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New evidence for prehistoric ploughing in Europe

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For the past four decades, the ‘Secondary Products Revolution’ model, i.e., the exploitation of animal resources that do not involve killing the animal, such as the production of milk and wool and the use of animals for physical labour has been the object of heated discussion between Neolithic scholars. According to this model, the use of animal strength arrived relatively late in Europe—during the socio-economic changes of the Late Neolithic in the 4th millennium BCE. Plough marks are the most convincing direct evidence of the use of animal traction. However, few are preserved making them relatively rare throughout Europe and dating them is difficult and often imprecise. Recent research at the Anciens Arsenaux site in Sion, Valais, Switzerland has revealed the presence of the oldest known plough marks in Europe, dating from the beginning of the 5th millennium BCE. They bear witness to the use of animal traction quite soon after the establishment of an agro-pastoral economy in the Alpine region. This is corroborated by recent archaeozoological studies and suggests that this important innovation could already be part of the Neolithic package introduced into Europe during the 6th millennium BCE.

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Introduction

During the 6th millennium BCE, continental Europe was marked by a fundamental innovation in the development of the producing mode of subsistence. Based on cereal farming and livestock breeding, this "Neolithic Revolution" (Childe, 1936) was followed by a series of important technical innovations, such as copper metallurgy and the introduction of animal traction. The latter was part of what Andrew Sherratt has described as the "Secondary Products Revolution", i.e., the exploitation of "renewable" animal resources (physical strength, milk, wool and manure) that did not involve killing the animal (Sherratt, 1981, 1983). From this perspective, the "animal traction complex" is a late phenomenon directly linked to socio-economic changes that occurred in Europe during the 4th and 3rd millennia BCE. Despite the criticism it has provoked (Vosteen, 1996), this model continues to enliven discussions on the "Neolithic Revolution", the subsequent innovations and their social consequences (Bogaard, 2004; Greenfield, 2010; Gaastra et al., 2018; Kamjan et al., 2022).

Archaeological data from around Europe such as parietal engravings depicting harnessed ards and carts, bone pathologies linked to harnessing or repeated pulling, and the discovery of objects such as wheels, travois, yokes, ards or archaeological features that like plough marks, presuppose the use of animal traction (Sherratt et al., 2006).

Plough marks are the most tangible, widespread and convincing evidence. They consist of linear depressions filled with sediment of a different texture and colour than that of the surrounding deposits. Such marks can be followed over dozens of meters to form parallel or criss-crossing networks. They imply the use of a specific tool, the ard and its traction by a powerful animal such as an ox (Thrane, 1989).

The discovery of prehistoric plough marks and how archaeologists interpret them as an indicator of animal traction has come up against several major obstacles. The furrows are shallow and often erased by erosion or modern farming practices. They are therefore an extremely fleeting type of evidence and are only observed if they were rapidly covered by sediment to offer sufficient contrast between the underlying ground and the fill of the furrows (see Vanzetti et al., 2019). In addition, these remains are usually very difficult to date. The elements they contain (archaeological finds or organic materials that can be radiometrically dated) are unlikely to be contemporary with the furrows. The only reliable dating comes from their stratigraphic position. They are logically older than the sediments that cover them or the pits that cut them. It is therefore not surprising that discoveries of proven Neolithic plough marks are a relatively rare phenomenon (Fig. 1 and Table 1).

Evidence for the use of ards is best documented in northern Europe, especially in Denmark and northern Germany, where the earliest features date to the first half of the 4th millennium BCE (Thrane, 1989; Tegtmeier, 1993; Fries, 1994; Andersen, 2000; Louwe-Kooijmans, 2006; Mischka, 2011; Sørensen and Karg, 2014; Gron and Sørensen, 2018). The Mont Bégo and Val Camonica rock engravings in Southern France and Italy that date to the 3rd millennium BCE illustrate ards pulled by a pair of oxen (Forni, 1998; Huet, 2017). Earlier evidence of soil tillage has been

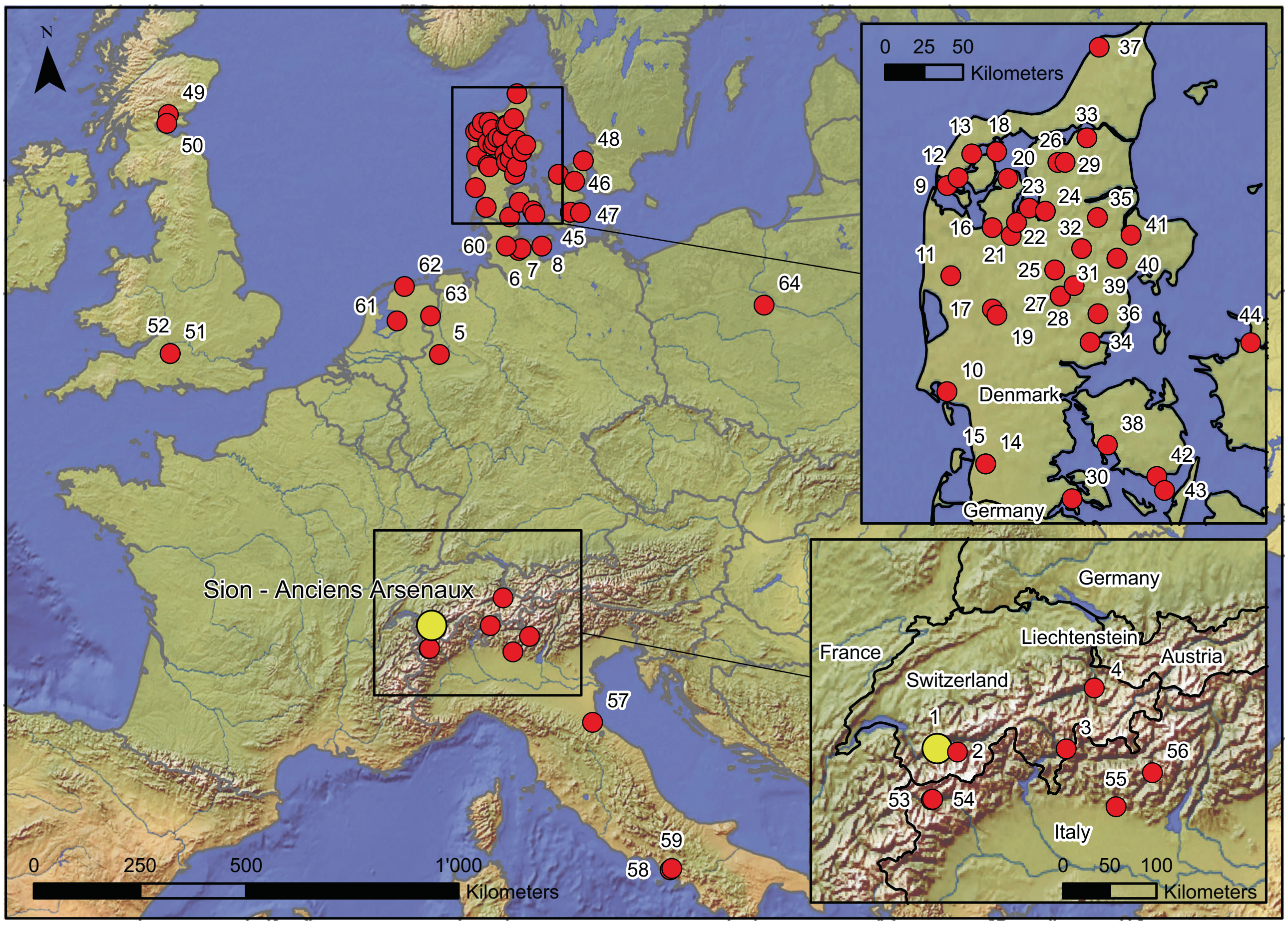

Fig. 1 Map showing the location of the Anciens Arsenaux site (Sion, canton of Valais, Switzerland; yellow dot) and European sites with traces of ploughing dating from before 2000 cal BC (red dots). Detailed data in Table 1. Map base: Natural Earth.

Table 1 List of European sites with ard tracks dated before 2000 BCE.

