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Periglacial landforms of Dartmoor: an automated mapping approach to characterizing cold climate geomorphology

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ABSTRACT

A systematic mapping approach characterizes Dartmoor periglacial landform signatures using the geomorphology of nine summit areas displaying well developed tor and blockfield landforms. This combines manual vectorisation with automatic classification and surface boulder identification, using spectral signatures to reveal patterns and distribution. Tors were classified using a three-fold scheme: T0 - summits with no tors; T1 - summits with castellated and high relief tors; T2 - summits with subdued or low relief tors. Clitter (blockfield and blockstream) features identified by automated mapping include boulder lobes and stripes and boulder-fronted lobes and terraces, arranged according to distance downslope from parent tors. This zonation of periglacial landforms is proposed as a landsystem signature for areas exposed to periglacial and permafrost processes for significant time during the Quaternary. It represents a process-form regime in which cold climate processes, acting on partially deeply weathered and pneumatolysised granite, produce castellated tors, cryoplanation benches and autochthonous blockfield (clitter), and permafrost creep develops boulder lobes that elongate and evolve downslope as allochthonous blockslopes with boulder stripes and boulder-fronted lobes and terraces. This demonstrates that automated mapping can be applied to areas of upland periglacial landforms to rapidly and systematically compile quantifiable patterns of landform assemblages.

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Automated mapping; periglacial landsystem; Dartmoor

1. Introduction

Dartmoor is an upland landscape traditionally associated with long term weathering, fluvial and periglacial processes. Its prominence is due to the presence of the Cornubian Batholith, a granitic intrusion whose relatively high resistance to denudation compared to surrounding country rocks is the reason for its strong control over topography (Figure 1). A two-stage evolutionary model proposed by Linton (1955) involved landscape development by deep chemical weathering, followed by periglacial slope processes and tor development. The deepest incisions (valleys) on Dartmoor are related either to: 1) pre-existing weathered zones, regarded as tropical by Linton (1955), sub-tropical to

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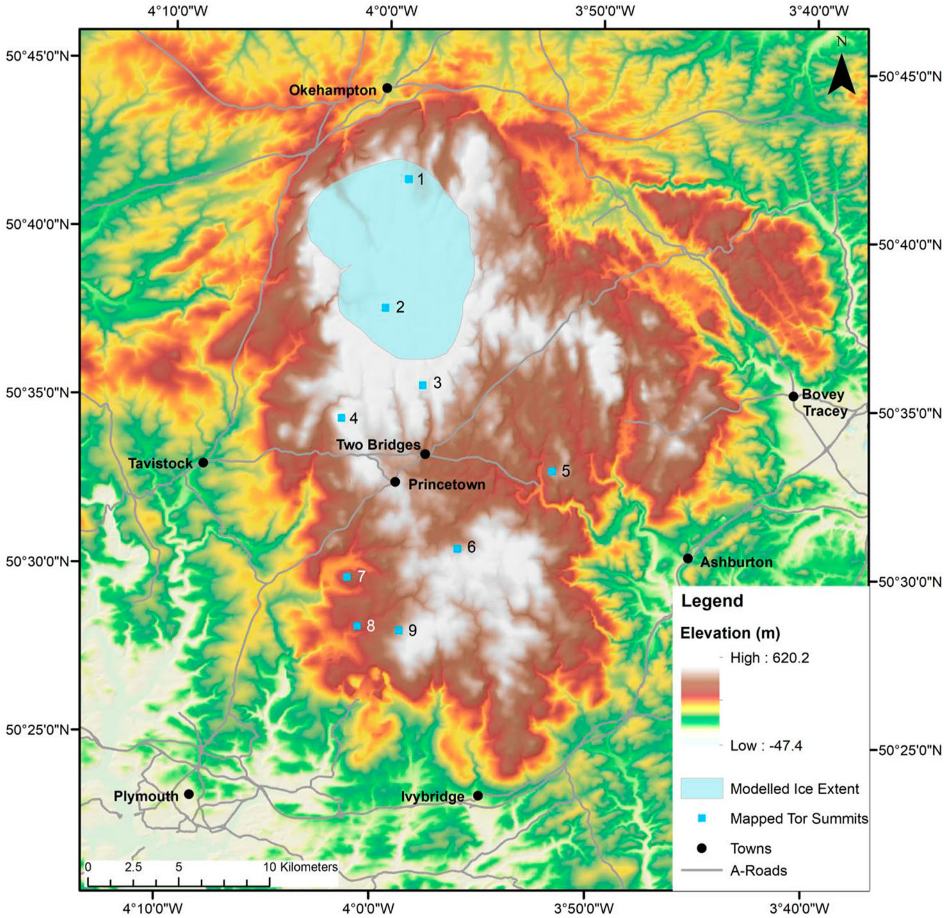


Figure 1. Topographic map of Dartmoor and surrounding areas, showing the locations of the summit sites used in this study (1 – East Mill Tor; 2 – Fur Tor; 3 – Crow Tor; 4 – Great Mis Tor; 5 – Yar Tor; 6 – Fox Tor; 7 – Sheepstor; 8 – Legis Tor; 9 – Hen Tor). The numerically modelled extent of a potential former plateau icefield, as proposed by Evans et al. (2012), is also depicted in light blue.

temperate by Waters (1964) and Brunsden (1964), and temperate (possibly interglacial) by Eden and Green (1971); or 2) pneumatolysis (Palmer & Neilson, 1962). Combinations of these controls (e.g. Doornkamp, 1974) have also been entertained. The chemical weathering stage was not regarded as necessary to Dartmoor landscape evolution by Albers (1930) and Palmer and Neilson (1962), who invoked an entirely periglacial origin.

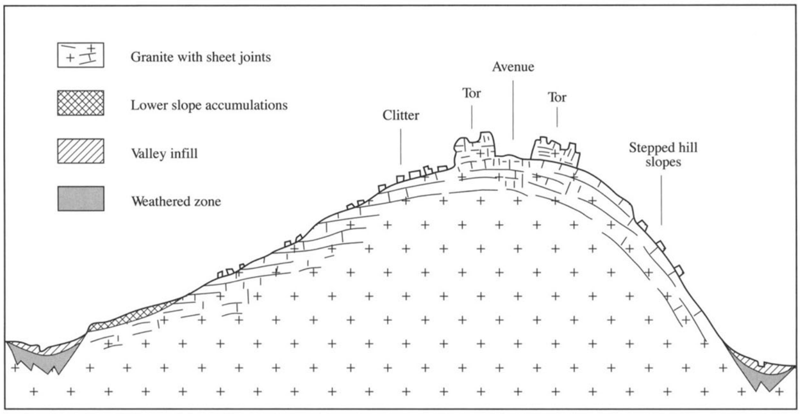
This established Dartmoor as an exemplar of a well-developed or mature upland periglacial landscape that had escaped glaciation. The traditional assumptions of extreme age (i.e. maturity, cf. Peltier, 1950) for the Dartmoor tors, as well as lengthy periods of periglacial activity rather than glaciation during the Quaternary cold stages (Palmer & Neilson, 1962), have only recently been questioned due to the advent of cosmogenic nuclide dating. This has delivered the first quantitative estimates of tor ages (Hägg, 2009; Gunnell et al., 2013), revealing that they may only be as old as MIS 3.

More recently, the unglaciated character of Dartmoor has also been questioned, reviving early propositions that glaciers had formed on the uplands at some time during the

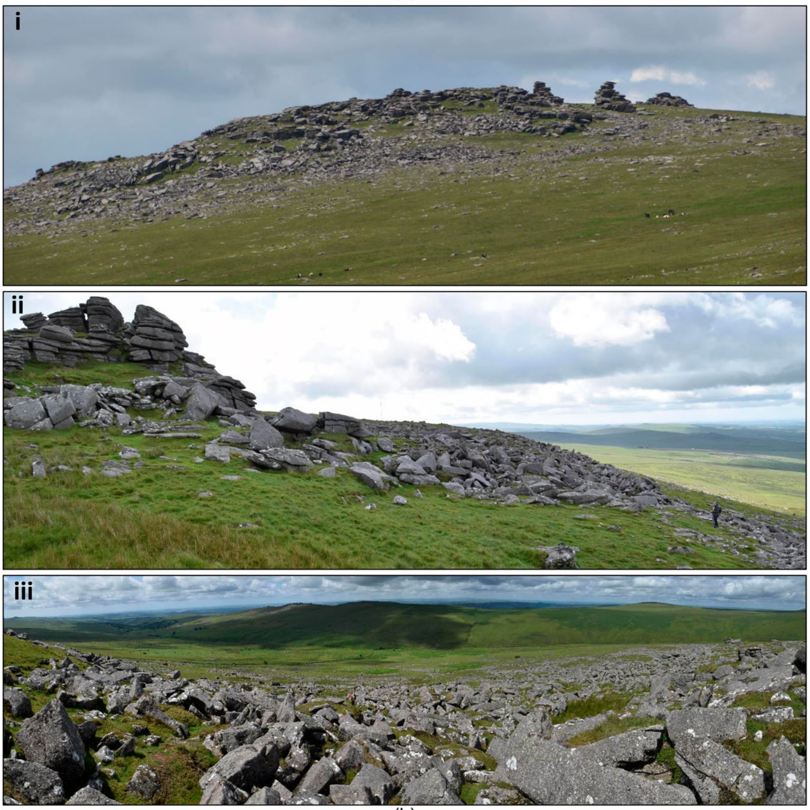
Quaternary Period (cf. Ormerod, 1869; Pillar, 1917; Pickard, 1943). Numerical ice sheet modelling exercises (Hubbard et al., 2009) indicate that Dartmoor, like every other upland area in the British Isles, has both the requisite altitude and precipitation to grow a plateau icefield during glacial cycles. Moreover, an expanding knowledge base on the geomorphology of marginally glaciated terrains and plateau icefield styles of glacierization, has highlighted a subtle glacial geomorphological signature indicative of cold-based glacier ice on high elevation dispersal centres as well as localised moraine construction in the valley heads incised into plateau margins (Dyke, 1993; Rea et al., 1996a, 1996b, 1998; Rea & Evans, 2003, 2007; Evans, 2016). This signature of a plateau icefield style of glaciation has been invoked for southwest England, for example on Exmoor (Harrison et al., 1998, 2001) and north Dartmoor (Harrison, 2001; Evans et al., 2012; Figure 1).

