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Holocene environmental changes and human impact in the northern Swiss Jura as reflected by data from the Delémont valley

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Abstract The construction of the A16-Transjurane motorway revealed evidence of Holocene sediment sequences in the Delémont valley (Canton of Jura, Switzerland). Certain processes begin during the Younger Dryas. Pine forests dominate this cold period, which was unfavourable for pedogenesis; they remain throughout the first half of the Holocene. The meandering river system then becomes stable for more than four millennia. The first signs of human impact on the vegetal cover begin to appear around 3,500 cal BC (Middle Neolithic). An increase in hydric activity occurs between 3,600 and 2,500 cal BC. However, the earliest evidence of the cultivation of cereals dates only to about 2,000 cal BC (Early Bronze Age). Extensive forest clearing and the emergence of cultivated plants occur after 1,400 cal BC. On the cleared slopes the soil erodes and at their foot colluvium deposits accumulate. The densification of the settlement from the Late Bronze Age (1,350–800 cal BC) until the beginning of the Iron Age (800–650 cal BC) contributes to alluvial destabilization. A palaeosol has been identified in all of the Holocene deposits in the valley. The deforestation intensifies between 400 and 100 cal BC while hydric activity decreases. The first centuries of our era record very limited pedo-sedimentary phenomena. However, human presence becomes less marked after 350 cal AD. The slopes are stabilized and the soil develops. From 550 cal AD, an important increase in hydric activity takes place, a probable consequence of a wet fluctuation in the climate. Contemporary forest clearing causes deep gullies. After 750 cal AD, drier conditions set in. This period of stability, marked by occasional rises in the water level, continues until 1,250–1,300 cal AD (Late Middle Ages). Then superficial flows resume and entrenchment of the main waterways occurs, combined consequences of the Little Ice Age and the upsurge in human activity.

Keywords Switzerland · Canton Jura · Quaternary · Alluvial sediments · Palynology · Palaeohydrology · Archaeological sites

Résumé La construction de l'autoroute A16-Transjurane a permis de reprendre la problématique de l'Holocène dans la vallée de Delémont (Canton du Jura, Suisse). Certains processus s'amorcent au Dryas récent. Au cours de cet épisode froid défavorable à la pédogenèse, les forêts de pin dominent; elles perdureront durant la première partie de l'Holocène. Le système méandrisant va ensuite être stable pendant plus de quatre millénaires. Les premiers indices d'anthropisation du couvert végétal apparaissent à partir du Néolithique moyen (environ 3500 cal BC). Une augmentation de l'activité hydrique a lieu entre 3600 et 2500 cal BC. Ce n'est que vers 2000 cal BC, au Bronze ancien, qu'est identifiée la culture des céréales. Un déboisement important lié au développement de l'agriculture n'intervient qu'à partir de 1400 cal BC. Sur les versants défrichés, le sol se dégrade et des colluvions s'accumulent à leur pied.

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A partir du Bronze final (1350–800 cal BC) et jusqu'au début de l'âge du Fer (800–650 cal BC), la densification du peuplement contribue à une déstabilisation alluviale. Un paléosol est repéré dans l'ensemble des dépôts holocènes de la vallée. Entre 400 et 100 cal BC, les défrichements ont tendance à s'intensifier alors que l'activité hydrique décroît. Les premiers siècles de notre ère enregistrent des phénomènes pédosédimentaires très limités. Cependant, au cours de l'Antiquité tardive, dès 350 cal AD, la présence humaine se fait plus discrète. Les versants se stabilisent et les sols se développent. Dès 550 cal AD, une forte reprise de l'activité hydrique a lieu, conséquence probable d'une oscillation humide du climat. Les déboisements contemporains engendrent de profonds ravinements. Après 750 cal AD et jusqu'au début du Bas Moyen Age (environ 1000 cal AD), des conditions plus sèches s'installent. Cette phase de stabilité, marquée de crues épisodiques, se prolonge jusque vers 1250–1300 cal AD. Ensuite, les écoulements superficiels reprennent et les principaux cours d'eau s'enfoncent, conséquences conjuguées du Petit Age Glaciaire et de la recrudescence des activités humaines.

Mots-clés Suisse · Canton du Jura · Quaternaire · Formations fluviatiles · Palynologie · Paléohydrologie · Sites archéologiques

1 Introduction

Intense monitoring of the construction of the A16-Transjurane allowed us to reconsider the basic problem of the Quaternary in the Jura mountain range, in particular that of Holocene deposits. Essentially, the motorway project affected many diverse environments, cutting through archaeological sites as well as zones with little or no traces of human activities. It was therefore logical that a geologist was present from the beginning to study the typology, the genesis and the transformation of these different environments. Stratigraphic sections of sediments and soils impacted to varying degrees by a succession of human occupations were systematically described. Better protected from human influence, wet biotopes such as palaeo-meanders and wetlands were also the subject of in-depth studies. These environments were, in fact, likely to preserve micro- and macro-remains which could inform archaeologists about the evolution of the environment in the occupation zone, or more broadly, in the whole region. This paper is the result of a confrontation between the data gathered by a geologist and data from analyses performed by a palaeobotanist. Our objective is to synthesize the numerous interdisciplinary results, which still remain mostly unpublished.