No.	Site	Country	Date	Long.	Lat.	Reference
1	Sion, Anciens Arsenaux	CH	First half of 5th millennium	7.355	46.232	This paper
2	Bramois, Pranoé, villas Bitschnau	CH	Before middle of 3rd millennium	7.407	46.233	Mottet et al. (2011)
3	Castaneda, Pian del Remit	CH	End of 4th millennium	9.143	46.258	Zindel and Defuns (1980)
4	Chur, Welschdörfli	CH	Middle of the 4th millennium	9.527	46.848	Rageth (1998)
5	Billerbeck-Heidberg, Fundstelle 393	D	Before end of 3rd millennium	7.291	51.978	Thrane (1989)
6	Grevenkrug, Grabhügel LA 5	D	Before middle of 3rd millennium	10.011	54.212	Thrane (1989)
7	Flintbek LA 3	D	Middle of the 4th millennium	10.1	54.25	Mischka (2011)
8	Oldenburg-Dannau, Siedlung LA 191	D	Before middle of 3rd millennium	10.848	54.301	Thrane (1989)
9	Gettrup, Oddersholm	DK	Before the end of the 3rd millennium	8.355	56.721	Thrane (1989)
10	Guldager, Nygård	DK	Before the end of the 4th millennium	8.402	55.531	Thrane (1989)
11	Torsted, Langagergård	DK	Before the end of the 4th millennium	8.415	56.201	Thrane (1989)
12	Ullerup, Lundehøj	DK	End of 4th millennium	8.468	56.768	Tegtmeier (1993)
13	Skjoldborg, Højgård	DK	Before the end of the 3rd millennium	8.606	56.907	Thrane (1989)
14	Døstrup, Brohøjgård	DK	Before the end of the 3rd millennium	8.808	55.118	Thrane (1989)
15	Døstrup, Steneng	DK	Before the middle of the 4th millennium	8.808	55.118	Thrane (1989)
16	Sahl, Aptrup	DK	Before middle of 3rd millennium	8.834	56.483	Thrane (1989)
17	Assing, Bukkær	DK	Before middle of 4th millennium	8.85	56.013	Thrane (1989)
18	Sejerslev, Skærbæk, Hügel A	DK	Before the middle of the 3rd millennium	8.867	56.922	Thrane (1989)
19	Skarrild	DK	Before the end of the 3rd millennium	8.898	55.978	Thrane (1989)
20	Åsted, Bodshøj	DK	Before the end of the 4th millennium	8.99	56.769	Thrane (1989)
21	Vroue, Skibshøj/Sjørup	DK	Before the middle of the 4th millennium	9.033	56.439	Thrane (1989)
22	Kobberup, Lærkenborg	DK	Before the end of the 3rd millennium	9.087	56.515	Thrane (1989)
23	Ølslev Kloster, Sønderhald	DK	Before the end of the 3rd millennium	9.217	56.599	Thrane (1989)
24	Låstrup, Borup	DK	Before the end of the 3rd millennium	9.386	56.582	Thrane (1989)
25	Serup, Tandskov	DK	Before the end of the 4th millennium	9.489	56.243	Thrane (1989)
26	Blære	DK	Before the end of the 3rd millennium	9.514	56.864	Thrane (1989)
27	Them, Rosenlund	DK	Before the end of the 3rd millennium	9.548	56.092	Thrane (1989)
28	Them, Løvenholt	DK	Before mid-4th millennium	9.548	56.092	Thrane (1989)
29	Skivum, Lynnerup II	DK	Before the end of the 4th millennium	9.589	56.865	Thrane (1989)
30	Nybøl, Nybøl Nor	DK	Before the middle of the 4th millennium	9.679	54.922	Thrane (1989)
31	Linå, Singelsbjerg	DK	Before the end of the 3rd millennium	9.69	56.153	Thrane (1989)
32	Hvorslev, Aldrupsgårde	DK	Before middle of 3rd millennium	9.767	56.367	Thrane (1989)
33	Frejlev	DK	Before middle of 3rd millennium	9.818	57.007	Thrane (1989)
34	Tyrsted, Præshøj	DK	Before the end of the 4th millennium	9.857	55.826	Thrane (1989)
35	Asferg Nørremark	DK	Before the middle of the 3rd millennium	9.931	56.547	Thrane (1989)
36	Hylke, Brørup Skovgård	DK	Before the end of the 3rd millennium	9.937	55.991	Thrane (1989)
37	Tornby, Hedelyken	DK	Before mid-4th millennium	9.947	57.531	Thrane (1989)
38	Dreslette, Snave	DK	Before the middle of the 4th millennium	10.033	55.233	Thrane (1989)
39	Ødum, Kikhøj	DK	Before the end of the 3rd millennium	10.133	56.311	Thrane (1989)
40	Ødum, Dejrhøj	DK	Before the end of the 3rd millennium	10.135	56.312	Thrane (1989)
41	Fausing, Tvillingehøj	DK	Before the end of the 3rd millennium	10.281	56.445	Thrane (1989)
42	Egense, Højensvej	DK	Before the middle of the 4th millennium	10.53	55.05	Beck, (2009; Sorensen and Karg, 2014)
43	Bjerreby, Capeshøj	DK	Before the middle of the 4th millennium	10.606	54.969	Thrane (1989)
44	Asnæs	DK	Before the end of the 4th millennium	11.502	55.815	Thrane (1989)
45	Vordingborg, Rosenfeldt	DK	Before the middle of the 3rd millennium	11.911	55.006	Thrane (1989)
46	Himmelev	DK	Before the end of the 4th millennium	12.102	55.659	Thrane (1989)
47	Stege Land, Jordehøj	DK	Before middle of 3rd millennium	12.283	54.991	Thrane (1989)
48	Hornbæk, Over Hornbæk	DK	Before the end of the 4th millennium	12.458	56.086	Thrane (1989)
49	Perth, Wellhill	GB	Before middle of 3rd millennium	−3.432	56.394	Brophy and Wright (2021)
50	Kinross, Cranberry	GB	Middle of 3rd millennium	−3.424	56.205	Brophy and Wright (2021)
51	Avebury, South Street Long Barrow	GB	End of 4th millennium	−1.854	51.428	Ashbee et al. (1979)
52	Avebury, South Street Long Barrow	GB	End of 3rd millennium	−1.854	51.428	Ashbee et al. (1979)
53	Aosta, Saint-Martin-de-Corléans	I	Before end of 5th millennium	7.297	45.735	Ferroni et al. (2018)
54	Aosta, Ospedale U. Parini	I	Before middle of 3rd millennium	7.315	45.741	Armirotti et al. (2018, 2022)
55	Trescuore Balneario, Canton	I	Before end of 5th millennium	9.837	45.703	Poggiani Keller (2004)
56	Capo di Ponte, Cemmo	I	End of 4th millennium	10.338	46.031	Poggiani Keller (2016)
57	Provezza	I	Middle of 3rd millennium	12.182	44.183	Bazzochi et al. (2017)
58	Gricignano d'Aversa	I	Before middle of 3rd millennium	14.231	40.977	Vanzetti et al. (2019)
59	Gricignano-viadotto Padulicella	I	Before middle of 3rd millennium	14.2808	41.00333	Marzocchella (1998)
60	Belder Beg	IRL	Middle of 3rd millennium	9.561	54.304	Caulfield (1978, p. 140)
61	Noordoostpolder, Schokland	NL	Before middle of 3rd millennium	5.774	52.644	Louwe-Kooijmans (2006)
62	Westdongeradeel, Bornwird	NL	Before middle of 3rd millennium	5.964	53.381	Louwe-Kooijmans (2006)
63	Emmen, Emmerhout	NL	End of 4th millennium	6.934	52.787	Louwe-Kooijmans (2006)
64	Zarębowo	PL	Before middle of 3rd millennium	18.593	52.746	Sherratt (1981, p. 270)

attested to around 4300–4000 BCE in the wetlands of the Swifterbant region of the Netherlands, but these marks appear to have been made using a hoe-type tool with no recourse to animal traction (Huisman and Raemaekers, 2014).