Emerging from these recent advances is the question of what constitutes a well-developed or advanced (mature) periglacial landsystem, specifically in mid-latitude upland terrains (cf. André, 2003; French, 2016; Murton, 2021). Instead of Dartmoor, should we not be reflecting on the suitability of other mid-latitude upland settings that have escaped Quaternary glaciations to be exemplars? These might include: 1) Bodmin Moor, where (Evans et al., 2017; Evans, 2020) identified the altitudinal arrangement of periglacial landforms from castellated summit tors with locally well-developed cantilevered corestones, grading downslope into blockfield derived from tor stack collapse and then into boulder lobes or patterned 'clitter' fields; 2) the Mount Kent uplands, east Falkland Islands, with its patterned boulder fields, remarkable stone runs (block streams) and summit tors (Joyce, 1950; Clark, 1972; Clapperton, 1975; Rosenbaum, 1996; Hansom et al., 2008); and 3) the Isles of Scilly, where Scourse and Furze (2001) and Hiemstra et al. (2006) use precariously balanced or cantilevered tor corestones as indicators of a non-glaciated terrain that is juxtaposed with a glaciated terrain characterised by glacially modified tors (cf. Hall & Phillips, 2006). Notwithstanding the suitability of these landscape examples and considering the restricted nature of proposed glacier cover on Dartmoor, its undoubted exposure to intense periglacial and permafrost conditions during the Quaternary cold stages of the last 2.6 Ma ensure that it should still contain areas of well-developed, non-glacial cold climate geomorphology.

Assessments of the suitability of these various locations to be periglacial landsystem exemplars requires systematic mapping of the periglacial landform signatures in order to characterise and quantify pattern and form (e.g. Evans et al., 2017). However, no such systematic mapping has been undertaken for Dartmoor specifically, with the exception of the relatively small areas centred on Cox Tor (te Punga, 1956; Gerrard, 1988; Miller, 1990) and Great Mis Tor (Harrison et al., 1996), where large, castellated tors are associated with cryoplanation benches or terraces and boulder lobes and stone-fronted gelifluction lobes (Harrison et al., 1996; Harrison & Evans, 2014). The landsystem model that has emerged for Dartmoor is depicted in Figure 2a (Gerrard, 1988; Campbell et al., 1998) and comprises prominent, castellated summit tors that have slowly fragmented, collapsed and moved downslope to form clitter (boulder fields or blockfields) and ultimately lower slope accumulations of crudely-stratified bouldery diamictons and finer-grained slopewash (e.g. Waters, 1964, 1965; Green & Eden, 1973; Miller, 1990). Stepped hillslopes also represent the evolution of cryoplanation benches created by tor reduction and recession (Figure 2b). Well established models of upland periglacial landscape evolution, while often acknowledging polygenetic origins in pre-Quaternary



(a)



(b)

Figure 2. Characteristics of the well-developed periglacial landsystem of Dartmoor: a) existing model of landform-sediment associations (landsystem) for Dartmoor, including summit areas with castellated tors, clitter fields and thin regolith, upper hillsides covered with cryoplanation benches/terraces, boulder lobes and clitter, and lower hillsides with deeper solifluction debris (after Gerrard, 1988 and Campbell et al., 1998); b) examples of the main landsystem elements and facets, including; i. hilltop profile of Great Staple Tor viewed from the northeast, showing summit tor stacks, cryoplanation bench at left and clitter slope/blockfield; ii. west face of Great Mis Tor, showing cryoplanation bench at the foot of the tor stack, fringed at the right by bolder lobes; iii. view down west slope of Great Mis Tor through the boulder lobes to the stone-fronted lobes of the lower slopes.

regimes, depict the gradual isolation of summit tors and downslope movement of frost shattered debris (blockfield) by solifluction over time. This leads to the development of cryoplanation benches through parallel slope retreat (Figure 2b; e.g. Boch & Krasnov, 1943; Demek, 1964, 1969a, 1969b; Lauriol & Godbout, 1988). In Peltier's (1950) periglacial landscape model (cf. Demek, 1969b), this stage of development is regarded as 'mature' in the Davisian sense, with the final removal of summit tors representing a later 'old age' phase in which surrounding valleys become plugged with the material removed over long timescales from the former summit blockfields. Although the process-form regimes involved in this conceptual model of periglacial landscape evolution are entirely feasible, cryoplanation has been a controversial topic (cf. Budel, 1982; Priesnitz, 1988; Thorn, 1988; French, 1996). Only more recently has this process of periglacial slope evolution been demonstrated (Nyland & Nelson, 2020a, 2020b; Nyland et al., 2020). Consequently, if we give this periglacial slope evolution process renewed credibility, re-visit Peltier's (1950) and Demek's (1969b) models, and apply them to Dartmoor as an unglaciated landscape, those areas conforming to the depiction in Figure 2a (e.g. Cox Tor) would be classified as 'mature' and those summits devoid of tors classified as 'old age'. The application of the latter becomes problematic in the Dartmoor context in that the absence of castellated summit tors, especially on the highest parts of north Dartmoor, has been interpreted in a different way by Evans et al. (2012; their Type 1 tors). They entertained the notion that the absence of a summit tor could conceivably indicate former glacier ice cover and the concomitant dampening of tor development.

As an attempt to resolve the lack of systematic mapping of cold climate landforms and hence to scrutinize the evidence for well-developed or advanced (mature) periglacial landsystem development on Dartmoor, this study aimed to map the geomorphology of multiple summits on north and south Dartmoor, employing an automatic classification procedure. Two of the north Dartmoor summits are also located within the extent of former glaciation proposed by Evans et al. (2012). Features specifically targeted were those deemed significant in the recognition of a periglacial landsystem signature. This included tors, for which the tor classification scheme of Evans et al. (2012) was employed to assess the periglacial development/maturity of summits in the sense proposed by Peltier (1950), and clitter (blockfield) features such as boulder lobes, stone-fronted lobes and stripes, as well as potential stone runs/block streams (Green & Gerrard, 1977). Potential zonation of such landforms, as implied by the model depicted in Figure 2a as well as by mapping on Bodmin Moor by Evans et al. (2017), was also assessed. This facilitated the evaluation of the theory that clitter is either the product solely of tor mass wasting (Waters, 1964) and migrates downslope in waves over long periods of time (Evans et al., 2017) or a combination of this process and the in situ macrogelifraction of mid-slope, near surface bedrock (Green & Eden, 1973).

2. Methods

In order to objectively characterise and map the variable morphology and distribution of periglacial landforms on summits across Dartmoor, a total of five summits on south Dartmoor and four summits on north Dartmoor (two located inside the glacial extent proposed by Evans et al., 2012) were selected for analysis (Figure 1). In order to enable comparison with the study of Evans et al. (2012), tor development or maturity was assessed by classifying tors/summits using their three-fold scheme, using a combination of aerial photography, satellite imagery and ground truthing. This involved a classification of summits with an absence of tors as T0, summits with a castellated and high relief tor (>5 m) as T1, and summits with a subdued or low relief tor (<5 m) as T2 (Figure 3).

Many periglacial landforms have a very low relief and therefore are difficult to identify through ground-based geomorphological mapping, recently prompting the first automated mapping approaches to studying periglacial landforms (e.g. Queen et al. 2021). Such an approach was pioneered on Dartmoor by Mather et al. (2018). Traditionally, periglacial landforms have been identified manually and vectorised using aerial imagery (e.g. Dabski et al., 2017; Evans et al., 2017); alternatively the landscape is categorised into a series of zones dominated by specific processes or landforms (Goodfellow et al., 2008). Individual landform identification in such approaches is time consuming, especially in areas dominated by clitter fields and loose regolith, and the zonation of forms limits the collection of the high-resolution information vital to reconstructing landform genesis. Therefore, this study combines manual vectorisation of some features (tors, anthropogenic structures) with the automatic classification and identification of surface boulders, using their spectral signatures in order to reveal patterns and distribution.

The high resolution aerial imagery necessary for mapping was acquired from Edina Digimap (https://digimap.edina.ac.uk/). The imagery was in a three band RGB format

Figure 3. Examples of tor types using the classification scheme of Evans et al. (2012): a) Type 2 on Broad Down, 2 km northwest of Postbridge, northern Dartmoor; b) Type 1, Little Mis Tor; c) Type 1 tor stack/cantilevered blocks, Great Mis Tor.

with a resolution of 25 cm. Images were available for the period 2008–2018 but exhibited significant variability in stone visualisation depending on the proportion of vegetation cover at the time of year when each image was acquired (cf. Mather et al., 2018).

For the mapping of periglacial landforms surrounding the summit tors, an automatic classification procedure was employed, whereby automatic machine learning classifiers utilise the spectral signatures of a series of user-defined classes in an image (Maxwell et al., 2018). Based on the spectral properties, class values are applied to unseen pixels in an image (Belgiu & Dragut, 2016). There is a range of machine learning algorithms that perform this function (Lu & Weng, 2007) and this study used a Decision Tree algorithm to classify each study site. Decision trees use a nodal hierarchy to split the data into a series of 'branches' based on attributes such as minimum distance and target thresholding (Pal & Mather, 2003). They are relatively simple classifiers, are computationally efficient, and have a more simplistic structure compared to algorithms such as Deep Neural Nets (Maxwell et al., 2018). This makes them less vulnerable to over-fitting, and more accurate when using small training sets, as is the case for this study (Pal & Mather, 2003).

