(arrowed)*

RSF incidence in the Lake District

all sites verified in the field by the authors as definite or probable RSF, except where noted as 'possible'

This is Fig 1 of the main paper

Northwestern Fells, Lake District
- anomalous landscape assemblage north of Grasmoor

glacial breach

Dove Crags cirque *(arrowed) stands out for boldness of form,*
Gasgale Gill valley *(above it) for arc and incision*

(note varying contrast intensity across image)

DOVE CRAGS RSF IN A LAKE DISTRICT CONTEXT

• overall incidence of RSF in the Lake District is low compared with bolder Highland massifs, but greater than peripheral Highland areas (Jarman, unpublished data).
• within the Lake District RSF is sparse to absent in many parts - only other recorded RSF in the NW Fells north of Newlands Hause (cataclasmic deposits below steep, gullied west face of Grasmoor - Wilson 2011).
• even the Helvellyn-High Street and Ennerdale-Buttermere clusters affect less than 3% of land area - cf. 6-10% for Highland clusters of comparable extent.
• although 12 of the 70 Lakes RSFs are large (>0.25 km^2), comparable with the Highlands, they are scattered.
• it is therefore hard to see a pattern in which to place Dove Crags, as an isolated large site.

RSF incidence seems to associate with locales with recent concentrated erosion of bedrock (CEB - Jarman 2006). Two main CEB locales into which Dove Crags might fit are :

glacial breaches

• most RSFs in dissected central / western Lake District are associated with glacial breaches and trough walls down-ice from them, e.g. Dale Head and Robinson (Wilson & Smith 2006), on N flank of large Honister Pass breach, and Burnbank Fell beside Loweswater diffluent breach (SI-03).
• however, at head of Gasgale Gill, Coledale Hause is a high paleic col (600 m OD) with minimal evidence of transfluent ice to augment erosion (SI-36).
• this is consistent on NW Fells watershed (SI-03): Sail Beck Hause 'paleic' col 465 m; Newlands Hause 330 m lowered ~20 m by minor breaching; only Honister and Whinlatter Passes substantially enlarged by breaching down to 355 and 315 m OD.
• Dove Crags is thus not a glacial breach CEB locale.

trough heads

• in E Lake District, breaching is minimal, RSFs in Helvellyn / High Street clusters associate with flanks of side-troughs with closed heads - inferred to be 'late developers' in a precipitation lee, still enlarging later Pleistocene.
• Dove Crags is a typical side-trough-flank locale - its confined 'hanging' character has affinities with upper Grisedale and Hartsop side valleys in E Lakes.
• Scope End RSF on NE Hindscarth ridge (previously unreported) is also on flank of a side trough (Fig. SI-03).

Gasgale Gill valley sequence

1. *head at Coledale Hause (600 m)*
2. *upper fluvial incision deflected off-axis by Hause Crags slips (upper fluvial tributaries undercut)*
3. *middle reach arcs below main RSF bulge, undercutting Whiteside gullied crags*
4. *interlocking spur partly in bedrock, exaggerated by slipmass projection*
5. *lower reach major fluvial ravine possibly slightly deflected by subdued slipmass on Grasmoor flank (Brackenthwaite Fell)*
6. *Liza Beck exit deflected off fall-line to Crummock Water by rock rib and debris cone, to flow NW*
7. *anomalous large debris cone 40 m high (10m contours)*
8. *deltaic fan, issues from ravine but no feeder stream – deflected by 7 ?*

note smooth, well modelled paleic relief of Grasmoor (right side) and around Coledale Hause

Gasgale Gill hanging valley into Buttermere--Lorton trough

- deeply incised fluvial exit ravine

Gasgale Gill fluvial character

- headwaters - interlocking spurs - ravine exit

BF - Brackenthwaite Fell cavity

outer edge of Dove Crags mass movement

failed mass displacing valley axis north, promoting erosion of opposite side

Whiteside

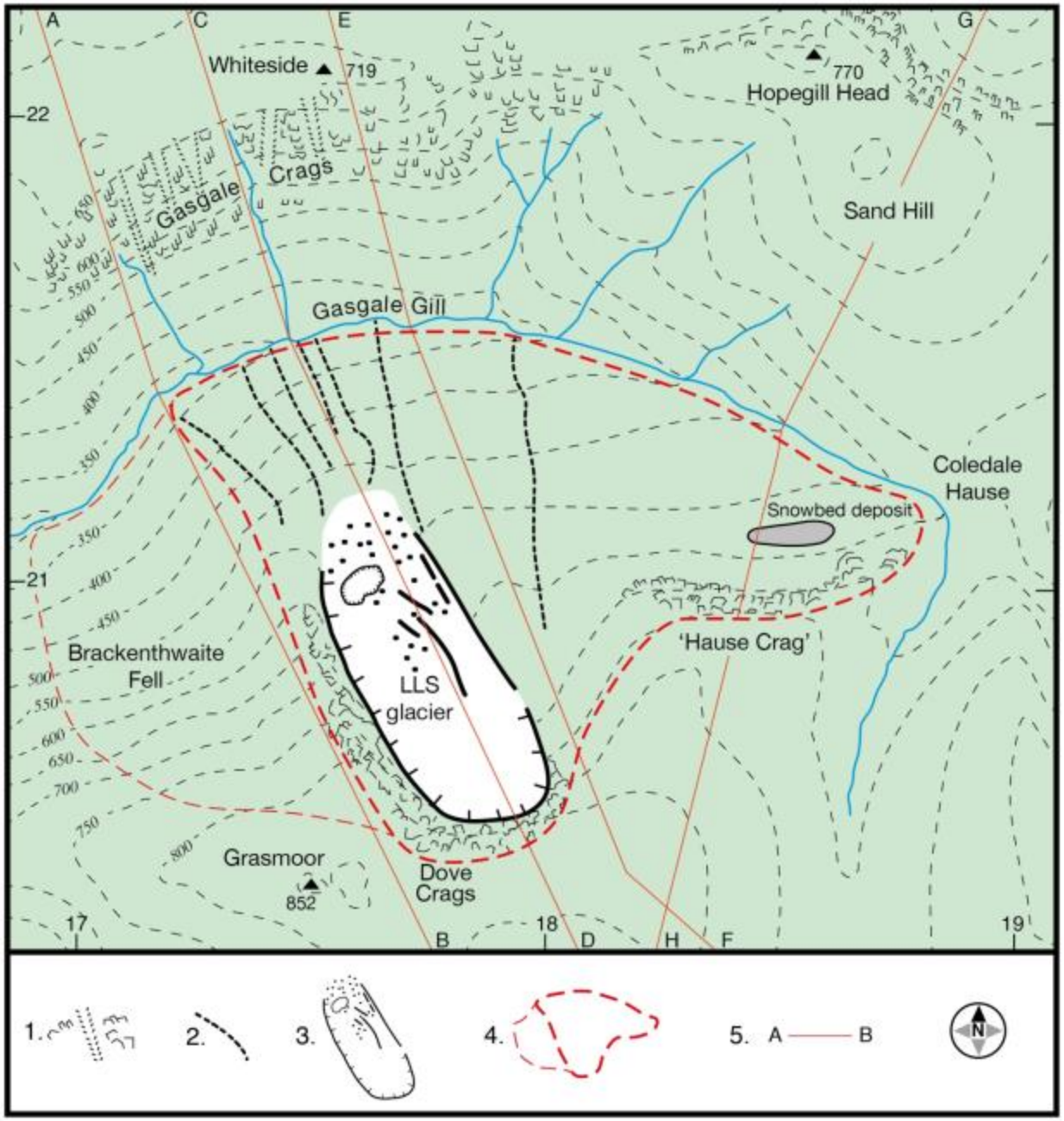
down valley from Sand Hill, Hopegill Head

Gasgale Gill hanging valley into Buttermere--Lorton trough

deeply incised, long-adjusted fluvial exit ravine

Whiteside
anomalously steep and gullied in Skiddaw 'slates' (Gasgale Crags)

Gasgale Gill
marked asymmetry
from head below Coledale Hause



Dove Crags 'cirque'

LLS glacier extent (white) is reasonably well constrained by moraines

1. *cliffs, outcrops and gullies*
2. *dry channels*
3. *moraine ridges, dry hollow in cavity floor*
4. *proposed RSF extent (bold) with adjacent possible RSF (faint)*
5. *cross-sections*

(Fig 8 in main paper)

this is Fig 3 in main paper

Dove Crags 'cirque'

oblique GoogleEarth image from north

- subtle indications of large-scale RSF

6m flank scarp on SI-20, 21

dry channel exits on SI-29 marked with asterisks

tectonic features :

 # paleic surface, carried down

** fresh slump scar in SI-30*

1. axis of sharp E-W anticline (valleyward dip 40-60 degrees) - purple line

2. lineament family (arrowed yellow) - feature on cirque floor may be cognate, carried down or reactivated

3. secondary wedge cavity below Hause Crag (marked red)

Dove Crags asymmetric cirque and anomalous slopes of Gasgale Gill *Grasmoor 852m*

indications of RSF on cirque apron
1 - dry channels, offsets, cross-falls
2 - fossil channels not cutting brow
3 - tension furrows on brow

* *fresh slump scar in SI-26*

this is Fig 2 of the main paper

Dove Crags cirque
- headwall cosmodating difficulties

SE flank scarp : blocky/shaly slope, vegetated talus at foot, only one outcrop crag (arrowed)
- has RSF source scarp character but samples from such friable, unstable slopes unlikely to be reliable (inset left)

SW cirque wall : deeply eroded during LGM and since, large active talus

rock type - Skiddaw Group 'slates' unsuited to cosmodating (low quartz fraction, few quartz veins)

concavity below Dove Crags

- upper part (1) enclosed by LLS moraines, probably excavated in LGM and LLS

- lower part (2) is heathery 'tarnless hollow' enclosed by disturbed hummocky ground

(noted by Wainwright 1964, who concludes that the screes must act as soakaways, preventing tarn waters accumulating !)

Whiteside 719m

Hopegill Head 770m

Dove Crags cirque from Grasmoor plateau rim

- threshold projects slightly into Gasgale Gill valley
- lower (left / west) side projects further

Whiteside asymmetric ridge and gullied craggy trough wall opposite

W Cumberland plain beyond

LLS moraine *down the convexity flank*

possible LGM (end-Dimlington) moraine *enhancing apparent convexity, highlighted left, skyline top left image*

the tarnless hollow below Dove Crags

closed contour basin asterisked

dry furrows on
threshold of
dry cirque hollow

6m-high flank scarp beside threshold of lower (west) slipmass

- *location on SI-12, and next slide*

rare surface boulder

flank scarp, Beinn Bhreac, Glen Douglas, Loch Lomond

outer margin of RSF unclear
- could be next lineament west (dashed)

6m-high flank scarp beside threshold of lower (west) slipmass

Hause Crag scar and slipmass

- Sissons 'snowbed deposits' superimposed on slipmass

- secondary wedge scarp invades these deposits (marked green)

this is the source for Fig. 6 (main paper)

Hause Crag slipmass sector

- note continuity of character from main convex slipmass out of 'cirque' cavity

*'**snowbed features**' of Sissons (1980)*

- beyond figure (above)
- well out from crags (right)

here reinterpreted as subdued slipmass surface dislocations

surface drainage from ephemeral pool (inset) within snowbed hollows of Sissons (1980) - flows over surface - sinks in rushes

***Liza Beck cutbank** 1 - basal springs beneath Hause Crag slipmass*

Liza Beck cutbank 2 - exposed section below cirque apron, with layer of subangular blocks

location at yellow asterisk, SI-13 *[Fig 7 in main paper]*

Liza Beck cutbank 3 - striated clasts from section below cirque apron

these crudely shaped specimens might have been striated by ice or during RSF translation

Liza Beck cutbank 4 - exposed section below main cirque apron *(location - SI-13)*
- thick till cover mapped by BGS

Liza Beck cutbank 5
- sections below main cirque apron

abandoned gully, outer apron >>>

location - red asterisk ***SI-11***

dry gully, inner apron
- occasional flow, but minimal debris cone

location - yellow asterisk ***SI-11***

Liza Beck cutbank 6 - exposed section beyond downstream end of main cirque apron

(location - SI-12)