This paper is divided in five chapters. After a short presentation of context and used methods, the results of palynological and sedimentological studies on floodplain deposits are presented. The details of these appear in the Supplementary Electronic Material (Online Resource 1: explanation; Online Resources 2–8: tabulated data from the eight main sites described in text). The compilation of all these data leads to a palaeo-environmental synthesis and to conclusions.

1.1 Regional context

Located in the north-western Switzerland, in the northern section of the Jura Mountains, the Delémont valley (canton Jura) is in the centre of the folded part of the mountain range, halfway between the Rhine rift valley and the Swiss plateau (Fig. 1). This wide valley, occupying a syncline in the folded structure, stretches over 25 km in an E–W direction, with a maximum width of 8 km, and a total surface of about 200 km^2. It is delimited by anticlinal structures forming ridges of more than 1,000 m in height, formed by upper Jurassic marls and limestones. At an average altitude of 450 m, the valley bottom is covered with Oligocene molasse and, in places, by Miocene sand and gravel derived from the Vosges Mountains to the north (Kälin 1997). Under these terrains, overlying karstified Jurassic limestone, Eocene formations ("Siderolithic") are found, whose exploitation for the iron and steel industry which in the Delémont valley only ceased at the beginning of the 20th century.

The Quaternary sediments, which can be more than 5 m thick, mainly consist of fluviatile formations, slope deposits and peat. Earlier works on these terrains are quite rare, although an attempt at stratigraphic dating was already published in the 19th century (Greppin 1855). The principal stratigraphic units are defined in the first defined in the first 1:25,000 geological map published in the Geological Atlas of Switzerland (Keller and Liniger 1930). The geomorphological approach of Barsch (1969) shows no major changes in the stratigraphic units defined in this map. With the construction of the A16 motorway beginning in the 1990s, a considerable amount of new data has been published, particularly environmental studies related to the archaeological excavations (Guélat et al. 1993). For an overview of the stratigraphic and archaeological subdivisions used for the Upper Pleistocene and Holocene of the present area, see Table 1.

The reference sites for this paper are located in the very centre of the basin, within a radius of 6 km south of the town of Delémont (Figs. 1, 2). This sector of roughly 30 km^2 is near the confluence of three rivers, the Pran, the Sorne and the Birse, which flow northwards to join the

