Colluvial sediments originating from past land-use activities in the Erzgebirge Mountains, Central Europe: occurrence, properties, and historic environmental implications

Knut Kaiser[1] · Johann Friedrich Tolksdorf[2] · Anna Maartje de Boer[3] · Christoph Herbig[4] · Falk Hieke[5] ·
Marek Kasprzak[6] · Petr Kočár[7] · Libor Petr[8] · Matthias Schubert[9] · Frank Schröder[9] · Alexander Fülling[10] ·
Christiane Hemker[9]

Abstract

Colluvial sediments originating from soil erosion on slopes have proven to constitute significant evidence for tracing past human impact on mountain landscapes. In the Central European Erzgebirge (Ore) Mountains, colluvial sediments are associated with specific landforms (footslopes, slope flattenings, dells) and cover a share of 11% (11,905 ha) of the regional soil landscape. Thirteen pedosedimentary sections with colluvial layers were investigated at five forested sites (520–730 m a.s.l.) within a context of mining archaeology, integrating data from pedology, archaeology, palaeobotany, and geochronology. The thickness of the gravel-bearing loamy, silty, and sandy colluvial layers is up to 70 cm, which are mostly located on top of the sections. The geochronological ages and archaeological data reveal a high to late medieval to post-medieval age of the colluvial sediments. Pollen data show a drastic decline of the mountain forests in the late twelfth to fifteenth centuries AD accompanied by an increase of pioneer trees and spruce at the expense of fir and beech. The primary cause of soil erosion and subsequent colluvial deposition at the sites investigated is medieval to post-medieval mining and other early industrial activities. A compilation of 395 radiocarbon and OSL ages, obtained from colluvial sediments at 197 upland sites in Central Europe, shows that anthropogenically initiated colluvial dynamics go as far back as the late Bronze Age to the early Iron Age. Most ages derive from the medieval to post-medieval period, corresponding to the general intensification of settlement and land-use activities including deforestation and widespread ore mining.

Keywords Hillwash · Soil erosion · Mining · Medieval · Late Holocene · Ore Mountains

✉ Knut Kaiser
kaiserk@gfz-potsdam.de

1 GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

2 Section Schwaben/Mittelfranken, Bavarian State Office for Monument Protection, Klosterberg 8, 86672 Thierhaupten, Germany

3 Soil Geography & Landscape Group, Wageningen University and Research, P.O. Box 47, 6700 AA Wageningen, The Netherlands

4 Institute of Archaeological Sciences, University of Frankfurt, Postfach 11 19 32, 60054 Frankfurt am Main, Germany

5 Büro für Bodenwissenschaft, Nonnengasse 28, 09599 Freiberg, Germany

6 Institute of Geography and Regional Development, University of Wrocław, pl. Uniwersytecki 1, 50-137 Wrocław, Poland

7 Institute of Archaeology, Czech Academy of Sciences, Letenská 4, 118 01 Praha 1, Czech Republic

8 Department of Botany and Zoology, Faculty of Science, Masaryk University Brno, Kotlářská 2, 611 37 Brno, Czech Republic

9 Archaeological Heritage Office of Saxony, Zur Wetterwarte 7, 01109 Dresden, Germany

10 Institute of Earth and Environmental Sciences, University of Freiburg, Albertstraße 23b, 79104 Freiburg, Germany

Introduction

Sediments originating from anthropogenic soil erosion and deposited onto slopes possess a wealth of evidence for tracing past human impact on landscapes. Although distributed and studied practically worldwide (e.g. Eriksson et al. 2000; Bettis 2003; Kaiser et al. 2007; Dotterweich 2008; McIntosh et al. 2009), the main research focus during the last decades was on occurrences in Europe. Here, intensively used and, thus, heavily eroded cultural landscapes already exist over millennia. Intensive collaboration between various geosciences, archaeology, and palaeobotany resulted in a multitude of well-analysed records and local erosion histories centred around colluvial sediments (e.g. Brown 2009; Dreibrodt et al. 2010; Kaal et al. 2011; Kittel 2014; Leigh et al. 2016; Kappler et al. 2018).

Generally, there are two major types of mass movements on slopes, comprising (1) the synonymously termed slope-, hill-, sheet-, or rainwash, and (2) mass wasting. The former mostly generates fine-grained colluvial deposits sensu stricto, as discussed in this study. The latter is associated with solifluction, rockfall, and debris flow deposits, which is often coarse-grained (Millar 2014; French 2017; Fig. 1). Colluvial deposits originating from hillwash, i.e. formed by shallow surface water flow, can be formed by a variety of processes, of which deforestation, agriculture, and animal husbandry are the most important ones. Furthermore, once the terrain is used for agriculture, ploughing leads to a downslope step-by-step translocation of soil matter (Lang and Hönscheidt 1999; Leopold and Völkel 2007; Kleber et al. 2013; Miller and Juilleret 2020; Fig. 1). Consequently, colluvial sequences frequently contain a record of human impacts on landscapes. Colluvial sediments have the ability to bury and, thus, to preserve past surfaces at different spatial scales (French 2017).

Although the low (subdued) mountain ranges of Central Europe (up to c. 1500 m a.s.l.) have been the subject of Holocene landscape history studies for nearly a century (e.g. Tolksdorf et al. 2018a), colluvial sequences including their palaeosols were only rarely raised as a central study topic in this area (e.g. Dotterweich et al. 2013; Henkner et al. 2018a; Meyer-Heintze et al. 2020; Scherer et al. 2021). One reason for this is that colluvial sediments are preferably studied in the context of erosion research, thereby concentrating on landscapes currently used by intensive agriculture. In particular, heavily eroded hilly loess landscapes, widely located in Central Europe between the lowlands in the north and the uplands in the south (Böse et al. 2018), have been the focus in this respect (e.g. Lang 2003; Wolf and Faust 2013; Kühn et al. 2017; Kołodyńska-Gawrysiak 2019). By contrast, the
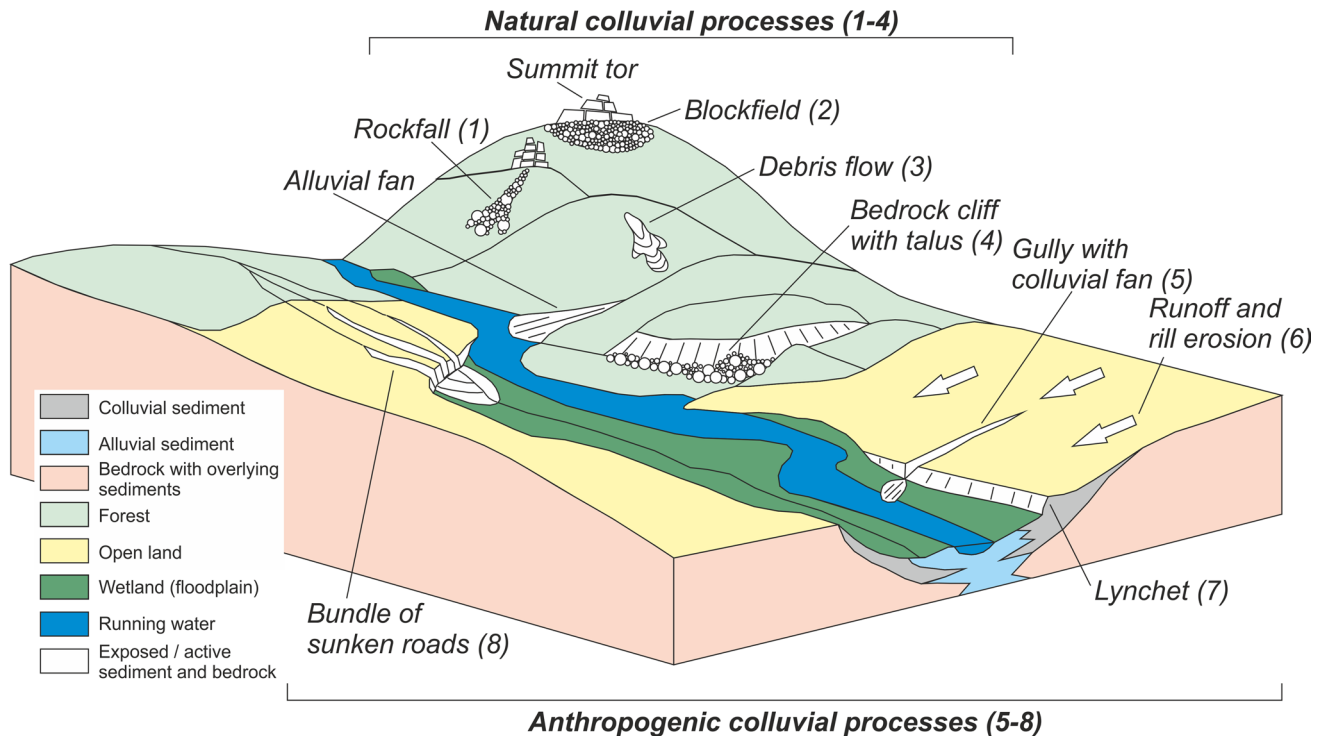

Fig. 1 Conceptual landscape model showing selected colluvial sedimentary sub-facies and further geomorphic and land cover properties of the Central European uplands (based on suggestions by Blikra and Nemec 1998; Zolitschka et al. 2003; French 2017; Migoń et al., 2020; Miller and Juilleret 2020)
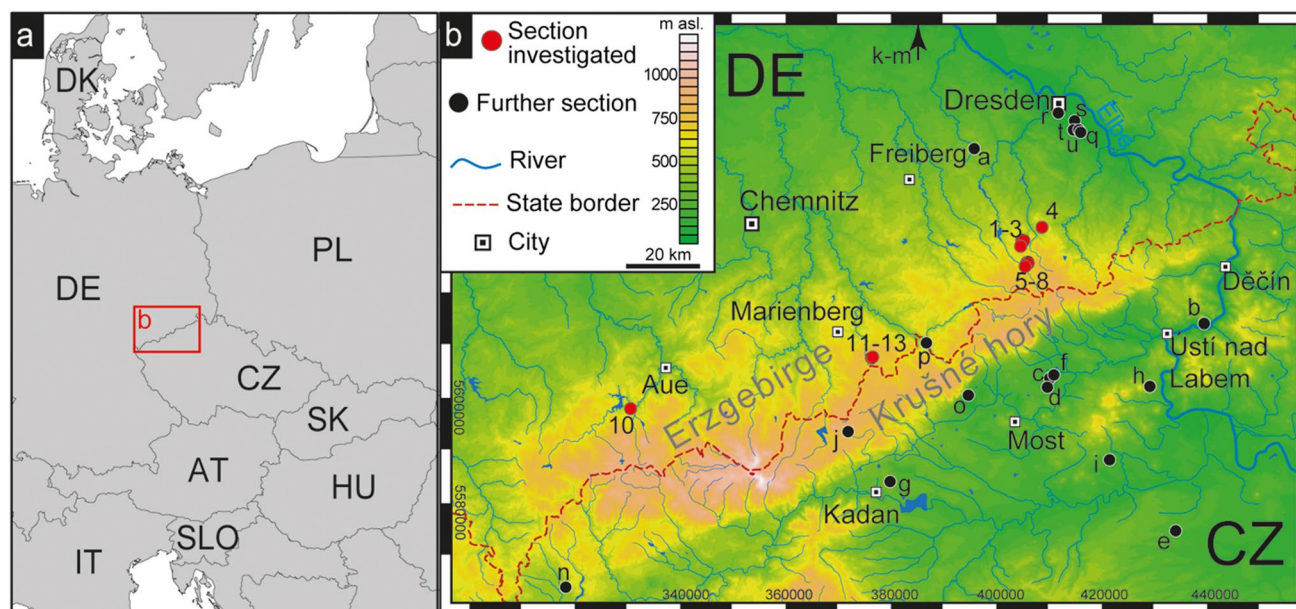
Fig. 2 **a–b** Location of the study sites. **a** Overview with the Erzgebirge Mountains marked. **b** Sections investigated and further sections in that area. For details on the first, see Table 1; for details on the latter, see Supplementary material 1

widely forested mountain areas, obviously far less influenced by current erosion processes, found much less interest (e.g. Latocha 2009; Fuchs et al. 2011; Stolz et al. 2012; Larsen et al. 2013; Henkner et al. 2018b; Steup et al. 2019). Accordingly, central research questions on colluvial sediments in the uplands, such as their spatial distribution especially in forested areas, litho-/pedostratigraphy and chronostratigraphy, as well as landscape-specific archive suitability to illuminate the regional history of settlement and land use, have only been rudimentarily answered so far.