Reconstructions of elements of the anomalous landscape assemblage

Dove Crags cirque cavity

smooth convex slipmass surface (toned) resembles in-situ paleic relief of Grasmoor plateau shoulder (top right)

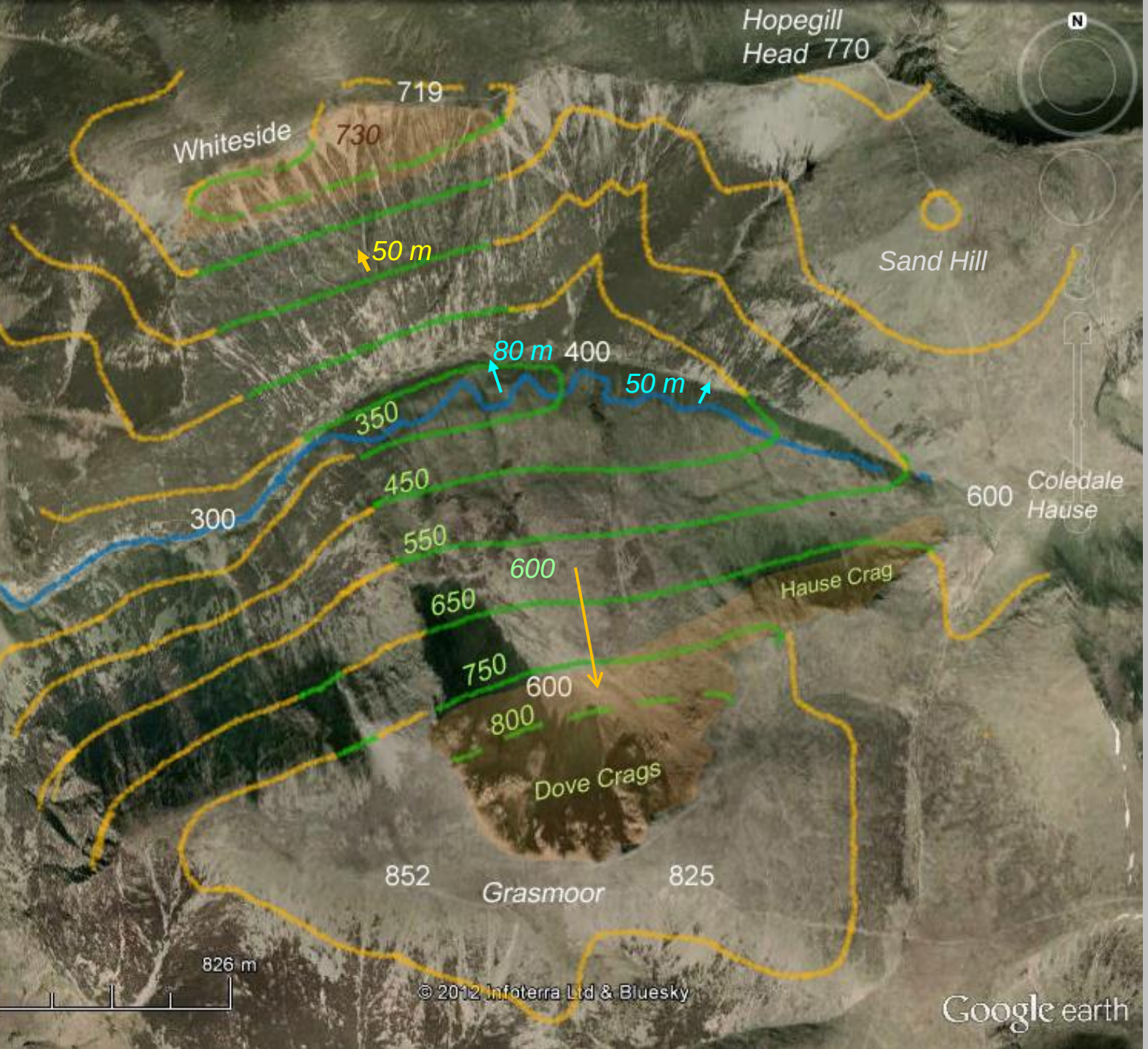
- arrow suggests quasi-intact translation down planar scarp

- reinstatement restores broad plateau with narrow gully incision, possibly becoming adapted into a small cirque

cirque mouth

in side profile from west

smooth, convex slope suggests :
- paleic surface translated from the plateau, smoothed and consolidated by a weak cirque glacier
- periglacial smoothing, with minor solifluction benching



Gasgale Gill / Dove Crags cirque reconstruction

Whiteside face 50m retreat

Liza Beck 50-80m displacement within pre-RSF glaciated hanging valley (fluvial head)

pre-RSF terrain contours - green
(50m interval at summits)

present terrain contours - brown = 300m DMAX retreat (at 600 m OD)

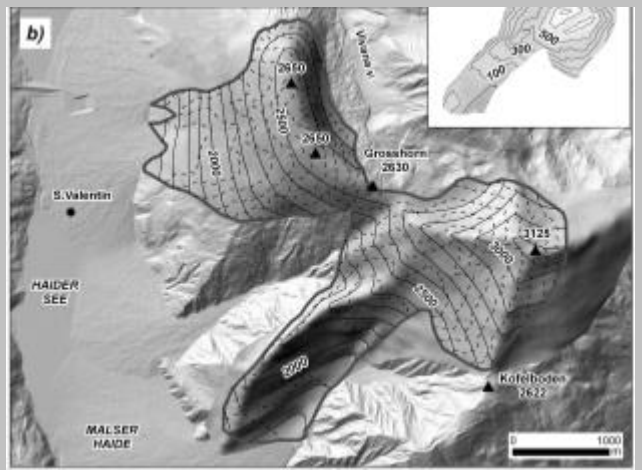
lost paleic upland surface - toned brown

Hopegill Head Sand Hill Coledale Hause Eel Crag NE shoulder of Grasmoor

reinstatement of Hause Crag and Dove Crags slipmasses (arrowed) achieves matching preglacial forms around Gasgale Gill valley head

reconstruction of lost mountain source to Malser Haide megafan, Sud-Tirol Alps by clone-stamping procedure

Jarman/Agliardi/Crosta GSL SP 351 2011



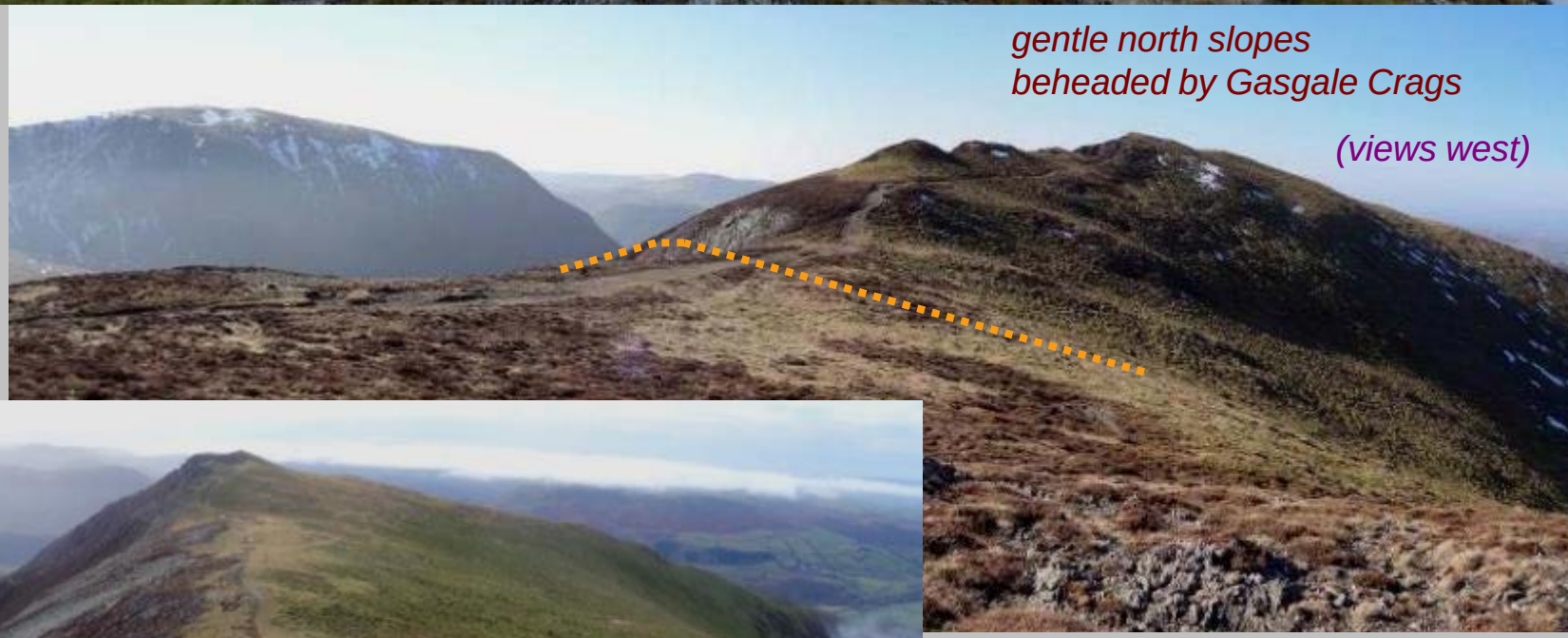
Whiteside edge (view east)

- created by Gasgale Crags truncating gentle north slopes of paleic ridge

Hopegill Head

gentle north slopes beheaded by Gasgale Crags

(views west)



Whiteside ridge reconstructed

- slightly-domed paleic ridge, lowered by ~10-20 m

- invaded by Gasgale Crags, valley-wall retreat ~50 m

(730m)

719m

50 m

Gasgale Gill valley evolution

Liza Beck displaced east in stages by Dove Crags slipmass

view down Hopegill Head SW fluvial head suggests offset valley axis

stream off plateau in open fluvial channel, now captured by Gasgale Gill (former route arrowed)

***Coledale Hause** from paleic slopes of Sand Hill (above) and from Whiteside (right)*

- *Hause (col) shows minimal signs of glacial breaching or Quaternary divide displacement (Tertiary ~1 km E)*

cirqueplex of Eel Crag / Crag Hill
at head of Coledale

- ***more conventional glaciated form***
- ***some affinities with Dove Crags, notably convex form below planar flank scarp***

Hope Gill

- *fluvial valley north of Whiteside*
- *Dodd anomalous scarp, projecting deposits*
- *too large to result from glaci-fluvial nick*
- *inferred RSF, small-scale version of Dove Crags ?*
- *age ? – dissected by LGM meltwaters*

location HG, next slide

Northwestern Fells cirques

Hope Gill (HG)
(fluvial valley, with Dodd RSF deflecting exit)

Hobcarton Crag
(trough-head cirque)

Coledale Hause

Dove Crags cirque (DC)

Eel Crag / Crag Hill
(trough-head cirque)

- note paler photography, not shallower crags

Dove Crags cavity can readily be reinstated, from extant slipmass plus some erosion (cirque headwall and slide toe)

other cirques lack associated anomalous masses/deposits

SEEDING OF CIRQUES BY RSF CAVITIES

This idea has a long pedigree (Clough 1897; Bailey & Maufe 1916; Peacock *et al*. 1992; Evans 1997).

• Jarman (2003*a*) identified a dozen RSF cavities in SW Highlands as potential 'Clough proto-cirques' but as they face west or south are unlikely to develop into true cirques. Cavities of more promising aspect would already have been exploited as cirques, so that their RSF origins would now be less recognisable.

• Turnbull & Davies (2006) and Evans (2013) debate extent to which cirques have developed from RSF cavities.

• Ballantyne (2013) illustrates gradation from extant and pre-LLS RSF cavities to more mature cirque forms.

A pre-LGM Dove Crags RSF would be a rare case of cirque seeding in the Lake District.