Earlier evidence of the use of plough-like tools comes from the Alpine arc. In Saint-Martin-de-Corléans, Italy ard tracks and bovine hoof-prints predate a series of storage pits dated through some 20 radiocarbon analyses to around 4300–4000 BCE (De

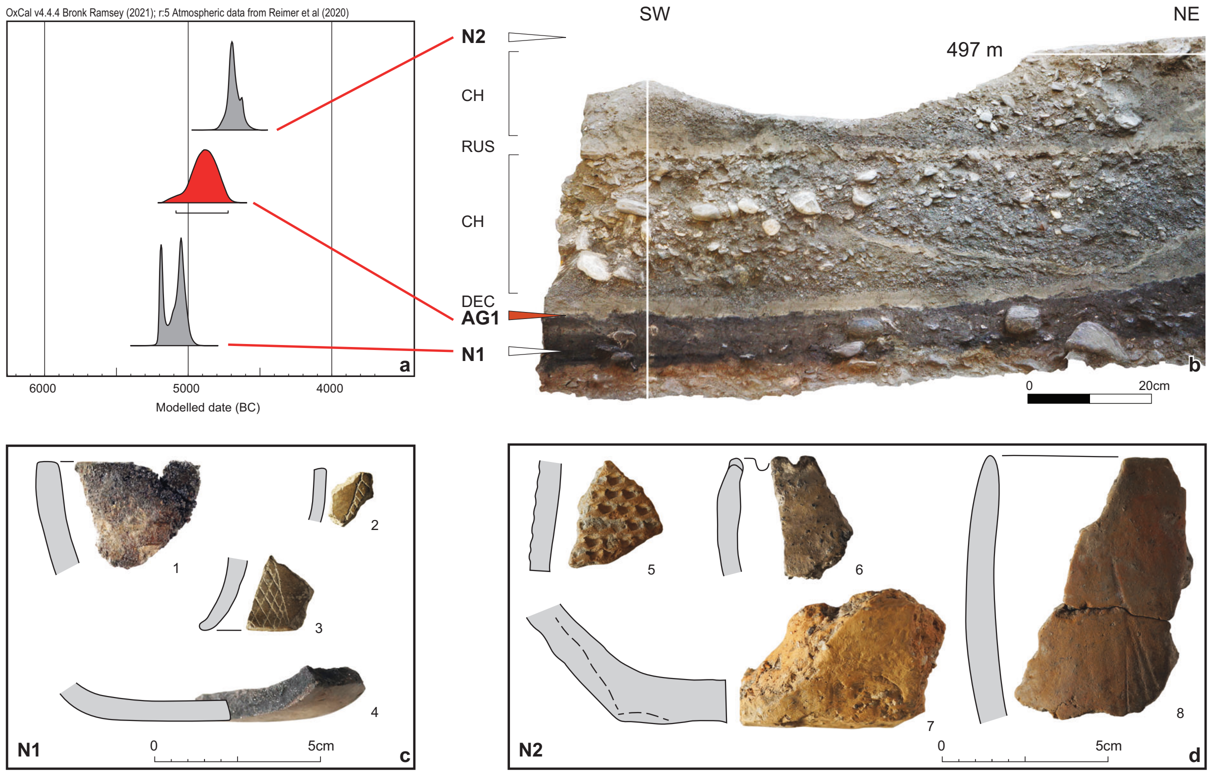

Fig. 2 Stratigraphy and chronology of Sion-Anciens Arsenaux. a Chronological summary of the Ensembles N1, AG1 and N2 (results of the Bayesian modelling). The red density plot shows the Ensemble AG1 comprising the ard marks. The full model is based on 30 radiocarbon dates (see Tables 2 and 3). **b** Photogrammetry of the lower part of the stratigraphy of the Anciens Arsenaux site, with Ensembles N1, AG1 and N2. **c** Selection of ceramics from Ensemble N1. Nos. 2–3 are fragments of a hollow-bottomed vase characteristic of the early phase of the Vasi a Bocca Quadrata culture in the Po plain, dated to the beginning of the fifth millennium BCE. **d** Selection of ceramics from Ensemble N2. No. 5 shows decorations typical of the Planig Friedberg group (about 4600 BCE), mainly found in the Rhine basin. Photogrammetry: ARIA SA; photographs and drawings of the sherds: S. van Willigen, InSitu SA.

Gattis et al., 2018). Excavations on the northern slopes of the Alps at the Welschdörfli site in Chur in Switzerland have brought to light ard furrows in a zone between two occupation levels dated to the first half of the 4th millennium BCE (Rageth, 1998). Although seemingly predating those of northern Europe, the plough marks in alpine regions lack a precise chronological framework and their exact age remains unknown.

The question of the appearance of ploughing techniques is even more important as it is supposed to play a central role in the increasing agricultural output, wealth inequality and social stratification (see Bogaard, 2004 with further literature; Bogaard et al., 2019).

In this paper, we aim to present the results of recent research carried out in the heart of the Alps, in the upper Rhône valley in Sion, Valais, Switzerland, where a robust chronological framework for a series of ard tracks observed in Neolithic levels has been defined.

The Anciens Arsenaux site and its chronological framework

The Anciens Arsenaux site is located in the town of Sion (Canton of Valais, Switzerland), on the alluvial cone of the Sionne, an Alpine torrent that flows through the town and into the Rhône. The site, which extends over 800 m^2, was discovered before the construction of an underground silo for the Valais Cantonal Archives and excavated in 2017, revealing alternating human occupation levels and alluvial deposits some ten meters thick. These documented occupation levels span most of the Neolithic period, from around 5200 to 3500 cal BC.

The earliest occupation (ensemble N1; Fig. 2a, right) is an early Neolithic settlement, made up of post-holes and hearths. The pottery, sickle blades, millstones, cereal seeds (wheat and barley; *Triticum/Hordeum* sp.) and domestic fauna (beef, goat and pig) indicate a mature Neolithic economy. Ten radiocarbon dates (Table 2) date this settlement between 5244 and 4914 cal BC (Fig. 2a, left; see below). These dates are consistent with the pottery (Fig. 2b) that is characteristic of the early phase of the Vasi a Bocca Quadrata, dated in the Po plain and Liguria (Italy) to around 5100–4900 cal BC (Del Lucchese and Starnini, 2021).

This first settlement phase (N1) is covered by humus soil (ensemble AG1; Fig. 2a, right), sealed by occupation levels and covered by sand and gravel from the overflow of the nearby torrent. At different locations in the excavation, groups of parallel furrows filled with sand and gravel extending over an area of some 30 square metres were observed (Fig. 3), as well as hoof prints left by domestic cattle and goats in a ditch where whitish clays have drained off (Fig. 4). Without any reliable information on the taphonomic processes that led to their deposit, we decided not to date the organic elements contained in the AG1 accumulation. However, Bayesian modelling including the 30 dates from the Anciens Arsenaux stratigraphic sequence dates the furrows of the AG1 accumulation between 5116 and 4708 cal BC (Fig. 2a, left; Tables 2 and 3).

A new settlement (ensemble N2; Fig. 2a, right) with several post buildings is separated from level AG1 by alluvial deposits. Six modelled radiocarbon dates place this occupation in the 4836–4527 cal BC interval (Fig. 2a, left). The archaeological material from this level including a Planig-Friedberg type sherd, a

Table 2 List of radiocarbon dates for the Neolithic sequence at the Anciens Arsenaux site.

Stratigraphic ensemble	Age BP	±	δ13C ‰	±
Stratigraphic ensemble N6				
Poz-100480	4825	35	−23.9	0.3
Stratigraphic ensemble N5				
Poz-100120	5420	40	−24	0.6
Poz-100118	5470	40	−19.8	1.1
Poz-112400	5675	35	−24.7	0.8
Stratigraphic ensemble N4				
Poz-100119	5580	40	−21.5	0.7
Poz-100449	5595	30	−24.2	1.1
Stratigraphic ensemble N3				
Poz-112262	5620	40	−21.3	0.3
Poz-113172	5640	40	−18.4	0.7
Poz-100450	5640	30	−29.6	5.3
Poz-100486	5650	40	−24.5	0.3
Poz-100696	5650	35	−24.5	0.3
Stratigraphic ensemble N2				
Poz-100694	5755	35	−23.7	0.2
Poz-112230	5760	50	−17.2	1.1
Poz-100693	5820	40	−23.9	0.4
Poz-100483	5840	40	−24.3	0.5
Poz-100692	5870	40	−25.5	0.1
Poz-112229	5870	40	−21.6	1
Stratigraphic ensemble AG1				
None				
Stratigraphic ensemble N1				
Poz-100451	6070	35	−28.3	5.2
Poz-112478	6090	40	−22.9	0.4
Poz-112261	6100	40	−25.2	1.6
Poz-112480	6120	40	−27.8	0.4
Poz-112401	6140	40	−23.5	1
Poz-112679	6140	35	−24.3	0.4
Poz-100482	6150	40	−21.3	0.5
Poz-112402	6190	40	−25.8	3
Poz-112477	6200	40	−25.6	0.4
Poz-112231	6230	40	−18.2	0.2
Stratigraphic ensemble N1inf				
Poz-100695	6375	35	−23.6	0.2
Poz-100484	6550	40	−26	0.6
Poz-112482	6550	30	−25.5	0.3

cultural group located in the Rhine basin dated to between 4690 and 4565 cal BC (Denaire et al., 2017), corroborate these dates.