Initial observations of the aerial imagery for each study site informed an assessment of the number of spectral classes that needed to be trained for each image. Within the same class type, there were significant differences in spectral appearance between sites on Dartmoor. Therefore, for each individual site, a series of training polygons was manually digitised for each identified class in an image and hence was not generalised between sites.

Clitter fields are conspicuous by their heterogeneous spectral appearance, characterised by the constant alternation of boulders, shadows and surrounding vegetation. Therefore, an additional texture layer was generated using the 'Make Texture Raster' script, which calculates the entropy feature from the co-occurrence matrix (cf. Haralick et al., 1973). The use of texture has been shown to significantly improve classification performance by providing an additional criterion to facilitate the differentiation of spectrally similar but texturally different classes (Busch, 1998). The use of texture provides an additional spatial dimension to the analysis, as it is calculated using a moving window of pixels; this means that texture values are assigned to a pixel based on the spatial relationships with neighbouring pixels (He & Wang, 1990). A 7×7 pixel moving window was chosen for texture extrapolation because of the closely spaced nature of the boulders, meaning that a higher resolution textural extrapolation was desired. Texture was calculated using the blue band due to the relatively higher spectral reflectance contrast between boulder cover and vegetation in the blue band in comparison to the red and green bands (Figure 4), making boulders more easily distinguishable to the algorithm. The red, green, blue and texture bands were used as inputs to the Decision Tree machine learning algorithm, using the Scikit-learn library installed in the QGIS Python environment. The output classification underwent minor post-processing, including reclassification of the output to remove additional classes and display only boulder cover. Periglacial landforms such as boulder lobes/stone-fronted lobes and patterned ground were then identified from the automatic classification outputs based on knowledge of the ontologies and common plan forms of these features.

Accuracy of the automatic classification was established through the F1 score, which is a harmonic mean of: a) the precision or the ability of the classifier to accurately identify boulder pixels; and b) the recall or the proportion of the total boulder class correctly

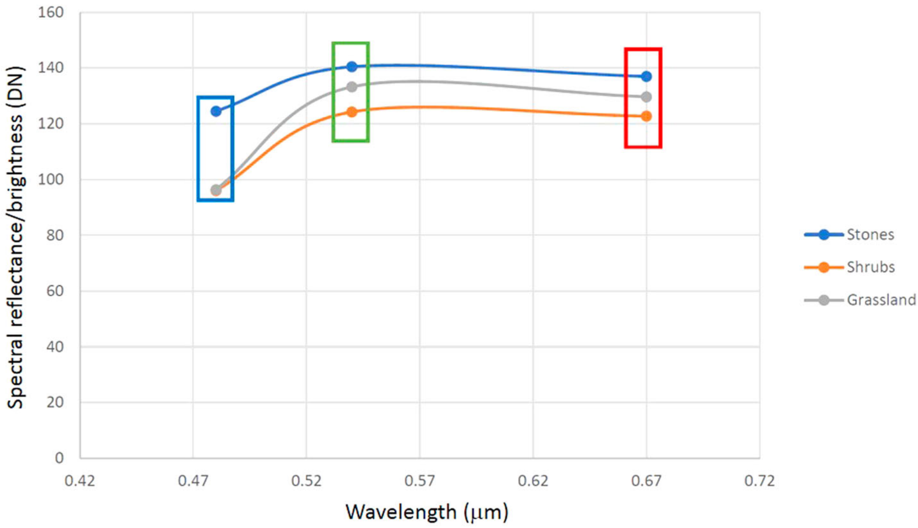


Figure 4. Spectral reflectance graph showing the different reflectance values for two types of vegetation and stone cover. The coloured boxes indicate the wavelengths of the red, green and blue bands used in the classification. Note the divergence in the spectral reflectance between vegetation and stone cover in the blue band.

classified. Carbonneau et al. (2020) demonstrated that the F1 score gives similar results to accuracy but is more sensitive to issues such as class imbalance and therefore seen as a better assessment metric for pixel-level classifications. This process was performed for the three study sites of Great Mis Tor, Hen Tor and Fur Tor (Table 1). This ensured that the classification approach yielded consistently high accuracy values across different images and that confidence could be placed in the outcome of the classification.

Some manual digitisation was also required, largely because vegetated features, such as non-sorted patterned ground, are not spectrally distinct enough from the surrounding land surface to be identified through automatic classification. In addition, there is a legacy of anthropogenic influence on the moor, with evidence of both Neolithic and Bronze Age settlements, earthworks relating to tinning, and extensive networks of boundary walls (Barber, 1970). Alongside settlements, human-made forms have also been identified in clitter fields. These consist of circle structures, cairns, barrows, and burial markers, and are distinguishable through their differential clast orientation and artificial geometry (Tilley et al., 2000). These landforms and anthropogenic structures were identified on aerial imagery and manually digitised over the classified clitter fields in ArcMap.

The influence of soil and, more significantly, vegetation masking of landforms is an issue that needs to be acknowledged at this juncture. The exact amount of such

Table 1. Precision recall and f1-scores for Great Mis, Hen and Fur tors

Tor Name	Recall	Precision	f1-Score
Great Mis Tor	0.95	0.91	0.93
Hen Tor	0.84	0.97	0.90
Fur Tor	0.87	0.98	0.92

masking is unknown, is likely highly variable and in some locations could be significant. In order to avoid the more extreme cases of masking, the areas selected for mapping were those where landform signatures were strong and hence soil, peat and vegetation development has not obscured the features being assessed. Future approaches to avoid masking completely might be to employ airborne or ground-based geophysical methods that could detect changes in electrical resistivity.

An additional qualitative accuracy assessment was made between manually digitised boulders in the clitter field around Sheepstor, and its automatically classified counterpart. Each boulder in the defined area was manually digitised using the 'Freehand Polygon tool' to produce a series of closed polygons. This analysis illustrated that at a larger tor-level scale, the two methods produce a similar output and represent large-scale patterns well (Figure 5). However, at smaller scales, the manually digitised version is superior in its ability to extract information about individual boulders and their respective orientations.

Despite this limitation, the use of an automatic classification approach is justified in that the aim of the investigation is to categorise the distribution and characteristics of features across Dartmoor on a landscape scale. Thus, a loss of resolution at smaller scales does not significantly impact the differentiation of periglacial landforms within clitter fields. The advantages of being able to quickly and efficiently map large areas of Dartmoor using automatic classification justifies its use as the primary methodology for this investigation.

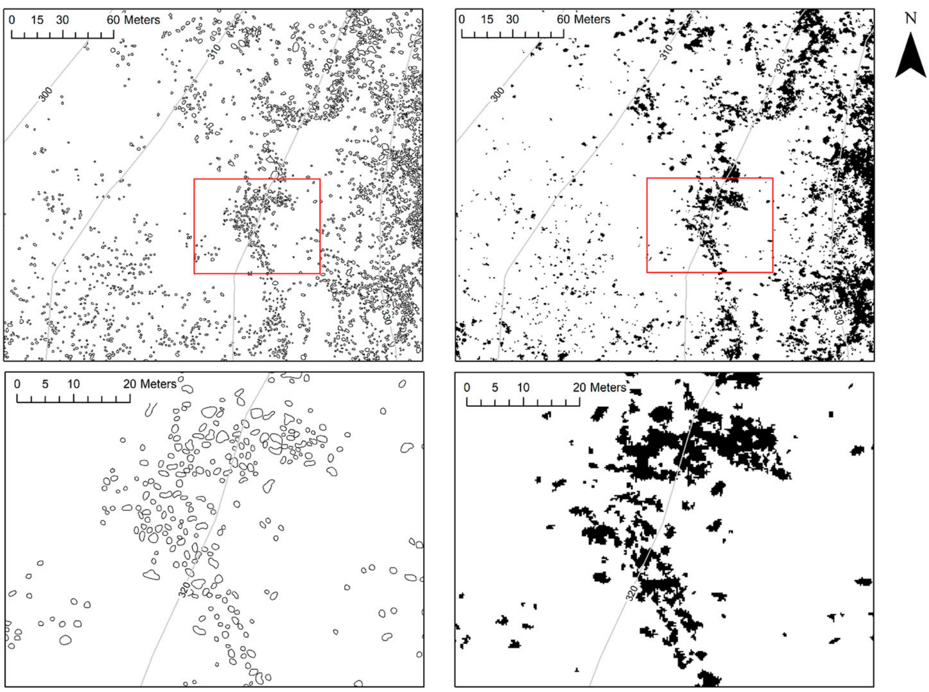


Figure 5. Comparison of the visualisation quality of large scale boulder structures and small scale individual boulders, between the manual digitisation (left) and automatic classification (right) approaches. Red frame marks the extent of the visualisations in the lower panels.

Statistical and field analyses of periglacial landforms were also undertaken. To combine statistical height and slope gradient data with the automatic classification outputs, they were overlaid on to 1 m digital terrain models (DTM's) downloaded from Edina Digimap (Tellus South West project -https://doi.org/10.5285/e2a742df-3772-481a-97d6-0de5133f4812). Where 1 m DTM's were unavailable for the study site, as in the case of Hen Tor and Yar Tor, 5 m DTM's were substituted. Subsequent quantitative analysis of periglacial landforms was undertaken using the 3D Analyst interpolation tool and the measurement tool in ArcMap and included feature length, width, distance from summit, hillslope gradient, hillslope long profile and slope curvature. This allowed for a statistical comparison of landform size, altitudinal arrangement, preferential hillslope development and hillslope angle between different study sites. In addition, field investigations were carried out on boulder lobes at Great Mis Tor. The heights of the risers of prominent lobe features were measured in the field, using clinometer and tape measure, along a downslope transect from the summit to the valley base.