• most LLS glaciers of Sissons (1980) fully occupy cirques of conventional form, but in the NW Fells, Dove Crags (and Eel Crag / Hobcarton Crag - SI-35-36) show small glaciers within unusually large, angular cirques.

• cf. Whelter Crags, Haweswater (SI-41, cirque rim 720 m, floor 400 m OD; E aspect) - anomalously large cirque invading peripheral open upland, LLS glacier of contested extent (Sissons 1980; McDougall 2013), no trace of any RSF slipmass, floor conventionally stream-coursed; if of RSF origins, it would well predate the LGM.

The two Lake District 'cirqueforms' already reinterpreted as large RSF cavities may have good cirque seeding potential (I.S Evans, pers. comm., 2014) :

• Cotley (SI-41) - despite peripheral escarpment location, floor only 200–350 m OD, has good snowblow catchment, east-facing headscarp element could shield a small cirque glacier. But if RSF is pre-LGM, why so few signs of LGM cirque-glacier activity, indeed head scarp is degraded ? [Dykes *et al*. (2010) do not discuss this].

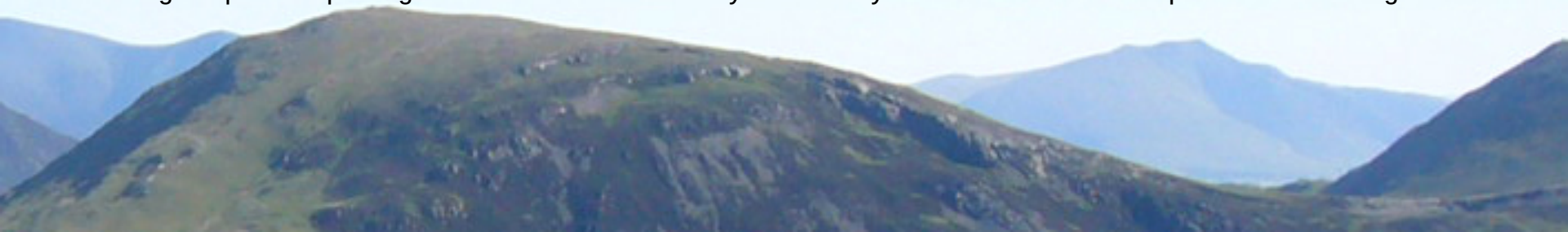
• Clough Head (SI-40) - NW aspect - some snow-blow catchment - high floor ~500 m OD (tho' convex form not ideally shaped for snow accumulation) : "It should readily be glacially occupied and thus seed a true cirque". No evidence of LLS cirque occupancy, but headscarp and east couloir are subdued, not typical 'fresh' RSF; and deep sinuous features across Threlkeld Knotts 'slipmass' resemble glacifluvial channels. [Davies *et al*. (2013) consider it postglacial; Dykes *et al*. (2010) do not consider its age].

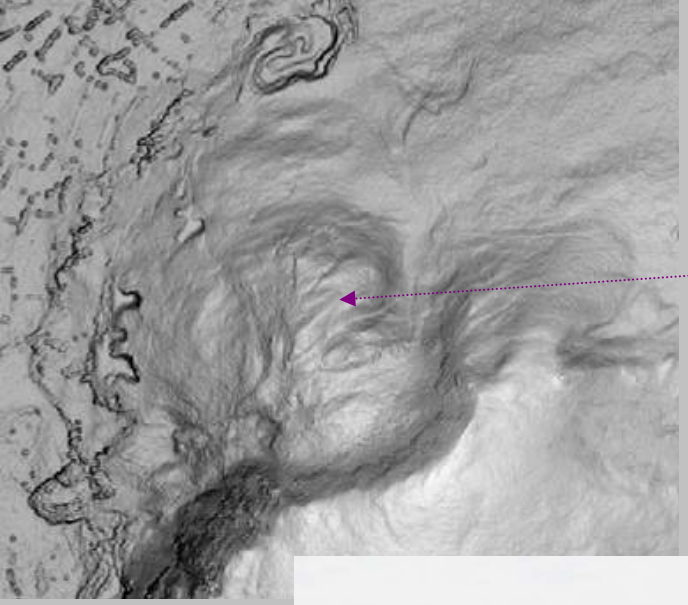
In the Scottish Highlands, cirque-seeding is blurred by complete LGM / wide LLS ice cover :

• 'debris-free scarps' (Holmes 1984) imply post-LGM origins; most have forms / aspects unlikely to seed cirques.

• Sgùrr an Fhuarail is a possible pre-LGM RSF cavity evolving as a 'proto-cirque' - discussed in SI-49.

Assessing cirque morphologies for anomalies is likely to identify more candidates for pre-LGM RSF origins.





COMPARATOR SITES

Clough Head RSF
(Keswick-Penrith gap) 1.20 km^2

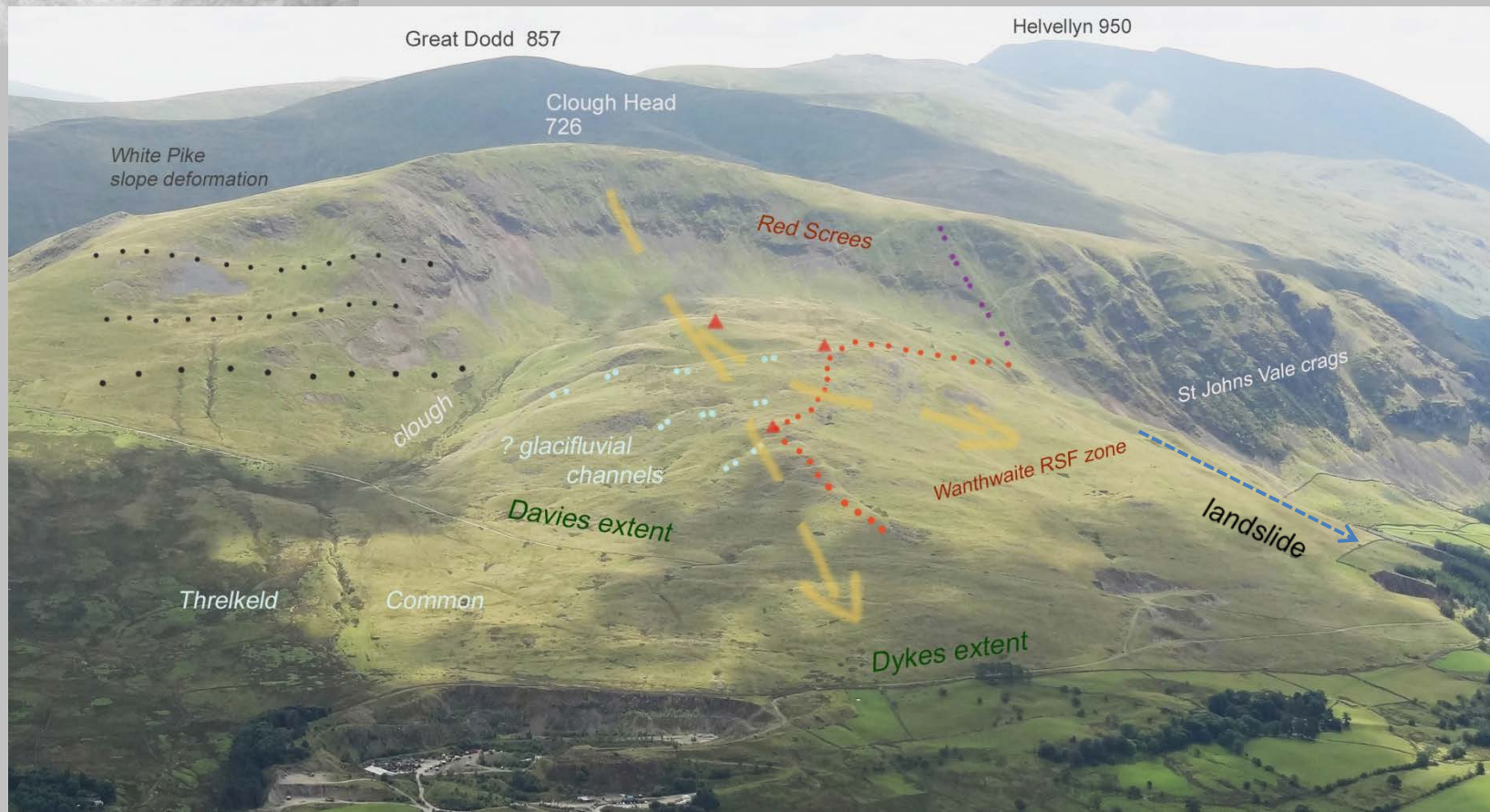
see also SI-63

Threlkeld Knotts (below scar) are dislocated orthogonally

slope on east is antiscarped deformation (remnant)

LiDAR image courtesy Tim Davies / Jeff Warburton, Univ Durham

view from Blencathra



assumed broad LGM icestream flowing SW into Irish Sea, may have trimmed base of pre-LGM RSF

surrounding slopes appear little affected by glaciation, with small hanging valleys of fluvial character

Cotley RSF (Black Combe) *0.85 km²*

300-400 m deep bite (yellow line)
80 m high headscarp

post-LGM slump

Robinson RSF *Buttermere*

1.75 km^2 in 'Skiddaw slates' large slope deformation (main)
(above) middle-lower antiscarps etc subdued, by LGM glacier ?
(right) erratic stream from Borrowdale Volcanics crags

Fairfield RSF
Helvellyn range

0.30 km²
in Borrowdale Volcanics

Revelin Crag RSF *Ennerdale Water*

0.55 km² *in 'Skiddaw slates'*
slipmass lowered ~30 m

Kirk Fell, Wasdale

comparator for Grasmoor prior to RSF cavity invading its plateau

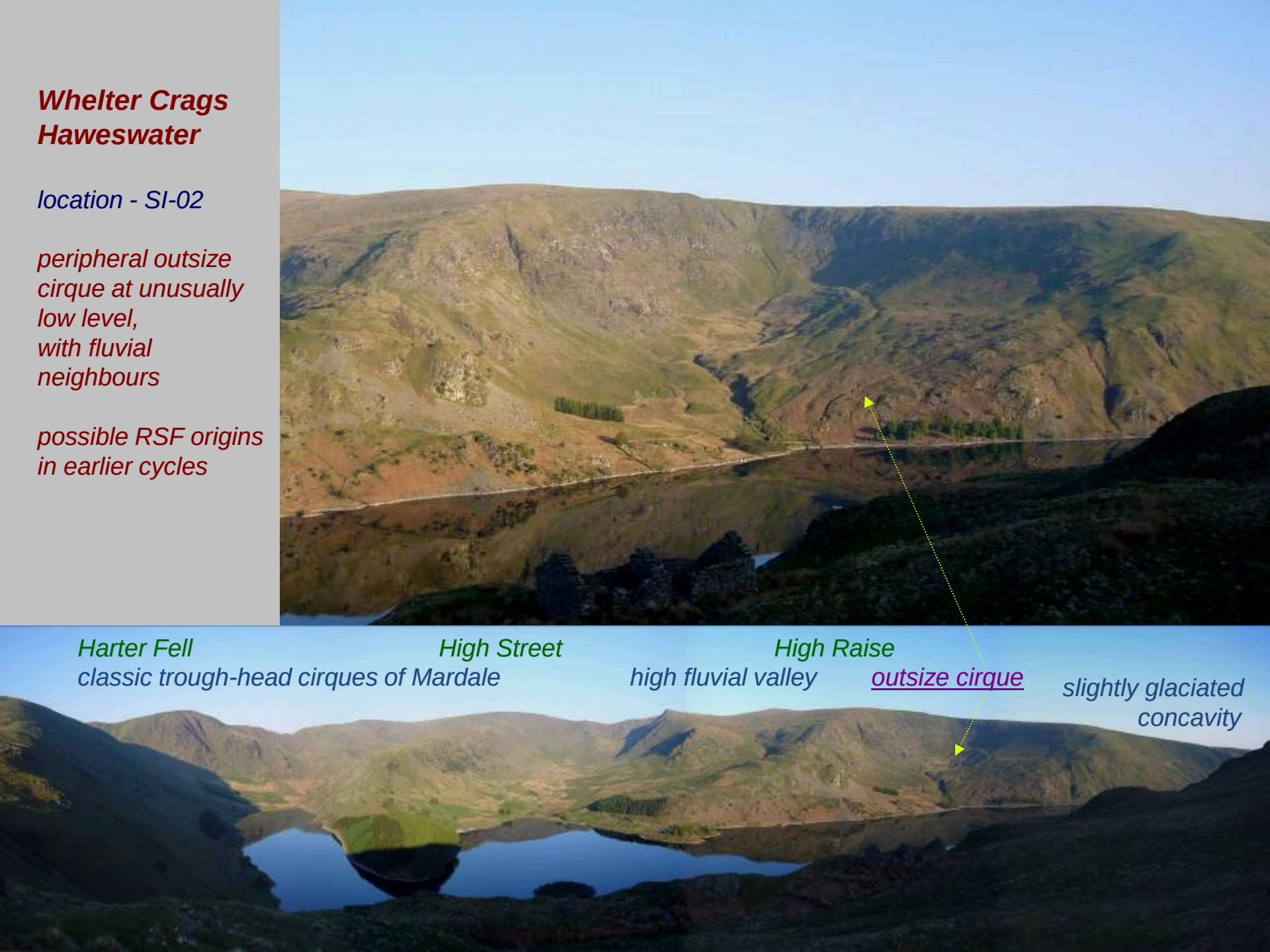
extensive antiscarp array indicates RSF slope deformation