Plough marks of the ensemble AG1

Micromorphological analysis. As the furrows in AG1 correspond in all respects to features generally interpreted as plough tracks (Thrane, 1989; Tegtmeier, 1993; Andersen, 2000; Deák et al., 2017; Rentzel and Guélat, in press), block samples were taken during excavation for micromorphological analysis (Figs. 3d and 5). This approach makes it possible to identify disturbances in the soil horizons caused by tillage (Gebhardt, 1995; Lewis, 2012; Deák et al., 2017). The technique involves examining sediments hardened with synthetic resin under a microscope. It has been successfully applied to archaeological sites for several decades (Courty et al., 1989; Gebhardt, 1995; Lewis, 2012; Deák et al., 2017). Micromorphological analysis was carried out on a 25 × 15 cm sample taken across one of the furrows observed in the AG1 horizon and comprising one of the linear tracks recognized during excavation (sample EM97-1; Fig. 3d). The sample was oven-dried and then impregnated several times with epoxy resin. After polymerization of the resin, the sample was cut with a large-plate diamond saw to produce five thin 42 × 62 mm sections. Micromorphological analysis of the thin slides was carried out using a binocular magnifier and a polarizing microscope (PPL: plane polarized light; XPL: crossed polarizers). After an initial microscopy, the sediments were first correlated, as far as possible, with the stratigraphic documentation from the excavation. Next, the individual micro-layers (mc) were described according to method-specific criteria (Bullock et al., 1985; Stoops et al., 2010).

The parallel furrows uncovered in AG1 have a "U-shaped" profile and measure a maximum of 3.5 m in length, with a width varying between 3 and 7 cm; the spacing between the features varies from 10 to 20 cm.

Thin section analysis has identified a microstratigraphy composed of four units (Fig. 5a, mc. 1–mc. 4). At the base, carbonate alluvia, a low-grade soil (Fig. 5b, mc. 2) cover fine torrential deposits (mc.1). Certain micromorphological features, such as the in situ verticalisation or fragmentation of elements, suggest that the soil was worked using a rudimentary tool, such as a hoe (Lewis, 2012; Gebhardt and Langohr, 2015). Traces of frost detected in the base gravels (mc. 1) could be the result of soil denudation at this stage (Curdy and Guélat, 2011). The sharp, undulating upper boundary is marked by a packed silty level. Above this, the matrix becomes homogeneous and contains degraded organic matter (Fig. 5c, mc. 3). This humus-bearing soil, eroded at the top, also contains anthropogenic components such as bone fragments and charcoal, perhaps added as a fertilizer (Lewis, 2012; Devos et al., 2013). This same soil contains at least three generations of splayed «U»-shaped features, 10 cm wide and up to 3 cm high, also individualized by layered gravel at their lower limit and corresponding to the bottom of the furrows (Fig. 5c). These features are located above the lower horizon contact, also marked by the compaction of the underlying sediment (mc. 2), the latter having also undergone internal silting.

Similar microscopic features are the main stigma that shows the use of implements (Deák et al., 2017). The U-shaped tracks can thus be interpreted as the bottoms of ard furrows. An analogy with Iron Age plough marks identified at the nearby site of Gamsen (Valais, Switzerland), also located on a torrential cone of the Rhône valley in a morphosedimentary context comparable to that of the Anciens Arsenaux corroborates this interpretation (Rentzel and Guélat, in press). At the top of the sample, alluvial sediments (Fig. 5d, mc. 4) fill the most superficial furrows that were observed during the excavation.

Micromorphological analysis therefore indicates that the furrows were formed by tillage, suggesting the repeated passage of an ard after the initial substrate preparation. The three generations of furrow bottoms show that this process was repeated several times. The anthropogenic input of nutrients (charcoal and bone fragments) into the ploughed soil confirms agricultural practices on the site.

Despite the small size of the ploughing area that has been preserved, the regularity and continuity of the traces, the compactness of the worked sediment and the similarity with the marks identified at Gamsen suggest that animal traction was used.

Dating the plough marks of the ensemble AG1: Bayesian modelling of radiocarbon dates

Stratigraphic information. The chronological model developed here relies on a series of 30 radiocarbon dates (Tables 2, 3) and the stratigraphic succession of eight ensembles of archaeological contexts. The first ensemble (N1inf), located at the base of the stratigraphic sequence, yielded three burnt tree stumps, each sampled and dated. These three dates represent a terminus post quem for the site's Neolithic sequence, itself made up of seven

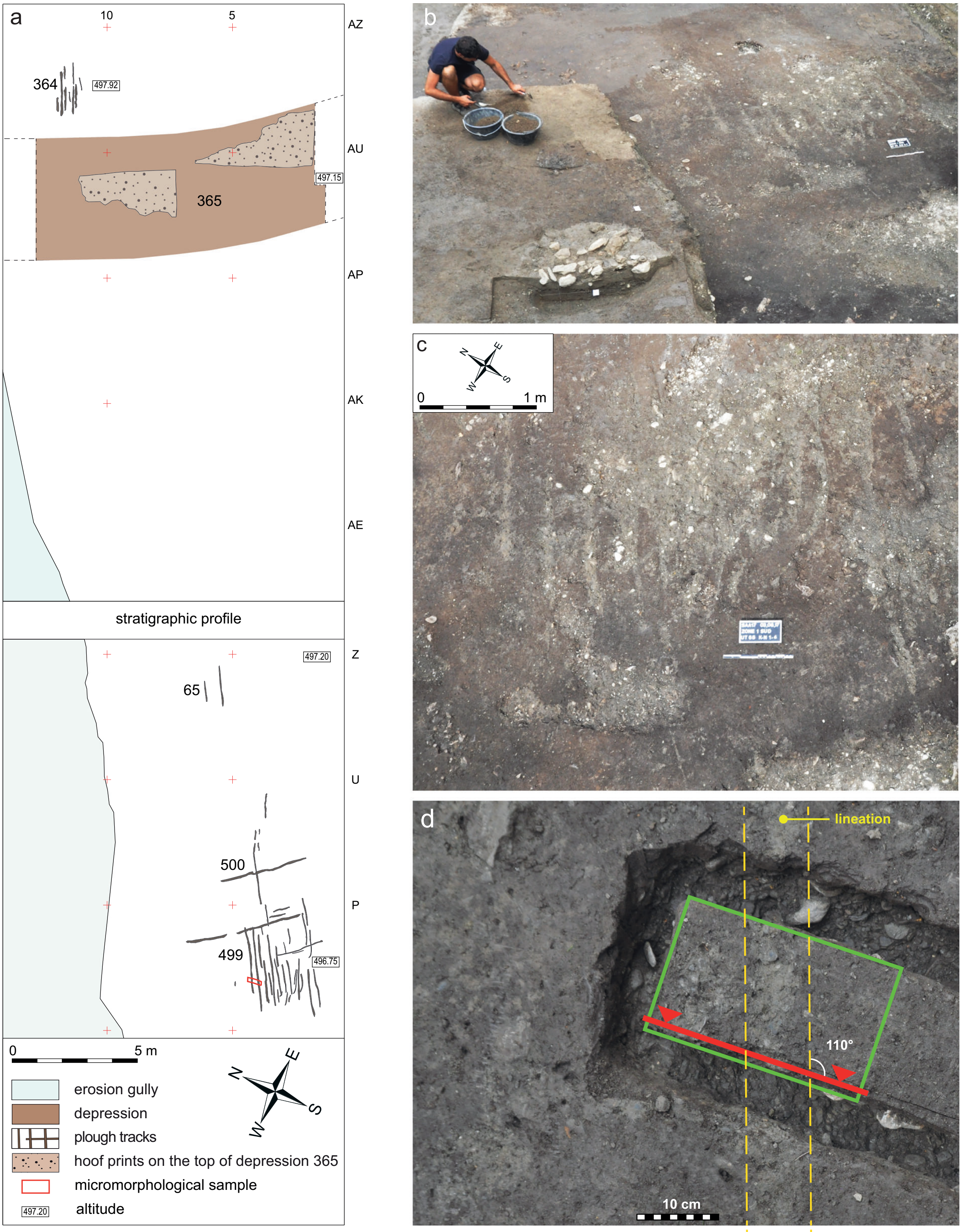

Fig. 3 The ploughmarks groups 364, 65, 500 and 499 at the Anciens Arsenaux excavations (ensemble AG1). **a** excavation plan; **b** ploughmarks (group 499 in **a**) during excavation; **c** ploughmarks (group 499 in **a**) after excavation; **d** excavating micromorphological block EM97 through one of the ploughmark grooves in group 499 (see Fig. 5a for its location), with the analysed thin section shown in red. Images: ARIA SA.

superimposed stratigraphic ensembles (N1–N6). Each of these sets has been radiocarbon dated: N1 (10 dates), N2 (6 dates), N3 (5 dates), N4 (2 dates), N5 (3 dates) and N6 (1 date). The ensemble AG1, characterized by the linear structures that are the subject of this article, yielded no diagnostic archaeological material or carpological or faunal remains suitable for radiocarbon dating. However, the stratigraphic insertion of AG1 is clearly established (AG1 is posterior to N1 and anterior to N2).

