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# **Distribution and characteristics of Pleistocene ground thermal contraction polygons in Europe from satellite images**

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## **Abstract**

The study of Pleistocene polygons in Europe carried out using the collection of satellite images available in Google Earth™ provides new data on the distribution of ground cracking by thermal contraction during glacial periods and sheds light on some factors controlling their formation. The distribution map shows that thermal contraction cracking affected terrain between latitude 43.5°N and the southern limit of the Fennoscandian Ice Sheet at 15 ka, with a concentration of polygons north of latitude 51°N. A clear asymmetry exists in relation to longitude, with a greater southward extension of polygons in France (43.5°N) than in central Europe (47°N). Analysis of the characteristics of polygons at the European scale reveals an association with lithology, latitude, and the age of the sediments in which they formed. The morphological evolution over time reconstructed from observations of polygons of contrasting ages indicates that a stable mature phase, characterized by small (mean size 15 m), regular polygons with numerous Y-junctions, is reached after ca. 4 ka of thermal contraction cracking activity.

**Keywords:** Ground thermal contraction polygons, Pleistocene permafrost, Europe

## **1. Introduction**

The extent of past permafrost in Europe during the Last Glacial has been extensively studied in recent decades based on the analysis of field data and palaeoclimatic simulations. Among the field data, structures created by ground thermal contraction, including polygons remaining as cropmarks, ice wedge pseudomorphs and relict sand wedges, have focused attention and their distribution was used as a basis for evaluating the simulations ([Andrieux et al., 2016a](#); [Stadelmaier et al., 2021](#)). Thermal contraction cracking occurs when the temperature of the frozen ground decreases rapidly and causes severe stress exceeding the tensile strength of the ground. The cracks are filled by ice due to the refreezing of water infiltrated from the surface (ice vein), by aeolian sands (sand vein) or close in summer without significant infilling ([Mackay, 1975](#); [Mackay and Burn, 2002](#); [Murton, 2013](#)). In a permafrost context, ice remains at depth and repeated cracking of the ground leads to the formation of large ice wedges. When the permafrost thaws, the cavity created by ice melting is filled by the collapse of the wedge walls and the former wedge shape is preserved as a pseudomorph. For a long time, polygonal cropmarks, related to the differential growth of vegetation above the wedges and in the center of polygons, have been interpreted as indicators of permafrost as they imply that wedges have undergone sufficient growth to influence vegetation. [Andrieux et al. \(2016a\)](#) in the European Pleistocene and [Wolfe et al. \(2018\)](#) in current Canadian Arctic, however, have shown that sand wedges up to 1 m wide can form at the periphery of aeolian sand sources in areas of deep seasonal frost (i.e., without permafrost) and are able to generate cropmarks. Polygons are therefore not

necessarily indicative of permafrost but of periglacial climates *sensu lato*. Polygons have also been the subject of much work since similar structures have been recognized on planets other than Earth, in particular Mars (e.g. [Mangold, 2005](#); [Ulrich et al., 2011](#)).

Satellite images accessible in Google Earth™ are a noteworthy data source for studying Pleistocene thermal contraction polygons and have been widely used for this purpose in France by [Andrieux et al. \(2016a,b\)](#). In particular, satellite images have an advantage over photos taken from airplanes as they are easily accessible and usable in a geographic information system (GIS) and are free of distortion. This paper proposes to extend the methodology used by [Andrieux et al. \(2016a\)](#) over entire Europe to map polygon occurrences and characterize their morphology and size. This analysis is then followed by comparison of the data with other layers of information, namely geographical location, substrate lithology and age of the sediments in which they developed. The processing of a large number of data located in various contexts gives hope that associations will appear more clearly between the various parameters than in the framework of local studies, where variability is reduced. After a brief review of literature, this paper presents the main results obtained on the distribution and characteristics of Pleistocene thermal contraction polygons in Europe. Contribution to permafrost mapping and to the evaluation of some factors involved in polygon formation is detailed. This study can be used as a basis for further field studies to investigate thermal contraction cracks in cross-section and to determine their nature and age.

## 2. Background

Ground thermal contraction polygons are remarkable figures in periglacial landscapes and, as such, have prompted much work to determine their formation process and explain their morphological variability. [Lachenbruch \(1962, 1966\)](#) laid the theoretical foundations for the mechanisms of soil cracking by thermal contraction and the factors responsible for their organization into polygons. The thermal stress to which a frozen soil is subjected leads to its fracturing. Cracks propagate perpendicularly to the direction of the strongest stress. Repeated cooling events cause new cracks to form in areas where stress has not been released by the opening of previous cracks. These cracks typically have orthogonal (T-shaped) junctions. When the stress field is homogeneous and the stress high relative to ground strength, the cracks are straight and generate regular orthogonal (rectangular) polygons. When the stress is lower, local variations of ground strength cause the deviation of the cracks that become sinuous and lead to the formation of irregular orthogonal polygons. Homogeneous materials where strong stress can build up before cracking lead to simultaneous crack initiation at distinct points and rapid crack propagation. This favors non-orthogonal (Y-shaped) junctions leading to the development of hexagonal polygons.

Cracking is largely dependent on the linear coefficient of ground thermal expansion (which is variable according to texture and ice content), thermal conductivity and strength (which is a function of temperature). Particularly, fine-grained soils have a high coefficient and are, therefore, the most prone to cracking. The progressive creation of new cracks causes the subdivision of polygons and increases their regularity. Finally, the lateral heterogeneity of the stress field linked to the presence of a water body and to slope can create orthogonal oriented polygons (i.e. polygons elongated along a preferential direction).

Subsequent work has documented the conditions under which sufficient thermal stress occurs to induce ground cracking in natural settings, identification of the factors driving variability in the

morphology of polygons, and description and simulation of their evolution over time. From sites in Canada and Svalbard, [Fortier and Allard \(2005\)](#) and [Matsuoka et al. \(2018\)](#) showed that cracking occurs when the surface ground temperature ( $T_s$ ) drops below  $-20^{\circ}\text{C}$  and the thermal gradient in the first meter of ground ( $G$ ) reaches  $10^{\circ}\text{C.m}^{-1}$ . At some sites studied by [Matsuoka et al. \(2018\)](#), slightly less drastic conditions ( $T_s = -15^{\circ}\text{C}$ ,  $G = 7^{\circ}\text{C.m}^{-1}$ ) could locally be sufficient for crack initiation.

[Sletten et al. \(2003\)](#) in Antarctica, [Ulrich et al. \(2011\)](#) in the Canadian High Arctic, and [Haltigin et al. \(2012\)](#) in Svalbard have analyzed the evolution of polygon morphology over time by studying structures formed in sediments of various ages. These studies indicate that at the beginning, polygons are large (20-50 m in diameter) and with mostly orthogonal junctions. With time, the polygons subdivide and become smaller, more regular and non-orthogonal. According to [Sletten et al. \(2003\)](#), evolution to a stable "mature" stage takes  $10^4$  to  $10^6$  years. [Haltigin et al. \(2012\)](#), however, suggest that hexagonal polygons do not derive from the subdivision of initial orthogonal polygons, but that the two types follow a parallel evolution. The predominance of T- or Y-junctions would depend primarily on cracking conditions at the time of their initial formation. [Ulrich et al. \(2011\)](#) observe variations along slopes in Svalbard, with orthogonal polygons dominating downslope in gravelly sediments and smaller hexagonal polygons in silt upslope. For the authors, the morphology of polygons would be mainly related to topography, probably due to the associated variations in water content and ground thermal conductivity.

[Plug and Werner \(2001, 2002, 2008\)](#) simulated the formation and evolution of thermal contraction polygons. Their results largely validate previous hypotheses, including that crack spacing (and thus polygon size) decreases with time while the number of 4-way (X-) junctions increases relative to 3-way (T- or Y-) junctions. Average crack spacing also increases nonlinearly with crack depth, but this pattern tends to be obscured by the subdivision of polygons. Although orthogonal T- or X-junctions are predominant, approximately equiangular (i.e. pseudo Y-shaped) 3-way junctions are formed when a crack propagates towards the bend of a pre-existing crack ([Fig. 1](#)). This process occurs more frequently as the heterogeneity of the ground increases, since crack sinuosity itself increases with heterogeneity. These authors found that a steady state is reached relatively quickly, after 800 simulated years, which corresponds to a significantly longer time in natural settings, as thermal contraction cracking does not necessarily occur every year (e.g. [Mackay and Burn, 2002](#); [Kokelj et al., 2014](#)). They also showed that thermal contraction is sensitive to climatic extremes and weakly related to average ground temperature.

Various regional, more rarely country-wide, studies of Pleistocene polygons visible as cropmarks in Europe have been conducted by [Williams \(1964\)](#), [Gemmell and Ralston \(1965\)](#), [Svensson \(1973, 1988\)](#), [Christensen \(1974\)](#), [Johnsson \(1984\)](#), [Heyse and Ghysels \(2003\)](#), [Hassenpflug \(2013\)](#), [Andrieux et al. \(2016a\)](#), [Ewertowski et al. \(2017\)](#), and [Beerten et al. \(2021\)](#), in addition to many reports of isolated sites. These studies illustrate the distribution of lands affected by Pleistocene thermal contraction and were used here as a starting point for a survey from satellite images. Among the studies, only a few focused on investigating the associations between polygon size or morphology and physical parameters, in particular ground lithology and topographic context. [Andrieux et al. \(2016\)](#) in France concluded that there is no clear relationship between these parameters. [Beerten et al. \(2021\)](#) in Belgium found that orthogonal polygons are preferentially found on valley borders while polygons on higher surfaces are dominantly non-orthogonal.