3. Geomorphology maps

Maps of summit tors and surrounding clitter compiled using the procedures of manual identification of tors and the automatic classification outputs of surrounding summit slopes are presented as Figures 6–14. These facilitate the identification of periglacial landforms based upon known process-form relationships as well as a detailed inter-comparison of the summit landform assemblages using the nine summits. Our clitter landform patterns are very similar to those recorded by Mather et al. (2018) in their pioneering use of automated mapping at Leeden Tor on Dartmoor. More specifically, their unsupervised classification approach used boulder distributions to depict boulder stripes and some lobate forms. In our automated map output, in addition to the tors, three genetically related hillslope landform types (lobes, terraces and stripes) are recognised based upon common recognisable patterns within the clitter fields and these are now described and interpreted in turn.

3.1 Tor morphology and distribution

Like the patterns reported for north Dartmoor by Evans et al. (2012), the spatial distribution of tor types across south Dartmoor shows a clear relationship with elevation and relief (Figure 15). The high and broad plateau surfaces in the central region of south Dartmoor are devoid of tors (T0) and clitter forms are also largely absent. This high elevation plateau area is fringed by a series of more subdued tor forms (T2) generally characterised by a single subdued corestone feature with no extraneous boulder structures or stacks. Beyond the central plateau, most of the low elevation, narrower summit surfaces are characterised by higher relief and more elaborate tor structures (T1), with cantilevered boulders and boulder stacks. This pattern was clearly depicted by Palmer and Neilson (1962) in their graphical relationship between elevation and the number of summits containing tors. The pattern they revealed showed that tors increase in number on summits between 427 and 457 m OD. Below that range they fall off rapidly in number. Above that range they gradually decline and oscillate in number. Their explanation was that tor formation was dictated by a combination of

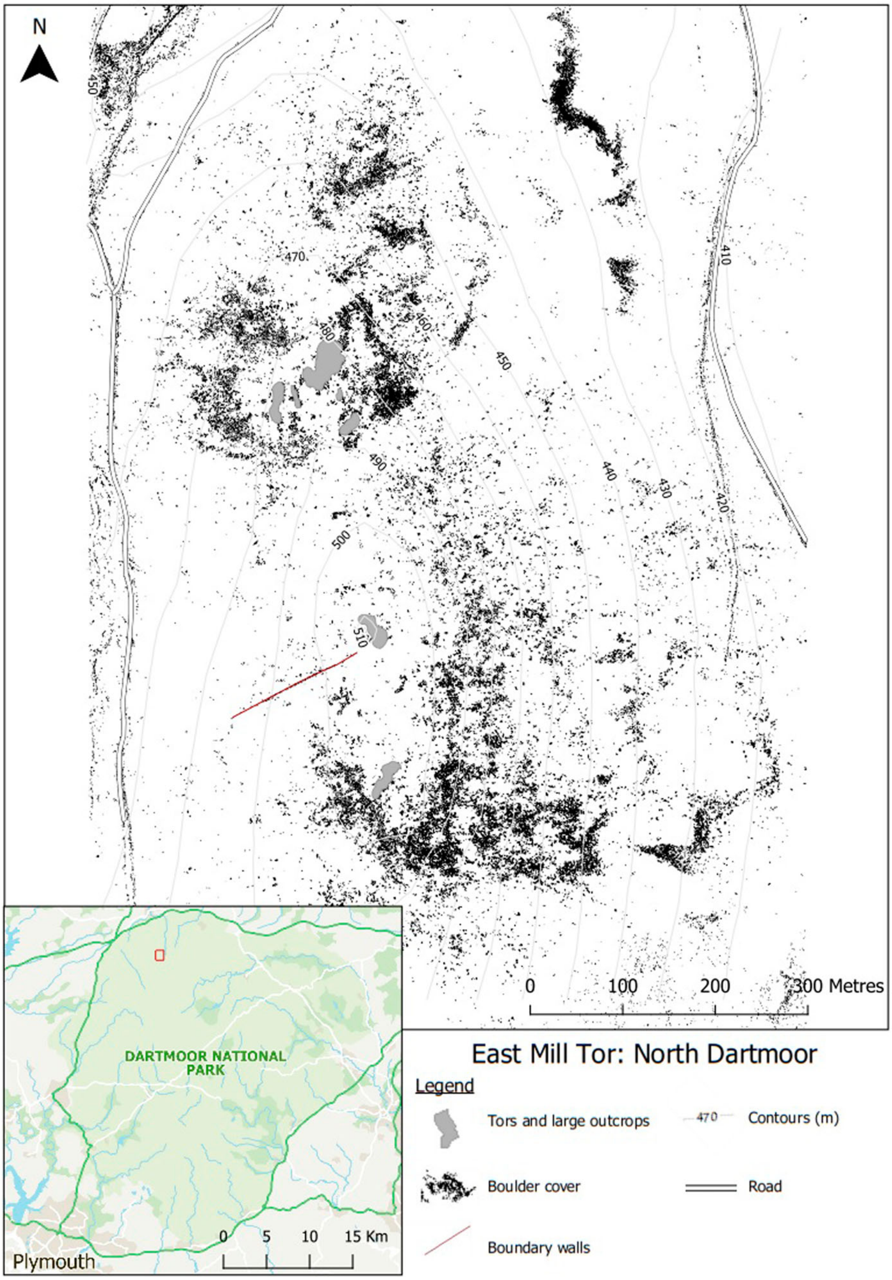


Figure 6. Geomorphology map of East Mill Tor, North Dartmoor.

pneumatolysis and periglacial processes, whereby the latter operated most effectively at higher altitudes during the Quaternary and hence did not create summit tors below 427 m OD. This does not account for the lack of tors above 457 OD, however, prompting Evans et al. (2012) to propose that average glacial conditions have either preferentially removed tors from the wider plateau surfaces or dampened their production rates.

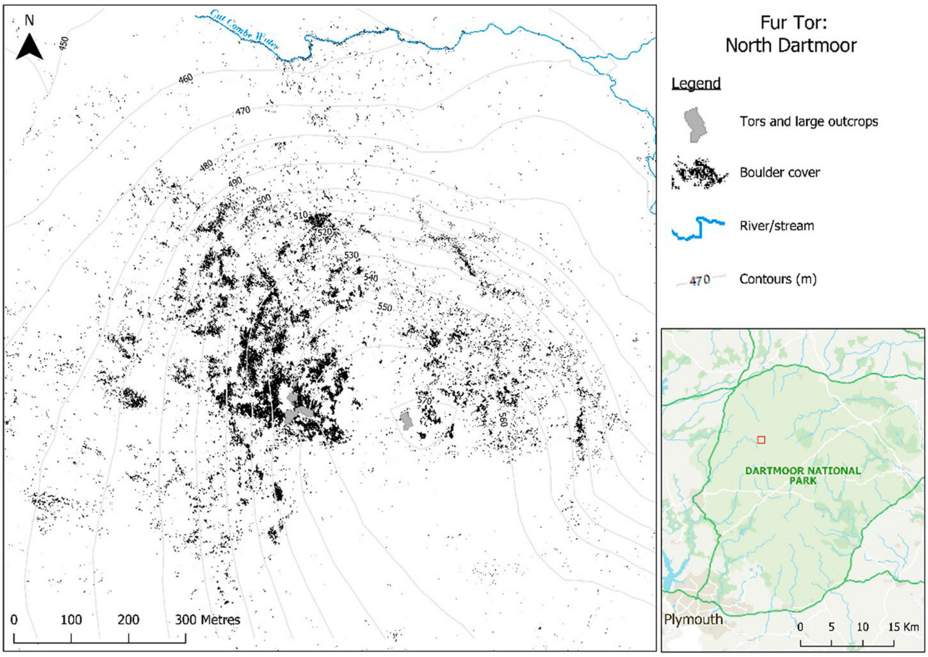


Figure 7. Geomorphology map of Fur Tor, North Dartmoor.

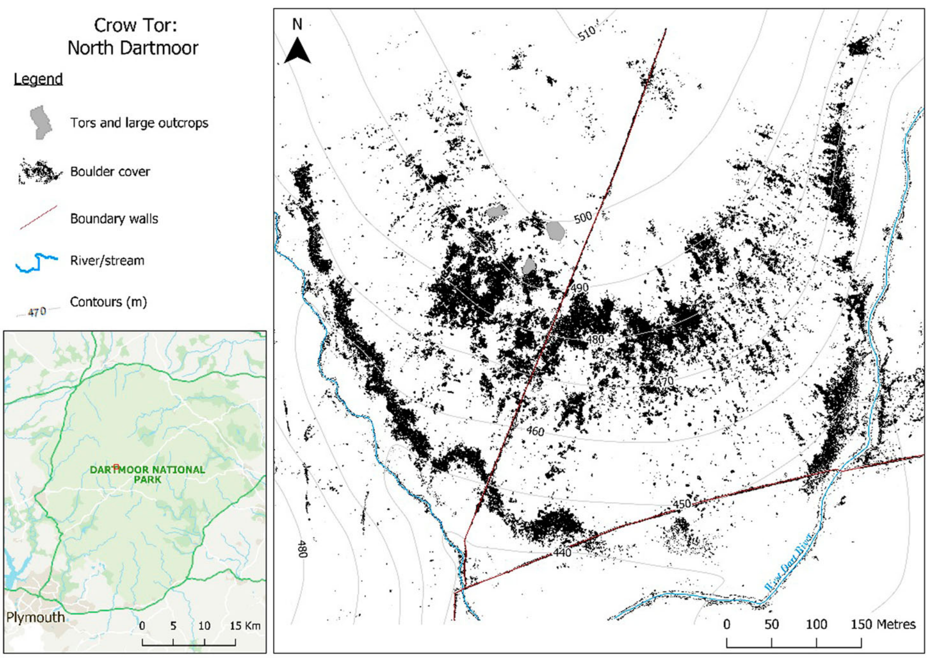


Figure 8. Geomorphology map of Crow Tor, North Dartmoor.