Whelter Crags
Haweswater

location - SI-02

peripheral outsize cirque at unusually low level, with fluvial neighbours

possible RSF origins in earlier cycles



Pen yr Helgi-du RSF

Cwm Eigiau, Carneddau, Snowdonia

0.25 km^2

- *slipmass lowered by 120 m (arrowed)*
- *coherent former summit plateau surface*
- *no lateral restraint*
- *projects well out into trough, high rampart*

missing cirque arm

The Cobbler, Arrochar Alps, Argyll

- *north arm of NE pocket cirque 'missing', plinth fractured (graben arrowed), planar, not much glaciated*
- *North Peak above deeply fissured, climbing routes within*
- *LLS icesheet covered area, little debris or moraine below*
- *suggests pre-LGM collapse/LGM removal, or collapse onto LGM glacier*

Streap RSF
Glenfinnan
W Highlands *0.35 km²*

- *a 150 m-deep wedge cavity*
- *slipmass lowered by 100 m*
- *much disrupted but still coherent former summit surface*
- *high toe rampart*

(c) Hamish Johnstone

Karkevagge RSF
Arctic Sweden *Jarman 2002*

cavity 42 M m³ above postglacial rock avalanche suggests initial form of Dove Crags wedge cavity

Sgurr an Fhuarail (Cluanie-Glenshiel) - a classic 'proto-cirque'

- *the sloping planar floor may have been lowered (arrows) or be a stripped slice scar*
- *the gully incising its apron reveals failed, deeply-weathered bedrock (inset top L)*
- *the high headwall is unrelated, possibly shorn by an earlier RSF*
- *RSF splits the broad summit behind (13m scarp, inset - people for scale), and abounds up the side valley*

Tullich Hill RSFs, Luss Hills, S Highlands

multiple-wedge cavities on left
apparently older cavity on right
- *degraded headscarp*
- *underfit, pared- back slipmasses*
- *reactivated toe*

is Dove Crags simply a pre-existing cirque, where the floor has failed ?

- the RSF here could simply be the cirque floor failing and its apron bulging outwards – since there is no longer any direct evidence for the 'cirque walls' being cavity scarps
- this is a variant on the 'rebound' model of RSF – where intense bedrock erosion creates unloading stresses causing the floor to rupture
- possible examples in the Highlands are

  - A'Chioch (Affric) [NH113162] - RIGHT
  - Binnein an Fhidhleir (Argyll) [NN 229 103] – BELOW

- however both are probably slipmasses which have reactivated after long descent and complete paring back by valley glaciers
- at Dove Crags, the volume and cavity-match of the extant bulge is the best argument against this 'rebound' interpretation

A'Chioch *– floor split by step-scarp, left half smooth, ungullied, fractured, antiscarps along projecting lip;*
– faces N so is developing as cirque

Fhidleir *– slippage from 'bathtub ring' scarp at foot of headwall*
– antiscarps, but surface streams indicate consolidation
– faces S so limited scope to develop as cirque

is Dove Crags a parafluvial RSF? as the V-form of Gasgale Gill might suggest

A small proportion of British upland RSFs occur in partly or wholly fluvial valley contexts and, where not directly attributable to fluvial undercutting, may be termed 'parafluvial' RSFs (*sensu* Jarman 2011; Jarman et al. 2014). While most Lake District RSFs are paraglacial (*sensu* Ballantyne 2002), nine are fluvial, such as those on Latrigg undercut by the (?glacifluvial) incision of the Greta gorge (Wilson & Smith 2006; Dykes et al. 2010), or parafluvial, notably a group north of Skiddaw.

In its present form, the Dove Crags RSF might appear to be a rare, large-scale parafluvial RSF in a deep V-shaped valley (Fig. 8). However, if as argued, Gasgale Gill had a U-shaped glacial profile earlier in the Pleistocene, then it is the large slipmass bulge which has created the asymmetric V-profile of non-fluvial origin (excluding the basal cutbank).

Dove Crags RSF is therefore proposed as being essentially paraglacial.

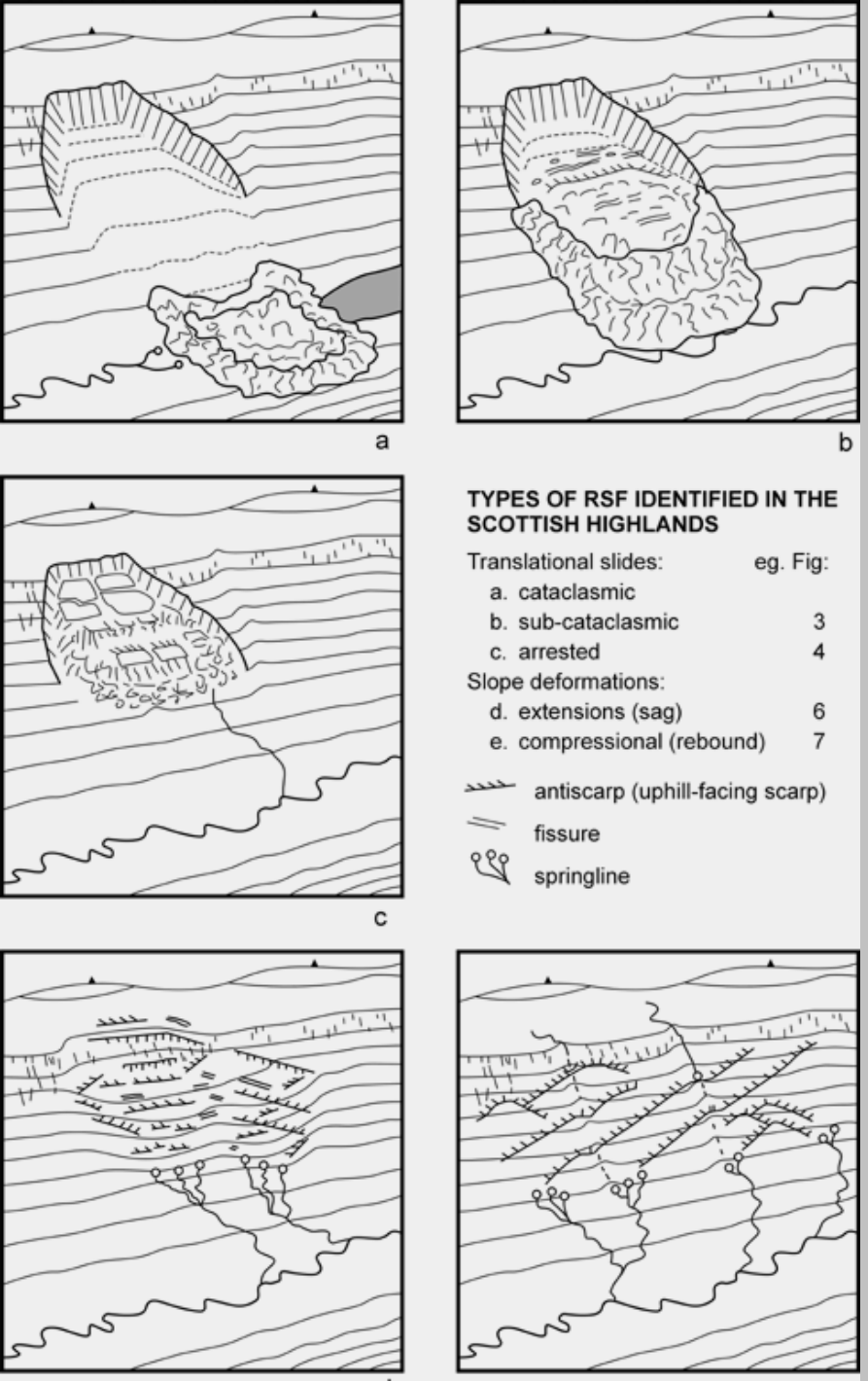
Beinn Buidhe parafluvial RSF, Arnisdale, W Highlands

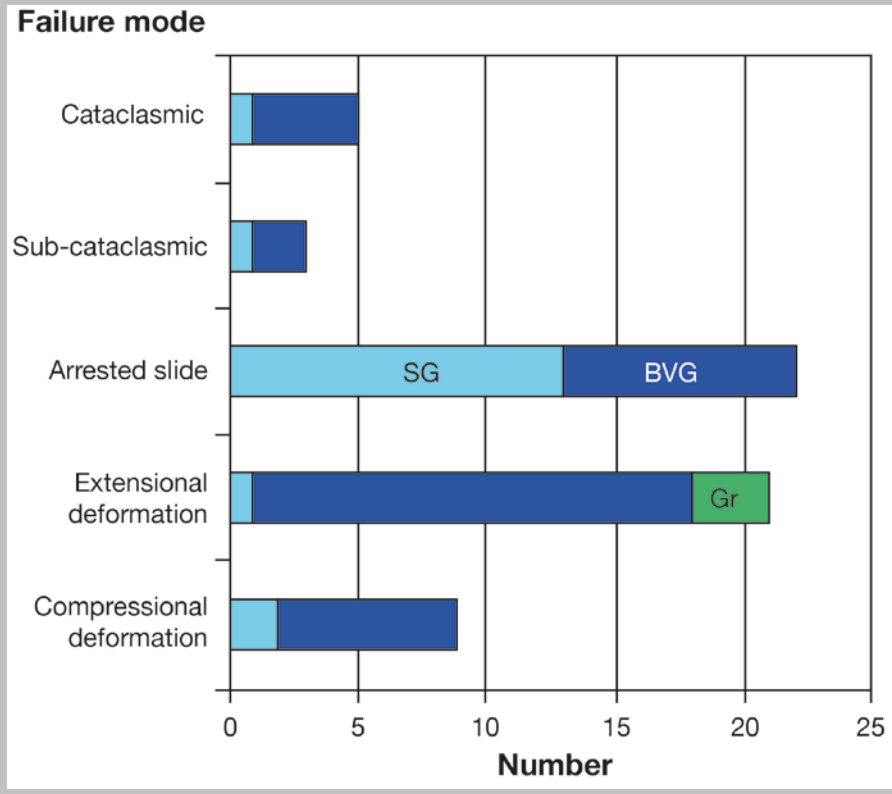
preglacial fluvial upper valley (interlocking spurs) incising down to glacial trough, glacifluvial inburst on R

A. RSF typology

DIAGRAMS

from Jarman 2006 'Large-scale in the Scottish Highlands' Engineering Geology Fig 2