### 3. Methods



Ground thermal contraction polygons were located from published data in the literature and from an examination as exhaustive as possible of collections of satellite images accessible in Google Earth™, following the method used for France by [Andrieux et al. \(2016a,b\)](#). Each site was named after the nearest town or village and numbered from 1 to n in the case of multiple neighboring sites. For each piece of land, a screenshot with a scale in meters was made and used as a basis, after contrast adjustment, for measuring the size of polygons and for describing their main characteristics. The size of polygons was measured where their visibility was sufficient according to the method proposed by the same authors using ImageJ, an open-source image processing software (US National Institute of Health, <http://imagej.nih.gov/ij/>), which allows for precise measurements. The number of cracks (more exactly the surface expression of underlying wedges) intercepting three profiles drawn across the polygon field was counted. The ends of each profile were set approximately at the center of a polygon. Whenever possible, the profiles were arranged at a 60° angle to each other to average out variations related to possible polygon elongation. The size of polygons corresponds to the total length of profiles divided by the number of cracks, i.e. between 25 and 40 counted cracks in each piece of land, with a few exceptions (for the largest polygons). The widths obtained in this way (which do not correspond to true polygon diameters, as the profiles do not necessarily intersect all polygons in their center) are comparable to the spacing of wedges such that it can be measured from cross-sections. They are also similar to the values used in the simulations by [Plug and Werner \(2002\)](#). The values are given in meters with one digit after the decimal point, although it is probably not significant. Statistical comparison of size means calculated from polygon subsets was made using PAST version 3.14 software ([Hammer et al., 2001](#)). The morphology of polygons was then classified according to the criteria outlined by [Lachenbruch \(1966\)](#) and [Ewertowski et al. \(2017\)](#), which involve the type of junction between cracks, the regularity of crack spacing, and the variability in crack width.

The coordinates of the polygon fields were used to generate a file using the GIS software QGIS version 3.10. The references and date of the satellite images shown in Google Earth™ were recorded. The altitude was determined using the EU-DEM with a horizontal resolution of 30 m (<https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1/>). The ground lithology was extracted from variable sources depending on the country. For France and the UK, the 1:50,000 digital geological map data (<http://infoterre.brgm.fr/> and <https://data.gov.uk/dataset/02af8783-e3f6-4516-8efa-1e7059ddde26/bgs-geology-50k>, respectively) were used. For Germany, the data are from the 1:200,000 geological map (<https://services.bgr.de/wms/geologie/guek200/>), while for the rest of Europe the data are from the 1:1,000,000 geological map (<http://onegeology-geonetwork.brgm.fr/>). In Central Europe, these data have been supplemented for aeolian deposits using the map proposed by [Lehmkuhl et al. \(2021\)](#). Some uncertainty remains in the precise determination of lithology because of the scale of the geological maps and the difficulty of assessing the thickness of the formations shown on these maps. Because of the large number of sites analyzed, it is assumed that this uncertainty does not obscure the preferred association of polygons with certain lithologies. Ice sheet limits at various times were taken from [Hughes et al. \(2016\)](#) for the Fennoscandian Ice Sheet (FIS) and British-Irish Ice Sheet (BIIS), supplemented by data from [Evans et al. \(2021\)](#), and [Ehlers and Gibbard \(2004\)](#) for the other ice sheets.

A total of 1311 polygon sites were identified. By nature, cropmarks are only identifiable in cultivated plots, and forest and urbanized areas did not yield any data. The ability to distinguish cropmarks depends largely on weather conditions and the stress under which the vegetation grows. Therefore, the date of the satellite images and the nature of the crops play a major role. On a local scale, regions

devoid of polygons may result from inappropriate observation conditions rather than actual absence. On a European scale, however, this issue has no real impact on the general distribution of terrains affected by thermal contraction cracking. Many polygons (referred to as 'incomplete/limited' in [Table S1](#)) are only visible in a limited area or are poorly distinct. Among the most legible polygons, 238 were measured and considered a representative set of the various lithological and latitudinal contexts. The number of measured polygons from areas deglaciated at the very end of the Last Glacial remains small, however, because of the limited extent of those areas compared to unglaciated areas.

## 4. Results

### 4.1. Distribution

The main observations that can be made from the polygon distribution map ([Fig. 2](#)) are as follows:

(1) Polygons occur in a band approximately bounded to the south by latitude 44°N and to the north by the ice sheet limit at 15 ka. Variations are visible according to longitude. In France, polygons exist southward up to 44.5°N in Aquitaine and 43.5°N in the lower Rhone valley as already reported by [Andrieux et al. \(2016a\)](#), whereas the southernmost polygons identified in central Europe (Hungary) do not exceed 47°N. In addition, a few polygons can be observed in Sweden in areas deglaciated between 14 and 15 ka at latitudes 56°N to 57°N, whereas no polygons have been identified in Scotland at the same latitudes in areas deglaciated after 16 ka.

(2) Polygons are abundant north of latitude 51°N, in the UK, northern Belgium, the Netherlands, northern Germany and Poland in various terrains. At lower latitudes, their distribution is reduced to clusters. In these regions, the proximity of aeolian sand sources that provided the filling material for thermal contraction cracks plays a decisive role. This factor was previously highlighted by [Andrieux et al. \(2016a\)](#) in France south of latitude 48°N, where the occurrence of polygons is restricted to the margins of coversands in Aquitaine, the Loire Valley ([Fig. 3A](#)), and the lower Rhone Valley. This also holds true in central Germany on the left banks of the Main and Regnitz rivers, where polygons developed in Keuper mudstones and sandstones at the periphery of aeolian sands ([Fig. 3B](#)), and in Hungary on the right bank of the Raab River. In agreement, [Andrieux et al. \(2018\)](#) in France and [Fabian et al. \(2013\)](#) in Hungary described relict sand wedges in cross-section in the same areas.

(3) Overall, the majority of the polygons are located in lowland, non-calcareous sedimentary terrain. The main lithologies are, in order of decreasing abundance ([Fig. 4](#)), fluvial gravel, till, glaciofluvial and aeolian sand, loess, and mudstone. The distribution is not homogeneous even in areas where polygons are abundant, but areas of high spatial concentration appear. These are determined primarily by a combination of favorable lithologies and a cover of appropriate satellite images. The geologic maps used in this study tend to ascribe a predominantly glaciofluvial origin to the sands outcropping in the Sand Belt at the periphery of the FIS, whereas other authors consider a large proportion of these sands to be of aeolian origin ([Zeeberg, 1998](#); [Kasse, 2002](#); [Bertran et al., 2020](#)). The relative proportion of the two types of substrate thus remains largely unknown.

(4) The influence of loess is variable. In Germany and Poland, many polygons are found in the Northern European Loess Belt between latitudes 51°N and 52°N ([Fig. 2](#)). Conversely, no polygons were identified in areas of thick loess cover in France and Belgium at latitude below 51°N. In these areas, the ice-wedge pseudomorphs described in cross-sections (e.g. [Lautridou and Sommé, 1981](#);

[Frechen et al., 2001](#); [Deschodt et al., 2008](#); [Antoine et al., 2014](#)) predate the latest loess depositional phase and, because of the loess cover, do not generate cropmarks. This is probably also the case for the loess areas of central Germany ([Isarin et al., 1998](#)).

(5) Large lowland regions north of latitude 48°N are devoid of polygons, particularly in Eastern Europe (east of Poland, Slovakia). The factors behind are possibly the lack of suitable satellite cover and/or insufficient survey, as lithology and the extent of agricultural land do not seem to be involved. Despite the limitations, the data set is considered representative of the overall distribution of lands affected by polygon development.

#### **4.2. Polygon size**

Polygon sizes range from 3.7 m to 59.0 m, with a clear dependence on lithology although there is significant overlap between size ranges ([Fig. 5A](#)). The mean size in mudstones and tills is close to 12 m with a lower limit of 4 m and an upper limit of 21 m (outliers excluded). Student's t-test ( $p=0.561$ ) suggests that the hypothesis of similar means for both lithologies cannot be rejected. In sand and gravel, the mean size is 19 m, with a lower limit of 8 m. This mean is significantly different from that of mudstone and till ( $p<0.001$ ). The largest polygons are found in sand and gravel, with many examples exceeding 30 m. Polygons in sandstone and loess are intermediate in size, with a mean close to 17 m. However, the Student's t test does not reject the hypothesis of similar means for sand, gravel, loess and sandstone at the 5% confidence level. The association with lithology essentially reflects the linear thermal expansion coefficient of the ground ([Lachenbruch, 1962](#)). Strong variability in size for a given lithology shows, however, that the thermal expansion coefficient alone cannot explain the size of polygons. Analysis of size as a function of the age of the sediments in which the polygons were formed also reveals a clear association ([Fig. 5B](#)). In Sweden, polygons from areas deglaciated after 15 ka are large (mean 28 m) ([Fig. 6](#)). As no polygons were observed in areas deglaciated after 14 ka, i.e. in the early Lateglacial, this suggests that thermal contraction, if active, only occurred for a few hundred years. Size decreases markedly for areas deglaciated after 17 ka (mean 22 m) and reaches in areas deglaciated after 19 ka, i.e. for ca. 4 ka of activity, a value comparable to that of areas that remained unglaciated (mean between 11 and 15 m depending on lithology). Because of the small number of polygons measured, t-test ( $p=0.353$ ) does not reject the hypothesis of similar means between polygons < 15 ka and polygons < 17 ka. Similarly, polygons in the proglacial lakes Humber and Fenland (UK), which were drained after 16 ka ([Fairburn and Bateman, 2016](#); [Bateman et al., 2018](#); [Evans et al., 2018a](#)), are characterized by a very large size (mean 39 m).

Large polygons also exist locally in unglaciated areas, including sandy loess south of Wroclaw, Poland (latitude 51°N), sands in Turnhout, Belgium ([Beerten et al., 2021](#); latitude 51.3°N), and fluvial gravels near Oxford, UK (latitude 51.7°N). Without precise data on the age of host sediments and/or the infilling of cracks, the factor behind these large polygons cannot be determined.

Overall, there is only weak association of polygon size with latitude ([Fig. 5C](#)) and the average is between 14 and 20 m (mean 17.3 m) over the entire latitudinal range. The mean size increases slightly with latitude, however. Excluding the outliers (which may correspond to young polygons) from calculation results in more similar size means, which cannot be distinguished by statistics (except for the 55-57°N subset). The most striking change remains the larger size range at latitudes > 49°N than at lower latitudes.

### 4.3. Polygon morphology

Following the nomenclature proposed by [Lachenbruch \(1966\)](#) and [Ewertowski et al. \(2017\)](#), polygon morphology was classified according to the dominant junction type, the regularity of the pattern created by polygons, and the homogeneity of wedge width.