Current research on landscape history in the Central European Erzgebirge Mountains (Engl.: *Ore Mountains*, Czech: *Krušné hory*), embedded in the German-Czech "ArchaeoMontan" projects on mining archaeology (Hemker and Tolksdorf 2017; Hemker 2018; Smolnik Goryczková 2018; Tolksdorf 2018), also led to the discovery and systematic documentation of pedosedimentary sequences containing colluvial layers. The five mid-altitudinal sites investigated (c. 520–730 m a.s.l.) have been forested since decades, sometimes since centuries, and show no properties of present-day soil erosion. However, geomorphic traces of past land-use activities are very common at and around all sites (e.g. sunken roads, mining heaps, collapsed shafts, charcoal kilns, gullies, lynchets, ditches).

The current study aims to (1) analyse the litho- and pedostratigraphy and the dating of colluvial pedosedimentary sequences, (2) characterise their palaeobotanical properties, and (3) explore the suitability of colluvial sediments for reconstructing historical environmental changes in a mountain landscape, which was strongly shaped by medieval and post-medieval mining. Moreover, coming from these local field records we address, (4) how widespread are colluvial sediments distributed in the soil patterns of the Erzgebirge Mountains, and, aiming at a supra-regional comparison, (5) which spatial and temporal distribution patterns show occurrences of dated colluvial sediments in other low mountain ranges of Central Europe?

Study area and sites

The Erzgebirge is a Hercynian fault-block mountain range with a steep scarp in the southeast and a gentle slope in the northwest. Metamorphic rock (gneiss) from the Palaeozoic dominates. Following Variscan orogeny and Permian erosion, in the Tertiary, the block was uplifted and tilted to the northwest (Sebastian 2013; Vilímek and Raška 2016). Highest mountains are Klínovec (1244 m a.s.l.) and Fichtelberg (1215 m a.s.l.). Their altitudes do not exceed the timberline. The mountain range has formed a natural border between the territories of Saxony (Germany) and Bohemia (Czech Republic) for around 800 years (Thomasius 1994). For centuries, this area played an important role in the mining and industrial history of Central Europe, delivering important contributions of ores, metallurgical, and further products as well as to technical innovations. In 2019, the region became the UNESCO World Heritage site "Erzgebirge/Krušnohoří Mining Region" (ICOMOS 2019).

The study sites are located on the German side of the mountain range, stretching over 90 km from eastern to

Table.1 Colluvial sections investigated at Erzgebirge with geographical data and analytical data available

Section ID	Site name, section	Northing	Easting	Altitude	Relief	Dating	Soil data	Botanical data
				(m a.s.l.)				
1	Niederpöbel, Sect. 1	50°48′16.6284″	13°39′10.728″	552	Stream valley floor	14C, OSL	Grain size, Ct	Charcoals
2	Niederpöbel, Sect. 21	50°48′48.3588″	13°39′30.042″	553	Stream valley floor	14C	Grain size, Ct	Charcoals
3	Niederpöbel, core 12	50°48′47.7252″ '	13°39′41.724″	523	Stream valley floor	14C	Grain size, Ct	-
4	Hohenwalde-Faule Pfütze, profile 4	50°50′15.1188″ '	13°42′26.9784″	555	Stream valley floor	14C, artefacts	Grain size, LOI	Macro-remains
5	Oberpöbel-Vorderer Grünwald, profile 1	50°46′36.624″	13°40′24.4524″	637	Lower slope	14C	-	Macro-remains
6	Oberpöbel-Vorderer Grünwald, profile 8	50°46′26.9004 ″	13°40′6.4632″	683	Upper slope	artefacts	-	-
7	Oberpöbel-Vorderer Grünwald, profile 6	50°46′19.9632″	13°40′17.7816″	690	Flat anthropogenic depression on plateau	artefacts	-	-
8	Oberpöbel-Vorderer Grünwald, profile 10	50°46′19.254″	13°40′18.9012″	689	Flat anthropogenic depression on plateau	artefacts	-	-
9	Oberpöbel-Vorderer Grünwald, profile 9	50°46′13.7352″	13°40′0.516″	629	Stream valley floor	14C, OSL	Grain size, geochemistry	Pollen, macro-remains
10	Eibenstock-Grün	50°30′38.9052″	12°36′55.1124″	541	Tin placer mining depression	14C	Grain size, LOI	Macro-remains
11	Ullersdorf, profile 2	50°36′29.4732"	13°15′29.8368″	728	Stream valley terrace	14C	Grain size, LOI, geochemistry	Pollen, macro-remains
12	Ullersdorf, profile 3	50°36′31.8384″	13°15′35.0136″	728	Stream valley floor	OSL	Grain size, LOI	Pollen
13	Ullersdorf, profile 5	50°36′32.9184″	13°15′40.9608″	730	Lower slope	artefacts	Grain size, LOI	-

western Erzgebirge (Fig. 2, Table 1, Supplementary material 2). Whereas the present-day climate of the sites is widely similar in the 1961–1990 period – the ranges of mean annual temperature and mean annual precipitation are 5–6 °C and 720–790 mm, respectively (www.climate-data.org) – local geology, landforms, sediments, and soils (www.boden.sachsen.de) as well as partly vegetation/land use differ as outlined below. All sites, located at floors or footslopes of small stream valleys, consist of various surface sediments covering basal metamorphic or volcanic rocks.

The Niederpöbel site (for coordinates of this and all further sites see Table 1), eastern Erzgebirge, is located at an altitude of 500–630 m a.s.l. in the valley of the Pöbelbach stream and of two tributary streams, draining to the Rote Weißeritz River (Figs. 2, 3a). The geology is dominated by gneiss varieties covered by Teplice quartz porphyry forming the hilltops. In the northern part of the site, rhyolite and sulphidic veins are present, which were used for silver and tin mining in the past. Cambisols and Podzols developed from periglacial cover beds (Kleber et al. 2013) dominate the slopes and hilltops, whereas Gleysols and Stagnosols developed from alluvial and colluvial sediments occur on the valley bottoms. The area is mainly covered by managed forests consisting of *Picea abies* and local stands of *Fagus sylvatica*.
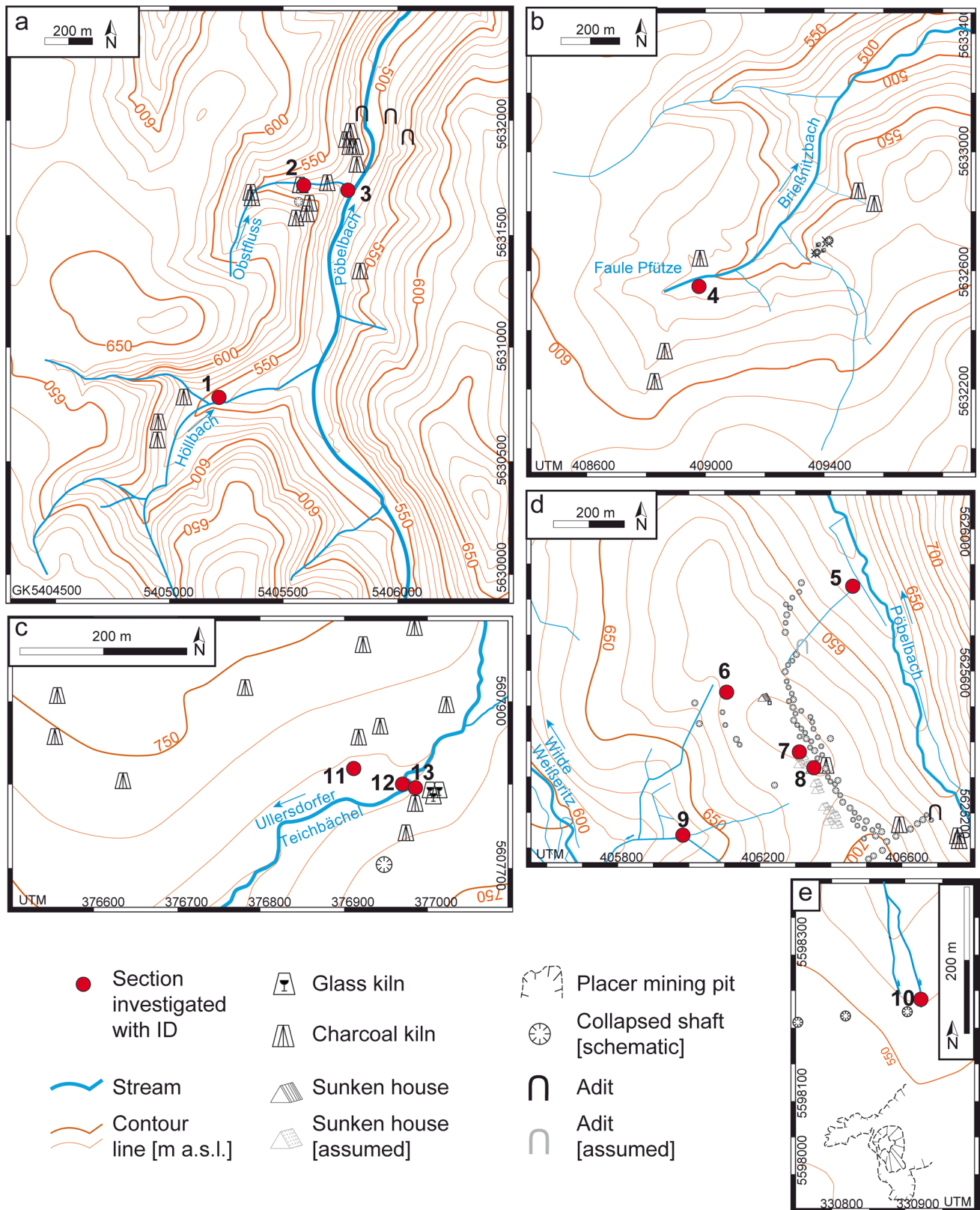
Fig. 3 **a**–**e** Topographies and sections of the study sites. **a** Niederpöbel site, eastern Erzgebirge. b Hohenwalde-Faule Pfütze site, eastern Erzgebirge. **c** Ullersdorf site, central Erzgebirge. **d** Oberpöbel-Vorderer Grünwald site, eastern Erzgebirge. **e** Eibenstock-Grün site, western Erzgebirge

In advance of the construction of a flood retention basin in the Pöbelbach valley in 2010, several hitherto unknown medieval mining relicts were uncovered and archaeologically documented until 2014 (Schröder 2015; Hemker 2018). Further, geoarchaeological investigations led to the discovery of pedosedimentary sequences including colluvial layers and charcoal kilns (Tolksdorf et al. 2015).