Fig. 4 Hoofprints at Sion–Anciens Arsenaux. Goat and domestic cattle hoofprints in depression 365 at the surface of AG1 (Photographs: ARIA SA).

This stratigraphic sequence enabled us to construct a model of strict succession of eight phases, incorporating chronological information derived from the radiocarbon dates of each assemblage: N1inf < N1 < AG1 < N2 < N3 < N4 < N5 < N6. Due to the scarcity of short-lived materials on the site, charcoal was favoured. Although an old wood effect in the sequence cannot be ruled out, its impact may be limited by the number of dates and the modelling.

Bayesian modelling. The stratigraphic diagram allowed designing a model of eight sequential phases using Oxcal software. The model includes start and end boundaries for each of the eight phases. The reason for modelling a sequence of phases was that, although the upper and lower boundaries of each ensemble were clearly defined, it was not possible to establish all the stratigraphic links between the different dated events within each ensemble and therefore to model these links within each ensemble as a sequence. Only the succession of three successive ploughing events identified in the micromorphological analysis of AG1 (Fig. 5a) could be modelled as a sequence (see below).

Calculations were performed using OxCal software (version 4.4.4; Bronk Ramsey, 2009a) and the IntCal20 calibration curve (Reimer et al., 2020; Table 3). They include a full outlier model (Table 4; Bronk Ramsey, 2009b). The chronological information corresponding to each phase was summarized using a Kernel density evaluation (KDE) with the KDE plot command (Bronk Ramsey, 2017). As no radiocarbon dating was available for ensemble AG1, the date of each of the three successive ploughing generations associated with this ensemble was estimated using Oxcal's Date command, with the succession of the three dates modelled as a sequence (see code in Supplementary Information). These three estimates do not provide any new chronological information, but they do enable us to estimate the ploughing date and calculate a KDE for the ensemble AG1. The model thus provides a complete overview of the entire sequence.

Modelling results. The results of Bayesian modelling generally show a very good correlation between radiocarbon measurements and the model, with an agreement index for the model of 86.7% (AModel) and an overall agreement index of 82.3% (AOverall) (Table 3). Only one modelled date has an agreement index below 60%, the threshold below which the date in question should be reconsidered. Outlier analysis shows that the vast majority of dates have an a posteriori probability of being an outlier of less than 7%, most of them being below the 5% threshold (Table 4). Only one of the three dates in ensemble N5 (Poz-112400) is questionable since it has a posterior probability of being an outlier of 50%. As ensemble N5 is at the top of the stratigraphic sequence, this problem only marginally affects the dating of assemblage AG1.

The modelled dates (95.4%) (Table 3) indicate that ensemble N1, corresponding to the early Neolithic, is set between a Boundary Start of 5244–5045 cal BC and a Boundary End of 5203–4914 cal BC. The estimated dates correspond to the three successive ploughing episodes identified in ensemble AG1 (AG1_Ev1 to AG1_Ev3) cover intervals between 5116 and 4708 cal BC. The N2 ensemble ranges from a lower bound of 4836–4625 cal BC and an upper limit of 4708–4527 cal BC.

Early emergence of animal traction in Europe

The plough marks at the Anciens Arsenaux site appear within a dilated stratigraphic sequence and are therefore reliably dated by both radiocarbon analysis and pottery typology to between 5100 and 4700 cal BC. They predate by around a millennium the earliest traces of ploughing in Denmark and northern Germany appear around 3700 BCE (Sørensen and Karg, 2014). The Anciens Arsenaux site therefore documents the early use of

Table 3 List of radiocarbon dates for the Neolithic sequence at the Anciens Arsenaux site with detailed results of calibration and Bayesian modelling (Oxcal 4.4).

Name	Age BP	±	Unmodelled (BC/AD)						Modelled (BC/AD)								
Amodel 86.7																	
Aoverall 82.3"																	
			from	to	%	from	to	%	from	to	%	from	to	%	A	P	C
Stratigraphic Ensemble N6																	
Boundary end N6									−3641	−3485	68.3	−3889	−3222	95.4			99.5
R_Date Poz-100480	4825	35	−3646	−3533	68.3	−3651	−3526	95.4	−3649	−3535	68.3	−3708	−3521	95.4	96.2	93.4	99.9
Boundary start N6									−3870	−3549	68.3	−4181	−3538	95.4			99.8
Stratigraphic Ensemble N5																	
Boundary end N5									−4332	−4218	68.3	−4349	−4024	95.4			99.8
R_Date Poz-100120	5420	40	−4335	−4250	68.3	−4352	−4070	95.4	−4340	−4262	68.3	−4352	−4240	95.4	111	96.9	100
R_Date Poz-100118	5470	40	−4353	−4261	68.3	−4442	−4243	95.4	−4351	−4265	68.3	−4362	−4252	95.4	109	97.1	100
R_Date Poz-112400	5675	35	−4541	−4456	68.3	−4611	−4371	95.4	−4406	−4267	68.3	−4420	−4228	95.4	7.2	49.6	99.8
Boundary start N5									−4417	−4332	68.3	−4430	−4274	95.4			99.7
Stratigraphic Ensemble N4																	
Boundary end N4									−4436	−4376	68.3	−4451	−4335	95.4			99.9
R_Date Poz-100119	5580	40	−4447	−4363	68.3	−4493	−4345	95.4	−4447	−4396	68.3	−4456	−4361	95.4	114	97.5	99.9
R_Date Poz-100449	5595	30	−4451	−4365	68.3	−4494	−4353	95.4	−4449	−4395	68.3	−4455	−4364	95.4	112	97.5	99.9
Boundary start N4									−4458	−4408	68.3	−4475	−4375	95.4			99.9
Stratigraphic Ensemble N3																	
Boundary end N3									−4482	−4445	68.3	−4504	−4412	95.4			100
R_Date Poz-112262	5620	40	−4493	−4368	68.3	−4537	−4359	95.4	−4495	−4453	68.3	−4530	−4443	95.4	109	97.2	100
R_Date Poz-113172	5640	40	−4536	−4403	68.3	−4546	−4361	95.4	−4495	−4456	68.3	−4528	−4446	95.4	135	97.4	100
R_Date Poz-100450	5640	30	−4533	−4406	68.3	−4542	−4367	95.4	−4495	−4455	68.3	−4529	−4446	95.4	134	97.6	100
R_Date Poz-100486	5650	40	−4540	−4446	68.3	−4585	−4361	95.4	−4495	−4456	68.3	−4531	−4446	95.4	137	97.5	100
R_Date Poz-100696	5650	35	−4536	−4448	68.3	−4551	−4363	95.4	−4495	−4456	68.3	−4531	−4447	95.4	134	97.6	100
Boundary start N3									−4523	−4468	68.3	−4562	−4452	95.4			99.9
Stratigraphic Ensemble N2																	
Boundary end N2									−4692	−4592	68.3	−4708	−4527	95.4			99.9
R_Date Poz-100694	5755	35	−4673	−4547	68.3	−4706	−4502	95.4	−4708	−4639	68.3	−4719	−4577	95.4	85.6	96.1	100
R_Date Poz-112230	5760	50	−4681	−4546	68.3	−4720	−4461	95.4	−4713	−4641	68.3	−4726	−4569	95.4	98.6	96.6	100
R_Date Poz-100693	5820	40	−4723	−4611	68.3	−4786	−4551	95.4	−4720	−4624	68.3	−4766	−4602	95.4	124	97.2	100
R_Date Poz-100483	5840	40	−4784	−4618	68.3	−4796	−4553	95.4	−4726	−4623	68.3	−4770	−4610	95.4	118	97.1	100
R_Date Poz-100692	5870	40	−4792	−4705	68.3	−4840	−4615	95.4	−4743	−4676	68.3	−4781	−4614	95.4	86.2	96.4	99.9
R_Date Poz-112229	5870	40	−4792	−4705	68.3	−4840	−4615	95.4	−4743	−4676	68.3	−4781	−4614	95.4	86.1	96.4	99.9
Boundary start N2									−4779	−4693	68.3	−4836	−4625	95.4			99.9
Stratigraphic Ensemble AG1																	
Boundary end AG1									−4901	−4736	68.3	−5028	−4687	95.4			99.9
AG1_Ev3									−4933	−4767	68.3	−5049	−4708	95.4			99.9
AG1_Ev2									−4961	−4796	68.3	−5079	−4729	95.4			99.9
AG1_Ev1									−4991	−4819	68.3	−5116	−4749	95.4			99.9
Sequence AG1																	
Boundary start AG1									−5018	−4840	68.3	−5157	−4771	95.4			99.8
Stratigraphic Ensemble N1																	
Boundary end N1									−5191	−4968	68.3	−5203	−4914	95.4			99.3
R_Date Poz-100451	6070	35	−5035	−4913	68.3	−5203	−4847	95.4	−5202	−5006	68.3	−5208	−4953	95.4	65.6	95.3	99.3
R_Date Poz-112478	6090	40	−5200	−4941	68.3	−5208	−4849	95.4	−5203	−5010	68.3	−5209	−4967	95.4	95	96.6	99.3
R_Date Poz-112261	6100	40	−5202	−4947	68.3	−5209	−4855	95.4	−5203	−5008	68.3	−5209	−4973	95.4	105	96.8	99.2
R_Date Poz-112480	6120	40	−5206	−4960	68.3	−5209	−4944	95.4	−5204	−5011	68.3	−5209	−4990	95.4	116	97	99.3
R_Date Poz-112401	6140	40	−5207	−5002	68.3	−5213	−4954	95.4	−5205	−5014	68.3	−5209	−4999	95.4	115	97.1	99.3
R_Date Poz-112679	6140	35	−5207	−5003	68.3	−5211	−4990	95.4	−5205	−5016	68.3	−5209	−4999	95.4	115	97.1	99.3
R_Date Poz-100482	6150	40	−5208	−5030	68.3	−5215	−4960	95.4	−5206	−5021	68.3	−5209	−5003	95.4	112	97	99.3
R_Date Poz-112402	6190	40	−5211	−5065	68.3	−5294	−5011	95.4	−5206	−5040	68.3	−5211	−5026	95.4	97.3	96.7	99.3
R_Date Poz-112477	6200	40	−5213	−5066	68.3	−5300	−5032	95.4	−5207	−5042	68.3	−5213	−5030	95.4	94.9	96.5	99.3
R_Date Poz-112231	6230	40	−5298	−5074	68.3	−5306	−5054	95.4	−5210	−5045	68.3	−5216	−5035	95.4	76	95.4	99.3
Boundary start N1									−5221	−5060	68.3	−5244	−5045	95.4			99.1
Stratigraphic Ensemble N1inf																	
Boundary end N1inf									−5465	−5288	68.3	−5476	−5169	95.4			99.9
R_Date Poz-100695	6375	35	−5463	−5311	68.3	−5472	−5223	95.4	−5473	−5336	68.3	−5478	−5305	95.4	81.7	94.1	99.9
R_Date Poz-100484	6550	40	−5552	−5476	68.3	−5617	−5390	95.4	−5525	−5474	68.3	−5603	−5386	95.4	110	96.7	99.9
R_Date Poz-112482	6550	30	−5533	−5477	68.3	−5612	−5473	95.4	−5519	−5476	68.3	−5604	−5408	95.4	109	96.5	100
Phase N1inf																	
Boundary start N1inf									−5582	−5487	68.3	−5729	−5425	95.4			99.6