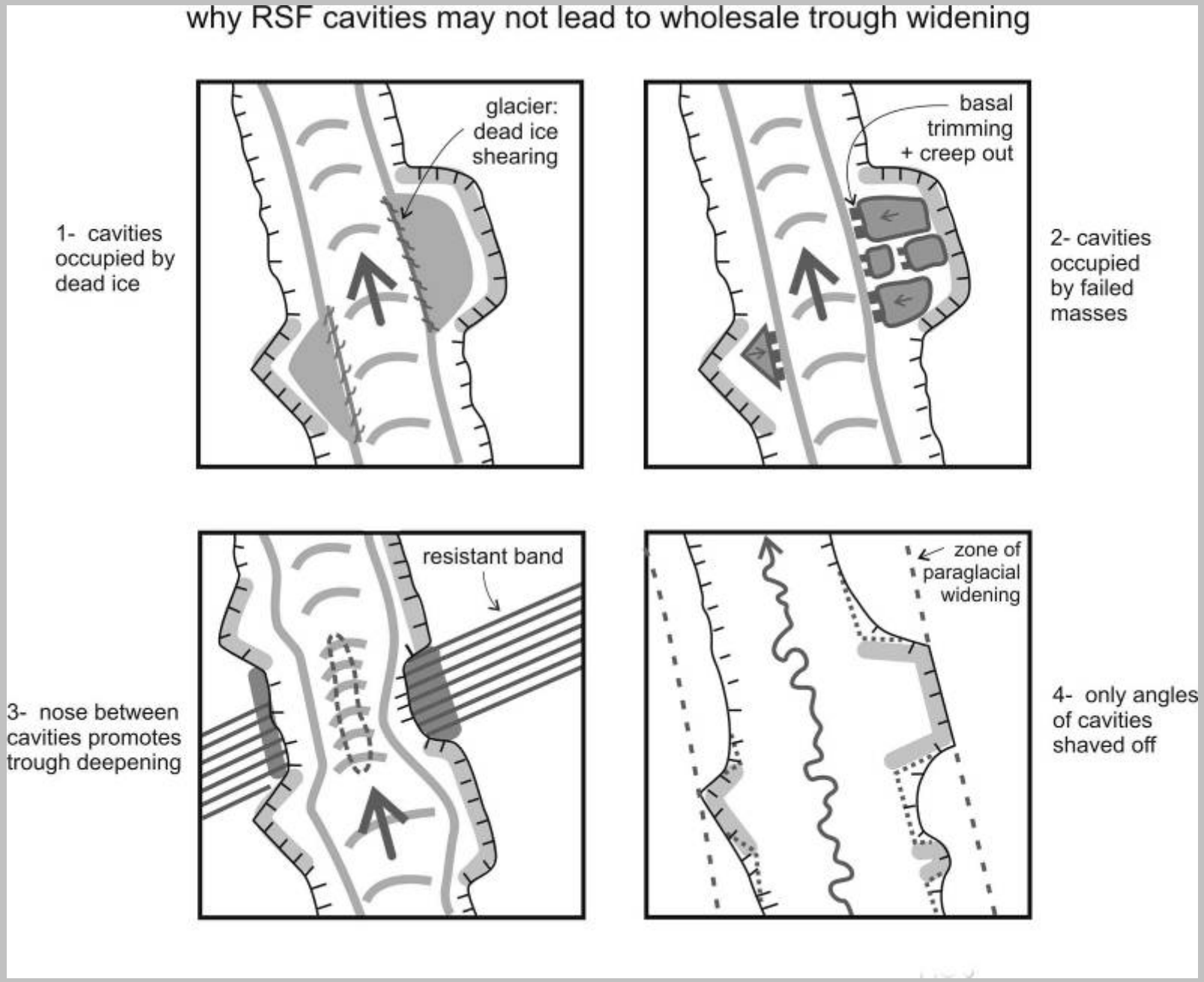




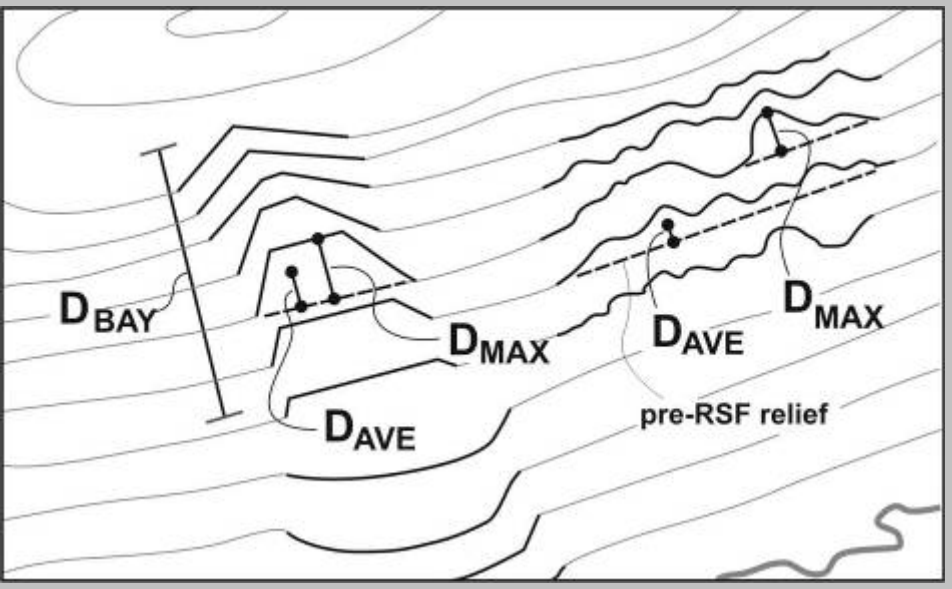
B. RSF failure mode relates strongly to bedrock geology

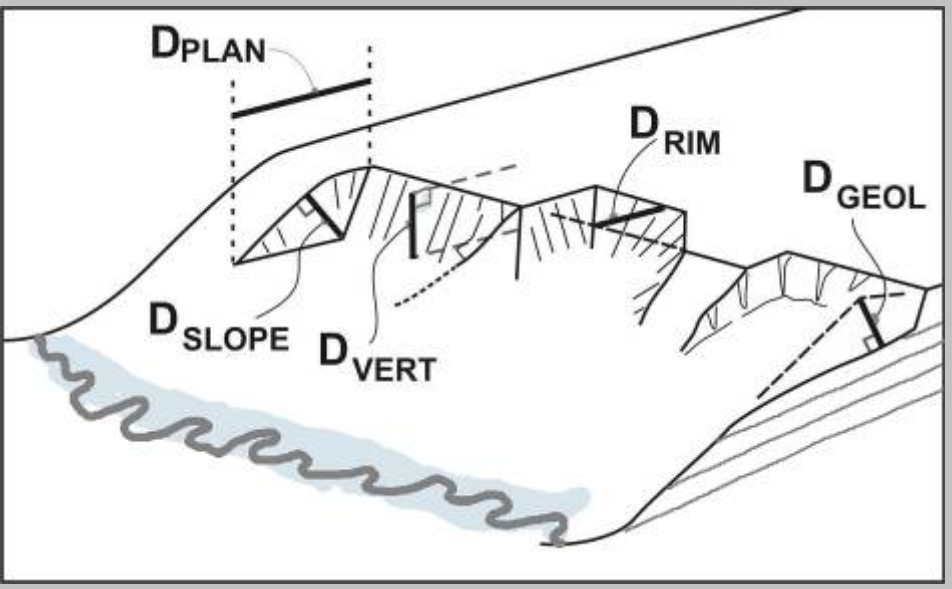
SG *(pale blue) - Skiddaw Group*
BVG *(dark blue) - Borrowdale Volcanic Group*
GR *(green) - granite*

(Figure 7 in main paper)