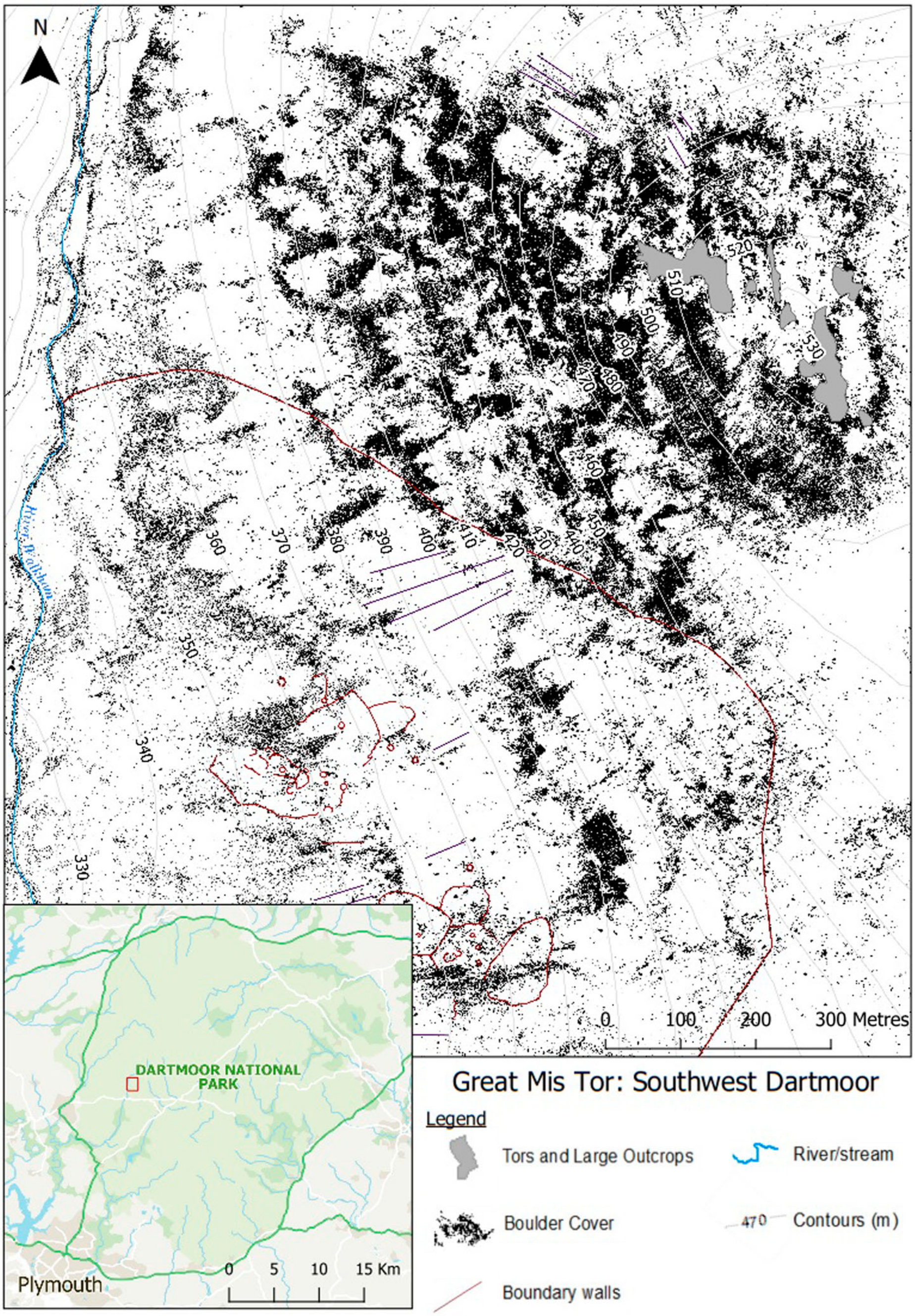


Figure 9. Geomorphology map of Great Mis Tor, Southwest Dartmoor.

Using the critical summit breadth concept of Manley (1955), they further explain T1 tors on narrow summits at the peripheries of the broader plateaux as areas that were not expansive enough to develop plateau icefields of significant thickness and/or were bypassed by faster moving ice in adjacent valleys; Type 2 tors represent areas glaciated

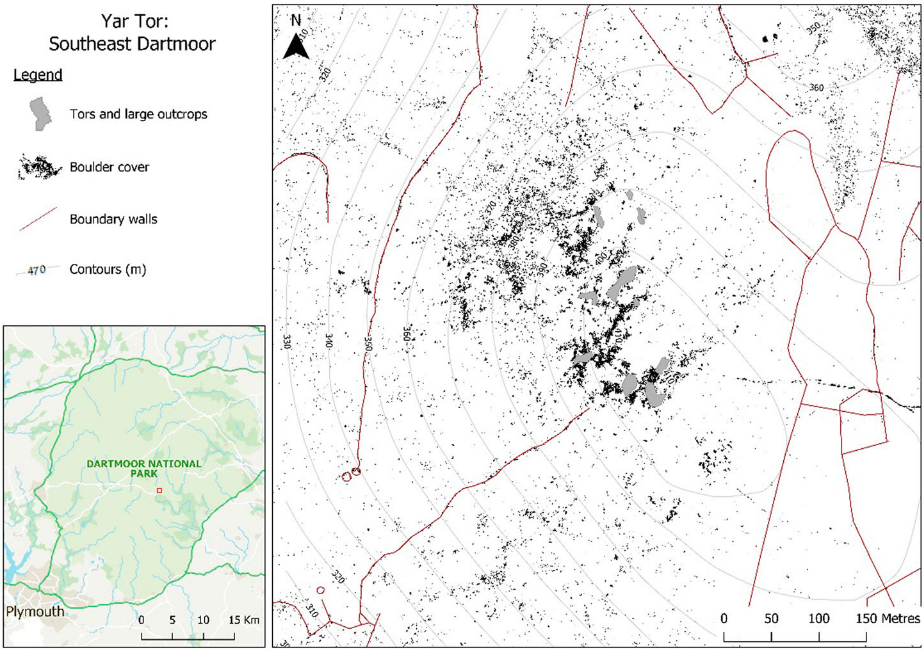


Figure 10. Geomorphology map of Yar Tor, Southeast Dartmoor.

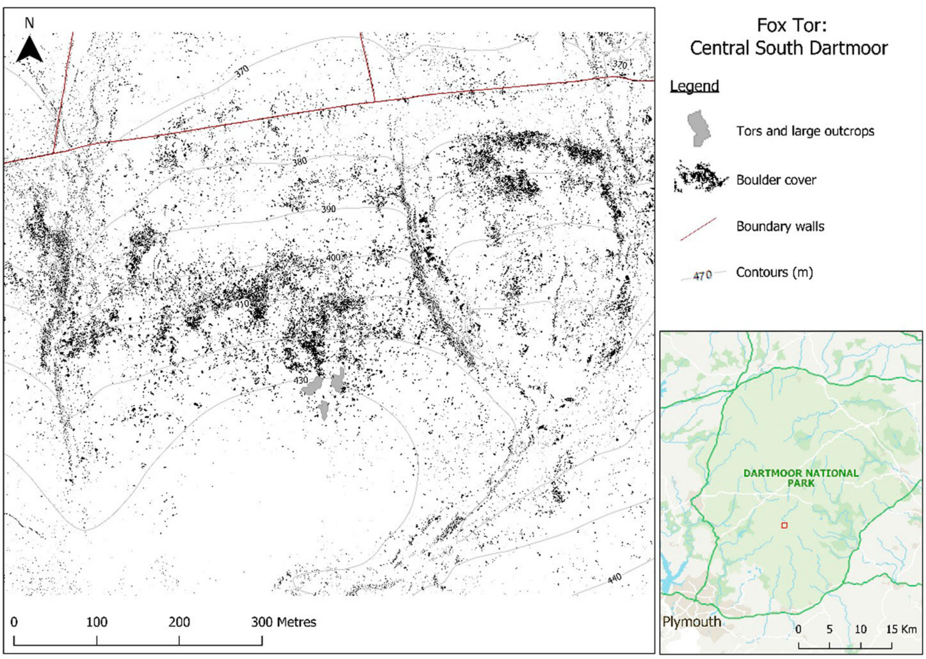


Figure 11. Geomorphology map of Fox Tor, Central South Dartmoor.

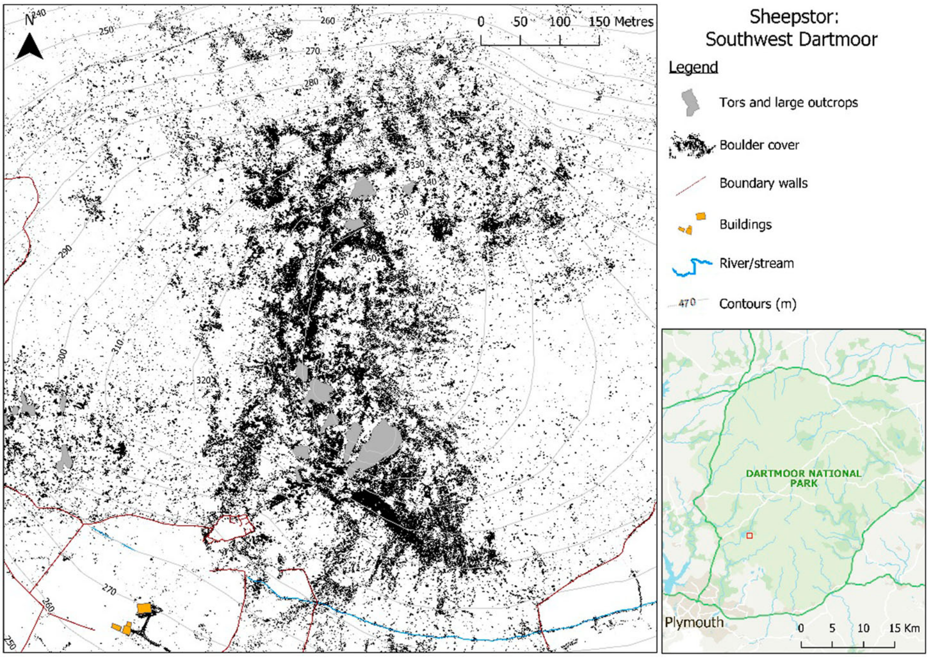


Figure 12. Geomorphology map of Sheepstor, Southwest Dartmoor.