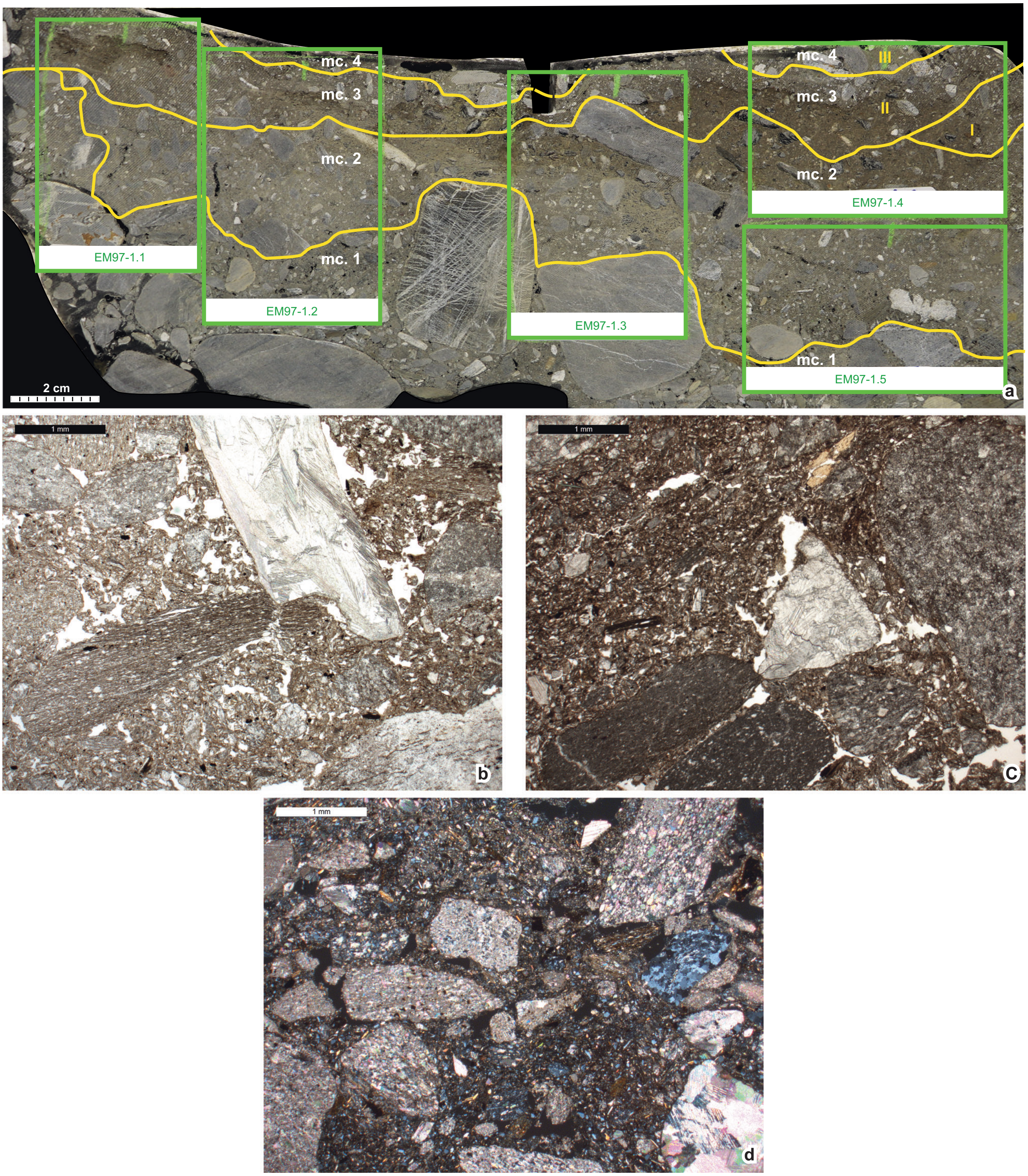

Fig. 5 Micromorphological analysis results. a View of the sawn face of the sample from which five thin sections were made. The microstratigraphy consists of four units (mc. 1 to mc. 4). In the ploughed horizon (mc. 3), at least three generations of furrow bottoms are recognized by analysis (I–III). At the top, the last generation is filled in by light-grey alluvial sediment (mc. 4) and corresponds to the lineations observed during excavation. **b** Microscopic view of the transition level (mc. 2). Fragmented and punched fine gravels in situ indicate an implementation with a rudimentary tool. **c** At the base of the ploughed soil (mc. 3), gravels are bedded according to the lower contact. They correspond to the bottom of ploughing furrows. Bone fragments are probably included in the soil as fertilizer. **d** View of the contact between, at the base, the ploughed horizon with humic matrix (mc. 3) and, at the top, the carbonated fill (mc. 4) of the upper furrows (III). Gravel layering is also found at the boundary. **b**, **c** PPL, **d** XPL.

animal power in the Alpine arc, already recorded in the area in more recent or contemporary contexts at Aosta-Saint-Martin-de-Corléans, Italy (before 4300–4000 cal BC) and at Chur-Welschdörfli, Switzerland (before 3500 cal BC).

The age and location of these tracks tend to corroborate the fact that evidence of Neolithic ploughing is only found on the geographical margins of the two major drifts of Neolithisation in Europe: to the north of the Danubian drift (Denmark, Northern

Table 4 Detailed results of the outlier analysis of radiocarbon dates from the Neolithic sequence at the Anciens Arsenaux site (Oxcal 4.4).