The Hohenwalde-Faule Pfütze site, eastern Erzgebirge, is located at an altitude of 550–570 m a.s.l. in the valley of the Brießnitzbach stream, which is a tributary of the Müglitz River, draining in to the Elbe River (Figs. 2, 3b). The site consists of quartz porphyries and porphyroid granites, covered by plantations of *Picea abies*. Cambisols developed from periglacial cover beds dominate this area. Alluvial sediments and very local colluvial sediments with Gleysols cover the lower parts. Archaeological studies at this site in 2015 and 2016 investigated an abandoned medieval settlement, "Hohenwalde", dating to the fourteenth/fifteenth centuries AD (Tolksdorf et al. 2019). LiDAR data reveal several sunken roads and abandoned mining features, such as collapsed shafts and mining heaps. Additionally, charcoal kilns in the form of round platforms occur on surrounding slopes.

The Oberpöbel-Vorderer Grünwald site, eastern Erzgebirge, is located at an altitude of 630–690 m a.s.l. in two tributary valleys (Pöbelbach and Wilde Weißeritz streams) of the Rote Weißeritz River and on the mountain plateau in between (Figs. 2, 3d). Geology is dominated by ignimbrite (pyroclastic). The mountain plateau and the slopes are covered by periglacial cover beds having Stagnosols and Cambisols, respectively. The valleys primarily contain alluvial sediments with local colluvial and peat deposits, forming Gleysols and Histosols. Plantations of *Picea abies*, stands of *Fagus sylvatica*, *Alnus glutinosa* and *Salix* spec. as well as grassland and arable land cover the area. Numerous mining relicts (e.g. collapsed shafts, mining heaps, adits), charcoal kilns, and an abandoned settlement prove local land use since the thirteenth century AD (Tolksdorf 2018; Schubert et al. 2018).

The Eibenstock-Grün site, western Erzgebirge, is located at an altitude of 540 m a.s.l. on the edge of a historic tin placer mining site in a tributary stream valley of the Zwickauer Mulde River (Figs. 2, 3e). The site consists of granite, covered by a wet forest primarily of *Picea abies*. The whole area shows manifold relicts of tin placer mining since the fourteenth century AD (Helm and Kinne 2014; Tolksdorf 2018). Due to the historical placer mining, the local relief and the surface sediments are strongly disturbed. Gleysols developed from partially relocated alluvial sediments dominate.

The Ullersdorf site, central Erzgebirge, is located at 730 m a.s.l., lying within the Ullersdorfer Teichbächel stream valley, a tributary of the Schwarze Pockau River (Figs. 2, 3c). The site consists of gneiss that is covered by forest plantations dominated by *Picea abies* and supplemented by *Fagus sylvatica*. Cambisols and Podzols developed from periglacial cover beds dominate the slope and hilltops, whereas Gleysols developed from alluvial and local colluvial sediments occur on the valley bottom. In the centre of the site, there is a small peat area that has developed on a stream terrace. Based on ceramic surface finds from the thirteenth century AD and the toponym "Ullersdorf", an abandoned medieval settlement has been assumed in this area (Geupel 1990). Surface finds of glass slags and glass crucibles prove glass production at this site. A geomagnetic survey identified at least three glass kilns (Křivánek 1995). A reinvestigation of the site was performed in 2016–2017, detecting sedimentary sequences with colluvial, alluvial, and peat sediments (Tolksdorf et al. 2020a).

Methods

Spatial delineation, fieldwork, and archaeology

We use the border between colline (hilly region level) and sub-montane ecologic-altitudinal zone (lowermost upland level) at 300 m a.s.l. (Leuschner and Ellenberg 2017) to delineate, i.e. to exclude and to include colluvial records for this study. This border line even roughly marks in the Erzgebirge Mountains the lower-closed natural (past) occurrences of spruce and fir (Hempel 2009; Kaiser et al. 2020) as well as the lower limit of the high medieval colonisation (Kenzler 2009), both likewise representing regional "mountain attributes". Also, further vegetation (change from colline hornbeam/beech-oak to sub-montane oak-beech forests) and climatic properties (decrease of summer temperature, increase of precipitation) markedly change in the altitude interval 300–400 m a.s.l. (Hempel 2009).

Thirteen sections from five sites were recorded during geoarchaeological prospections, generally aiming at stratigraphical information on hitherto unknown or poorly known archaeological sites representing mining settlements or production sites for metallurgy, charcoal, or glass (Figs. 2, 3, Table 1, Supplementary material 2). Nearly all sections were obtained by trenches except section ID 3, which was retrieved by percussion coring (with 5 cm diameter). The sections are described and sampled according to the German pedological standard (Ad-hoc-AG Boden 2005). Designations of soil horizons are given using this standard (in text, figures, tables) and an international standard (FAO 2006; only in Supplementary material 3), whereas soil types are classified according to the "World Reference Base for Soil Resources" (IUSS Working Group WRB 2015). Colluvial layers are determined according to specific pedological and sedimentological properties that comprise general texture

(fine matrix), coarse matter content, humic matter content, colour, and stratification (e.g. Ad-hoc-AG Boden 2005; Leopold and Völkel 2007; Zádorová and Penížek 2018).

The archaeological context of the sites is referenced in chapter "Study area and sites" above. Diagnostic archaeological finds such as ceramics, slags, and metal objects are described in the references given therein. In some sections (ID 4, 6, 7, 8, 13), ceramic artefacts provide age estimations for certain layers. This dating approach is based on the regional typochronology (e.g. Mechelk 1981; Geupel and Hoffmann 2006).

Sedimentology and digital soil mapping

From 9 sections and 45 samples, sedimentological laboratory analyses were performed on the soil matter < 2 mm in order to assist the designation of sedimentary facies and diagnostic soil horizons (Supplementary material 3). After air-drying, hand-crushing, and humus removal (by 30% H_2O_2), grain size composition was determined either by using a combination of wet sieving/sand fraction and sedimentation/clay and silt fractions (SediGraph III 5120, samples from section IDs 1, 2, and 3 analysed in the lab of the Institute of Geography of Leipzig University) or by laser diffraction (Beckman-Coulter particle analyser, samples from section IDs 4, 9, 10, 11, 12, and 13 analysed in the lab of the Geographical Institute of Humboldt University Berlin). Specific parameters were used for analysis with the Beckman-Coulter particle analyser (flow velocity 70 m/s, optical model Fraunhofer.rfd). The content of organic matter was estimated either by a vario EL cube system determining total carbon (samples from section IDs 1, 2, and 3) or by combustion at 550 °C determining loss-on-ignition (LOI, samples from section IDs 4, 9, 10, 11, 12, and 13). The use of these different methods to determine the grain size and the organic matter content is explained by different project contexts, i.e. laboratories commissioned with the analyses. Of course, the methodological differences make comparison difficult. But the lab analyses enable at least a better numerical estimate than field estimates alone would ever be.

Colluvial soils occurring in the Erzgebirge area were mapped using the digital soil map of Saxony on a scale of 1:50,000 (www.boden.sachsen.de). For identification and statistical processing, soil subtypes according to Ad-hoc-AG Boden (2005) were tagged and grouped. Both dry site and wet site (hydromorphic) colluvial soils occur, forming Terric Anthrosols and Stagnic/Gleyic Anthrosols (IUSS Working Group WRB 2015), respectively. The land cover type (i.e. forest, open land) on areas with colluvial soils was identified using the biotope type and land-use mapping of Saxony (www.natur.sachsen.de/biotoptypen-und-landnutzungskartierung-btlnk-22282). Quantum GIS 2.18 was used for blending and evaluating the data in vector format.

The delimitation of "soil landscapes" in the Erzgebirge follows Richter (1995). These landscape units differ in their soil inventory, which is primarily determined by climate, relief, and geology.

Geochronology

Radiocarbon (^{14}C) analyses were performed on 13 samples by the Curt-Engelhorn-Centre of Archaeometry at Mannheim (CEZA) and by the Max-Planck-Institute for Biogeochemie at Jena. The prevailing dating matter is charcoal supplemented by partly charred wood and spruce needles. The ages were calibrated according to the IntCal13 dataset (Reimer et al. 2013). All ages are given with their 2σ confidence interval (Table 2).

Four OSL measurements were carried out at the Humboldt University Berlin after standard sample preparation on the 90–200 μm quartz fraction running a SAR protocol (Murray and Wintle 2000) in a Risø TL/OSL-DA15C/D unit. The dose rate was calculated based on the content of ^{238}U, ^{232}Th, and ^{40}K measured by gamma ray spectroscopy as well as the cosmic dose at the sampling position and depth using the software DRAC (Durcan et al. 2015). Both central age model (CAM) and minimum age model (MAM; Galbraith et al. 1999) were applied to calculate the age of last exposure to light (= burial time or stabilisation time; Table 3).

Within the discussion chapter, a geochronological dataset from colluvial sediments in the uplands of Central Europe is used that was compiled for this study. It comprises a total of 395 radiocarbon and OSL data. Only data higher than 300 m a.s.l. (i.e. from the submontane ecological zone upwards) and up to 1100 m a.s.l., the highest dating point found in this area, have been considered. The data were classified into the categories event, maximum and minimum age (Lang et al. 1999). Further data parameters comprise altitude, relief position (landform), and attribution of formation (Supplementary material 9). Based on these parameters, each radiocarbon age has been selected critically and is only considered if the above-mentioned data parameters and soil profile information hinted towards a causal relationship between the dated material and its sedimentary matrix. Soil profile descriptions and sketches were studied thoroughly in order to prevent the incorporation of older relocated charcoal pieces in our dataset. Where possible charcoal obtained radiocarbon ages were compared with radiocarbon ages derived from other materials. Additionally, it is important to mention that only uncalibrated radiocarbon ages were retrieved from literature and subsequently calibrated using one standard calibration curve in the OxCal environment (https://c14.arch.ox.ac.uk/oxcal.html). Statistical analyses including calculations of cumulative probability density

Table.2 Radiocarbon data from the sites investigated

Section ID	Site name, section/core/ profile	Depth	Material dated	Soil horizon	Sedimentary facies	Lab ID	Age	Age calibrated	Age type
		[cm]		[KA5, simpli-fied]			[a BP]	[2sigma, cal AD/BC]	
1	Niederpöbel, Sect. 1	34	Charcoal	M	Colluvial	J-8544	842 ± 23	1161–1255	Event
2	Niederpöbel, Sect. 21	13	Charcoal	M-Ah	Anthropogen (charcoal kiln)	J-9002	417 ± 19	1430–1470	Minimum
2	Niederpöbel, Sect. 21	42	Charcoal	M	Colluvial	J-8543	665 ± 24	1278–1390	Event
2	Niederpöbel, Sect. 21	66	Charcoal	ylC	Anthropogen (charcoal kiln)	J-8542	737 ± 27	1224–1293	Maximum
3	Niederpöbel, core 12	51	Charcoal	M	Colluvial	J-8545	799 ± 23	1206–1274	Event
4	Hohenwalde-Faule Pfütze, profile 4	55	Charcoal	Go	Alluvial	MAMS-33862	953 ± 22	1023–1155	Minimum and maxi-mum
5	Oberpöbel-Vorderer Grünwald, profile 1	40–53	Charcoal	fAh	Alluvial	MAMS-28242	302 ± 22	1498–1648	Maximum
9	Oberpöbel-Vorderer Grünwald, profile 9	50	Charcoal	Go	Colluvial	MAMS-33866	276 ± 22	1521–1781	Event
9	Oberpöbel-Vorderer Grünwald, profile 9	85–100	Charcoal	Gor	Alluvial	MAMS-31408	556 ± 19	1319–1422	Maximum
10	Eibenstock-Grün	55	Partly charred wood	Gor	Alluvial	MAMS-32965	6962 ± 27	5967–5751	Maximum
11	Ullersdorf, profile 2	14	Charred nee-dles (*Picea abies*)	Hr	Peat	MAMS-30241	207 ± 17	1652–1950	Maximum
11	Ullersdorf, profile 2	18	Charred nee-dles (*Picea abies*)	Hr	Peat	MAMS-30242	408 ± 20	1439–1613	Maximum
11	Ullersdorf, profile 2	32	charcoal	Hr	Peat	MAMS-31790	1831 ± 24	93–244	Maximum

Data calibration was performed with program OxCal 4.3 (https://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey 2009) using the IntCal13 dataset (Reimer et al. 2013) with 2σ standard deviation for analysis. The age type refers to the dating of the colluvial sedimentation

functions and kernel density estimates for both radiocarbon and OSL data follow the procedures described in Kappler et al. (2019).