Polygons can be hexagonal (predominance of Y-junctions), orthogonal (T- or +-junctions) or mixed (coexistence of both types of junctions) ([Fig. 7](#)). In general, mixed polygons that combine both Y- and T-junctions largely dominate ([Fig. 8A](#)). The lithology does not appear to have a clear influence on the type of polygons, although orthogonal polygons are most abundant in tills ([Fig. 8B](#)). In contrast, latitude plays a significant role, with orthogonal polygons predominating at high latitudes whereas hexagonal polygons are mostly found in mid-latitudes ([Fig. 8D](#)). The influence of latitude may explain why orthogonal polygons are more frequent in till, which was deposited in northern Europe by the Pleistocene ice sheets. At the scale of a single piece of land, areas of orthogonal polygons are sometimes juxtaposed with areas of hexagonal or mixed polygons ([Fig. 7C](#)). Therefore, it is clear that in many cases the former did not derive from the latter as already indicated by [Halltigin et al. \(2012\)](#). Few sites with oriented orthogonal polygons were identified, i.e., 7 out of 1311 (0.5 %) ([Fig. 7F](#)). All formed on slopes and the direction of elongation changes laterally with slope. The relative elevation of polygons to the surrounding terrain was quantified by calculating the average elevation within a circular buffer of 1 km diameter centered on each site and subtracting this value from site elevation ( $\Delta alt$ ) ([Fig. 9](#)). Overall, the polygons are present on low relief terrain (mean  $\Delta alt \sim 0$ ). Orthogonal polygons tend to prevail in low-lying areas ( $\Delta alt < 0$ ) that are likely poorly drained, while hexagonal polygons are mostly located in elevated areas ( $\Delta alt > 0$ ).

Wedges can be straight and regularly spaced, creating polygons of similar size and shape ('regular polygons'). Conversely, wedges can be sinuous or wedge spacing can vary strongly ('irregular polygons'). Irregular polygons dominate at high latitudes ([Fig. 8E](#)) and are on average larger than regular polygons ([Fig. 8C](#)). In particular, large polygons formed in areas deglaciated at the very end of the Pleniglacial in Sweden are all irregular and characterized by cracks that are often discontinuous and of variable spacing ([Fig. 10](#)). In contrast, small regular polygons are most abundant in areas that remained unglaciated, especially in mid-latitudes.

In some cases, the wedges are approximately of similar width, while in other cases noticeable variations are visible ([Fig. 11](#)). The widest wedges generate a large network and are considered the first cracks to have appeared (primary cracks) ([Lachenbruch, 1966](#)). A network of narrower secondary wedges subdivides the large polygons. This category of polygons is referred to as 'subdivided'. A gradation can be observed between large irregular subdivided polygons and small regular polygons (< 15 m) with no identifiable hierarchy in wedge width. The latter appear to derive from the former due to the growth of secondary wedges. For the majority of the subdivided orthogonal polygons, secondary wedges form a net typified by more abundant Y-junctions than for primary wedges. At some sites, areas of large simple polygons are juxtaposed with areas of subdivided polygons in connection with variations of topography ([Fig. 11](#)). It seems that this results primarily from erosion, with the shallowest secondary wedges disappearing more rapidly than primary wedges. This factor, as well as the low potential of the narrowest wedges to create visible cropmarks, probably explains to a large extent the coexistence of subdivided polygons and simple polygons in the same area and on the same lithology. Subdivided polygons are present throughout the study area, except for the sectors deglaciated after 17 ka (Sweden).

The proportion of 3-way (T or Y) and 4-way (X) junctions was counted on a sample of polygons of contrasting ages. Comparison of the results obtained for young polygons, from areas deglaciated after 15 ka and 17 ka respectively, shows that the proportion of 4-way junctions increases with time in agreement with literature data ([Plug and Werner, 2002](#)) ([Fig. 12A](#)). In contrast, for longer periods of thermal contraction activity (areas deglaciated after 22 ka and unglaciated areas), an opposite trend is observed. This reflects the subdivision of polygons and the formation of secondary wedges with dominant Y-junctions as indicated above. The diagram proportion of 4-way junctions as a function of lithology ([Fig. 12B](#)) does not show a clear relationship between the two parameters but a large variability in the proportion of 4-way junctions for each lithology. Loess appears to be an exception with a low average proportion, reflecting a dominantly hexagonal morphology. However, the sample of loess polygons analyzed is limited ( $N = 6$ ) and probably not representative. Indeed, [Figure 8](#) shows that hexagonal polygons are in equivalent proportion in loess and other lithologies.

The nature of wedge fill when it could be determined from cross-sections does not seem to influence polygon morphology. Similar polygons may correspond to a network of ice-wedge pseudomorphs or relict sand wedges. Nevertheless, a few examples characterized by unusually wide wedges are specifically associated with ice-wedge pseudomorphs. This is the case at Great Milton, UK ([Fig. 11A](#)), where the wedges reach ca. 8 m width and are located near quarries showing large pseudomorphs ([Seddon and Holyoak, 1985](#); [Maddy et al., 1998](#)). Another example is Posthof\_2 in Germany where the wedges reach 5.5 m width and pseudomorphs have been reported nearby ([Isarin et al., 1998](#)).

## 5. Discussion

Overall, the distribution of polygons coincides with that of ice-wedge pseudomorphs and relict sand wedges described in the literature (e.g. [Watson, 1965](#); [Michel, 1969, 1975](#); [Svensson, 1973, 1988](#); [Haesaerts and Van Vliet-Lanoë, 1973](#); [Christensen, 1974](#); [Vandenberghe and Krook, 1981](#); [Johnsson, 1984](#); [Seddon and Holyoak, 1985](#); [Gozdzik, 1986](#); [Kolstrup, 1986, 2004](#); [Brandon and Sumbler, 1991](#); [Isarin et al, 1998](#); [Maddy et al., 1998](#); [Antoine et al, 2005](#); [Ghysels and Heyse, 2006](#); [Kovács et al., 2007](#); [Ewertowski, 2009](#); [Antoine et al., 2014](#); [Buylaert et al., 2009](#); [Jary, 2009](#); [Fabian et al., 2013](#); [Worsley, 2014](#); [Murton et al., 2015](#); [Ruszkiczay-Rüdiger and Kern, 2016](#); [Andrieux et al, 2016a](#); [Ewertowski et al., 2017](#); [Evans et al., 2018b](#); [Grube, 2021](#)), although in detail many areas where wedges were observed in cross-section are not associated with cropmarks ([Fig. 13](#)). This distribution helps delineate the area that was affected by permafrost or deep seasonal frost during the Pleistocene, in a context that was cold enough to allow repeated cracking of the ground by thermal contraction. As the age of polygons in unglaciated areas and the duration of their development remains unknown in most cases, uncertainty remains as to whether the observed distribution reflects that of the Last Glacial or whether polygons formed during earlier glacials contributed substantially.

The abundance of polygons in a band north of latitude 51°N suggests that thermal contraction leading to the growth of large ice- or sand wedges was active until 18-17 ka, particularly in the North European Loess Belt where loess deposition was still significant at that time ([Meszner et al., 2013](#); [Schmidt et al., 2021](#)). Many ice-wedge pseudomorphs have been described in the loess ([Isarin et al., 1998](#); [Jary, 2009](#); [Meszner et al., 2010](#)), whereas sand wedges or composite-wedge pseudomorphs dominate in the Sand Belt at the periphery of the FIS ([Gozdzik, 1986](#); [Buylaert et al., 2009](#); [Ewertowski, 2009](#); [Grube, 2021](#)). Further south, the lack of cropmarks in loess, particularly in France, indicates that the growth of large wedges did not affect the later phases of loess deposition. This is in



agreement with stratigraphic observations and numerical ages obtained on ice-wedge pseudomorphs, which show that the majority developed between 31 and 24 ka, during the period referred to as Last Permafrost Maximum (LPM, [Vandenberghé et al., 2014](#); [Bertran et al., 2014](#)).

On the FIS margins, the distribution of polygons suggests that thermal contraction associated with the growth of large ice- or sand wedges was not active in the areas deglaciated after 14 ka, i.e. during the Lateglacial. This finding is contrary to the hypothesis widely discussed in the literature of wedge development in northern Europe during the Younger Dryas (e.g. [Gemmell and Ralston, 1965](#); [Svensson, 1988](#); [Isarin et al., 1998](#); [Evans et al., 2018b](#)). Currently, few OSL ages obtained on sand fills are conclusive. In southern Sweden, a single OSL age indicates Weichselian Late Pleniglacial filling ([Kjaer et al., 2006](#)). In Poland, all conventional OSL ages also point to the Late Pleniglacial ([Ewertowski et al., 2017](#)). In France, however, [Andrieux et al. \(2018\)](#) using Single Grain OSL dating have documented the formation of sand veins in already existing sand wedges, confirming the existence of thermal contraction (associated with deflation) during the Younger Dryas. However, this period alone did not lead to the creation of large wedges and cropmarks in France.

Overall, the distribution of polygons shows a clear east-west asymmetry, with the southern limit of polygons reaching 43.5°N in France while it does not exceed 47°N in Hungary. This limit coincides with that of the relict sand wedges described in cross-sections and the observed difference cannot be attributed, therefore, to the lack of suitable satellite images. The main factor potentially involved in this pattern could be the insulation of the ground by snow and/or vegetation, which reduced the temperature gradient in the upper ground layer and limited thermal stress. Palaeoclimatic simulations (e.g. [Stadelmaier et al., 2021](#)) suggest that the mean depth of winter snow cover during the LGM (~21 ka) increased eastward from less than 10 cm on average in France to more than 50 cm in Hungary. In France, the southernmost relict sand wedges are mainly located in areas of active deflation (Aquitaine, lower Rhone Valley) where snow must have been blown away by the wind, as attested by numerous field evidence (ventifacts, yardangs, aeolian pans) ([Sitzia et al., 2015](#); [Bosq et al., 2018](#)). At the same time, simulations ([Strandberg et al., 2011](#); [Janská et al., 2017](#)) as well as reconstructions based on pollen records ([Magyari et al., 2014](#)) also show that the vegetation cover was denser and more shrubby in Eastern Europe than at the same latitude in Western Europe, thus contributing to soil insulation.