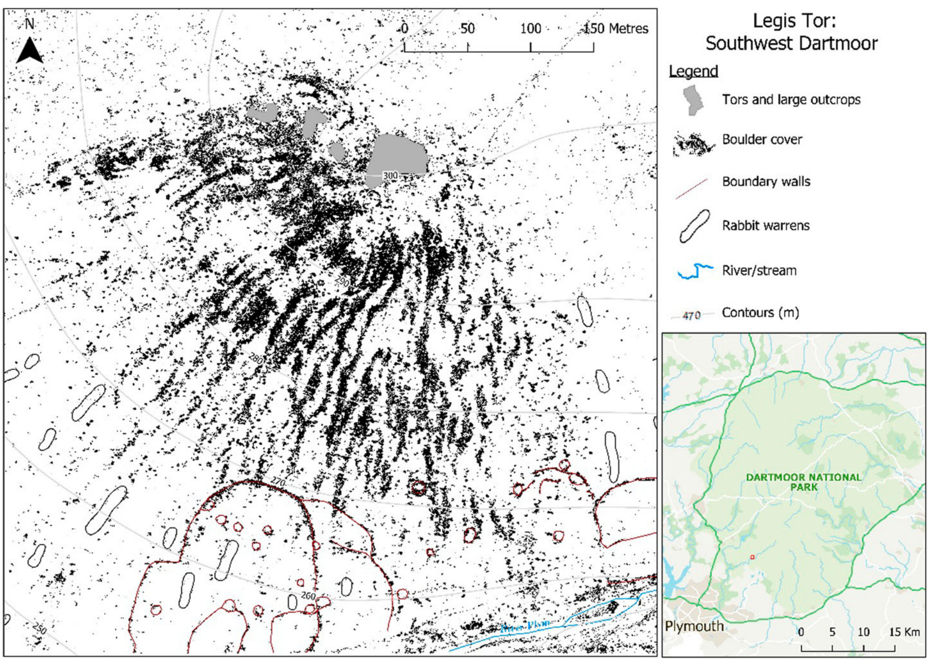


Figure 13. Geomorphology map of Legis Tor, Southwest Dartmoor.

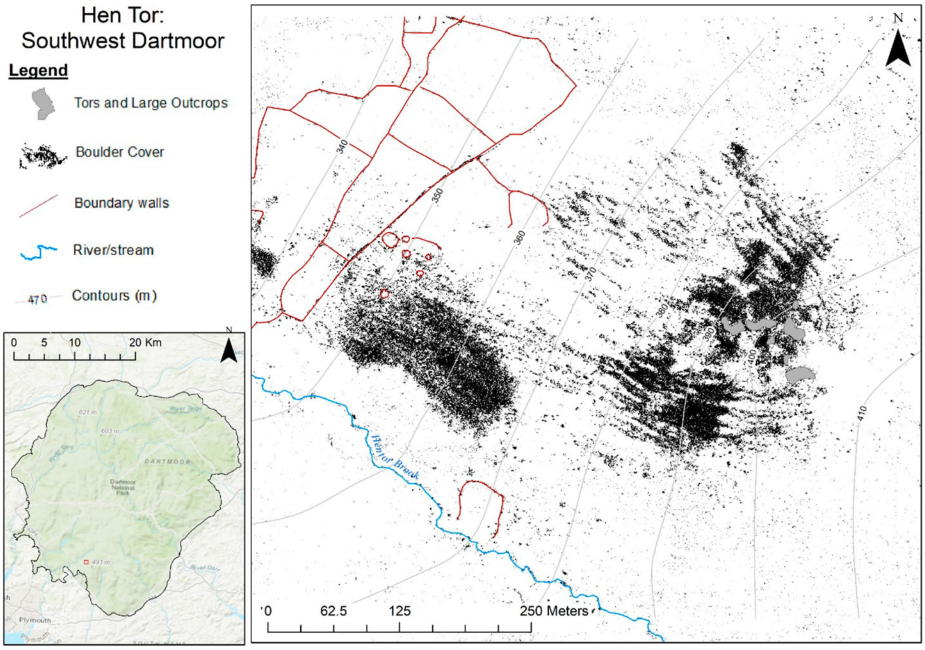


Figure 14. Geomorphology map of Hen Tor, Southwest Dartmoor.

less regularly during the Quaternary. The conspicuous lack of tors on the central plateau of south Dartmoor prompts a similar hypothesis that this area may have hosted glacier ice during average glacial conditions of multiple cold stages during the Quaternary, an hypothesis that requires further testing.

Figures 6–14 show that the summits selected for mapping contain multiple tor stacks. The tors occupy either the highest point of the summit and/or its outer edges (Figure 16). Only Crow Tor and Hen Tor (Figures 8, 14, 16a & b) comprise multiple stacks occupying an upper slope position, and only Fur Tor and Yar Tor (Figures 7, 10, 16c & d) feature a further, lower altitude mid slope subsidiary tor. Large volumes of clitter extend, in at least one direction but predominantly most directions (e.g. Great Mis Tor; Figures 9 & 16e), immediately downslope from all tor types in the form of lobes or garlands and stripes.

3.2 Clitter (blockfield) features: boulder lobes and boulder (stone)-fronted lobes and terraces and patterned ground (stripes)

Boulder lobes and stone fronted lobe forms are characterised by the presence of a coarse openwork accumulation of large granite boulders at the downslope end of a low gradient and largely stone free tread surface. The longest treads at each of the study sites range from 110 to 276 m. Boulder fronts commonly display a lobate shaped planform, with the most extreme pendant shapes occurring where treads are relatively long and bordered by lateral boulder berms; in contrast, partially overridden lobes with short treads appear as garland patterns (e.g. Figure 16e). The coalescent fronts of multiple lobes tend to form linear terraces trending largely contour-parallel across hillslopes. The boulder fronts are steeply inclined and have a relief commonly in excess of 1 m, with the most extreme relief

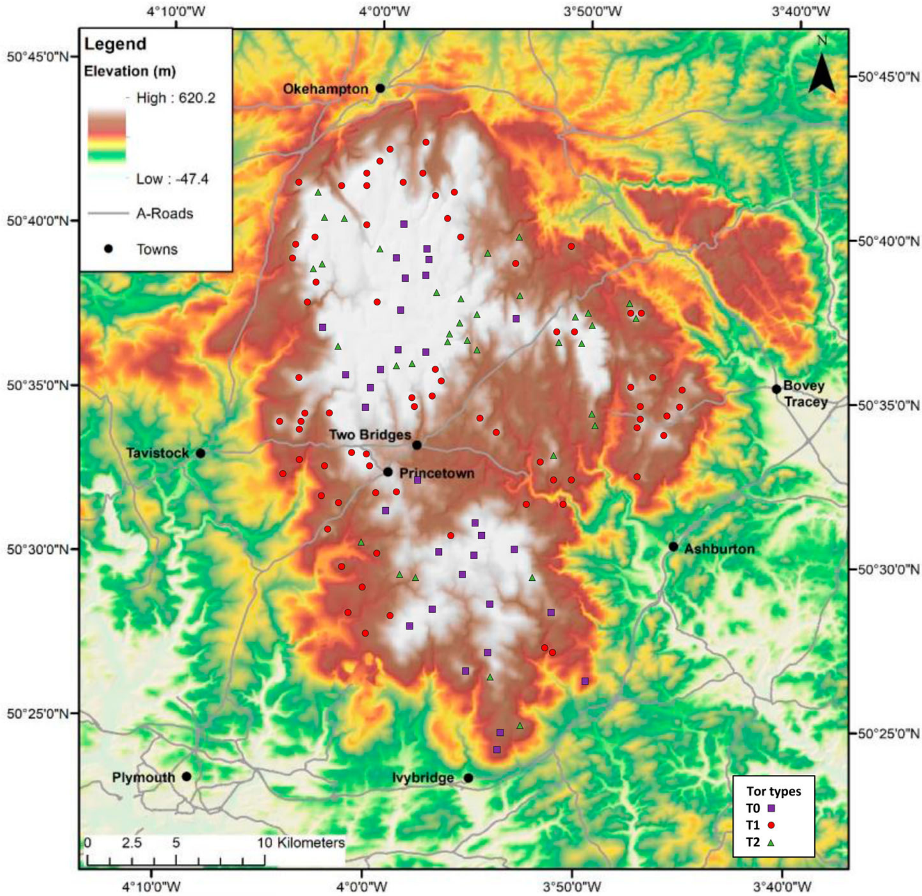


Figure 15. The spatial distribution of tor types across Dartmoor using the classification scheme of Evans et al. (2012) and combining their data with the results of this study.

of ≤25 m occurring at Great Mis Tor (Figures 16e & 17). Narrow treads with lateral boulder berms tend to appear as patterned ground or boulder stripes, especially where lobate fronts are less well developed (e.g. Legis Tor; Figure 18). Where such stripes have become well vegetated, for example on lower slopes, they appear as vegetated stripes with occasional surface boulders and can be traced to stone-fronted lobes on valley floors (e.g. Crow Tor; Figures 8 & 16a) which themselves can also be largely masked by vegetation (e.g. Yar Tor; Figures 7 & 16c).