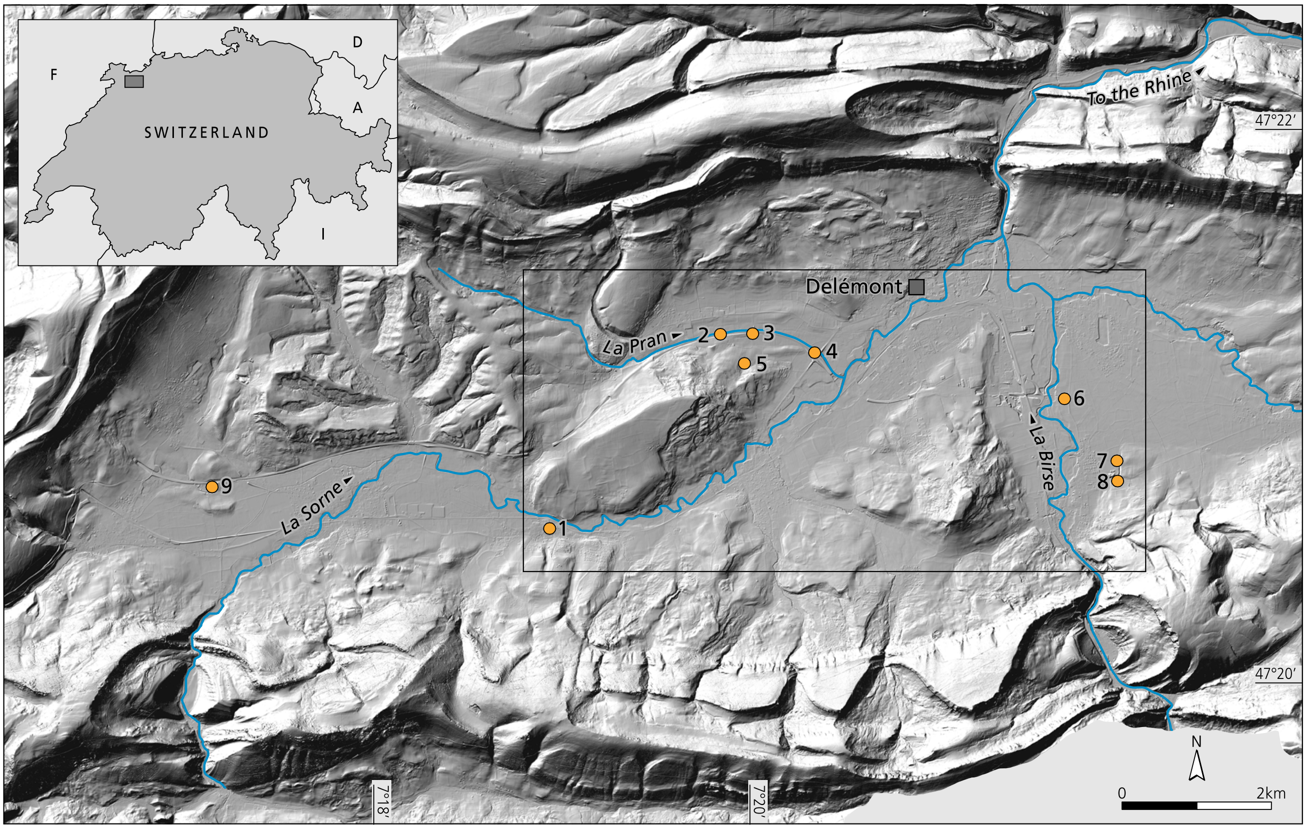


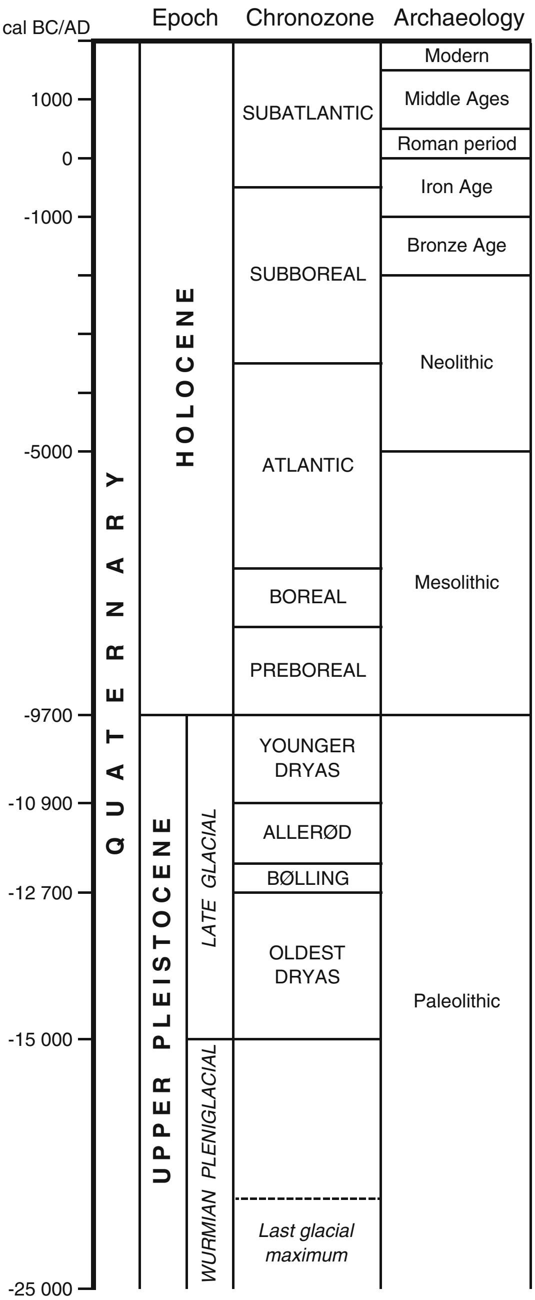
Fig. 1 Geographical position of the study area. The Delémont valley is located in north-western Switzerland, in the Jura Mountains (frame: map Fig. 2). In the central part of the basin, the reference sites are: *1* Courfaivre-La Faverge, *2* Develier-Courtételle, *3* Courtételle-Tivila, *4* Delémont-En La Pran, *5* Courtételle-La Rintche, *6* Courrendlin-Vers La Vieille Eglise, *7* Courrendlin-En Solé, *8* Courrendlin-Les Pécas; in the western part: *9* Boécourt-Les Montoyes (MNT laser du Canton du Jura, 2001–2007). Detailed tabulated descriptions of Sites 2–8 are to be found in the Electronic Supplementary Material, as Online Resources 2–8