Palaeobotany

Palaeobotanical analyses were carried out on the colluvial sediments, since in the Erzgebirge, in the altitudinal range investigated (520–730 m a.s.l.), mires or other depositional environments suitable for palaeoecological analyses are rare and the information potential of the colluvial sediments should be fully exploited. For pollen analysis, 35 samples of 0.5 cm³ sediment from sections ID 9 and ID 11 were prepared according to the standard acetolysis method (Moore et al. 1991; Supplementary material 4). A minimum of 500 palynomorphs was counted for each sample with identification based on the standard literature (Beug 2004). Local wetland taxa such as Cyperaceae, *Alnus*, *Sphagnum*, *Caltha*, and *Equisetum* were excluded from the calculation of the

Table 3 Optically stimulated luminescence dating (OSL) results and radioisotope concentrations from the sites investigated

Section ID	Site name, section/profile	Depth [cm]	Material dated	Soil horizon [KA5, simplified]	Lab ID	H_2O content [%]	^{238}U [ppm]	^{232}Th [ppm]	^{40}K [%]	Dose rate (Do) [Gy/ka]	Equivalent dose (De) [Gy]	OSL age [ka]	Age model	Age type
1	Niederpöbel, Sect. 1	80	Periglacial loam (cover bed)	Gr	HUB-0487	29.9	3.86±0.50	20.84±0.83	2.63±0.05	3.92±0.29	66.38±2.86	16.93±1.45	CAM	Maximum
1	Niederpöbel, Sect. 1	115	Periglacial loam (cover bed)	Gr	HUB-0486	31.6	3.80±0.47	21.17±0.79	2.70±0.05	3.94±0.28	82.66±7.40	21.01±2.41	MAM	Maximum
9	Oberpöbel-Vorderer Grünwald, profile 9	95	Alluvial silt	Gor	HUB-0755	40±10	7.85±0.47	14.64±0.95	2.82±0.24	4.01±0.27	3.11±0.39	0.78±0.11	MAM	Maximum
12	Ullersdorf, profile 3	25	Colluvial sand	Go-faAa	HUB-0749	40±10	4.31±0.19	10.05±0.52	2.84±0.05	3.29±0.19	0.49±0.13	0.15±0.04	MAM	Event

The age type refers to the dating of the colluvial sedimentation

pollen sum. The number of charcoal particles was recorded without further subdivision into size classes (Clark 1984).

Flotation and wet sieving (2-, 1-, 0.5-, 0.25-mm mesh width) were used to retrieve plant macro-remains from 13 samples from sections ID 4, 5, 9, 10, 21, and 12 (Supplementary material 5). The material was identified according to standard literature (Cappers et al. 2012) and a reference collection of domestic and wild plants.

Charcoal was extracted by flotation from four samples from sections ID 1 and 2 (Supplementary material 6). In total, 351 fragments were analysed. The charcoal fragments were identified microscopically according to taxonomical criteria (Schweingruber 1990). As they share many similar wood anatomical features, *Populus* and *Salix* as well as *Picea* and *Larix* were grouped together.

Results

Analysis of colluvial sections

Litho- and pedostratigraphy

The total thickness of the sections exposed varies from 40 to 140 cm. Most sections show rather thin colluvial layers (c. 10–50 cm) on top of the stratigraphy (Figs. 4, 5). In a few cases, colluvial layers alternate with alluvial layers (ID 4) or interbed with peat (ID 11). Partly, anthropogenic sediments/structures (pit filling, charcoal kiln, overburden) underlie (ID 2, 8) or cover (ID 2, 3, 7) colluvial layers. The bases of the sections mainly consist of periglacial cover beds with abundant gravels and stones, underlaid by weathered bedrock. The colluvial layers consist of clayey loams, sandy silts, or loamy sands (Supplementary material 3). Their organic contents broadly vary (LOI=2.2–24.8%, total C=0.9–3.9%; Supplementary material 3). The colluvial layers mostly bear gravel in varying shares (up to 20%).

Moderately humic Ah or strongly humic Aa (half-bog) horizons form the topsoils developed from different sedimentary facies (colluvial, alluvial, anthropogenic; Figs. 4, 5). Further pedological differentiation such as illuviation of sesquioxides and clay or brunification could not be observed in the surface soils except gleying. In one case, a Hv horizon (peat) forms the topsoil (ID 11) overlying a thin colluvial layer. Most surface soil types represent Terric and Gleyic Anthrosols supplemented by Gleysols. Seven colluvial sections have buried (fossil) horizons forming palaeosols (Figs. 4, 5). Most of them represent fAh horizons. Further can be identified as fAh-fBv (formed by silicate weathering) and fHv (peat) horizons. The palaeosols can dominantly be classified as Terric Anthrosols and Histosols supplemented by Cambisols and Gleysols.

Dating by geochronology and archaeology

Most of the radiocarbon ages from the sections reveal a (high to late) medieval to post-medieval age (Fig. 5, Table 2). The four ages directly obtained from colluvial layers (ID 1, 2, 3, 9), thus with all due caution of potential relocation of older dating material representing event ages, have a total age interval from 1161 to 1781 cal AD. However, they cluster in the thirteenth-fourteenth centuries AD. One further radiocarbon age gives a maximum age for a colluvial layer (ID 5), dating after the fifteenth–seventeenth centuries AD. In section ID 4, one radiocarbon age derived from an alluvial layer (1023–1155 cal AD) provides both minimum and maximum ages for colluvial layers below and above, respectively. The maximum age of 5967–5751 cal BC on charcoal from alluvial sediment for an overlying colluvial layer in section ID 10 can be considered as an outlier (relocated charcoal), as the local landform and alluvial layer demonstrably originate from post-medieval tin placer mining (Tolksdorf 2018).

OSL dating has obtained, apart from two late Pleistocene ages on periglacial cover beds (ID 1), a maximum age of 780 ± 110 in section ID 9 and an event age of 150 ± 40 in section ID 12 (Fig. 5, Table 3). The latter is, together with a radiocarbon dated maximum age in section 11 (1652–1950 cal AD), the most recent geochronological dating on colluvial sediments. Both sections belong to same site (Ullersdorf).

Ceramic artefacts provide age estimations for five of the investigated colluvial sections (ID 4, 6, 7, 8, 13). Only in one case (ID 4), additional geochronological dating is available from the same section. The ceramic fragments in section ID 4 date to the fourteenth century AD. In other sections, occurring at the same site (Oberpöbel-Vorderer Grünwald), the ceramic artefacts date from the thirteenth century AD (lower part in ID 8) to the fourteenth century AD (upper parts in ID 6, 7, and 8). The ceramic material in ID 13 with high collared rims and lids indicates a deposition of the artefacts during or after the fourteenth century AD. Further, fragments of glass crucibles, crushed quartz, and glass slags can be linked to the contemporaneous glass kilns situated immediately next to this profile. In all of these sections, abundant charcoal pieces occur together with the ceramics, which can also be interpreted as artefacts.

Palynology, plant macro-remains, and anthracology

Two pollen spectra from the lower alluvial layer in section ID 9 generally show similarities with high shares of arboreal pollen and dominance of *Picea abies*, *Abies alba*, and *Fagus sylvatica* (samples P1 and P2 in Fig. 5, Supplementary material 4a). Very low percentages of synanthropic pollen occur in the upper sample, such as Cerealia-type pollen, *Plantago lanceolata*, and *Centaurea cyanus*. They prove human impact on the wider surroundings, but without agriculture

directly on-site. Further pollen properties of sample P2, such as the increase of pioneer shrubs/trees (*Corylus avellana*, *Betula*), could indicate the regeneration of a forest, which was probably influenced by timber extraction and charcoal production. By contrast, sample P3 from the colluvial layer above shows a decreasing share of arboreal pollen and increasing shares of taxa representing synanthropic and open vegetation (e.g. Cerealia, Poaceae).

A pollen diagram in section ID 11 (31 samples), covering nearly the whole sequence up to a depth of 78 cm, shows a full Holocene record, starting on the base with the Preboreal palynozone (Fig. 5, Supplementary material 4b). High pollen percentages of Poaceae and the presence of *Rumex acetosella* type and *Secale* above 18-cm depth (colluvial layer between 7 and 14 cm) indicate human activities and an open landscape close to the study site from about 1450 AD to the eighteenth/nineteenth century AD.

Six pollen spectra from alluvial and colluvial layers in section ID 12 contain not only the arboreal taxa (80–90%) *Picea abies*, *Abies alba*, *Fagus sylvatica*, *Alnus*, *Ulmus*, *Tilia*, and *Carpinus betulus*, but also pollen indicative of a more open vegetation caused by human activities, such as *Secale cereale*, *Plantago lanceolata*, *Calluna vulgaris*, and *Rumex acetosella* type (Fig. 5, Supplementary material 4c). Both palynology and geochronology (OSL age of 150 ± 40 a) as well as the palynostratigraphical comparison with the nearby section ID 11 indicate colluvial and alluvial deposition in the late medieval to modern period, occurring in an open landscape heavily used by man.

Plant macro-remain analyses provide further information on local palaeobotany from selected colluvial and alluvial layers (Fig. 5, Supplementary material 5). Frequently, charred and uncharred needles from *Abies alba* (ID 4, 5, 9) and *Picea abies* (ID 4, 5, 9, 10, 11, 12) were detected, showing a dominance among the macro-remains. Further trees could be proven only sporadically, such as *Pinus sylvestris* (ID 10) and *Fagus sylvatica* (ID 12). Rare finds of shrubs (*Sambucus nigra* and *Rubus idaeus* in ID 4 and 9) most probably growing on fringes and clearances and some taxa representing wetlands or river banks (*Juncus* in ID 4; *Glyceria fluitans*, *Lychnis flos-cuculi*, *Sagina procumbens*, and *Montia fontana* in ID 9; Poaceae indet. in ID 10) supplement the macro-remain record.