Clitter patterns when viewed at a summit map scale, reveal clear distributions of lobe morphologies (Figures 6–14). Most sites exhibit dense and closely spaced garland-type or overridden, crenulate boulder ridges on upper slopes, proximal to the summit (e.g. Figure 16c, e). These patterns become more elongate downslope so that intermediate slopes are characterised by boulder stripes or vegetated stripes linked to pendant lobes whose fronts become increasingly coalescent so that they form crenulated steps on the hillside (e.g. Figures 16b, e & 18). Finally, lower slopes display less crenulated boulder-ridged steps, with valley floors containing clear evidence, in the form of partial superimposition and cross-cutting, that steps have migrated over one another (Figure 16a, c, d, e);

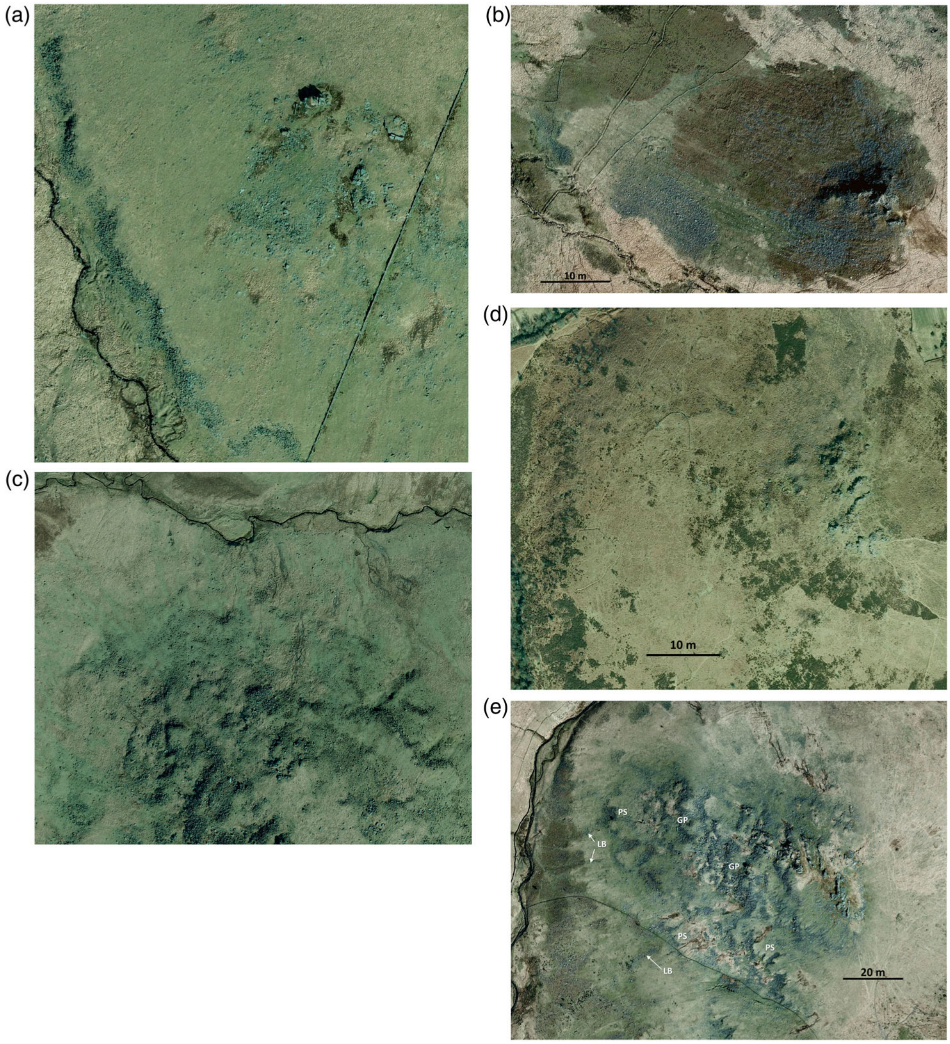


Figure 16. Google Earth aerial images of selected summit tors used in this study, illustrating tor morphology and associated clitter patterns: a) Crow Tor, distance across image is 350 m; b) Hen Tor; c) Fur Tor, distance across image is 800 m; d) Yar Tor; e) Great Mis Tor, with some examples of lateral boulder berms (LB), pendant shapes (PS) and garland patterns (GP) identified.

such superimposition is reflected also in the stacked periglacial slope deposits reported from valley floors (Waters, 1964; Miller, 1990; Evans et al., 2017). Here, boulder-fronted terraces are more common, in places displaying crenulated plan forms indicative of lobe coalescence. This is best exemplified by Crow Tor (Figures 8 & 16a) but is also very clear in the Walkham Valley, below Great Mis Tor (Figures 9 & 16e). This is interpreted as the product of downslope evolution in clitter forms from the lobate patterns initiated below summit tors to terraces near valley floors. Comparing this evolutionary stage of periglacial landscape development to that of a mid-latitude upland setting that has never been glaciated, for example the Mount Kent uplands in the east Falkland Islands, we suggest, using ergodic principles (Paine, 1985; cf. Peltier, 1950), that a

Figure 17. Large boulder fronted lobes on the upper west slope of Great Mis Tor, interpreted as relict permafrost creep features.

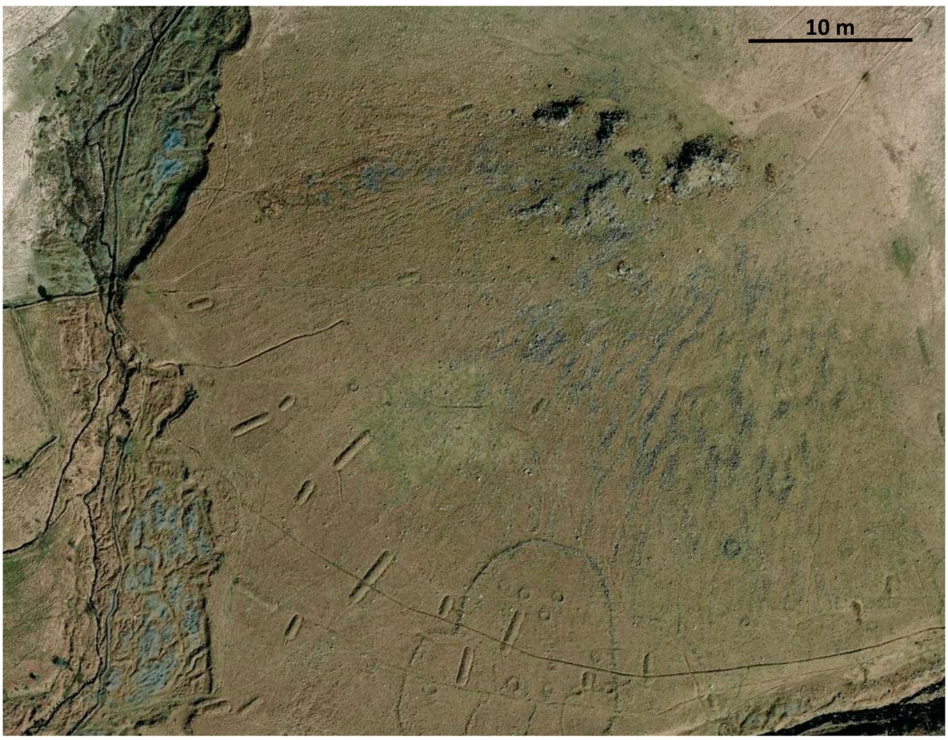


Figure 18. Google Earth aerial image of Legis Tor and its associated blockslope features on its western and southern slopes. This illustrates lateral boulder berms on either sides of narrow and long treads, which appear as boulder stripes on upper slopes and vegetated stripes with occasional surface boulders on lower slopes. Other features representative of all the study sites are human archaeological and cultural remains such as walled enclosures, hut circles, pillow mounds (rabbit warrens), and channelled hummocky topography indicative of tinning activity in the Legis Lake valley to the left of the image.

further stage in this evolutionary cycle is the development of stone runs or blockstreams. These are not particularly prominent in the Dartmoor landscape, possibly reflecting the relatively lower cumulative impacts of periglacial activity on Dartmoor compared to unglaciated mid-latitude stone run case studies such as the Falkland Islands (Joyce, 1950; Clark, 1972; Clapperton, 1975) and Wiltshire and Dorset (Williams, 1968; Small et al., 1970). It is important to reflect, however, that in most locations where stone runs may have developed, the intensive disturbance created by the tinning industry has potentially destroyed blockstream morphology (e.g. Figure 18).

The clitter patterns are best developed on summits where boulders are more ubiquitous, and hence tend to be associated with the largest Type 1 tors, the best example therefore being Great Mis Tor, but also exemplified by Crow Tor and Sheepstor (Figures 9, 8 & 12, respectively). The clitter patterns are less well developed around the summits of East Mill Tor, Fur Tor and Hen Tor (Figures 6, 7 & 14, respectively), although the boulder stripes of the latter are very prominent and particularly long (Figure 16b).

The downslope continuum of clitter forms is typical of allochthonous blockslopes in upland Britain, defined genetically by Ballantyne (2018) as a debris mantle that has 'migrated downslope by some combination of frost creep, gelifluction, debris flow and possibly permafrost creep' (Ballantyne, 2018, p. 190). These features typically merge into the autochthonous blockfields that develop around disintegrating tor stacks and can be contiguous with blockstreams or stone runs. The processes driving the downslope movement of such openwork blockfields are complex but it is acknowledged that a key driver is the fact that mean annual temperatures in the boulder debris are often a few degrees lower than in adjacent soils or the mean annual air temperature (Harris & Pedersen, 1998; Gorbunov et al., 2004; Juliussen & Humlum, 2008). The implication of this is that relatively deep seasonal freezing or even permafrost can be present. Hence, permafrost creep can generate features like boulder lobes in a process-form regime effectively similar to that of rock glaciers (Harrison et al., 1996; Harrison & Evans, 2014).