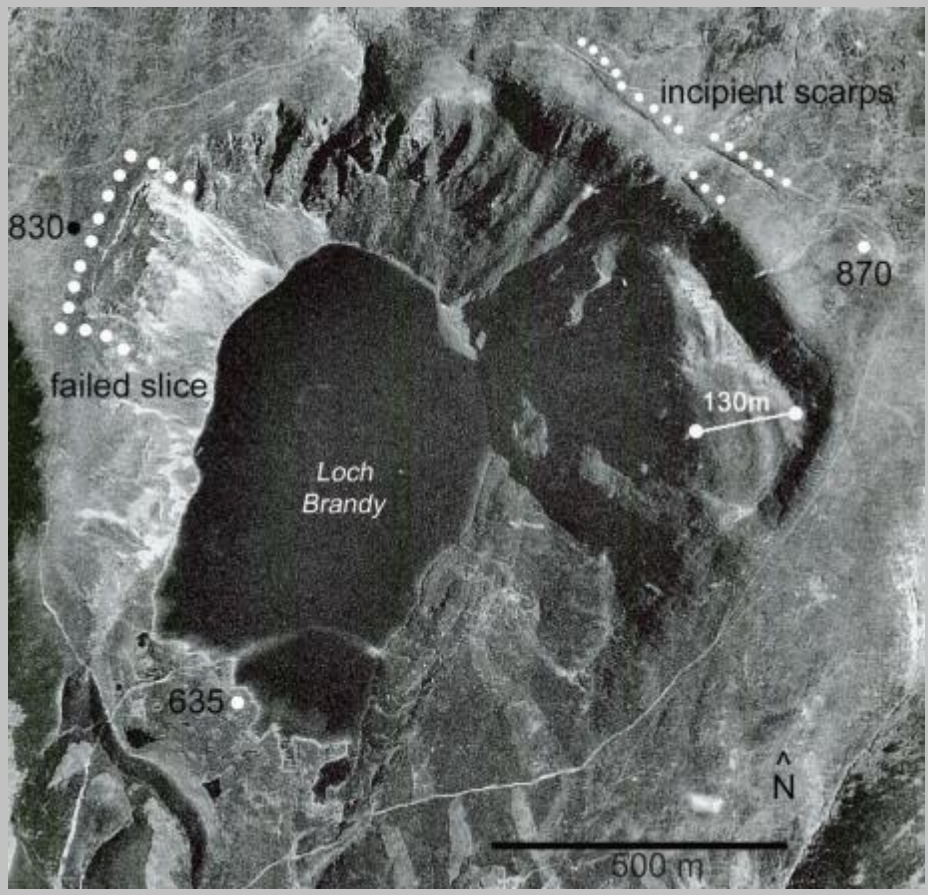


from Jarman 2009 'Paraglacial trough widening' GSL SP 320 Fig.19



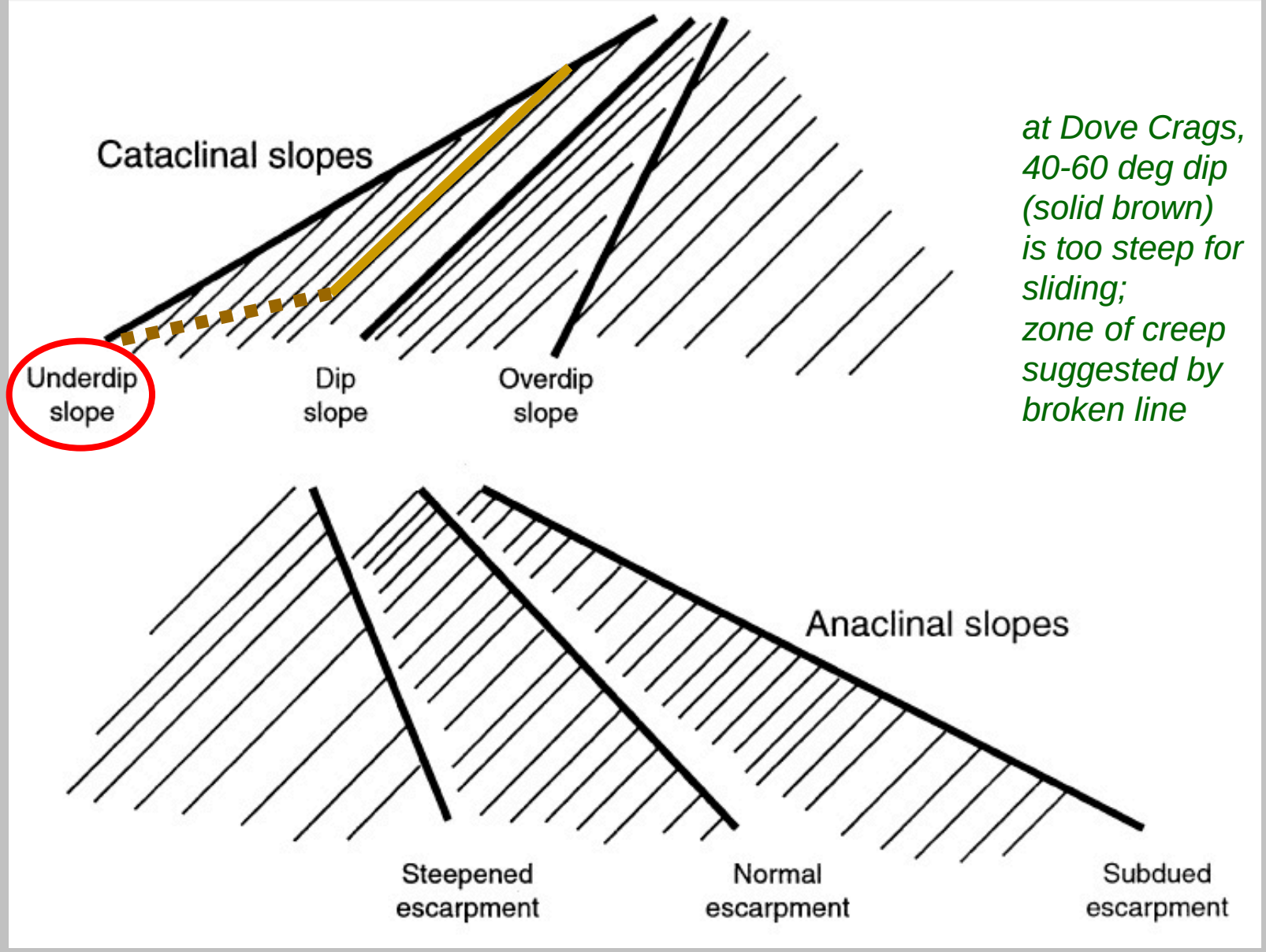


A. measures of cavity depth



B. Corrie Brandy - *one of the largest recorded D^{MAX} slipmasses*

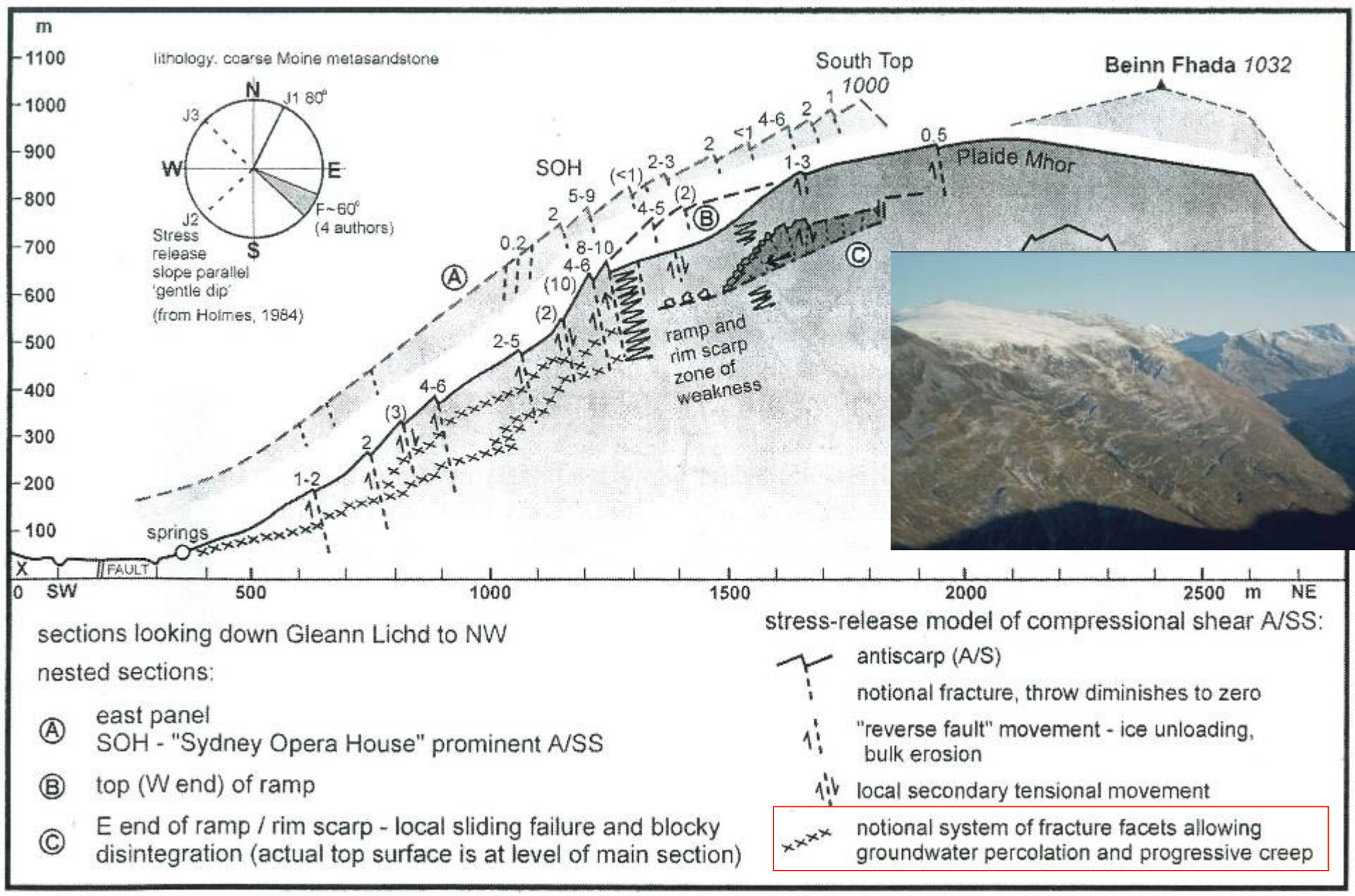
from Jarman 2009 'Paraglacial trough widening' GSL SP 320 Figs 4-5, 15a



at Dove Crags, 40-60 deg dip (solid brown) is too steep for sliding; zone of creep suggested by broken line

slope classification schema from Cruden 2000 (Fig. 1)

structural controls on RSF form and movement



Beinn Fhada RSF, W Highlands *from Jarman (2006)*

in absence of suitably inclined sliding planes, creep along a 'zone of crush' or fracture facets is inferred

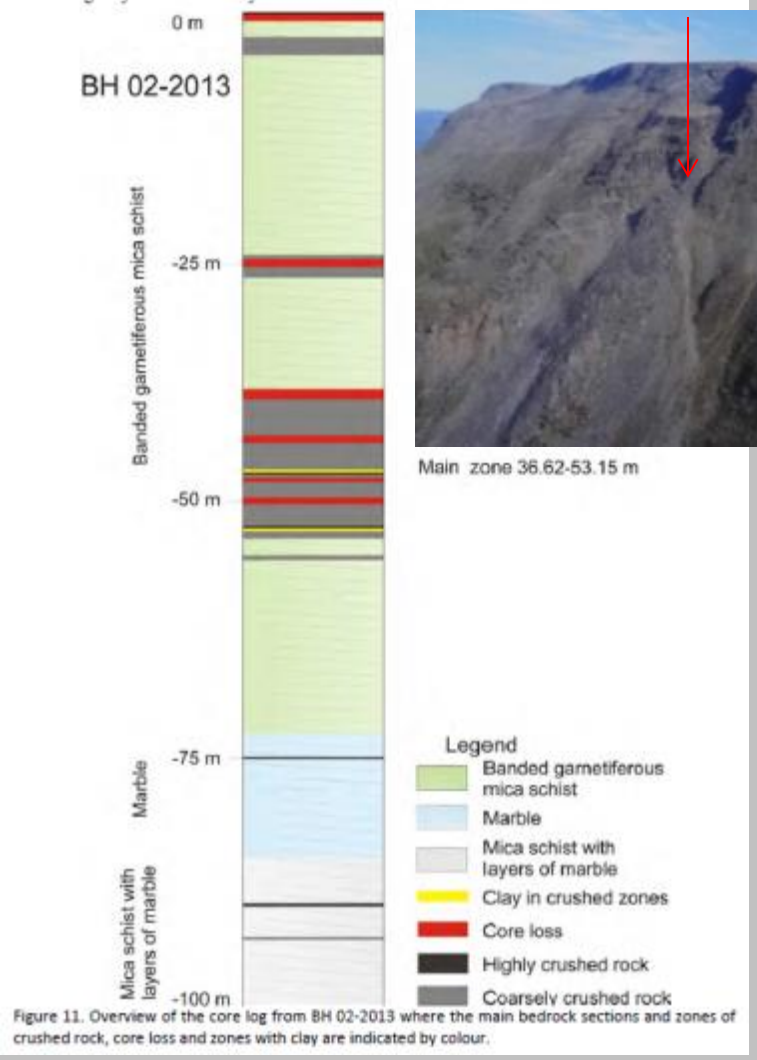
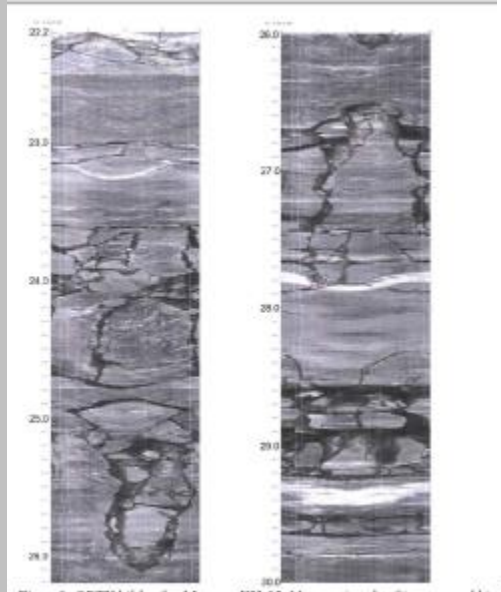
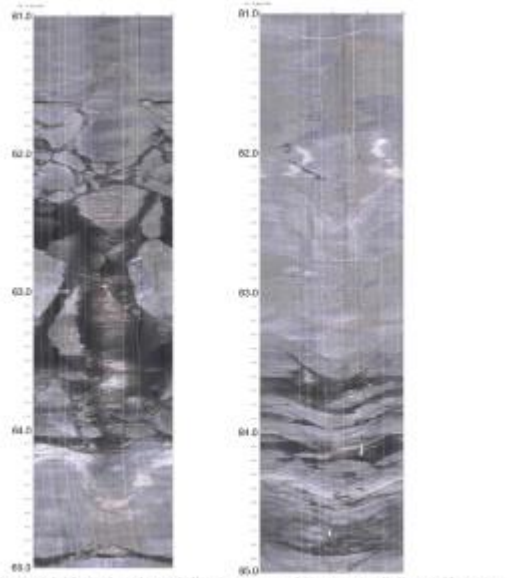


Figure 11. Overview of the core log from BH 02-2013 where the main bedrock sections and zones of crushed rock, core loss and zones with clay are indicated by colour.