Date	Prior	Posterior	Model	Type	
Poz-112482	5	3	General	t	
Poz-100484	5	3	General	t	
Poz-100695	5	6	General	t	
Poz-112231	5	5	General	t	
Poz-112477	5	4	General	t	
Poz-112402	5	3	General	t	
Poz-100482	5	3	General	t	
Poz-112679	5	3	General	t	S
Poz-112401	5	3	General	t	
Poz-112480	5	3	General	t	
Poz-112261	5	3	General	t	
Poz-112478	5	3	General	t	
Poz-100451	5	5	General	t	
Poz-112229	5	4	General	t	
Poz-100692	5	4	General	t	
Poz-100483	5	3	General	t	
Poz-100693	5	3	General	t	
Poz-112230	5	3	General	t	
Poz-100694	5	4	General	t	
Poz-100696	5	2	General	t	
Poz-100486	5	3	General	t	
Poz-100450	5	2	General	t	
Poz-113172	5	3	General	t	
Poz-112262	5	3	General	t	
Poz-100449	5	3	General	t	
Poz-100119	5	3	General	t	
Poz-112400	5	50	General	t	
Poz-100118	5	3	General	t	
Poz-100120	5	3	General	t	
Poz-100480	5	7	General	t	

Germany, Netherlands) and to the north of the Mediterranean drift (major Alpine valleys) (Fig. 1 and Table 1). This observation can be interpreted in two different ways:

- The beginnings of ploughing are the result of a late phenomenon of adaptation at a time when Neolithisation was affecting areas less suitable for agriculture than the great European plains.

- The map of known Neolithic ard tracks does not show the real distribution of the use of this tool during the Neolithic. It indicates the differential preservation of plough marks between the lowland areas where the intensive farming practised after the Neolithic has all but erased these features and specific contexts such as dunes, tumuli, and volcanic ash layers (see the case of the Bronze Age fields in Campania; Saccoccio et al., 2013; Vanzetti et al., 2019) or alluvial deposits with a high sedimentation rate that has led to their preservation.

New discoveries from the Anciens Arsenaux site contradict the first hypothesis of the development of animal traction when reaching new environments during a late phase of Neolithisation. Traces of ard tracks discovered at the Anciens Arsenaux site, dated between 5116 and 4708 cal BC, are the oldest known in Western Europe and show that the use of animal traction appeared very early in the Alpine Arc, in a chronological interval immediately after the first appearance of a production economy in this region.

As already suggested (Lüning, 1980; Helmer et al., 2018), these new agricultural techniques could well be an integral part of the original Neolithic European package. This model is consistent with archaeozoological studies that suggest the early use of animal power, at least occasionally or not very intensively in several areas in southern Europe. The evidence dates to the middle of the 9th millennium BCE in northern Mesopotamia (Helmer et al., 2018), the beginning of the 7th millennium BCE in Anatolia (Kamjan et al., 2022), the 7th millennium BCE in Crete (Isaakidou, 2006), between the end of the 7th millennium and the middle of the 5th millennium BCE in the western Balkans (Gaastra et al., 2018) and the end of the 6th millennium BCE in the western Mediterranean (Helmer et al., 2018).

The absence of ard tracks on the great European plains, which are among the first areas to see early Neolithic farming, is therefore likely to be linked to taphonomic conditions unfavourable to the preservation of these fleeting vestiges. The great Alpine valleys, on the other hand, where human settlements are often located on alluvial fans, have the capacity to preserve such traces because they were protected by sedimentation. Moreover, these traces are found in dilated stratigraphic sequences rich in organic remains that guarantee their correct dating. Future research in comparable environments is likely to provide new, reliable and precise data on the introduction of animal traction in Western Europe.

Conclusion

Our research has provided a solid chronological framework for the earliest known plough marks in Europe, dated between 5100 and 4700 BCE. These remains demonstrate that the use of animal power appeared quite soon after the first evidence of a production economy in the Alps. The new data indicate that the use of animal traction did not develop during a late phase of the Neolithic in Europe but was probably an integral part of the initial processes of the continent's Neolithisation.

Animal traction is an important innovation that may have had considerable implications for economic and social development during the Neolithic period, mainly in terms of increased output and subsequent wealth inequality. Early emergence of ploughing in Europe, as suggested by new discoveries in the major Alpine valleys, should at least prompt a reconsideration of certain points in A. Sherratt's "Secondary Products Revolution" model, in particular the question of farming practices and social organisation during the early Neolithic.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files. The datasets generated during the excavation are available from the corresponding author on reasonable request.

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References

Andersen ST (2000) Early agriculture. In: Hvaas S, Storgaard B (eds) Digging into the past. 25 years of digging in Denmark. University Press, Aarhus, pp. 88–91

Armirotti A, De Davide C, Wicks D (2018) Aosta in epoca preistorica et protostorica alla luce delle recenti indagini archeologiche preventive in ambito urbano. Riv Sci Preistoriche LX VIII:109–140

Ashbee P, Smith IF, Evans JG (1979) Excavation of three long barrows near Avebury, Wilts. Proc Prehist Soc 45:207–300

Armirotti A, Joly N, Nisbet R (2022) Nel solco: semi e carboni delle arature dell'età del bronzo ad Aosta. In: Brogiolo GP, De Carlo S, Uboldi M (eds) Oltre le stratigrafie. storie di siti, ambienti e popoli, omaggio a Lanfredo Castelletti nel 2022. Documenti di Archeologia 70. Società Archeologica, Quingentole. pp. 159–168

Bazzochi M, Mazzoni C, Milantoni C (2017) Tracce di paesaggio agrario: le arature preistoriche e il sistema di canalizzazioni del villaggio della fine del III millennio a.C. di Provezza (FC). In: Bernabò Brea M (ed.) Preistoria e protostoria dell'Emilia Romagna, vol I, Studi di preistoria e protostoria 3(I). Istituto Italiano di Preistoria e Protostoria, Firenze. pp. 455–459