In the southern fringe of the polygon extent, the distribution is restricted to areas at the periphery of coversands, indicating that wedge growth was primarily due to sand infiltration into the cracks. In France, the lack of ice-wedge pseudomorphs in adjacent terrain strongly suggests that thermal contraction occurred in a deep seasonal frost context ([Andrieux et al., 2016a](#); [Stadelmaier et al., 2021](#)). In Hungary, the periglacial structures mentioned in the literature are still few and do not allow a clear statement on the presence or absence of permafrost. Nevertheless, palaeoclimatic simulations suggest that the case of Hungary is similar to that of southwestern France (deep seasonal frost). In central Germany, the same simulations indicate that the sand wedges developed in a discontinuous permafrost context. Ground cracking would have been limited to areas where snow deflation, associated with sand transport, was active.

Analysis of the characteristics of polygons at the European scale reveals an association with lithology, latitude, and sediment age that could not be identified in regional analyses ([Andrieux et al., 2016a](#); [Ewertowski et al., 2017](#); [Beerten et al., 2021](#)). Particularly, the average size of polygons is smaller on fine-grained sediments and, therefore, in association with higher linear thermal expansion

coefficient, in agreement with the model of [Lachenbruch \(1966\)](#). Contrary to the assumption that crack spacing increases with crack depth ([Plug and Werner, 2002](#)) and, therefore, with colder climates, no clear association of polygon size with latitude appears when outliers are excluded from calculation, probably because of the subdivision of polygons over time. Increased size range at high latitudes may reflect greater variability in the age of host sediments, because of widespread deposition of variable sediments (glaciofluvial sand, aeolian sand, loess) during the Weichselian Late Pleniglacial.

This study also shows that orthogonal polygons, sometimes extremely regular (rectangular), are mainly located in high latitudes ( $>50^{\circ}\text{N}$ ), in areas that were not glaciated or were deglaciated before 17 ka. Such a distribution could reflect the role of climate. In agreement with [Lachenbruch \(1966\)](#), the stress generated by very cold temperatures and a high temperature gradient in the subsurface ground layer would be much greater than ground strength and would result in straight-line crack propagation. Topography could also have played a role, orthogonal polygons being located in depressions where ice could form in abundance in soils, whereas hexagonal polygons are located on well-drained reliefs.

The duration of thermal contraction activity is also a key parameter for the size and regularity of polygons. A long duration causes the subdivision of polygons that become small and regular, as already indicated by the majority of authors (e.g. [Lachenbruch, 1966](#); [Sletten et al., 2003](#); [Ulrich et al., 2011](#)). It helps explain a large part of the variability observed in Europe. Observations made on series of polygons of contrasting ages allow us to propose an evolutionary sequence, whose main steps are as follows:

(1) After a few hundred years of activity, thermal contraction cracks give rise to large (typically 30 m) and irregular (cracks with variable spacing), poorly formed polygons.

(2) After about 2 ka, the number of cracks and their continuity increases while the size of the polygons decreases significantly (typically 22 m). Regular orthogonal (rectangular) polygons develop in very cold areas at high latitudes, whereas irregular polygons form preferably in less cold regions due to increased crack sinuosity.

(3) After about 4 ka, the polygons are well developed and their size becomes comparable to that of polygons in areas exposed for a long time to thermal contraction. This size is of the order of 15 m for all lithologies combined. The polygons become subdivided; primary cracks widen and contrast with narrow secondary cracks. The latter have Y-junctions in greater proportion than primary cracks, possibly because of greater homogeneity of the ground on a small scale than on a field-wide scale.

(4) In the longer term, the difference in width between primary and secondary cracks diminishes due to the growth of ice- or sand wedges. The polygons form a regular pattern in which Y-junctions are in high proportion (hexagonal or mixed polygons). Dominant Y-junctions may result from intensive subdivision and from the evolution of orthogonal 3-way junctions formed in crack bends into Y like junctions ([Fig. 1B](#)). The size stabilizes around 15 m on average. It is possible that the speed with which this maturity phase is reached is variable depending on the nature of the wedge filling. Ice has a significantly lower strength than frozen sand and the surrounding sediments. Preferential cracking of ice leads to rapid wedge growth (e.g. [Plug and Werner, 2002](#)). This factor, combined with the collapse of the walls during ice melting, probably accounts for the formation of polygons with wide primary wedges contrasting with narrow secondary wedges. The contrast in strength between the



host sediment and the sandy fill is smaller, so that subdivision likely progresses more rapidly, favoring the evolution towards a stable mature phase. According to [Burn and O'Neill \(2015\)](#), the location of polygons in the landscape (i.e. in depressions or on hillslopes) may also affect the speed of subdivision and secondary ice-wedge growth.

In unglaciated areas, the age of polygons and the duration of development remains unknown in most cases. Available stratigraphic data and ages obtained on the infill and host sediments suggest that ground thermal contraction cracking must have been repeatedly active during the Last Glacial (e.g., [Vandenberghe and Krook, 1981](#); [Buylaert et al., 2009](#); [Worsley, 2014](#); [Andrieux et al., 2018](#)) and, therefore, may correspond to several millennia of cumulated evolution. In some cases, there is evidence of activity spanning the Mid- to Late Pleistocene (e.g., [Andrieux et al., 2018](#)). Extensive dating would be necessary to better evaluate this point.

## 6. Conclusions

The study of Pleistocene polygons in Europe carried out using the collection of satellite images available in Google Earth™ provides new data on the distribution of ground cracking by thermal contraction during glacial periods and sheds light on some factors controlling their formation. Overall, the distribution map indicates that this process affected terrain between latitude 43.5°N and the southern limit of the FIS at 15 ka, with a concentration of polygons north of latitude 51°N. A clear asymmetry is visible in relation to longitude, with a greater southward extension of polygons in France (43.5°N) than in central Europe (47°N), potentially related to thicker snow cover and denser vegetation towards the east insulating the ground from temperature variations. In the southern fringe of the polygon extent, these are mainly present in areas at the margin of aeolian sands. In these areas, sand wedges were formed in a context of deep seasonal frost (France and probably Hungary) or possibly of discontinuous permafrost (central Germany). Further investigations in the latter region would be necessary to investigate this in more details.

The morphological evolution over time reconstructed from observations of polygons of contrasting ages in Europe broadly confirms that already described in current periglacial environments. The stable mature phase, characterized by small (average size 15 m), regular polygons with numerous Y-junctions, seems to be reached after ca. 4 ka, faster than previously mentioned. Further field investigations to document wedge morphology as well as the nature and age of their infill should allow for a better characterization of the glacial environments and the mapping of the Pleistocene permafrost.

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## Supplementary information

Table S1: List of polygon sites identified from satellite images with their location and indication of elevation (alti\_DEM, in m a.s.l. rounded to the nearest integer), lithology and size (in m) measured from the images. French polygons are taken from [Andrieux et al. \(2016b\)](#), with some additions. When available, the geological codes are taken from the geological maps listed in the main text.

## Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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673

#### 674 **Figure captions**

675 Figure 1: Types of crack junctions. A – initial cracks; B – after substantial wedge growth.

676 Figure 2: Distribution map of polygons in Europe. Ice sheet limits are from [Hugues et al. \(2016\)](#) for the  
677 Fennoscandian Ice Sheet (FIS) and British-Irish Ice Sheet (BIIS) and from [Ehlers and Gibbard \(2004\)](#) for  
678 the other ice sheets. The map of aeolian deposits is from [Bertran et al. \(2021\)](#). AU: Austria, BE: Belgium,  
679 CZ: Czech Republic, DK: Denmark, FR: France, GE: Germany, HU: Hungary, IT: Italy, NE: Netherlands,  
680 PO: Poland, SP: Spain, SW: Sweden.

681 Figure 3: Association between the distribution of polygons and aeolian sand sources in mid-latitudes.  
682 A - Loire Valley (France), the map of aeolian deposits from [Bertran et al. \(2021\)](#) is superimposed on a  
683 simplified 1:250,000 geological map; B - Main Valley, Central Germany on 1:200,000 geological map  
684 background (<https://services.bgr.de/wms/geologie/guek200/>).

685 Figure 4: Number of polygons identified according to lithology.



686 Figure 5: Size of the polygons. A - Size according to lithology, whole dataset; B - Size according to  
687 sediment age, selected areas from northern Europe; C – Size according to latitude, whole dataset.

688 Figure 6: Size of polygons as a function of age. A - Denmark and southern Sweden, ice sheet limits are  
689 from [Hughes et al. \(2016\)](#) except for the boundary at 17 ka (2), which is from [Evans et al. \(2021\)](#); B –  
690 UK, the map of the Fenland, Humber, and Pickering proglacial lakes is from [Fairburn and Bateman](#)  
691 [\(2016\)](#).

692 Figure 7: Types of polygons. A - Regular hexagonal polygons, Chevrolières\_3, France; B - Irregular  
693 mixed polygons, Dimbach\_2, Germany; C - Orthogonal polygons (top of the picture) juxtaposed to  
694 hexagonal polygons (bottom), Isengerode, Germany; D - Regular orthogonal polygons, Bielawy,  
695 Poland; E- Subdivided orthogonal polygons, Dziewa, Poland; F - Oriented orthogonal polygons,  
696 Bedford, UK.

697 Figure 8: Types of polygons, whole dataset. A - Regularity as a function of type; B - Types as a  
698 function of lithology; C - Size as a function of regularity; D - Types as a function of latitude; E -  
699 Regularity as a function of latitude.