Anthracological spectra are available from sections ID 1 and 2 (Niederpöbel site). Whereas the spectrum from the colluvial topsoil horizon in ID 1 (sample 1-c) shows dominance of *Fagus sylvatica*, the three spectra from charcoal kilns and a colluvial layer reveal dominance of *Populus/Salix* (samples 21–3 and 21–c) or of *Abies alba* (sample 21–2; Fig. 5, Supplementary material 6). Thus, distinct differences of the wood composition become apparent, reflecting changes of the preferences of wood exploitation and/or tree vegetation at these sites.
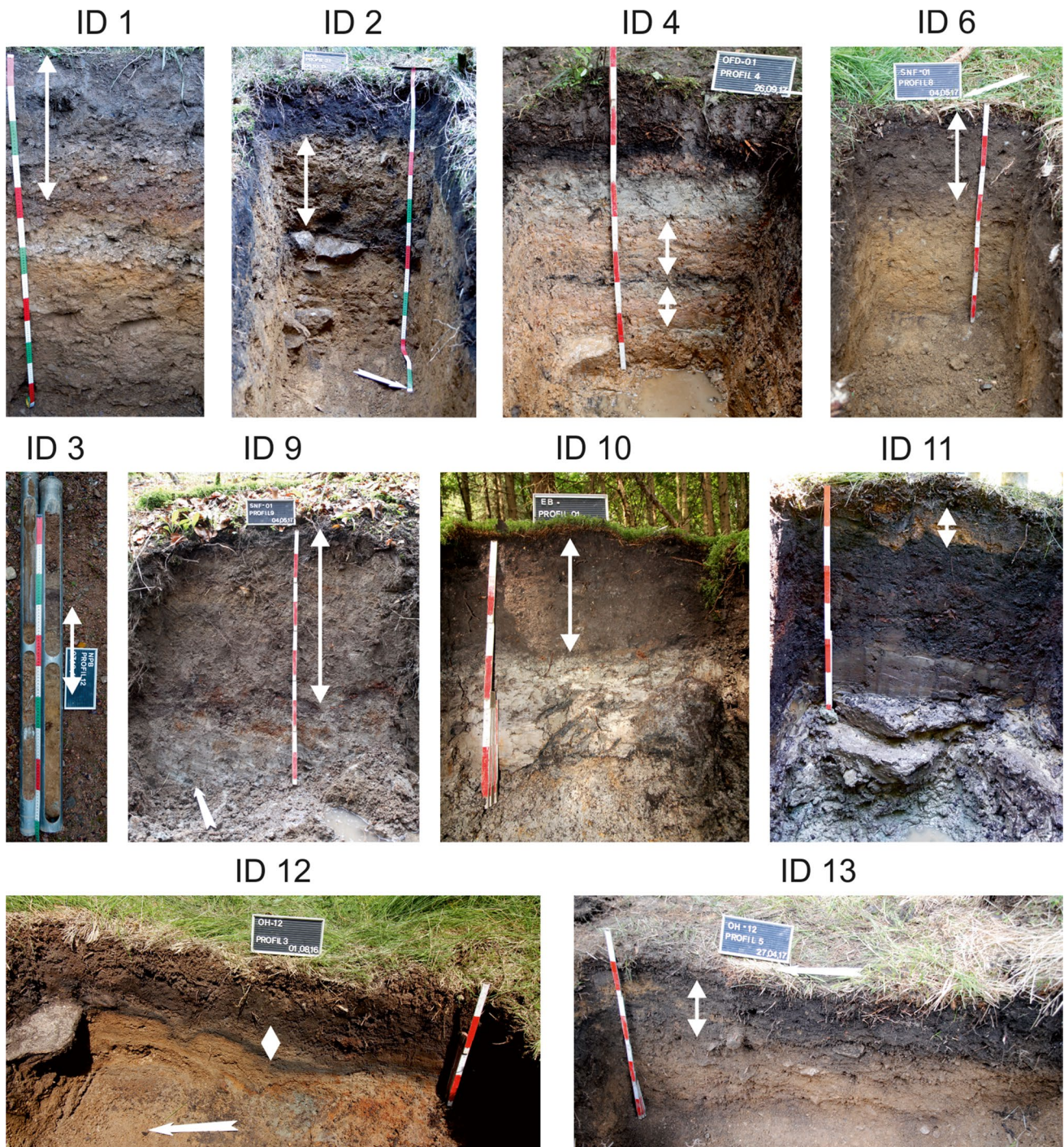
Fig. 4 Photographs of selected sections with colluvial layers in the Erzgebirge Mountains. Colluvial layers are indicated with white arrows. The total length of the ruler varies between 40 and 130 cm. One coloured section is equivalent to 10 cm

Distribution of colluvial soils in the Erzgebirge Mountains

At Erzgebirge, colluvial sediments occur in typical relief positions, primarily comprising footslopes, slope flattenings, and dells. Their occurrence is generally determined by local erodibility of the soil substrate, relief energy, and landform as well as land use (Supplementary materials 7, 8). Specific soil landscapes exist in the region, whose proportion of colluvial sediments (i.e. colluvial soils categorised as Terric Anthrosols and Stagnic/Gleyic Anthrosols) strongly differ (Fig. 6a, Table 4). Most areas with colluvial soils are mapped

Fig. 5 Lithological logs showing the sections investigated with geochronological data as well as sampling positions for palaeobotanical and archaeological analyses. Further details, e.g. on horizontation, are given in Supplementary material 3

for the northern declivity of Erzgebirge (soil landscape 3) and the western and eastern rim (soil landscapes 2 and 5; Fig. 6b). Thin loess and periglacial cover beds mostly overlying gneiss dominate all these areas, which represent mostly open land used by agriculture. By contrast, soil landscape 1,

dominated by granite, and soil landscape 4, the widespread plane to slightly undulating mountain crest area of Erzgebirge with large peatbogs, show only marginal proportions of colluvial soils. Both soil landscapes are widely forested. Most of our study sites belong to the soil landscapes 3 and 4.

From the total area of all five soil landscapes, i.e. 404,071 ha, a share of 11% (11,905 ha) makes up colluvial soils. This indicates a considerable proportion of younger erosion processes in the formation of the surface soil pattern at Erzgebirge (Table 4). However, 1354 ha of colluvial soils occur in forested areas, i.e. in currently geomorphodynamically stable areas.

It is interesting to note the absence of colluvial soils in the southwestern part, in the central part between Marienberg and Eibenstock and in the northern part northwest of Marienberg. The widespread absence east of Altenberg is also striking (Fig. 6a). This could be a summary effect of local land-use history as well as mapping intensity and resulting data quality for soil mapping.

Discussion

Inferring and attributing historical environmental changes

For the first time, precisely dated colluvial records for the Erzgebirge could be obtained on the basis of our methodically multifaceted studies on past human impact. The record for the Eibenstock-Grün site, however, plays only a marginal role, as the colluvial deposition at this site cannot be dated precisely due to a very old maximum age (Fig. 5, Table 2). It is, therefore, not taken into further consideration.

If all the findings, including pedo-sedimentological, geochronological, paleobotanical, and archaeological data from these sites are considered (Fig. 7), it then becomes obvious that mining, other industrial activities (i.e. charcoal and glass production), and settlements associated with these industries are responsible for the formation of local colluvial deposits. In all cases, preceding or parallel deforestation was the prerequisite for local soil erosion. Relief changes often took place, e.g. incision of gullies and sunken roads, in many cases independently from soil erosion processes (e.g. formation of collapse structures from shafts, mining heaps). Furthermore, the joint consideration of geochronological data from human legacies (e.g. mining heaps, charcoal kilns) and colluvial and alluvial sediments suggests that the normally relatively thin (ca. 1 m) fine sediments in the river and stream floodplains of the region have only been deposited largely since the twelfth/thirteenth centuries AD as a result of anthropogenic soil erosion in the catchments (Tolksdorf and Bertuch 2018). Corresponding findings are available for the Bohemian side of Erzgebirge (Kočár et al. 2018). According to the current state of knowledge, permanent settlement, especially in the higher elevations in the Erzgebirge (> 500 m a.s.l.), did not begin until the high medieval period (Kenzler 2009; Tolksdorf et al. 2018a). Thus, colluvial sediments caused by large-scale prehistoric

anthropogenic soil erosion are not (yet) to be expected. This assumption can of course change if the knowledge of early settlement should improve, analogous to other low mountain ranges in Central Europe (e.g. Henkner et al. 2018b; Dreslerová et al. 2019; Knopf et al. 2020). Further, at least along traffic routes through the Erzgebirge that were already used in prehistoric times (Ruttkowski 2002), or at prehistoric mining sites (Tolksdorf et al. 2020b), local occurrences of prehistoric colluvial sediments might to be expected.

The pollen data available from the sites and from further records at Erzgebirge (e.g. Stebich and Litt 1997; Seifert-Eulen 2016; Houfková et al. 2019; Kaiser et al. 2020) reveal a drastic decline of the mountain forests in the late twelfth to fifteenth centuries AD period. Even where forest-like structures ("woodlands") have been preserved after incomplete cutting of trees, the wood species proportions changed largely (e.g. increase of spruce at the expense of fir and beech). On the other hand, agricultural activities at or close to a site are only partially apparent (ID 9, 11, 12). Thus, soil erosion caused by mining and other industrial activities appears to be the primary cause of colluvial deposition at the sites investigated. Of course, this has primarily to do with the mining archaeological focus of our investigations, which explicitly dealt with mining or other industrial sites. However, agriculture could have been the cause of potential colluvial deposits at other medieval activity areas.

A specific contextualisation of our past environmental findings requires a closer look at the economic and settlement development of the Erzgebirge. Profound transformation of the regional mountain landscape started during the twelfth century AD in the course of rural colonisation (Billig and Geupel 1992; Kenzler 2009). This can be associated with local evidence for forest clearances at Freiberg (Tolksdorf et al. 2018b) and Raschau (Hoffmann and Heußner 2013), where especially an early decline of fir in the forest composition becomes apparent. This development is accelerated by the discovery of silver deposits at Freiberg in 1168 AD that triggered the first regional mining boom (in German "Erstes Berggeschrey"; Wagenbreth and Wächtler 1990; Cappenberg et al. 2020; Fig. 7) fostered by liberal policies towards mining rights. The fast development of mining infrastructure in the eastern part of the Erzgebirge is illustrated by the site Dippoldiswalde, where a broad dendrochronological dataset from mining structures illustrates intensive mining activities from the late twelfth century AD onwards (Westphal et al. 2014). These data are supplemented by archaeological results on this mining settlement (Schubert and Wegner 2014). Remains from explorative mining at Niederpöbel (Schröder 2015) and from small permanent mining settlements, such as Oberpöbel-Vorderer Grünwald (Schubert et al. 2018) and Kremsiger (Derner 2018), suggest that it took only decades until permanent mining operations were established in the late thirteenth century AD higher
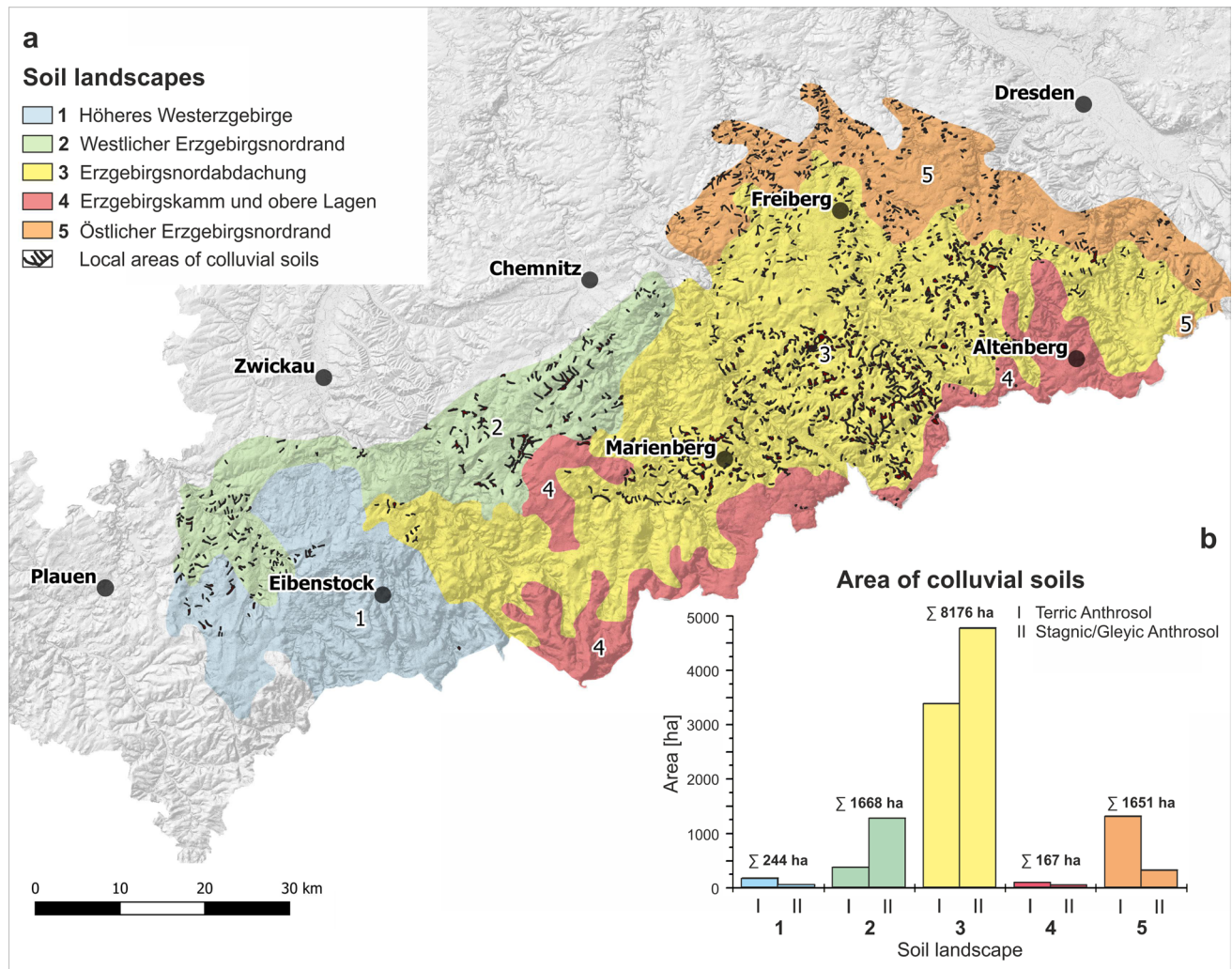
Fig. 6 a–b Distribution of colluvial soils in the Erzgebirge Mountains. **a** Soil landscapes with local areas of colluvial soils. **b** Histogram showing the spatial shares of colluvial soils, i.e. Terric and Stagnic/Gleyic Anthrosols, in that soil landscapes. The representation is based on data and with the permission of the Saxon State Office for the Environment, Agriculture, and Geology