Beck MR (2009) Lå Danmarks første pløjemark ved Egense? Svendborgs Museums Årbog, pp. 7–16
Bogaard A (2004) Neolithic farming in Central Europe: an archaeobotanical study of crop husbandry practices. Routledge, London and New York
Bogaard A, Fochesato M, Bowles S (2019) The farming-inequality nexus: new insights from ancient Western Eurasia. Antiquity 93(371):1129–1143. 2019
Bronk Ramsey C (2009a) Bayesian analysis of radiocarbon dates. Radiocarbon 51(1):337–360
Bronk Ramsey C (2009b) Dealing with outliers and offsets in radiocarbon dating. Radiocarbon 51(3):1023–1045
Bronk Ramsey C (2017) Methods for summarizing radiocarbon datasets. Radiocarbon 59(2):1809–1833
Brophy K, Wright D (2021) Possible Neolithic ard marks and field boundaries at Wellhill and Cranberry, Perth and Kinross, and an evaluation of current physical evidence for Neolithic farming in Scotland. Proc Soc Antiqu Scotl https://doi.org/10.9750/PSAS.150.1295
Bullock P, Fedoroff N, Jongerius A (1985) Handbook for soil thin section description. Waine, Albrighton
Caulfield S (1978) Neolithic fields: the Irish evidence. In: Bowen C, Fowler P (eds) Early land allotment. British archaeological reports, vol 48. BAR Publishing, Oxford, pp. 137–143
Childe VG (1936) Man Makes himself. Watts, London
Courty MA, Goldberg P, Macphail R (1989) Soils and micromorphology in archaeology. University Press, Cambridge
Curdy P, Guélat M (2011) Terroirs et habitats préhistoriques dans la région de Vercorin (Valais, Suisse). Une approche pluridisciplinaire. In: Studer J, David-Elbiali M, Besse M (eds) Paysage…Landschaft…Paesaggio… L'impact des activités humaines sur l'environnement du Paléolithique à la période romaine. Cahiers d'archéologie romande, Lausanne, pp. 73–82
De Gattis G, Curdy P, Ferroni AM, Martinet F, Poggiani Keller R, Raiteri L, Sarti L, Zidda G, Mezzena F (2018) Area megalitica di Saint-Martin-de-Corléans—Una visione aggiornata. Documenti, vol 13. Le Château, Aosta
Deák J, Gebhardt A, Lewis H, Usai MR, Lee H (2017) Soils Disturbed by Vegetation Clearance and Tillage. In: Nicosia C, Stoops G (eds) Archaeological soil and sediment micromorphology. John Wiley & Sons, Hoboken, pp. 233–264
Del Lucchese A, Starnini E (2021) Aggiornamenti sulla fase antica della Cultura dei vasi a bocca quadrata in Liguria da una revisione dei materiali ceramici in corso. In: Mottes E (ed.) Vasi a Bocca Quadrata—Evoluzione delle conoscenze nuovi approcci interpretativi. Ufficio beni archeologici, Trento, pp. 37–50
Denaire A, Lefranc P, Wahl J, Bronk Ramsey C, Dunbar E, Goslar T, Bayliss A, Beavan N, Bickle P, Whittle A (2017) The cultural project: formal chronological modelling of the Early and Middle Neolithic sequence in Lower Alsace. J Archaeol Method Theory https://doi.org/10.1007/s10816-016-9307-x
Devos Y, Nicosia C, Vrydaghs L, Modrie S (2013) Studying urban stratigraphy: dark Earth and a microstratified sequence on the site of the Court of Hoogstraeten (Brussels, Belgium). Integrated archaeopedology and phytolith analysis. Quat Int 315:147–166
Ferroni AM, Curdy P, Pizziolo G, Poggiani Keller R, Sarti L, Mezzena F (2018) L'aratura, Il primo intervento. In: De Gattis G, Curdy P, Ferroni AM, Martinet F, Poggiani Keller R, Raiteri L, Sarti L, Zidda G, Mezzena F (eds) Area megalitica di Saint-Martin-de-Corléans – Una visione aggiornata. Documenti, vol 13. Le Château, Aosta, pp. 163–168
Forni G (1998) Évolution et typologie de l'araire et autres instruments agricoles dans les gravures rupestres des Alpes. ArcheAm 5:47–56
Fries JC (1994) Vor- und frühgeschichtliche Agrartechnik auf den Britischen Inseln und dem Kontinent: eine vergleichende Studie. Marie Leidorf, Espelkamp
Gaastra JS, Greenfield HJ, Vander Linden M (2018) Gaining traction on cattle exploitation: zooarchaeological evidence from the western. Bull Inst Archaeol 19:107–122
Gebhardt A (1995) Soil micromorphological data from experimental and traditional agriculture. In: Barham AJ, Macphail RI (eds) Archaeological sediments and soils: analysis, interpretation and management. Routledge, London, pp. 25–40
Gebhardt A, Langohr R (2015) Traces de roulage ou de labour? Le diagnostic micromorphologique. Rev d'Archéom 39:31–38
Greenfield HJ (2010) The Secondary Products Revolution: the past, the present and the future. World Archaeol 42(1):29–54
Gron KJ, Sørensen L (2018) Cultural and economic negotiation: a new perspective on the Neolithic Transition of Southern Scandinavia. Antiquity 92(364):958–974
Helmer D, Blaise É, Gourichon L, Saña-Seguí M (2018) Using cattle for traction and transport during the Neolithic period: contribution of the study of the first and second phalanxes. Bull Soc Préhist Française 115(1):71–98
Huet T (2017) Les gravures piquetées du mont Bego (Alpes-Maritimes). Organisation spatiale et sériation (VIe–IIe millénaire av. J.-C.). Mémoires de la Société Préhistorique Française, vol 63. Société Préhistorique Française, Paris
Huisman DJ, Raemaekers DCM (2014) Systematic cultivation of the Swifterband wetlands (The Netherlands). Evidence from Neolithic tillage marks (c. 4300-4000 cal. BC). J Archaeol Sci 49:572–584
Isaakidou V (2006) Ploughing with cows: knossos and the secondary products revolution. Anim Neolit Br Eur 7:95–112
Kamjan S, Erdil P, Hummel E, Çilingiroğlu Ç, Çakırlar C (2022) Traction in Neolithic Çatalhöyük? Palaeopathological analysis of cattle and aurochs remains from the East and West Mounds. J Anthropol Archaeol. https://doi.org/10.1016/j.jaa.2022.101412
Lewis H (2012) Investigating Ancient Tillage. An experimental and soil micromorphological study. British Archaeological Reports, Oxford
Louwe-Kooijmans LP (2006) Les débuts de la traction animale aux Pays-Bas et ses conséquences. In: Pétrequin P, Arbogast RM, van Willigen S, Bailly M (eds) Premiers chariots, premiers araires. La diffusion de la traction animale en Europe pendant les IV^{e} et III^{e} millénaires avant notre ère. CNRS Éditions, Paris, pp. 191–206
Lüning J (1980) Bandkeramische Pflüge? Fundber Hess 19/20:55–68
Marzocchella A (1998) Tutela archeologica e Preistoria nella Piana campana. In: Guzzo PG, Peroni R (eds) Archeologia e Vulcanologia in Campania. Atti del Convegno. Arte Tipografica, Napoli, pp. 97–133
Mischka D (2011) The Neolithic burial sequence at Flintbek LA3, north Germany and its cart tracks: a precise chronology. Antiquity 85(329):742–758
Mottet M, Gentizon Haller AL, Haller M, Giozza G (2011) Les bâtiments semi-enterrés de Bramois. Un habitat du Néolithique final en Valais (Suisse). Cahiers d'Archéologie Romande 126. Archeologia Vallesiana 8, Lausanne
Poggiani Keller R (2004) Il sito di Trescore Balneario (BG), fra Neolitico ed età del Rame. In: Bianchin Citton E (ed.), L'area funeraria e culturale dell'età del Rame di Sovizzo nel contesto archeologico dell'Italia settentrionale. Quaderni di Archeologia 1:103–122
Poggiani Keller R (2016) I santuari dell'età del Rame di Cemmo, Ossimo-Pat, Borno e Corni Freschi di Darfo B.T. Organizzazione, chronologia e rituali. Bull Musée d'Anthropol Préhist Monaco 56:47–67
Rageth J (1998) Chur-Welschdörfli, Schutzbau Areal Ackermann: urgeschichtliche und römische Funde und Befunde. Archäologische Führer der Schweiz 29. Archäologischer Dienst Graubünden, Chur
Reimer P, Austin W, Bard E, Bayliss A, Blackwell P, Bronk Ramsey C, Butzin M, Cheng H, Ed-wards R, Friedrich M, Grootes P, Guilderson T, Hajdas I, Heaton T, Hogg A, Hughen K, Kromer B, Manning S Muscheler R, Palmer J, Pearson C, van der Plicht J, Reimer R, Richards D, Scott E, Southon J, Turney C, Wacker L, Adolphi F, Büntgen U, Capano M, Fahrni S, Fogtmann-Schulz A, Friedrich R, Köhler P, Kudsk S, Miyake F, Olsen J, Reinig F, Sakamoto M, Sookdeo A, Talamo S (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62: 725–757
Rentzel P, Guélat M (in press) Modalités de l'occupation humaine au cœur du village protohistorique de Gamsen-Waldmatte. Analyse micromorphologique des séquences sédimentaires des terrasses C2 et C15. Cahiers d'Archéologie Romande, Lausanne
Saccoccio F, Marzocchella A, Vanzetti A (2013) The field system of Gricignano d'Aversa (Southern Italy) and the agrarian impact in the Piana Campana, ca. 3900 cal BP. Quat Int 303:82–92
Sherratt AG (1981) Plough and pastoralism: aspects of the Secondary Products Revolution. In: Hodder I, Isaac G, Hammond N (eds) Pattern of the Past: studies in Honour of David Clarke. University Press, Cambridge, pp. 261–306
Sherratt AG (1983) The secondary products revolution of animals in the old world. World Archaeol 15:90–104
Sherratt AG (2006) La traction animale et la transformation de l'Europe néolithique. In: Pétrequin P, Arbogast RM, van Willigen S, Bailly M (eds) Premiers Chariots, premiers Araires. La Diffusion de la Traction Animale en Europe pendant les IV^{e} et III^{e} millénaires avant notre ère. CNRS Éditions, Paris, pp. 329–360
Sørensen L, Karg S (2014) The expansion of agrarian societies towards the north—new evidence for agriculture during the Mesolithic/Neolithic transition in Southern Scandinavia. J Archaeol Science 51:98–114
Stoops G, Marcelino V, Mees F (2010) Interpretation of micromorphological features of soils and regoliths. Elsevier, Amsterdam
Tegtmeier U (1993) Neolithische und bronzezeitliche Pflugspuren in Norddeutschland und den Niederlanden. Deutsche Gesellschaft für Ur- und Frühgeschichte, Bonn
Thrane H (1989) Danish plough-marks from the Neolithic and Bronze Age. J Dan Archaeol 8(1):111–125
Vanzetti A, Marzocchella A, Saccoccio (2019) The Campanian agrarian systems of the late Copper–Early Bronze Age (ca. 4550–3850 cal BP): a long-lasting agrarian management tradition before the Pomici di Avellino eruption. Quat Int 499:148–160
Vosteen M (1996) Unter die Räder gekommen: Untersuchungen zu Sherrats «Secondary Products Revolution». Archäologische Berichte, vol 7. Deutsche Gesellschaft für Ur- und Frühgeschichte, Bonn
Zindel C, Defuns A (1980) Spuren von Pflugackerbau aus der Jungsteinzeit in Graubünden. Helv Archaeol 11:42–45

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Author contributions
SvW directed and designed the research performed Bayesian analysis and co-wrote the paper; SO helped to design the research, performed supplemental Bayesian analysis and cartography and co-wrote the paper; MG conducted sample treatments, performed micromorphological analysis and co-wrote the paper; ALG and MH supervised archaeological excavations and co-wrote the first draft of the paper. All co-authors contributed to the final draft of the manuscript.

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