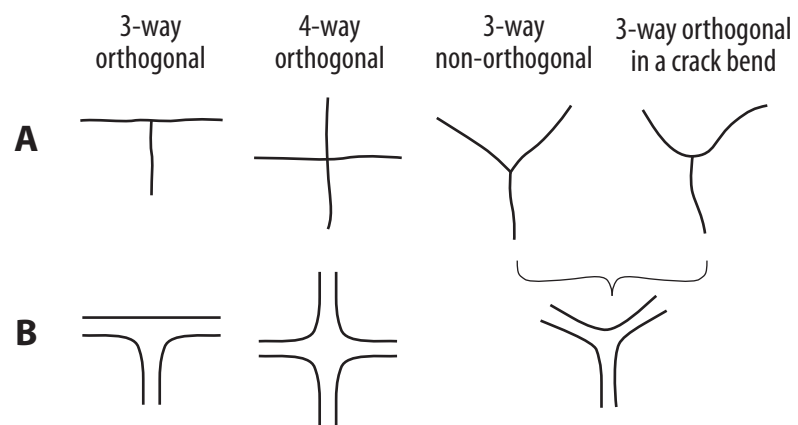
700 Figure 9: Difference in altitude ( $\Delta alt$ ) between polygons and surrounding terrain (1 km buffer).  
701 Negative values indicate that the polygons were formed in a depression.

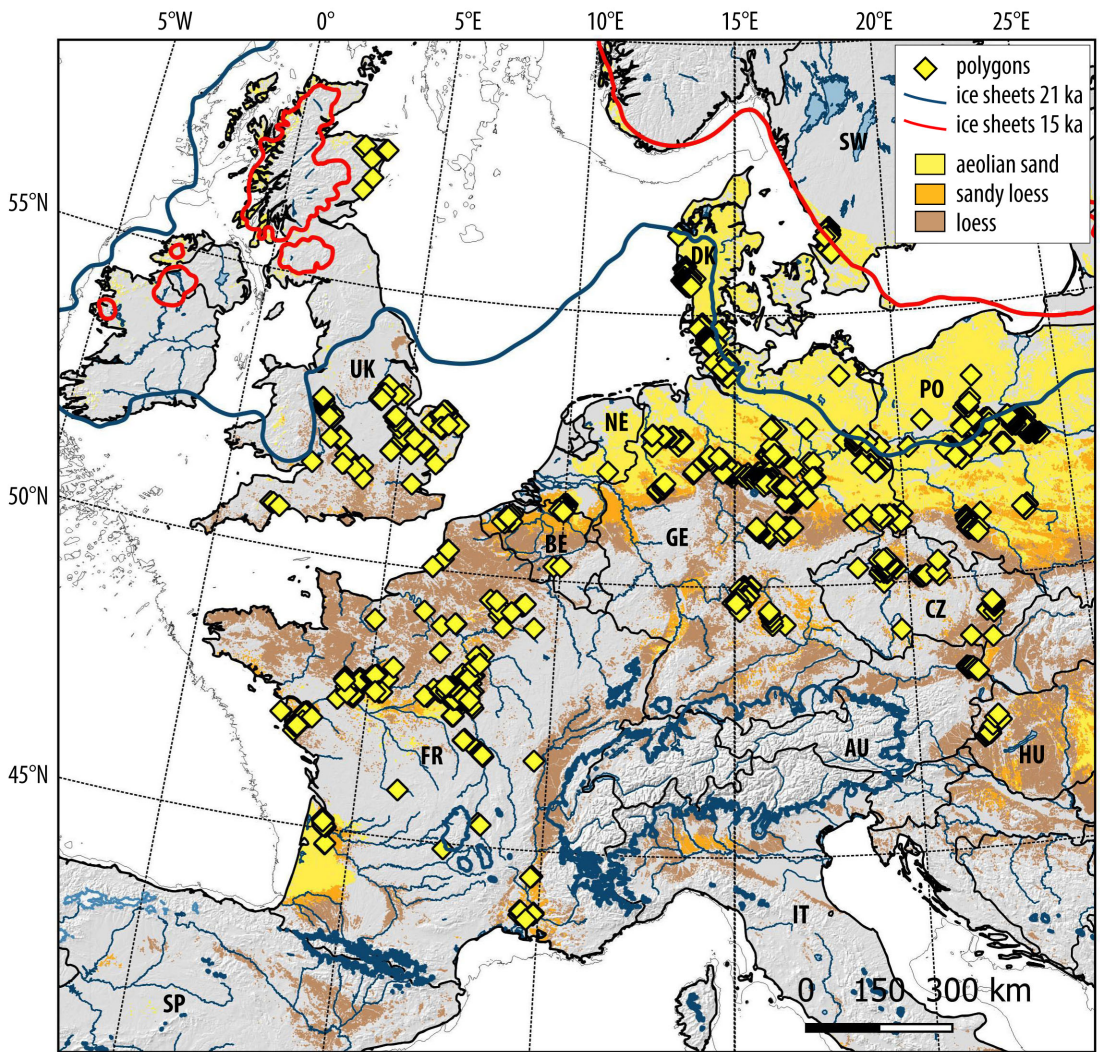
702 Figure 10: Irregular young polygons. A - Skogaby, Sweden (deglaciation < 15 ka); B - Össjö\_3, Sweden  
703 (deglaciation < 17 ka); C – Grabionna, Poland (deglaciation < 19 ka); D – Friedersdorf\_2, Germany  
704 (deglaciation < 21 ka).

705 Figure 11: Subdivided polygons. A - Great Milton, UK; B - Gerholzhofen, Germany.

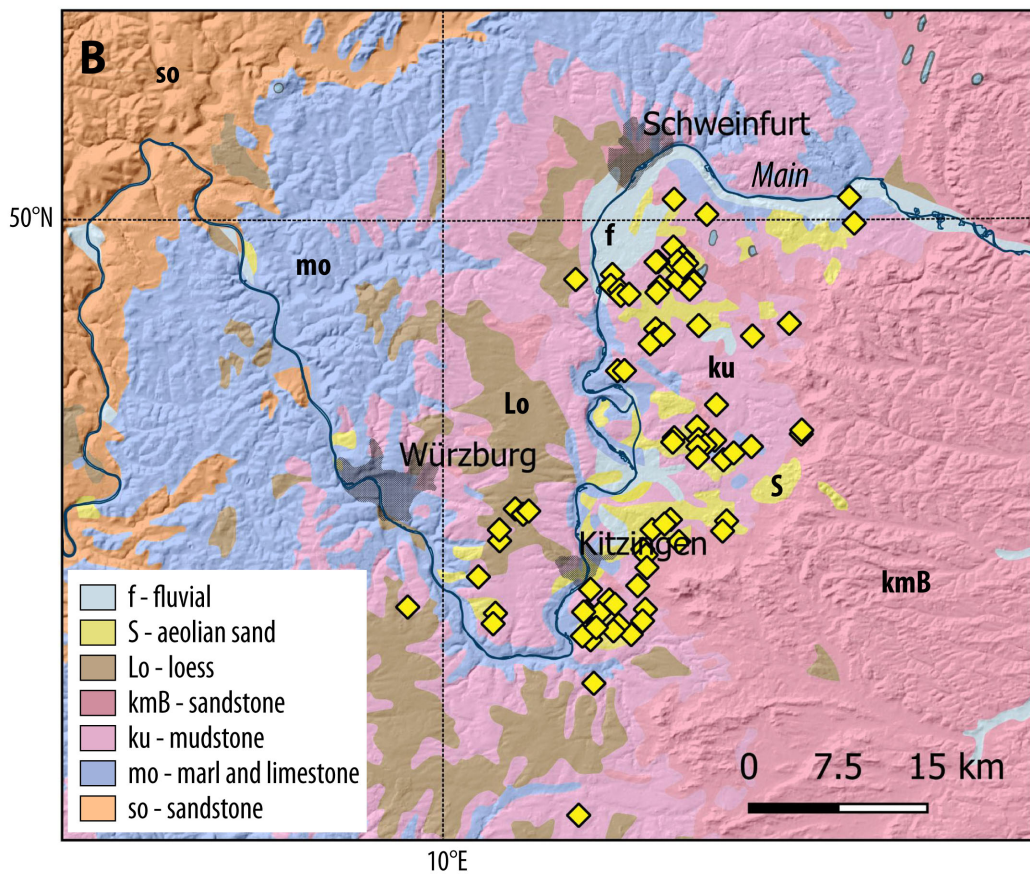
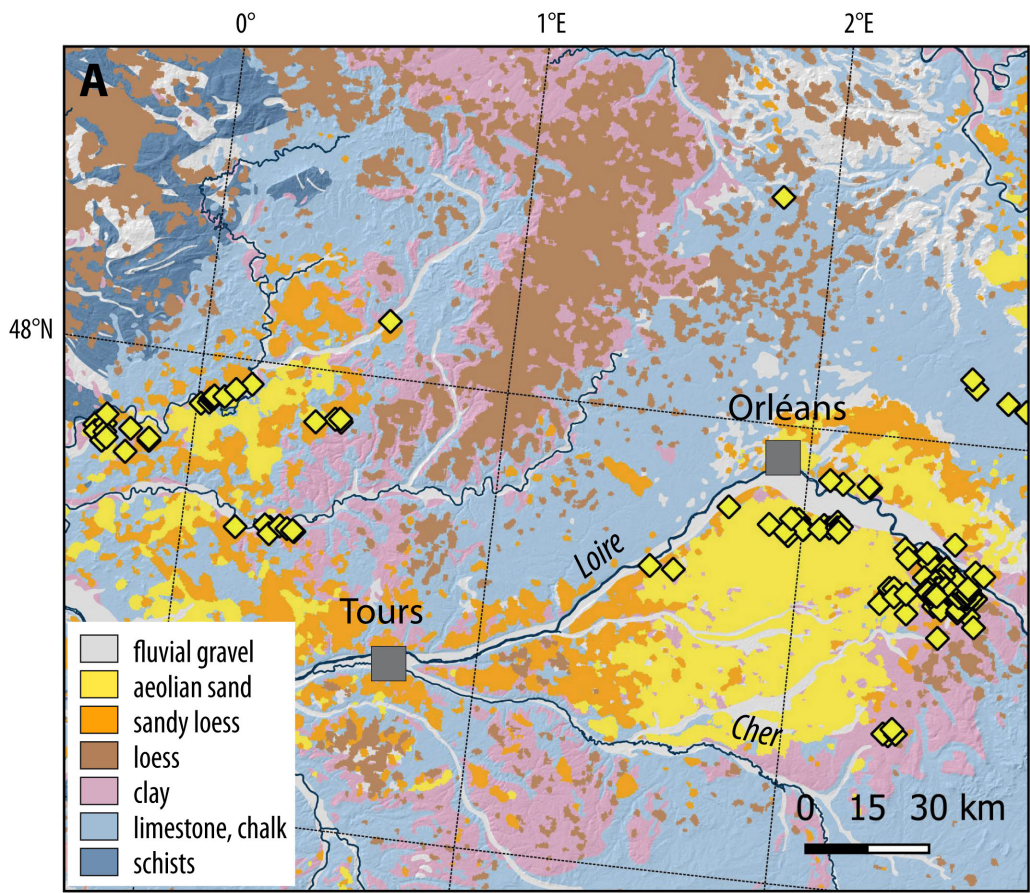
706 Figure 12: Proportion of 4-way junctions as a function of polygon age (A) and lithology (B).