than 500 m a.s.l. How this development affected the local vegetation, relief and soils have been studied in detail for Niederpöbel (Tolksdorf et al. 2015) and Oberpöbel-Vorderer Grünwald (Tolksdorf 2018). Further, glass kilns were established in the upper reaches of Erzgebirge during the thirteenth–fourteenth centuries AD (Kirsche 2003; Černá 2016), but they seem to have affected the local land cover (vegetation) as well as relief and soil far less than later mining and charcoal production as illustrated by a case study at Ullersdorf (Tolksdorf et al. 2020a).

Following a mining crisis around the mid-fourteenth century AD with a still disputed set of causes and effects (Schwabenicky 2009; Derner et al. 2016), a restart of the mining activities occurred in 1470 AD, when new silver deposits were discovered in the western part of Erzgebirge, causing the second mining boom (in German "Zweites Berggeschrey"; Fig. 7). A new and unprecedented wave of

colonisation, deforestation, infrastructure formation, and city foundation captured the Erzgebirge (Kenzler 2009; Schattkowsky 2013; Cembrzyński 2017). However, this regional periodisation of mining must not always fit to very local developments, where local rulers probably had a decisive role for initiating mining and related infrastructure and supply activities. This is suggested by sites where a change of territorial rule coincides with intensified mining activities during the early fifteenth century AD such as Hohenwalde (Tolksdorf et al. 2019) and the tin placer district at Schellerhau (Tolksdorf et al. 2020b). Despite several following crises (Thirty Years' War, Seven Years' War, competition by mines outside Europe), mining remained the economic backbone of this region until the twentieth century AD, reflected by the third (eighteenth–nineteenth centuries AD) and fourth mining boom (mid-twentieth century AD; Fig. 7). A high number of charcoal kilns attributed to the sixteenth century

Table 4 Areas of soil landscapes and colluvial soils (Terric and Stagnic/Gleyic Anthrosols) in the Erzgebirge (data: Saxon State Office for the Environment, Agriculture and Geology; own compilation and analysis)

Soil landscape Name	Soil landscape Area	Terric Anthrosols Area	Terric Anthrosols Area	Stagnic/Gleyic Anthrosols Area	Stagnic/Gleyic Anthrosols Area	Anthrosols total Area	Anthrosols total Area	Anthrosols land cover Open land area	Anthrosols land cover Open land area	Forest area	Forest area
	(ha)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
1 Höheres Westerzgebirge	59,012.0	189.2	0.3	54.7	0.1	243.9	0.4	191.4	0.3	52.5	0.1
2 Westlicher Erzgebirgsnordrand	58,275.0	385.5	0.7	1282.0	2.2	1667.5	2.9	1517.1	2.6	150.5	0.3
3 Erzgebirgs-nordabdachung	185,809.0	3392.6	1.8	4783.5	2.6	8176.0	4.4	7218.7	3.9	927.7	0.5
4 Erzgebirgskamm und obere Lagen	47,733.6	102.9	0.2	63.8	0.1	166.7	0.3	155.2	0.3	11.5	0.0
5 Östlicher Erzgebirgsnordrand	53,241.0	1319.1	2.5	331.6	0.6	1650.7	3.1	1438.6	2.7	212.0	0.4
Sum	404,070.6	5389.3	5.5	6515.6	5.6	11,904.9	11.1	10,521.0	9.8	1354.2	1.3

AD onwards are present at nearly all study sites. They prove the importance of charcoal production to supply smelting facilities and further consumers. The results from the sites Oberpöbel-Vorderer Grünwald and Ullersdorf have highlighted the importance of this industry for initiating local soil erosion and formation of colluvial deposits.

Some of the ecological effects of the early economic boom periods in the Erzgebirge are also illustrated by contemporaneous artwork from this area and beyond. While soil erosion is not shown directly, a number of potentially triggering land-use activities, such as deforestation, urban foundation, expansion of traffic routes, construction of water infrastructure, mining, charcoal production, and not least agriculture, are shown with impressive details (Fig. 8). In particular, the images in Agricola (1556), on the mountain altar (1522/23 AD) by Hans Hesse (1497–1539 AD) in the St. Anne's Church at Annaberg-Buchholz (Sandner 1983), and in the "Schwazer Bergbuch" from 1556 AD (Brandstätter et al. 2015) give the impression of profound reflections on the ecological status of mountain landscapes at that time. Contemporary literature also reflects overexploitation including soil erosion in the medieval to post-medieval Erzgebirge. For example, Paulus Niavis (1460–1514 AD), for a while living as a school principal at the foothills of the Erzgebirge in Chemnitz, had the gods hold a virtual tribunal about late medieval mining in this region with its dramatic damages to the environment and people (Kramarczyk 2013).

The colluvial deposits at our sites reflect historic processes that can be conceptualised even by the "landscape memory" approach (e.g. Brierley 2010; Latocha et al. 2019). All these sites are forested and currently geomorphodynamically stable, preventing noteworthy soil translocations. Thus, they form a geoarchive, which is now well-protected against loss by erosion up to the recent future. However, as both the remarkably large spread of colluvial soils in the open land of Erzgebirge (i.e. 10,521 ha; Fig. 6, Table 4) and assessments of the actual soil erosion risk for this area show (e.g. Fohrer et al. 2003; Schindewolf and Schmidt 2012), wide parts are at high to extreme risk for soil erosion on-site and deposition of colluvial matter off-site. This is due to specific landscape characteristics such as strong relief gradients, long slopes, and susceptible soil substrates in combination with the often occurrence of erosive rainstorms during summer and widespread intensive agriculture. Obviously, the "colluvial story" goes on at those sites, referring to problematic losses of soil fertility, landscape integrity, and even landscape memory or, in other words, cultural wealth (i.e. archaeological sites; Vogt and Kretschmer 2019) at Erzgebirge in the longer run.
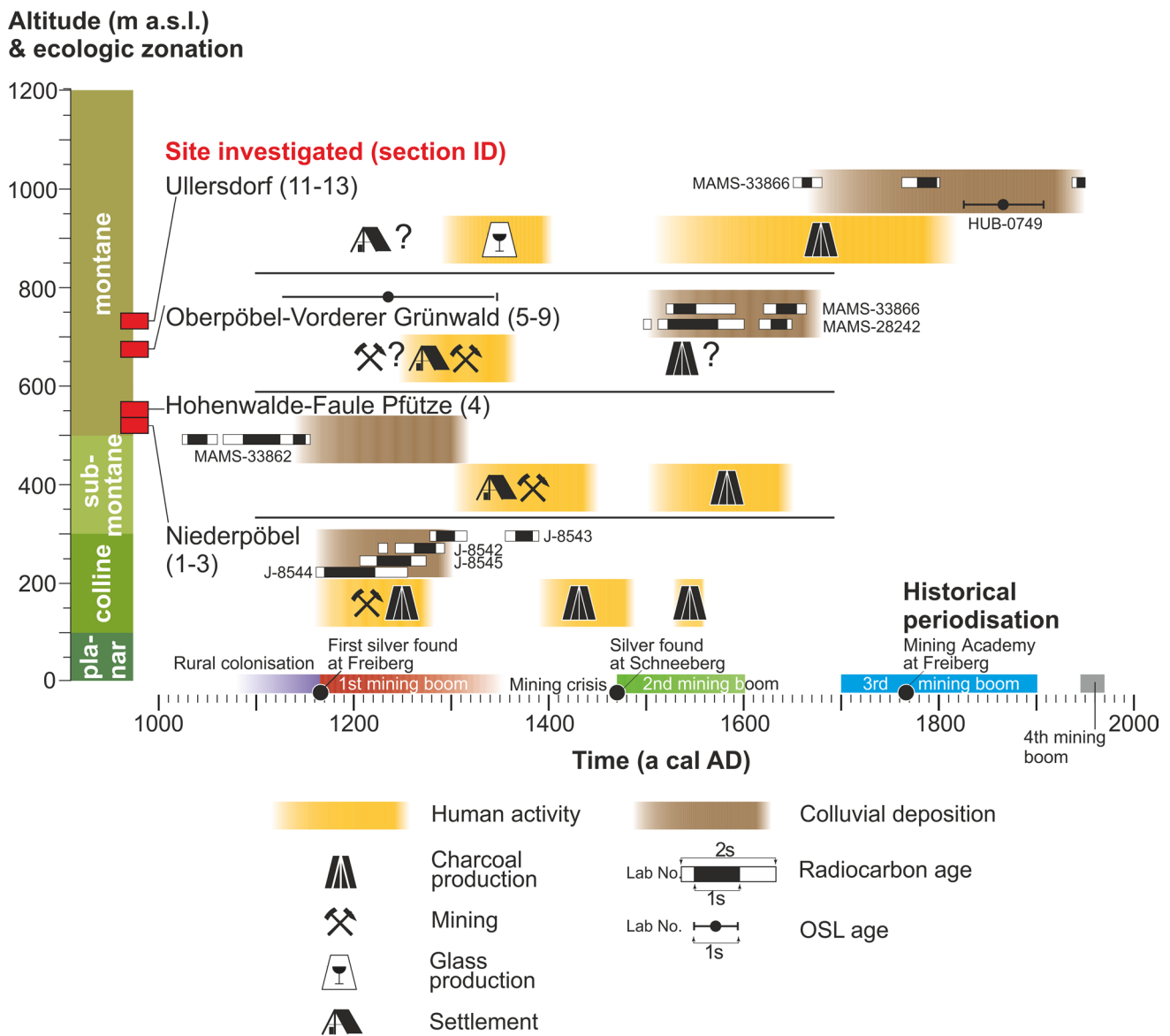
Fig. 7 Synthesis of colluvial dynamics and human activity for the sites investigated at Erzgebirge Mountains. Ecological zonation follows Leuschner and Ellenberg (2017); historical periodisation follows Wagenbreth and Wächtler (1990)