4. Discussion - towards a periglacial landsystem signature

Models of upland periglacial landsystems have been compiled for mountain areas in Britain (e.g. Ballantyne, 1984, 1987, 2018; Murton & Ballantyne, 2017), with Dartmoor's periglacial legacy being long established as an exemplar of a well-developed or mature (*sensu* Peltier, 1950) and non-glaciated terrain. Following on from the attempt by Evans et al. (2017) to compile a landsystem for well-developed or mature periglaciation for SW England using the systematic manual mapping of clitter fields on Bodmin Moor, this study has for the first time produced a similarly areally extensive representation of periglacial features across Dartmoor based on selected tor summits. Although this constitutes the base data for further discussions concerning the evolution of the periglacial landscape signature on the uplands of SW England, it does not fully tackle the problem of identifying diagnostic criteria for periglacial landscape maturity. However, some important trends and observations can be taken forward from the mapping database presented here and are summarised in a landsystem model for Dartmoor in Figure 19.

If we reflect on Peltier's (1950) ergodic model of upland modification in periglacial environments, the impact of periglacial processes at higher altitudes results in well-developed or castellated (T1) tors over the timespan of the Quaternary Period in terrains like Dartmoor, even if part of that timespan was associated with temperatures and moisture characteristics that were sub-optimal for macro and microgelivation. However, Type 1 tors and their surrounding clitter/blockfields are not developed on every summit on Dartmoor, being instead characteristic of steeper relief summits located predominantly around the periphery of the granite massif (Figures 2 & 15). The distinct lack of these features on the highest and broadest central summit areas on both north and south Dartmoor is conspicuous and has been explained either as the result of long term 'planation surfaces' or etchplains (Palmer & Neilson, 1962; Orme, 1964; Gerrard, 1974, 1978; Brunsden, 2007) or repeated glaciation of summits high enough and broad enough to develop plateau icefields during glacial cycles (Evans et al., 2012). Hence advanced periglacial landsystem development is represented by summits such as those presented here in Figures 6–14. Notably, East Mill Tor (Figure 6) and Fur Tor (Figure 7) lie within but towards the margins of the glaciated zone proposed by Evans et al. (2012), and therefore their periglacial landsystem signature should by inference be representative of relative immaturity. However, both tors occupy narrow summit areas and therefore their peripheral positions and summit breadths were likely insufficient to develop anything other than thin and cold based glacier ice and/or it they were bypassed by faster moving ice.

The lobate morphology of boulder-fronted risers and their upslope marginal boulder stripes within the clitter fields of the tors mapped in this study are consistent with field observations of stone-banked solifluction/gelifluction lobes and terraces (Benedict, 1970). Typical riser heights for relict solifluction lobes across the UK are in the region of 1-3 m (Ballantyne & Harris, 1994), broadly consistent with riser heights on Dartmoor. These characteristics are consistent with widespread solifluction/gelifluction processes operating across Dartmoor (Matsuoka et al., 2005), but the 25 m high risers of the largest boulder lobes at Great Mis Tor are anomalously large to be representative of

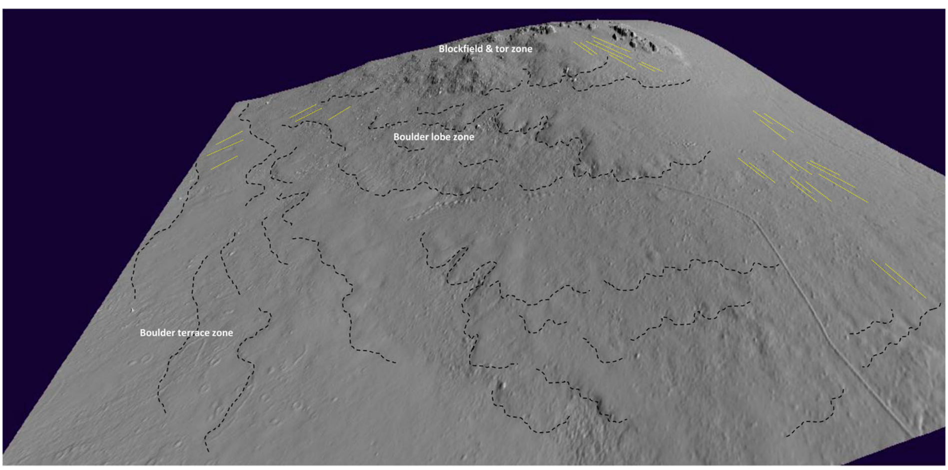


Figure 19. Annotated LiDAR extract (Environment Agency, UK) of the southern and western slopes of Great Mis Tor (view looking towards northeast), illustrating the spatial distribution of periglacial landforms and representative of a periglacial landsystem for Dartmoor. Black dashed lines are the fronts of lobes and terraces. Yellow lines are stone stripes.

such processes (Harrison et al., 1996). This has prompted suggestions that some of the lobes on the uppermost slopes of Great Mis Tor in particular are essentially relict rock glaciers (Harrison et al., 1996; Harrison & Evans, 2014), whereby the openwork and matrix free nature of the boulders dominating the risers are explained as the products of past permafrost creep. Importantly, both solifluction and gelifluction processes require the presence of a soil matrix and hence the boulder lobes, if they originated as small rock glaciers, record the occurrence of permafrost on Dartmoor.

The increase in vegetation cover, reduction in apparent boulder cover, and the reduction in riser relief of successive terrace and lobe structures downslope, particularly well-illustrated at both Great Mis Tor and Sheepstor, is indicative of the increasingly greater impact of the action of mechanical weathering and concomitant breakdown of these forms over time. This occurs through the process of macrogelifraction, whereby rocks are frost shattered, and in the case of granite, successively rounded over time. This suggests that lower boulder lobes and stone-fronted lobes have been exposed to a greater cumulative duration of periglacial weathering. By extension, this suggests that the relative age of clitter landforms increases downslope, which is potentially indicative of discrete waves of periglacial activity over time. The exact influence of downslope accretion of finer-grained slopewash and gelifluctate in clitter modification, presumably augmented by aeolian inputs, has not been assessed in this study, but based on the matrixes of valley floor deposits (Waters, 1964, 1965; Green & Eden, 1973; Miller, 1990; Evans et al., 2017) was likely significant in generating diamictic treads on lower slope lobes. Indeed, thick sequences of fine-grained and weakly stratified diamictons are characteristic of stone runs in other mid-latitude settings (Hansom et al., 2008).

The temporal aspect of periglacial landsystem development (maturity) is one that clearly requires further examination. Recent attempts to solve this issue indicated that the tors may only date back to MIS 3 (Hägg, 2009; Gunnell et al., 2013). Although blockslopes and boulder lobes in particular can be relatively young in age (e.g. Cunningham & Wilson, 2004), their evolution as part of a periglacial slope system has been demonstrated to be of great antiquity by Barrows et al. (2004), who report an increasing age of boulders (range of 22–498 ka) with distance from their upslope source outcrop. Older ages have been reported for blockstreams on the Falkland Islands by Wilson et al. (2008), who suggest activity from 731 to 182 ka but more recent ages of 398–42 ka on processes operating on the feeder blockslopes.

Although locations like Bodmin Moor and Great Mis Tor in this paper (Figure 19) are presented as potential British exemplars of periglacial landscape maturity and by inference unglaciated enclaves in mid-latitude settings, diagnostic criteria for such maturity must ultimately be derived from landscapes known to have escaped glaciation while being peripheral to ice cover during the Quaternary Period. Hence a valuable avenue for further analysis of this problem is to employ automated mapping techniques to investigate landform compatibility between the uplands of SW England and those of the Falkland Islands for example, where the well-known stone runs record tor disintegration and downslope movement of clitter in highly elongate boulder lobes over the course of multiple Quaternary cold stages (Hansom et al., 2008; Wilson et al., 2008). In the Falkland Islands setting, elongation of lobes into stone runs is exaggerated over time due to the movement of boulder lobes off the slopes surrounding the tors and into valley floors. Hence tread lengths (more specifically run lengths) are orders of magnitude larger than those on Dartmoor slopes. Moreover, stone runs are not recognised, either geomorphologically or stratigraphically in the Dartmoor valleys, even on valley floors unaffected by historical tinning procedures.

6. Conclusion

The progression of debates concerning the landscape signature of periglaciation demands the systematic mapping of landforms and the landsystem characterization for areas proposed to have been exposed to periglacial and permafrost processes for significant time during the Quaternary Period. Dartmoor has traditionally been regarded as a prime example and regardless of any potential impacts of restricted plateau icefield glaciation, contains landform assemblages related to the dominance of periglacial and permafrost conditions during the Quaternary cold stages. Although the demonstration of extreme antiquity requires further dating control, the potentially diagnostic signatures of periglacial landscape maturity can be evaluated only through the compilation of a landsystem model. Despite this, only small areas of Dartmoor have been subject to systematic mapping. This study has demonstrated that an automated mapping technique can be applied to areas of upland periglacial landforms in order to rapidly and systematically compile quantifiable patterns of landform assemblages. A conceptual periglacial landsystem for nine summits with well-developed tors has also been assembled as a representation of periglacial landscape relative maturity in which cold climate processes, acting on partially deeply weathered and pneumatolysised granite, produce castellated tors and autochthonous blockfield (clitter), and permafrost creep develops boulder lobes that elongate and evolve downslope as allochthonous blockslopes displaying boulder stripes, stone-fronted lobes and boulder-fronted terraces.

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