Main zone 36.62-53.15 m



Figur 8. OPTV bilder fra Mannen KH-02-11 som viser kraftig oppsprekkin



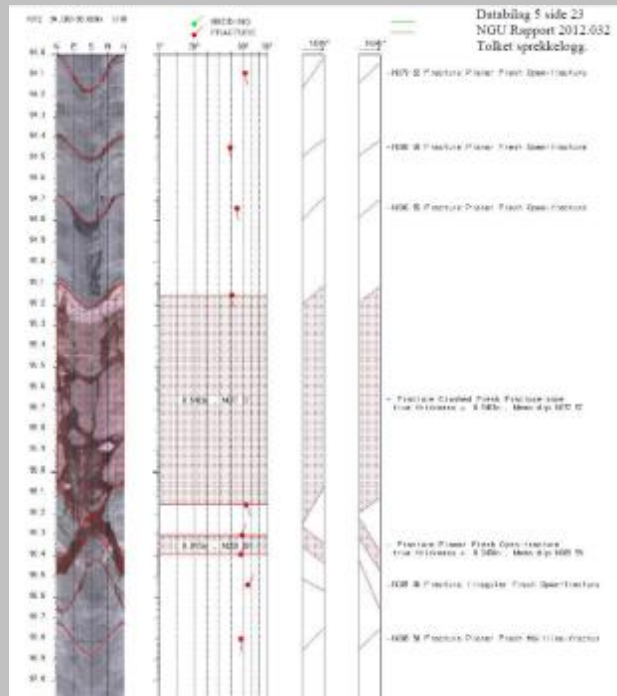
Figur 16. OPTV bilde med oppknust fjell 62 – 65 m, og fallasjonsparallelle sprekker 83.5 - 85 m dyp i KH-02-11.

televiewer down-hole
(360 deg images)
with sample interpretation

logged 'fracture zones' :

Jettan (left)
- *up to 15 m thick*
- *at ~45 m depth*

Mannen (right, above)
- *ten x 0.5-1.5m*
- *to ~100 m depth*



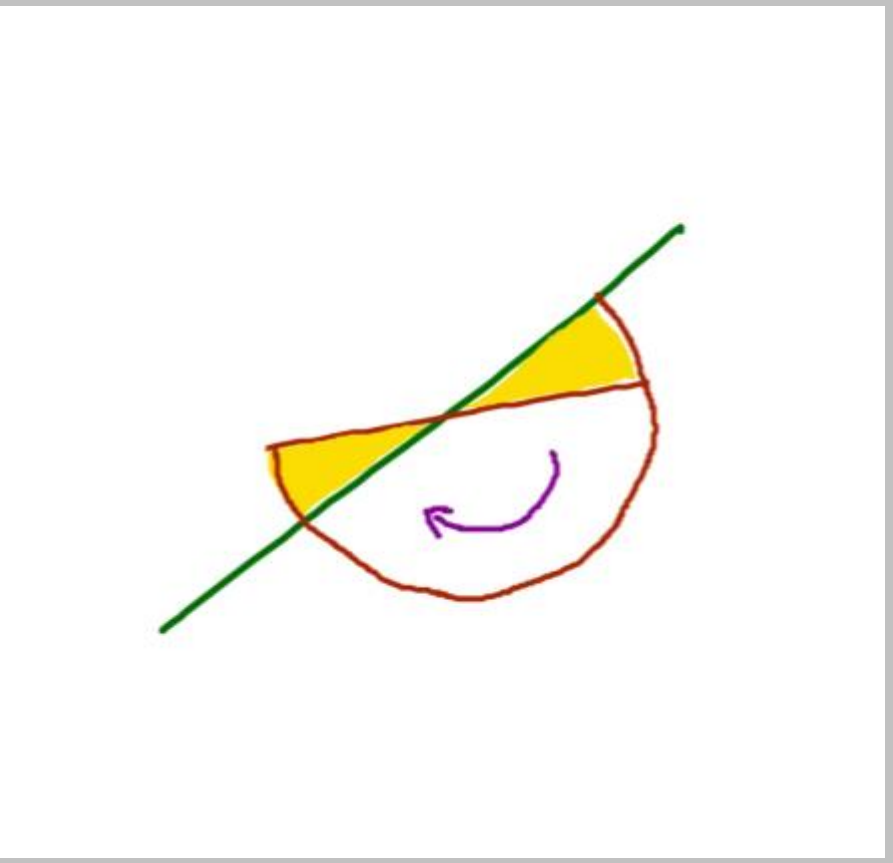
Jettan, Troms, N Norway ***Mannen, Romsdal, W Norway***

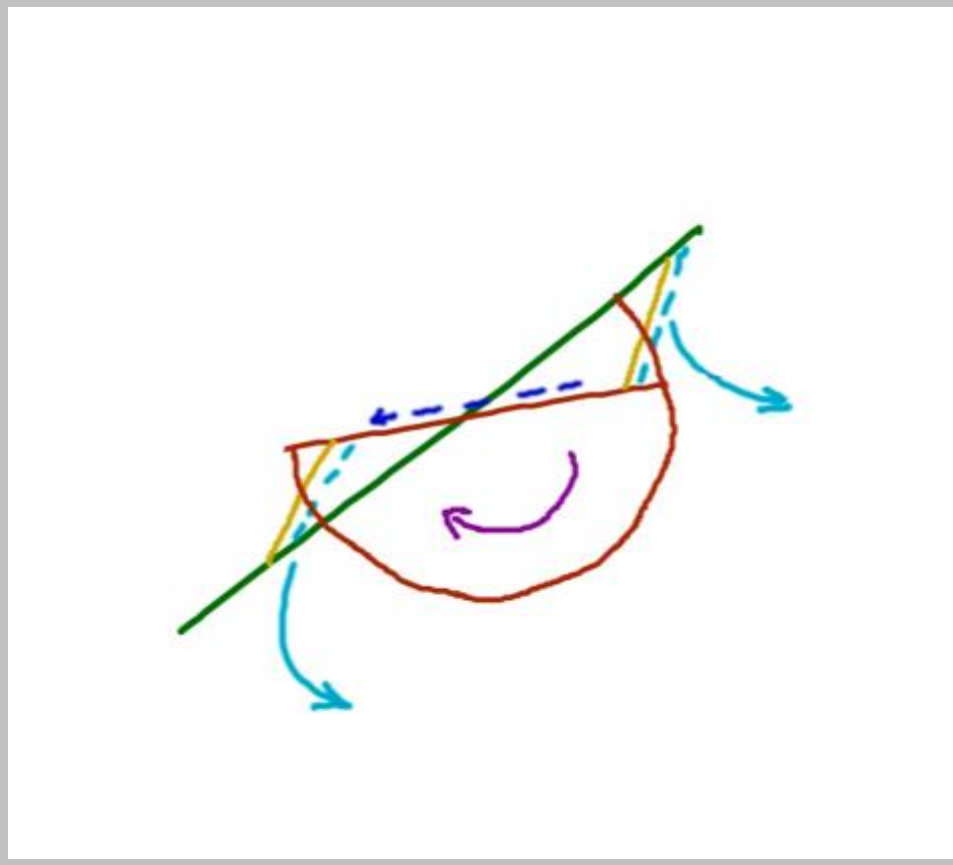
boreholes through slipped wedges

'zones of crush' enable slow creep of failed mass (dip too shallow for sliding)

from published NGU reports, courtesy Lars Blikra / Ingrid Skrede, Aknes/Tafjord Beredskap IKS, Norway

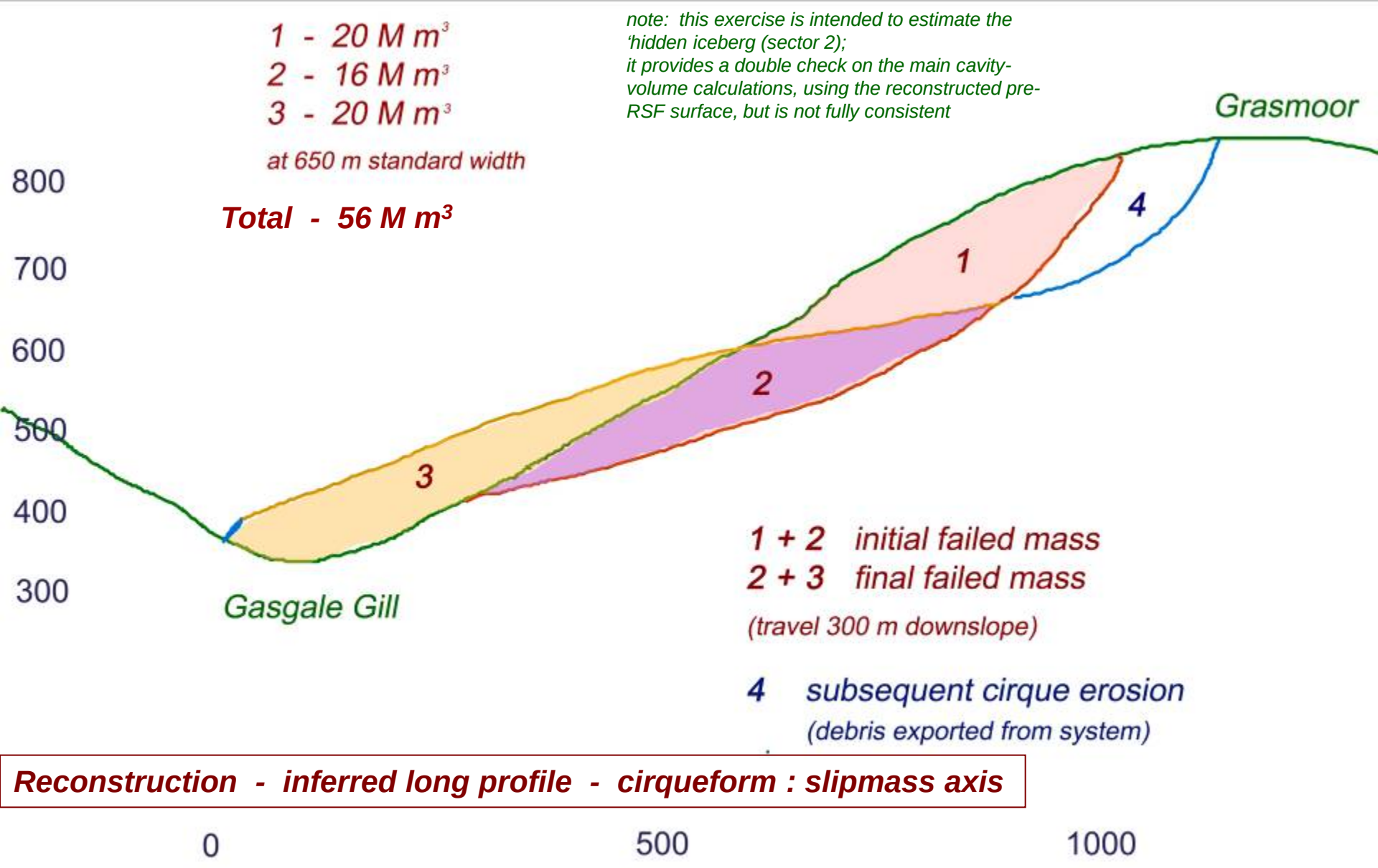
axiomatic : RSF visible cavity and visible slipmass must be 'in balance'