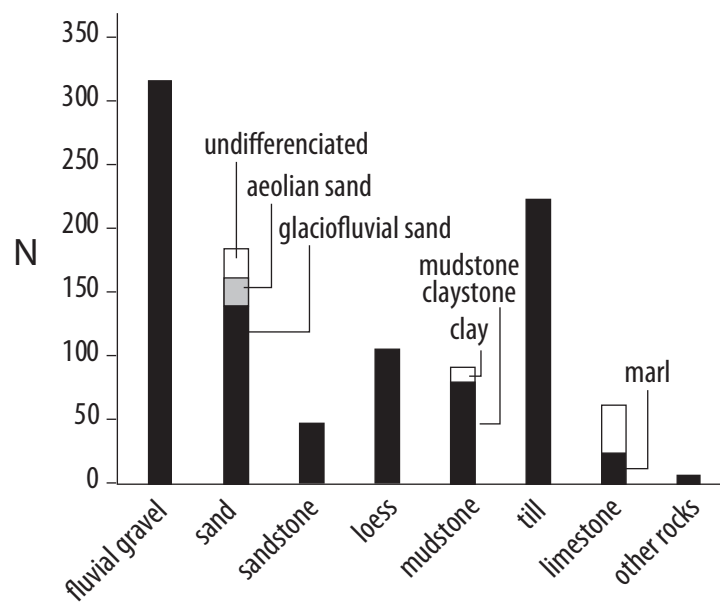
707 Figure 13: Distribution of Pleistocene (mostly Weichselian) ice-wedge pseudomorphs, composite  
708 wedge pseudomorphs and relict sand wedges, after [Isarin et al. \(1998\)](#), [Andrieux et al. \(2016a\)](#) and  
709 this study. The limits of continuous permafrost and discontinuous to sporadic permafrost at 21 ka are  
710 from [Stadelmeier et al. \(2021\)](#).

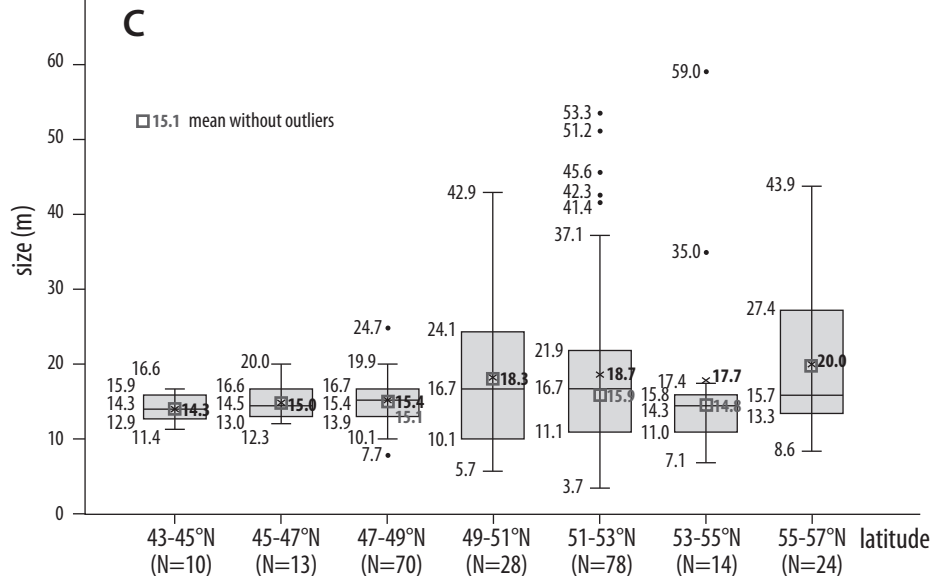
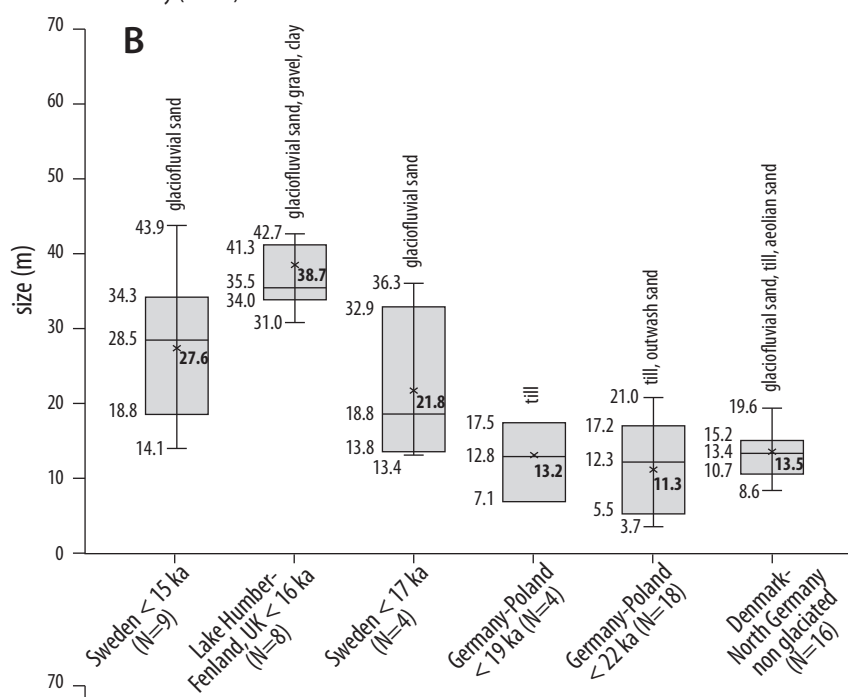
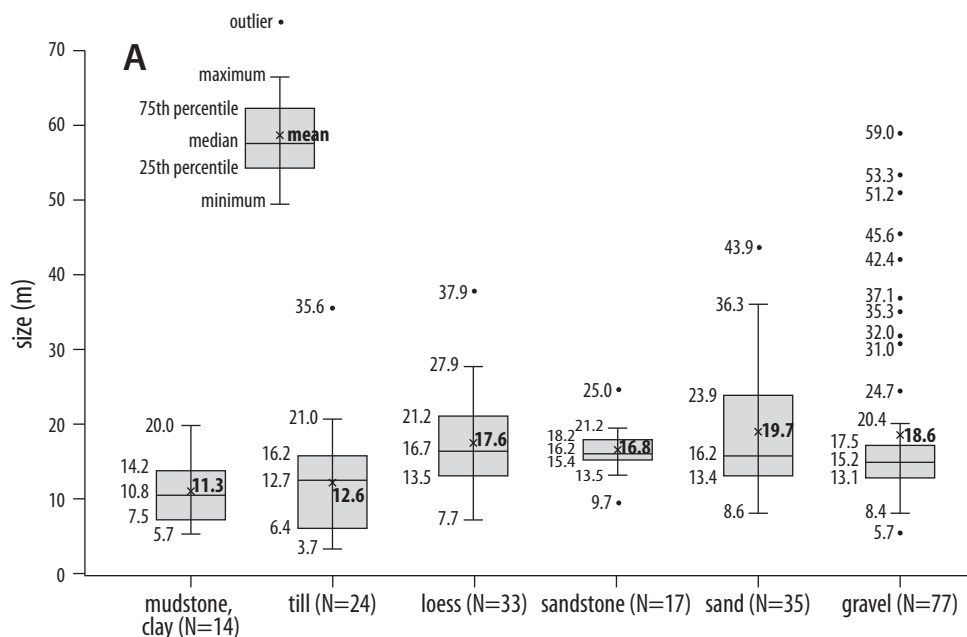