Further colluvial sedimentary records in the Erzgebirge Mountains

With view to the whole Erzgebirge/Krušné hory Mountains, only a few further records (Fig. 2, Supplementary material 1) are available from the higher altitudes on the Czech side. They show, on the one hand, remarkably early ages (3348–2934 cal BC to 884–1013 cal AD) for colluvial deposits at the Nový Kostel-Kopanina site (c. 500 m a.s.l.; Štěpančíková et al. 2019) and, on the other hand, post-medieval colluvial deposition (1479–1644 cal AD) at the Spindelbach site (c. 850 m a.s.l.; Houfková et al. 2019). Whereas the former is attributed to Holocene surface faulting by

neo-tectonics, the latter is attributed to agriculture, as pollen evidence suggests. Although the upper zones of Erzgebirge/ Krušné hory can generally be considered as agriculturally unfavourable areas, cereals, potatoes, and garden fruits could be cultivated even in the rather cold eighteenth to nineteenth centuries AD (i.e. the later part of the Little Ice Age) for subsidence economy up to the mountain crest area at around 1000 m a.s.l. (Sigismund 1859). Furthermore, large pastures replacing forests permanently spread in the crest area, as Saxon cartographic sources since the sixteenth century AD reveal (Göldner 2011). This means that even at higher altitudes, local rural settlements and their vicinity, be they still

existing or already abandoned, bear the potential of colluvial sediments deposited due to forest clearing and agriculture.

From the lower altitudes in the immediate vicinity of the Erzgebirge/Krušné hory Mountains (c. 120–440 m a.s.l.), far more colluvial records exists. Most of them cluster in basin and plateau landscapes covered by loess next to the Elbe/Labe and Eger/Ohře rivers (Fig. 2, Supplementary material 1). These areas are considered as agriculturally very favourable land, not least indicated by a number of warmth-loving special crops (e.g. grapes, hops), with a rather dense population already since the older Neolithic, i.e. linear pottery culture (Řídký et al. 2015). Although numerical event ages on colluvial layers normally lack there, dated palaeosols and cultural (occupation) layers provide maximum and minimum ages for these deposits. They show several periods of colluvial sedimentation since the Bronze Age (Linnemann 1994; Beneš 1995; Wolf and Faust 2013; Dreslerová et al. 2019).

Holocene colluvial sediments in the Central European uplands

The question remains, which dated evidence of Holocene colluvial deposits is available in the other upland areas in Central Europe and what general conclusions can be drawn from these data on the anthropogenically initiated soil erosion and land-use history from an overview perspective. For this reason, all accessible radiocarbon and OSL data from these areas with the exception of the Alps and Tatras (as geomorphodynamically clearly different areas) were compiled, evaluated, and statistically analysed. While the findings from the Erzgebirge presented above are based on a very small and spatially restricted database, this geochronological compilation approach enables a statistically based analysis of general developments in a large area. Previous studies dealing with the meta-analysis of geochronological data have shown that this approach is potentially a powerful tool to gain new insights on the timing of colluvial and fluvial geomorphodynamics on larger temporal and spatial scales (e.g. Hoffmann et al. 2008; Jones et al. 2015; Kappler et al. 2019; Dreibrodt and Bork 2021).

A total of 325 radiocarbon and 70 OSL data could be compiled, spreading over 197 localities mostly in Germany but in small numbers also in Luxembourg, Czech Republic, and Poland (Figs. 9, 10). Ages from sites in the lower mountain ranges (up to ca. 450 m a.s.l.) dominate compared to scarce data from high altitudes (> 1000 m; Fig. 10a). Lower slopes, slope depressions, and linkages with floodplains (colluvial and alluvial fans; Fig. 1) are evident as preferred relief positions showing colluvial deposits (Fig. 10c). The authors of the particular studies attribute forest clearing, generally intensified land use, settlement development, mining, and agriculture as dominating reasons for the formation of the local colluvial deposits dated (Fig. 10d).

For dating the colluvial dynamics, so-called event ages are particularly relevant, which, in contrast to minimum ages (post-date/*terminus ante quem*) and maximum ages (predate/*terminus post quem*), allow a sufficiently precise age estimate of the respective colluvial layer (Lang et al. 1999; Pánek 2015). Already the consideration of all data, although this "bulk" perspective is of course associated with serious dating inaccuracies, shows that in addition to an absolute medieval to post-medieval data maximum (from ca. 1200 cal BP = ca. 800 AD onwards), there is a secondary maximum in the late Bronze Age to the Roman period (ca. 3200 to 1800 cal BP = ca. 1200 BC to 200 AD; Fig. 10e). If one only considers the radiocarbon event ages (*n* = 137), it becomes evident (Fig. 10f) that in the late Holocene, the number of data generally increases from ca. 5200 cal BP onwards. A relative maximum is present between ca. 2600 and 2200 cal BP (= ca. 600–200 BC). In general, the data increase significantly from ca. 1200 cal BP (ca. 800 AD) onwards with an absolute post-medieval maximum, i.e. around 400 cal BP (ca. 1600 AD). The OSL event ages, although comprising a far lower data number (*n* = 46), indicate similar dynamics, albeit with deviations in detail (Fig. 10g). Their absolute maximum is clearly in the post-medieval (ca. 400 cal BP = ca. 1600 AD), and relative maxima occur between ca. 2300 and 2000 cal BP and ca. 1200 to 800 cal BP. The frequency distribution of all radiocarbon and OSL event ages younger than 3000 cal BP, using a class (bin) width of 100 years, shows a higher temporal resolution with clusters of radiocarbon ages from the medieval onwards and clusters of OSL ages in the post-medieval (Fig. 11).

We would like to underline that the relationship between the radiocarbon ages and the colluviation process is ought to be a causal relationship. In principle, it can occur that charcoal ages appear older than the colluvial sediment formation due to potential relocation of older charcoal pieces. However, we assume that the dated charcoal material is highly likely not originating from relocation since the general radiocarbon age distribution agrees with the main trends in the OSL distribution. Alignment of both independently obtained age datasets underlines the causality of the relationship between the dated charcoal pieces and their colluvial nature.

A special category are data from the western Carpathians in Poland (e.g. Margielewski 2018) and Czech Republic (e.g. Šímová et al. 2019) mainly from the late Holocene, which primarily represent natural mass wasting processes caused by landslides. But at the same time, human erosion impact partly becomes evident indicated by parallel pollen diagrams from peat bogs, which show minerogenic sediment layers derived from hillwash.

Altogether, this geochronological data compilation shows for the Central European uplands that anthropogenically initiated colluvial dynamics, thus, soil erosion, in the course

of land use already occurred in the late prehistory, i.e. late Bronze Age to Roman period. Nevertheless, this somewhat surprising evidence corresponds well to the increasing number of archaeological records, which indicate land-use activities even in rather "remote" upland areas at that time (e.g. Valde-Nowak et al. 2004; Rösch and Tserendorj 2011; Kozáková et al. 2015; Valde-Nowak 2013; Henkner et al. 2018b; Dreslerová et al. 2020), being considered widely uninhabited/unexplored still in the older research literature. Not surprising, however, is the fact that most data are

distributed over the medieval to post-medieval period. This corresponds to the general intensification of settlement and land-use activities including mining and deforestation in the uplands, which in some western areas dates back to the early medieval (e.g. Harz around 800–1000 AD; Linke 2000). In most of the eastern areas, that is, the low mountain ranges east of central and southern Germany; however, this did not take place until the high medieval (e.g. Erzgebirge around 1150–1250 AD; Kenzler 2009) or even in the late medieval to early post-medieval period (e.g. Jizera Mountains/Sudetes

◀**Fig. 8 a–h** Land-use structures and activities potentially triggering colluvial processes as reflected by late medieval to post-medieval artwork from Central Europe. **a** Settlement construction / urbanisation as exemplified by the mining town of Annaberg/Erzgebirge, which was founded in 1496 AD in the course of a silver mining rush (source: veduta by Matthäus Merian d.Ä., 1650, https://commons.wikimedia.org/wiki/File:Annaberg-1650-Merian.jpg). Note the agriculturally used open land in the immediate vicinity of the town. **b** Deforestation in a mining landscape (source: Georg Agricola, 1556, http://diglib.uibk.ac.at/ulbtirol/content/structure/782989). Note the tree stumps in the lower part and the remaining tree vegetation in the upper part. **c** Mining landscape at Erzgebirge in the surroundings of the mining town Schneeberg. Note the dense road network (brown curved lines) connecting mines and settlements (source: Map of Schneeberg 1588, Bergarchiv Freiberg, L9389, CC-BY 3.0, https://archiv.sachsen.de/archiv/bestand.jsp?guid=4868320d-ced0-4ab2-9ffd-358544d16f4e#digitalisat). **d** Foundation of the mining town Freiberg illustrated by the artist Heinrich Göding in 1598 AD, some centuries later compared to the actual date the city was founded (ca. 1168/70 AD). Note the deforested slopes around the town with mining and metallurgic facilities (source: Sächsischen Landesbibliothek – Staats- und Universitätsbibliothek Dresden SLUB). **e** The "Markersbacher Oberhammer" (hammer mill), western Erzgebirge, with a complex setting of functionally differentiated facilities around 1530 AD (central part of the image). It is the oldest known depiction of an iron hammer in the region (Richter 2013). Note the widely deforested river valley and adjacent slopes as well the water infrastructures to the right (source: Sächsisches Hauptstaatsarchiv Dresden). **f** Construction and operation of water infrastructure with floating timber (source: Schwazer Bergbuch, 1556, https://commons.wikimedia.org/wiki/File: Schwazer_Bergbuch_Abbildung_103.jpg). Note the logging adjacent to the watercourse. **g** Mining landscape at Erzgebirge (source: Hans Hesse, Annaberger Bergaltar, 1522, https://de.wikipedia.org/wiki/St._Annenkirche_(Annaberg-Buchholz)). Note the widespread occurrence of mining heaps delivering huge quantities of erodible mining waste and the few remnants of tree vegetation (conifers). **h** Charcoal production using kilns/hearths (source: Schwazer Bergbuch, 1556, https://upload.wikimedia.org/wikipedia/commons/1/19/Schwazer_Bergbuch_ Abbildung_104.jpg). Note the large dimension of the kilns and the provision of timbers on the deforested slope on the right side

around 1500–1600 AD; Kajukało et al. 2016). During this time, the greatest landscape change of the late Holocene evidently occurred in the Central European uplands (e.g. Rösch 2015; Tolksdorf 2018; Cembrzyński 2019). The consequences, including, for example, erosion-affected soil pattern, silting-up of stream and river valleys, fundamental land-cover structure, and widely non-site-adapted secondary (i.e. managed spruce) forests, have shaped the appearances and realities of these landscapes until today.