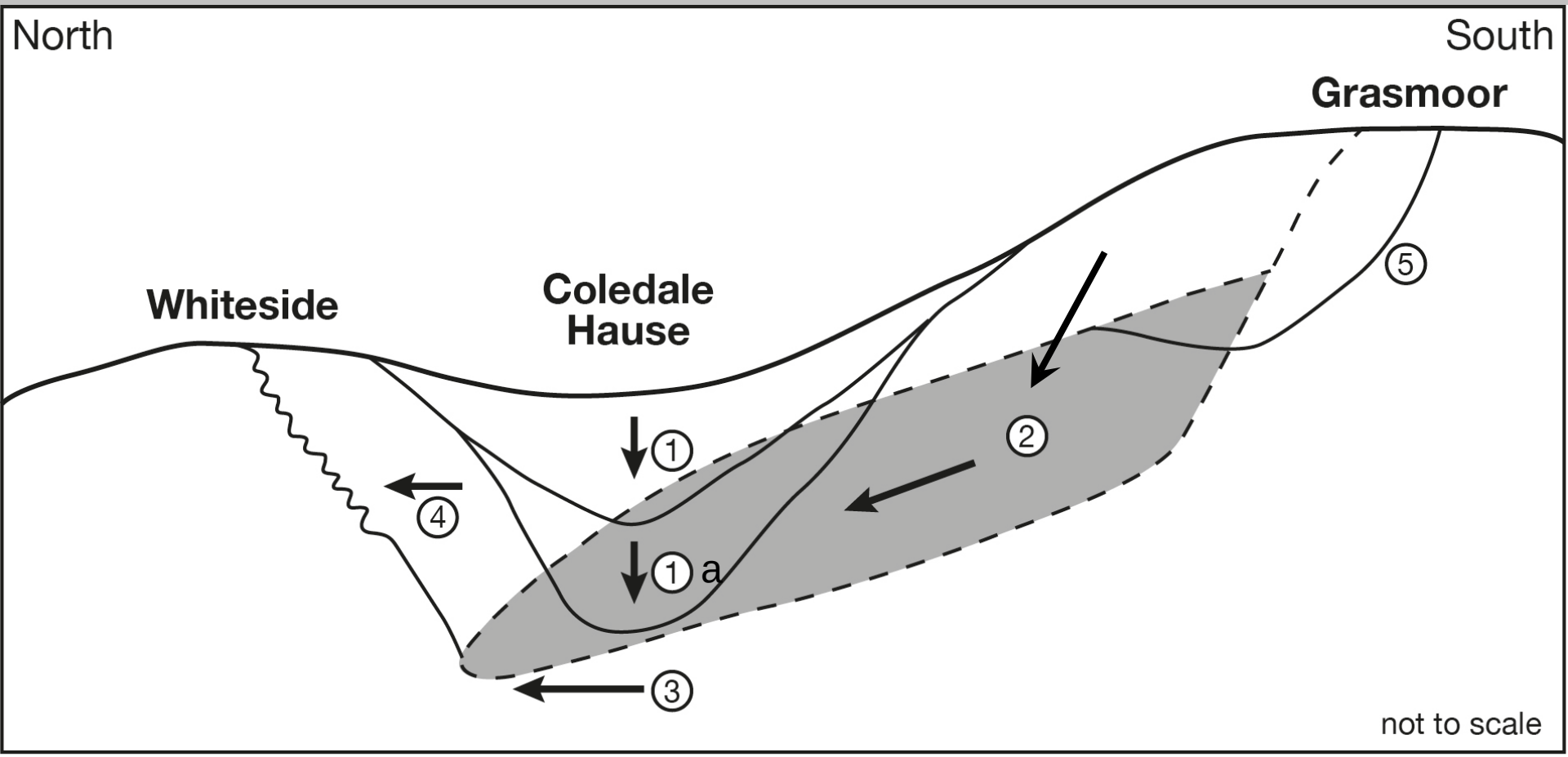
- *pivoted failure*
- *no downslope movement*
- *large 'hidden iceberg'*
  (sector 2 in next slide)

- *degradation of headwall and toe remain in balance (on-site)*
- *LLS cirque erosion and moraines remain in balance*
- *LGM cirque erosion and paring of toe alter balance if exported from system*



- *true to scale, no vertical exaggeration*
- *present land surface is above 3 and 2, below 4*
- *reconstructed land surface is green (glaciated valley)*
- *basal failure zone is behind 1 and below 2 - zone of crush not shown, curve is idealised*

- reconstruction based on typical depths / angles, readily gives balanced cavity-slipmass volumes



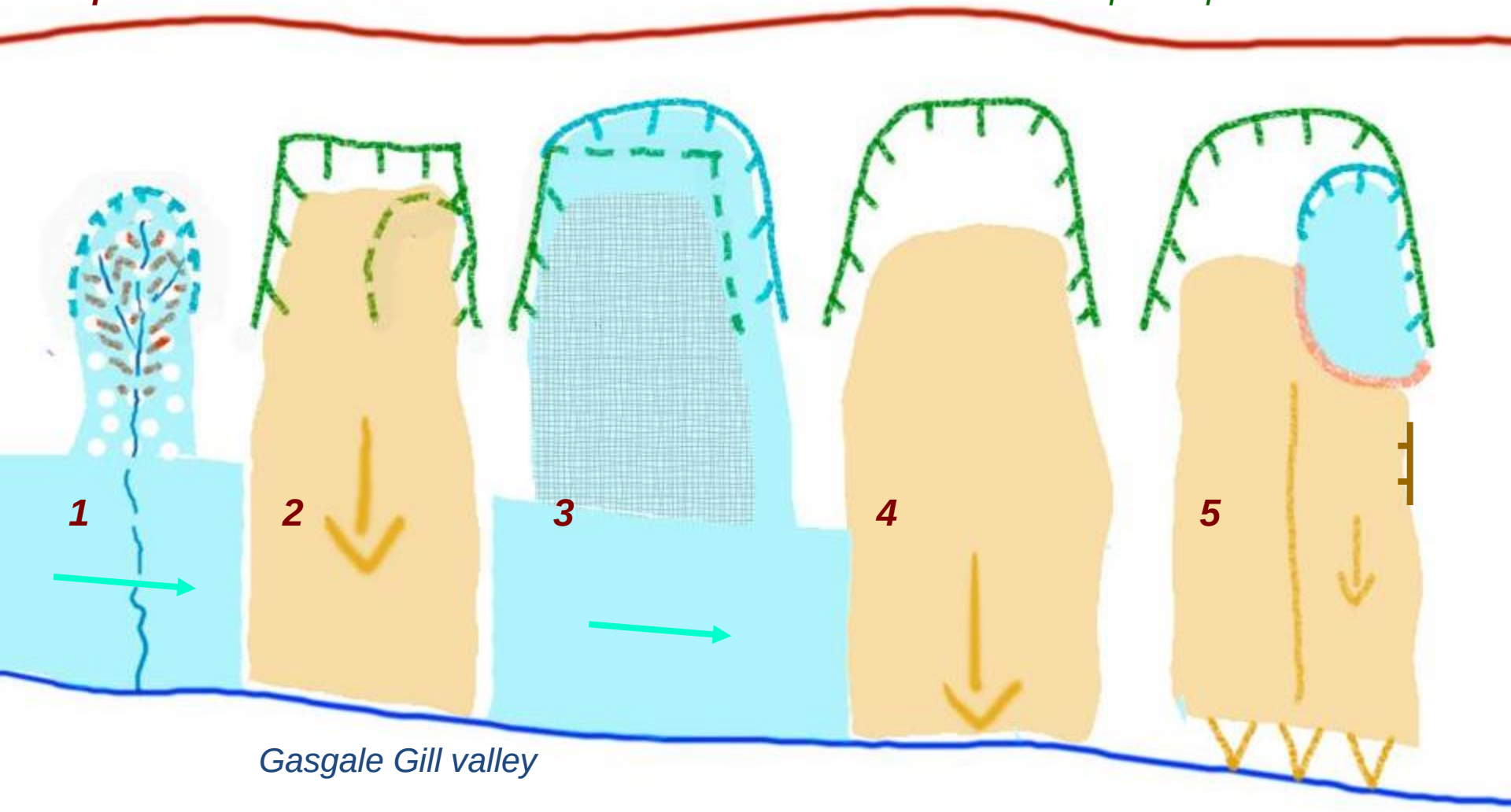
interaction of events - no timescale *(proposed timescale - next slide)*

1. *long-term fluvial incision of Gasgale Gill into rolling paleic (pre-Quaternary) upland surface*
1a. *periodic enlargement by relatively modest valley glacier*
2. *mass movement (hybrid creeping translational slide RSF) from Grasmoor into valley*
3. *valley axis displaced north*
4. *Liza Beck undercuts Whiteside, valley wall steepens and retreats, sharpening crest to half-arête.*
5. *mass movement cavity partially modified into glacial cirque, invading Grasmoor plateau.*

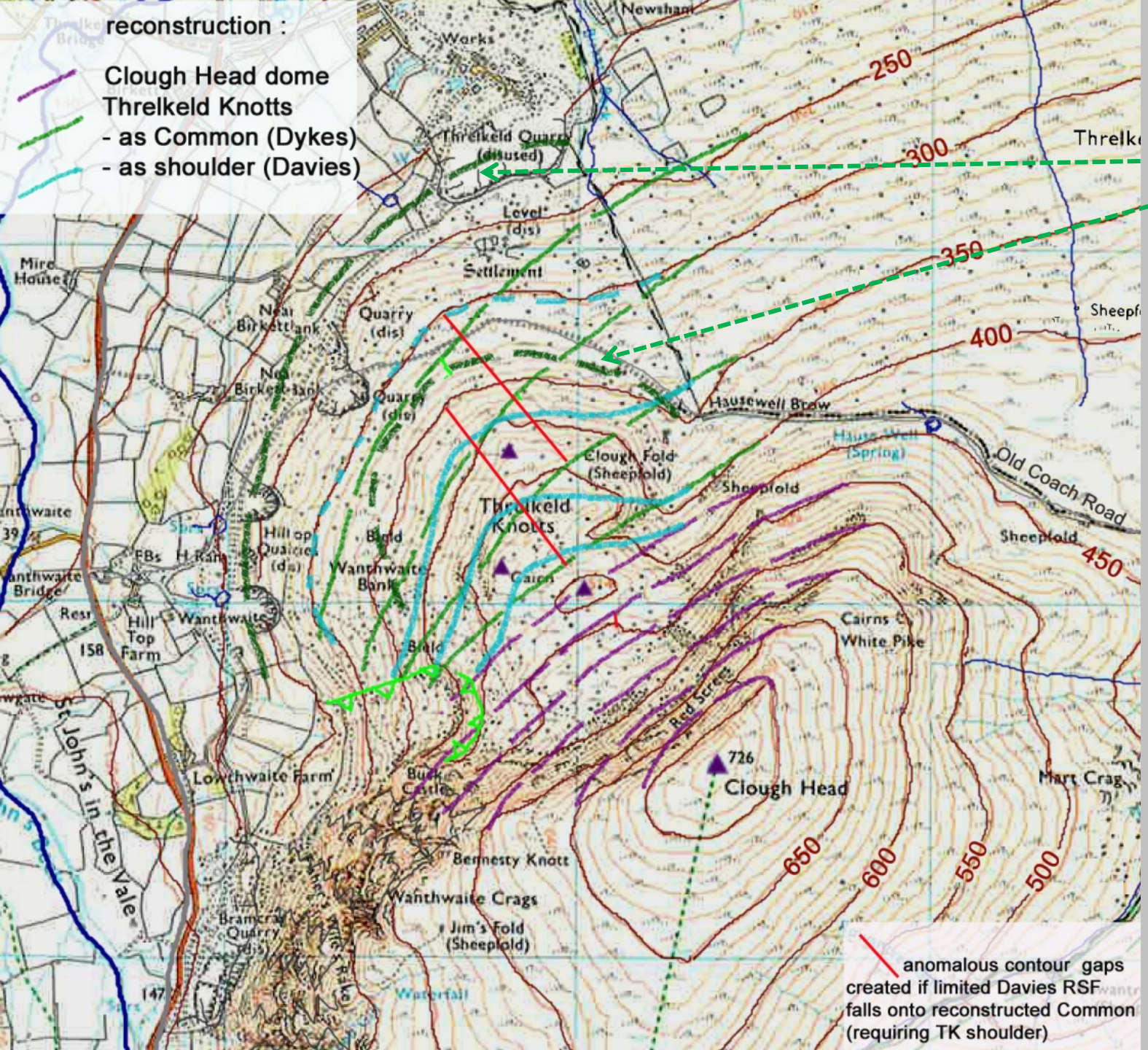
(Figure 10 in main paper)

sequence of events - timescale

Grasmoor paleic plateau



1 *main Pleistocene glaciations : fluvial valley >>> glacial trough, possible ravine / niche cirque*
2 *pre-LGM : large RSF cavity, slipmass descends to narrow valley floor*
3 *LGM : cirque glacier enlarges cavity, feeds valley glacier; it pares slipmass, emplaces till*
4 *post-LGM : slipmass reactivates, descends to narrow valley to 'fluvial' form*
5 *LLS : niche cirque glacier and moraine; minor west side descent; cutbank toe*



outer limits proposed by Dykes et al 2010 Davies et al 2013

Clough Head RSF

reconstructions Jarman & Wilson 2015 Fig 3

the Davies limit requires a proto-Knotts shoulder, on the microgranite laccolith