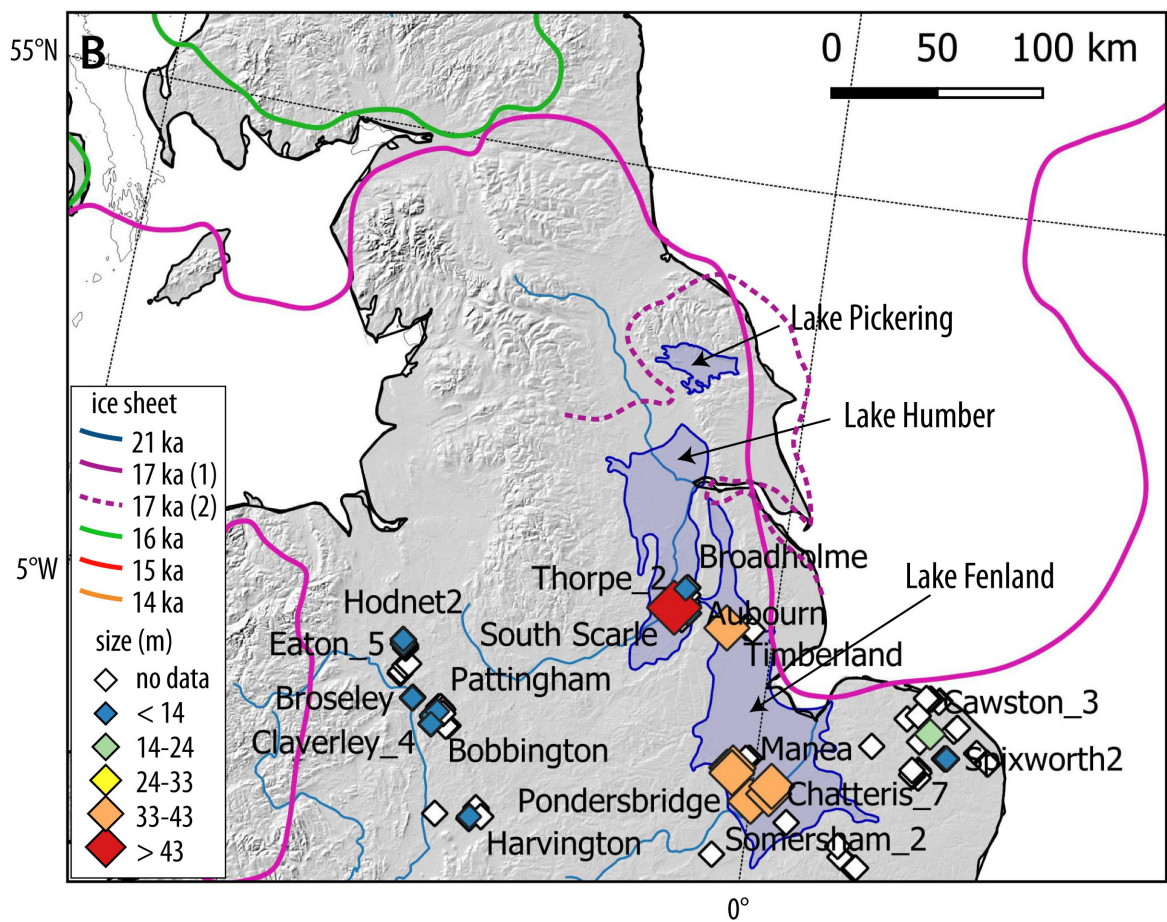
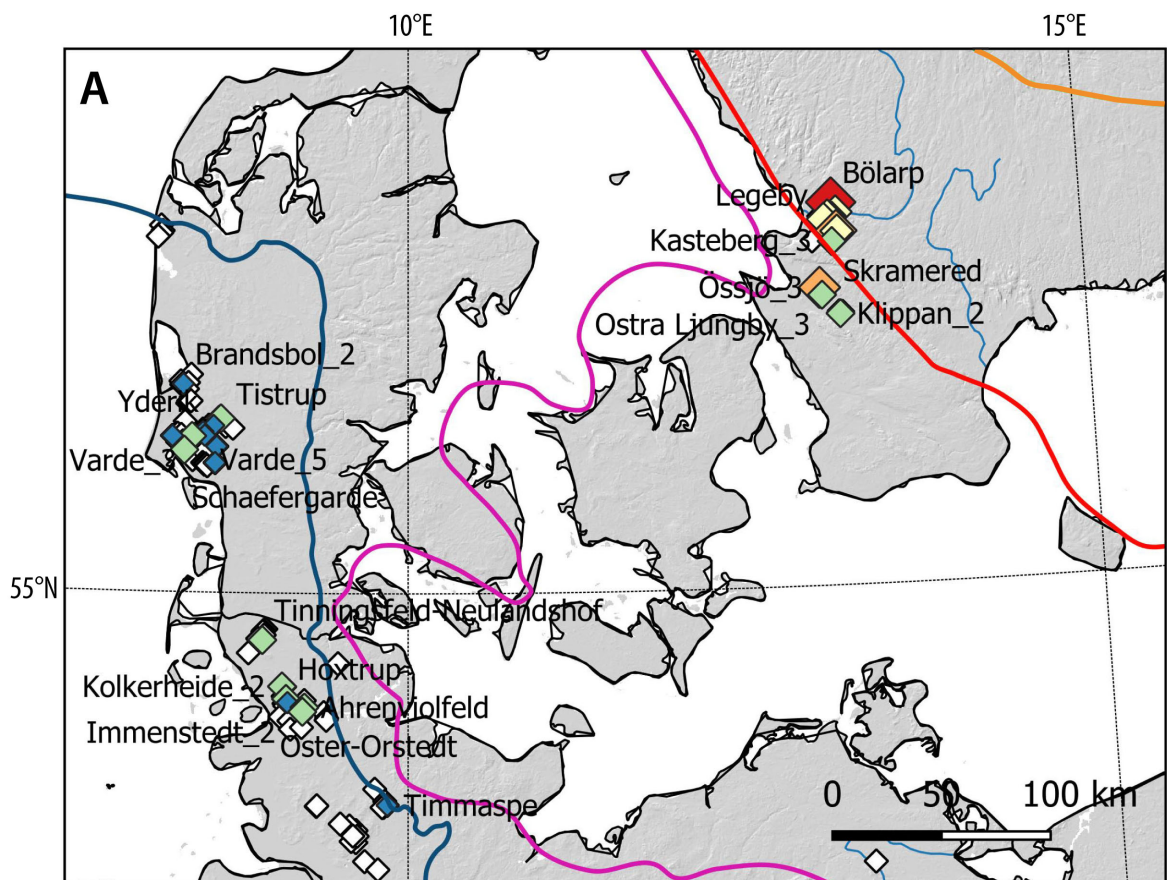




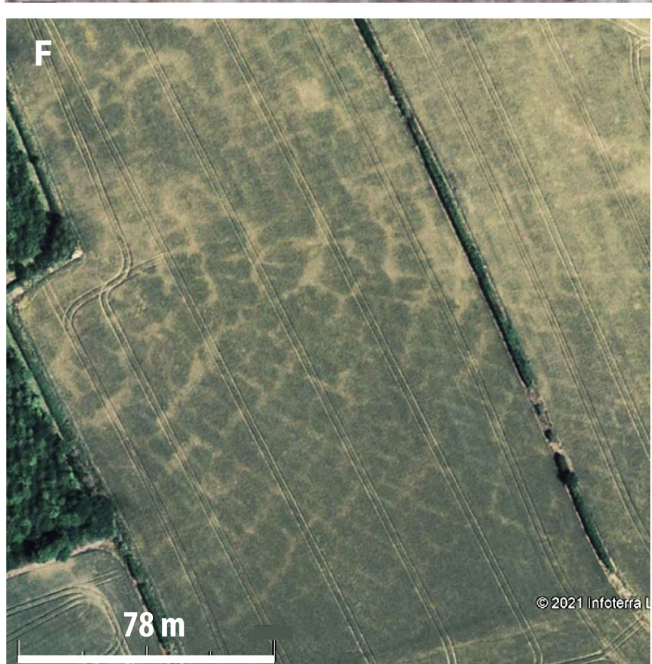
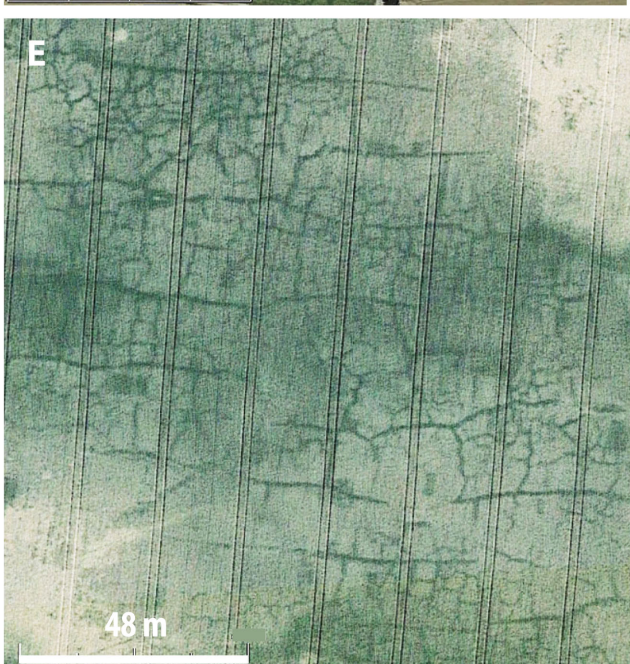
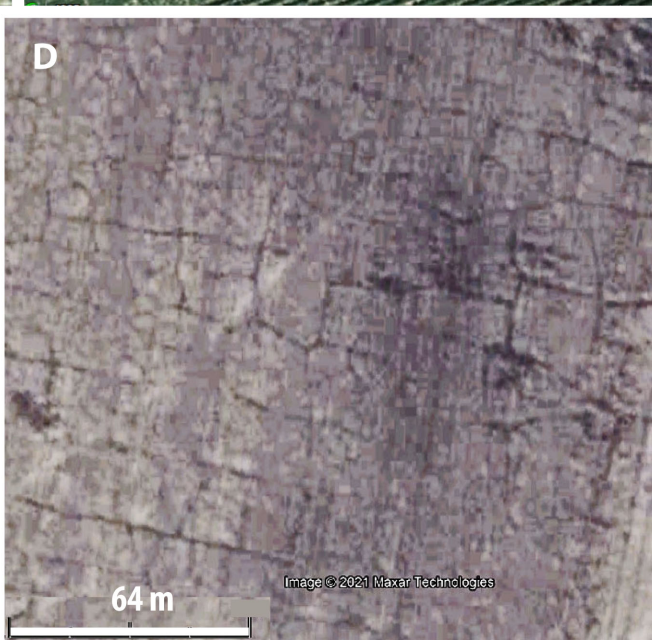
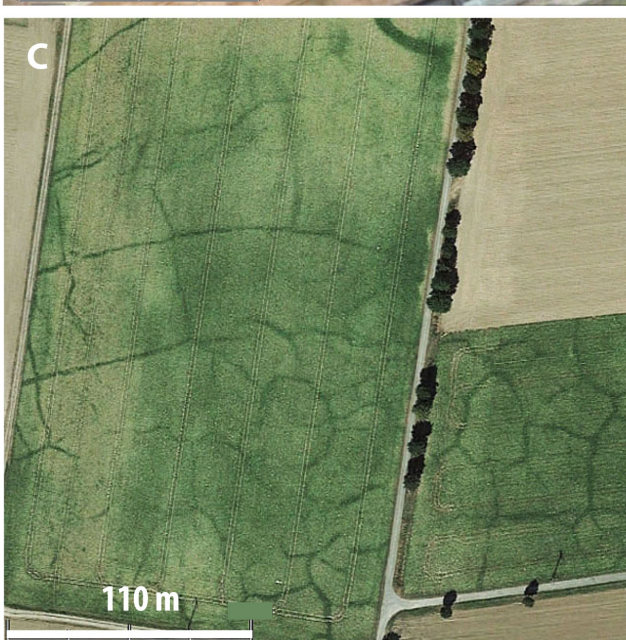
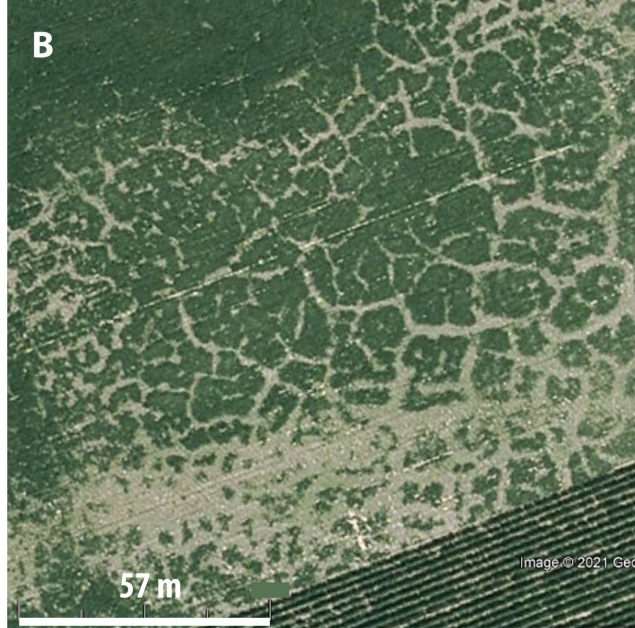