Conclusions

Late Holocene colluvial deposits originating from hillwash reflect anthropogenic impacts on upland landscapes. Formation of these sediments requires forest clearing or thinning and often shorter or longer lasting land-use activities, for example, agriculture, mining, glass production, settlement construction, or traffic. Evidence of colluvial layers has been systematically documented at five forested mid-altitudinal sites in the Central European Erzgebirge Mountains. Applying a multiproxy approach to characterise the properties of colluvial sediments and their potential to reconstruct historical environmental changes in a low mountain range, we were able to draw the following conclusions:

- The colluvial layers investigated consist of up to ca. 70-cm thick gravel-bearing silts, sands, and loams, which are mostly at the top of the profiles. Both dry and wet colluvial soil types (Terric and Stagnic/Gleyic
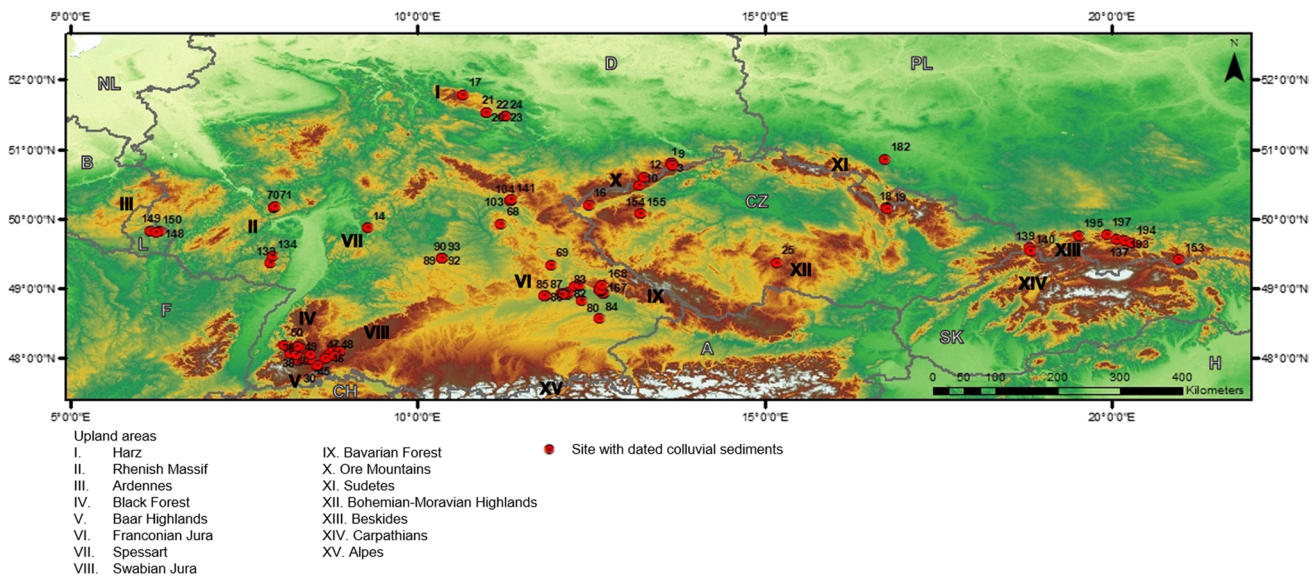

Fig. 9 Spatial distribution of dated colluvial sequences with their site IDs in the low mountain ranges of Central Europe. Details on the sites compiled are given in Supplementary material 9
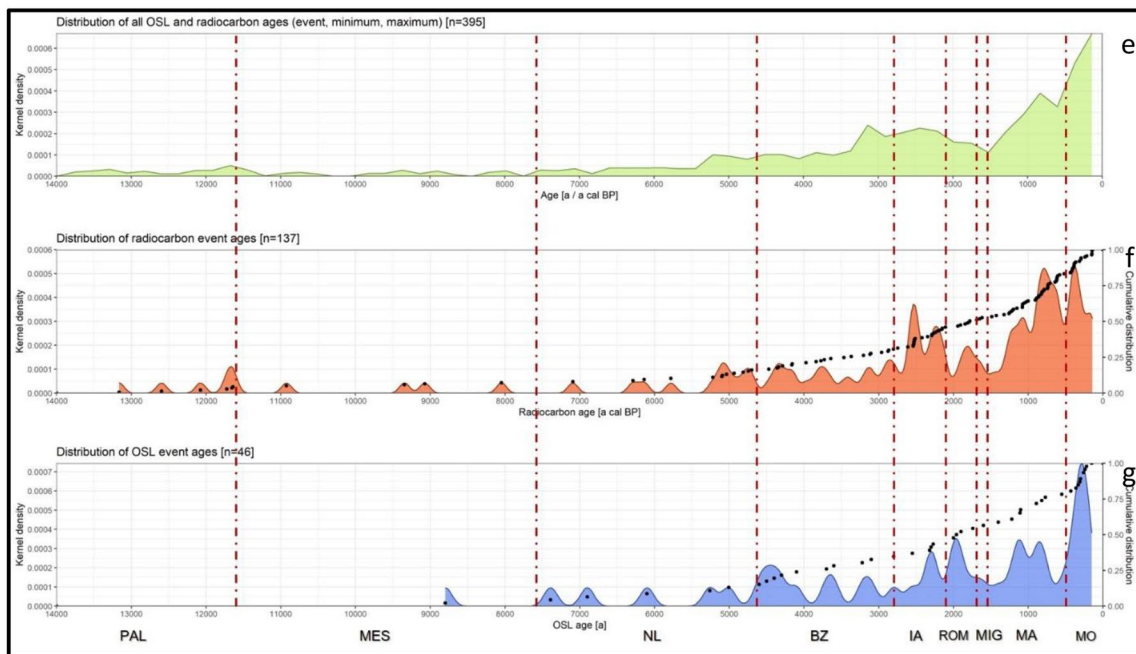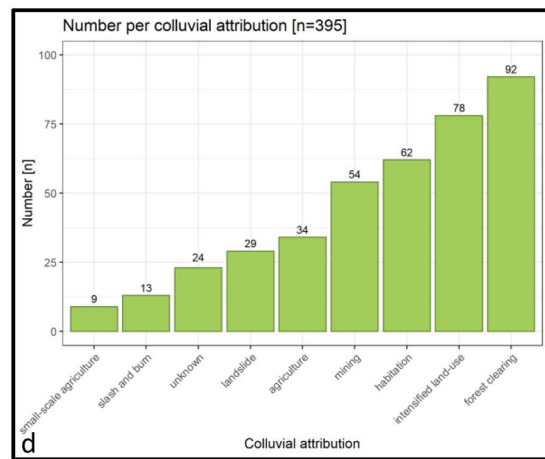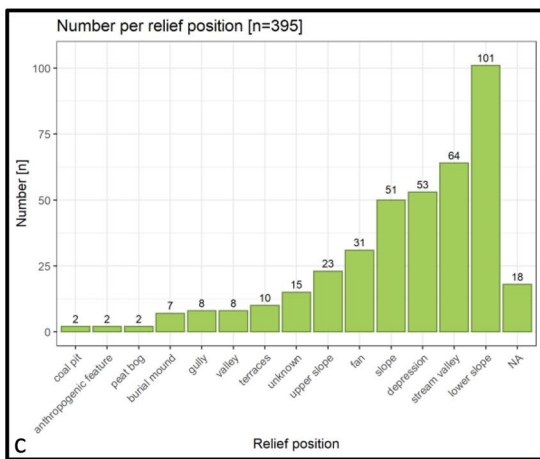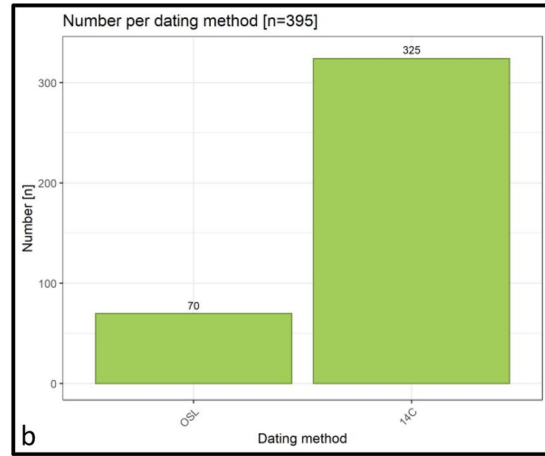
a. Number per altitude category [n=395]

b. Number per dating method [n=395]

c. Number per relief position [n=395]

d. Number per colluvial attribution [n=395]

e. Distribution of all OSL and radiocarbon ages (event, minimum, maximum) [n=395]

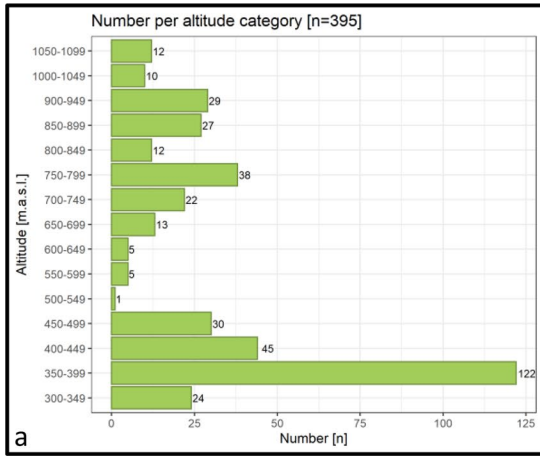f. Distribution of radiocarbon event ages [n=137]

g. Distribution of OSL event ages [n=46]

◄**Fig. 10 a–g** Analysis of data from dated colluvial sequences in the low mountain ranges of Central Europe. **a** Number of ages per altitude. **b** Number of ages per dating method. **c** Number of ages per relief position. **d** Number of ages per attribution of the colluvial process. **e** Temporal distribution of all OSL and radiocarbon ages (event, minimum and maximum ages). Meaning of the abbreviations for archaeological periods: PAL = Final Palaeolithic, MES = Mesolithic, NL = Neolithic, BZ = Bronze Age, IA = Iron Age, ROM = Roman Period, MIG = Migration Period, MA = Medieval, MO = Modern Period. **f** Temporal distribution of all radiocarbon event ages. **g** Temporal distribution of all OSL event ages

Anthrosols) occur. Common are fossil topsoil horizons, which are either buried by the colluvial layers or appear within. Geochronology and archaeology reveal a high to late medieval to post-medieval age of the colluvial sediments.

- The colluvial sediments have sufficient contents of pollen, plant macro-remains and charcoal. This ensures analysis of the palaeobotanical and historical-ecological conditions at the sites. The data show a drastic decline of the mountain forests in the late twelfth to fifteenth centuries AD period and a change of the wood species composition, i.e. increase of pioneer trees and spruce at the expense of fir and beech.

- In contrast to many other sites in both the lowlands and uplands, mining and further industrial activities as well as settlement have caused the formation of colluvial deposits by local soil erosion. In each case, deforestation preceded this.

- In the Erzgebirge, late Holocene colluvial sediments mostly spread on footslopes, slope flattenings, and dells. Their occurrence is determined by local erodibility of the soil substrate, relief energy and (former) land use. From the total area of the soil landscape, a rather high share of 11% (11,905 ha) consists of colluvial soils. Most areas with colluvial soils occur on the northern declivity of Erzgebirge and on the western and eastern rim. Colluvial soils in forests, although only proven on a relatively small area (1354 ha) so far, clearly point to historical erosion processes at those sites.

- By meta-analysis of 395 geochronological data from colluvial sediments occurring at 197 upland sites in Central Europe, a dominance of these data for the German uplands becomes obvious. Only a few additional data are available from some mountain areas in Luxembourg, Poland, and Czech Republic. Although anthropogenically initiated colluvial dynamics in the uplands has already occurred from the late Bronze Age to Roman period onwards, the majority of ages dates in the medieval to post-medieval period, corresponding to the intensification of settlement and land-use activities in that time.

Fig. 11 Temporal frequency distribution of all radiocarbon and OSL event ages younger than 3000 a/a cal BP from colluvial sediments in the low mountain ranges of Central Europe. Class (bin) width is 100 years

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