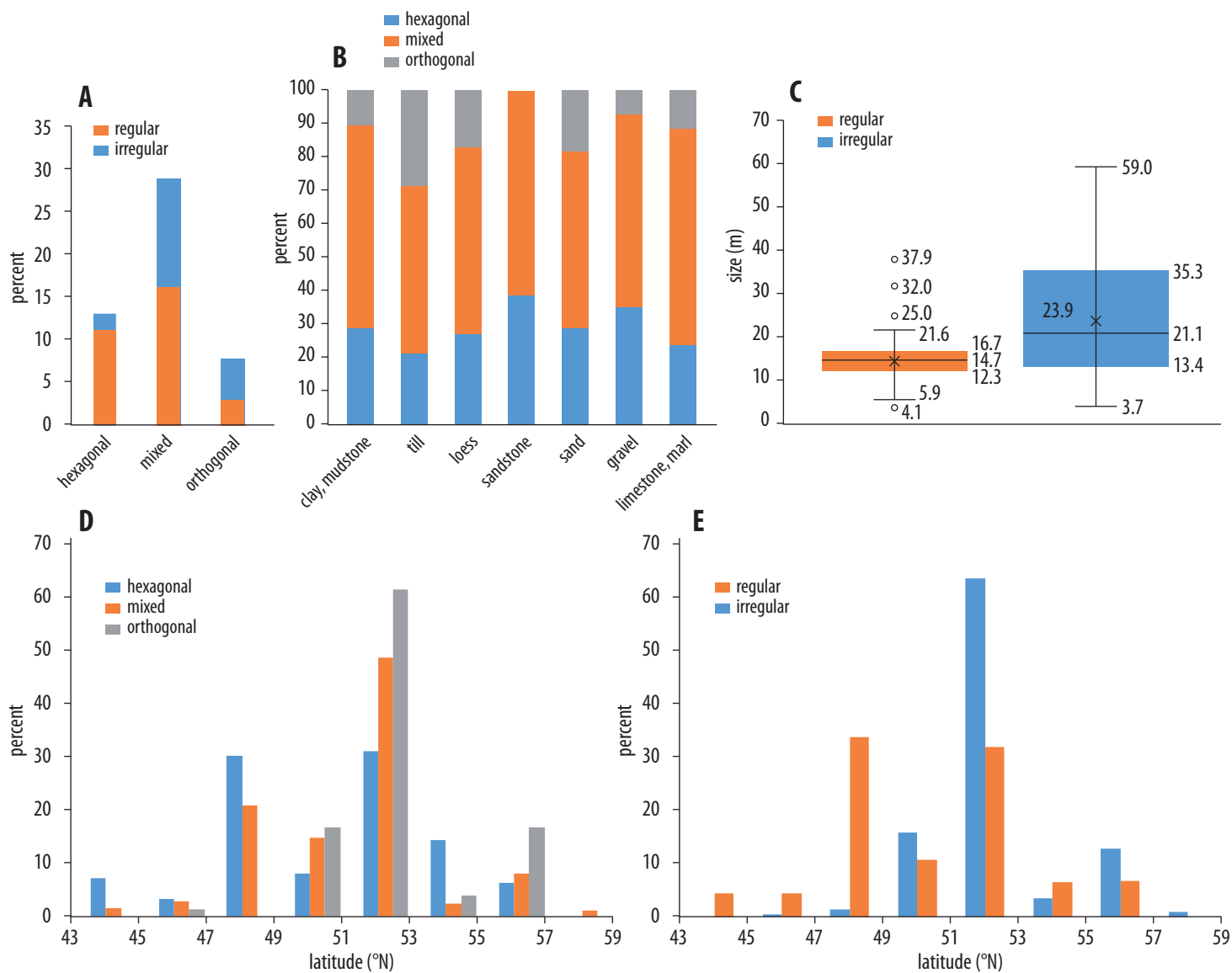


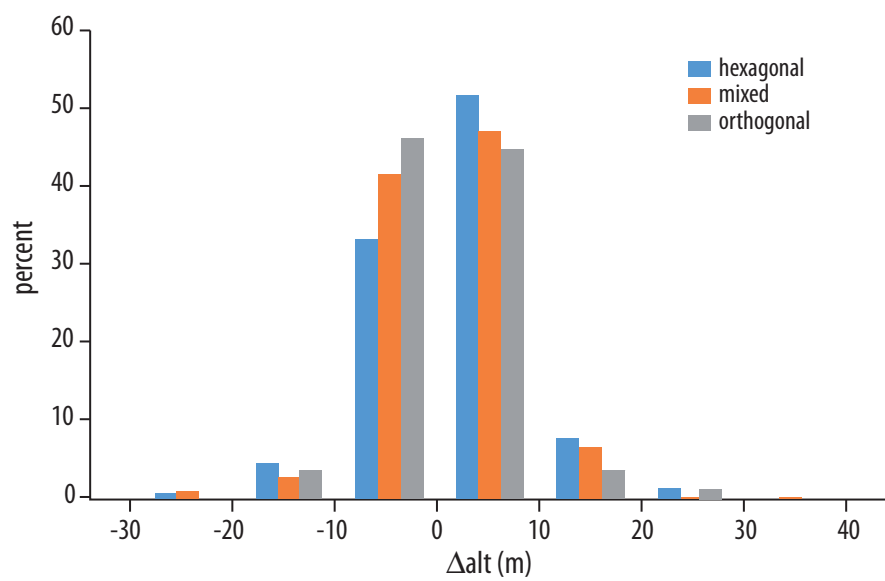


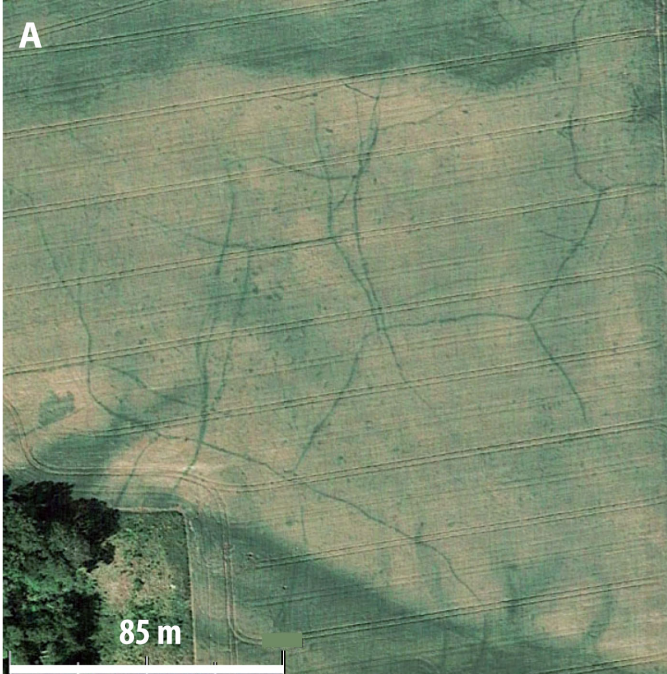
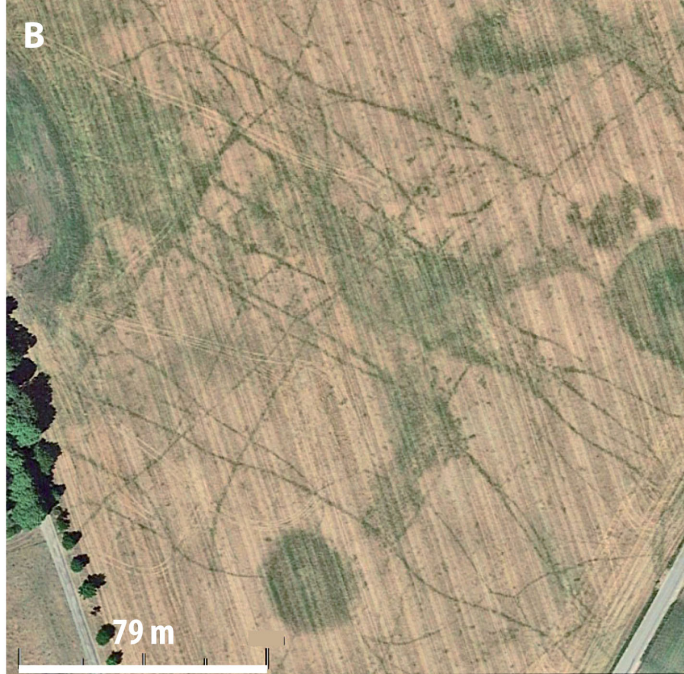










**A****B****C****D**