Rhine in Basel. This zone shows a maximum development of the Quaternary alluvial sheets. The highest position in the landscape is occupied by discontinuous fluviatile gravel forming the T3 terrace, whose genesis dates from the lower to middle Würmian Pleniglacial (Braillard and Guélat 2008). A second gravel sheet with a rather large lateral extension, terrace T2, extends to the foot of the slopes. As indicated below, it was formed during the upper Würmian Pleniglacial. The third individualized alluvial unit, T1, occupies the bottom of the valley along the waterways. It includes deposits from the Late Glacial to the Holocene (Table 1); these can also overlay sedimentary bodies related to T3 and especially T2 units, in particular in the lateral valleys. This is the case on the floodplain of the small river “La Pran”, a tributary of the Sorne localised to the west of Delémont, where four of the eight reference sites are found (Fig. 2, Sites 2–5). Three other sites (Fig. 2, Sites 6–8) are located in the plain of the Birse, southwest of the town, while southwest of the study area, the wetlands sequence of Courfaivre-La Faverge (Fig. 2, Site 1) provided a record of the vegetal cover history.

1.2 Vegetation

In the Jura, the vegetation of the Delémont valley is characteristic of the “middle region”, located at an altitude between 400 and 700 m, as defined by Thurmann (1849). The centre and the lower slopes of this basin are characterized by the dominance of beech groves in which species such as oak, wild cherry or fir only have secondary importance. Ash and alder are limited to flooded or marshy areas; the rocky areas are the domain of lime and maple forests, and the exposed scree-covered slopes are occupied by oak. The composition of the forest massif is characteristic of the sub-mountain level of Ellenberg’s (1996). The lower hillsides are more temperate and here beech gives way to more thermophilic species: oak, hornbeam and wild cherry. This association is not present as such in the Delémont valley, but the well-exposed rocky slopes above the town, covered by oak groves, constitute a hillside microclimate. The cooler climate of the mountain stage eliminates the thermophilic species and is more favourable for fir than beech. Nevertheless, the forest has occupied

Table 1 Chronological subdivisions used in the text



less than half of the surface of the region for a long time, and fields, meadows and pastures dominate. Until the middle of the 20th century, the variety of soils, the diversity of the local climates and the different types of agricultural land use resulted in a large variety of vegetal associations. The intensification of agriculture, the carrying out of land improvements and the use of fertilizers have obscured this rich ecological diversity to the point where calcareous or wet meadows have almost disappeared, resulting in a drastic depletion of the flora.

Data gathered during the recent excavations allowed us to reconstruct the history of the vegetal cover in this part of the Jura. The higher zones were investigated very early by pollen analysis, as exemplified by the founding works of Wegmüller (1966) and Matthey (1971). Other sequences followed (Hubschmid and Lang 1985; Beaulieu et al. 1994; Schoellammer 1997; Magny et al. 1998; Richard and Eschenlohr 1998; Bichet et al. 1999; Di Giovanni et al. 2002), but they now appear somewhat obsolete and less precisely dated than more recent studies. In-depth studies have also been carried out to the south, on alluvial plains of the central Swiss plateau (for example: Ammann 1989; Ammann and Lotter 1989; Gaillard 1984; Richoz 1998; Wehrli et al. 2007), and more to the west in the vicinity of lakes Neuchâtel, Biel and Morat (Borrello et al. 1986; Hadorn 1992, 1994; Rachoud-Schneider 1997; Richard 2000). The Delémont valley remained as an “intermediate zone” where the most detailed palynological studies were carried out by A.-M. Rachoud-Schneider (Guélat et al. 1993, 2008).

2 Methods

2.1 Stratigraphy and sedimentology

The local stratigraphy, the sedimentology and the phasing of each site are shown in the summary tables (Online Resources 1–8). These also include the main sedimentological data from analyses carried out by the Integrative Prehistory and Archaeological Science laboratory at the University of Basel. Further diagnostics on the buried soils were made using micromorphology, a technique consisting of a microscopic examination of loose sediments which had been subjected to induration.

2.1.1 Granulometry

Based on bulk samples taken from soil profiles and cross sections, the gravel fraction (>2 mm) was tested using the dry sieve method and the sandy fraction with a wet sieve on a vibrating column (Fritsch Laborette). The clayey silt fraction (<63 µm) was analysed with a laser granulometer (Malvern MasterSizer MS20). An Excel application was specially developed to process the raw results (Guélat et al. 2008). This program also calculates the median of the granulometric curve and the Trask sorting index, and allows a characterization of the fluviatile formations using Passega’s (1964) method.

2.1.2 Geochemistry

Chemical analyses were done on a fraction <0.5 mm of the samples and include: the total percentage of carbonates

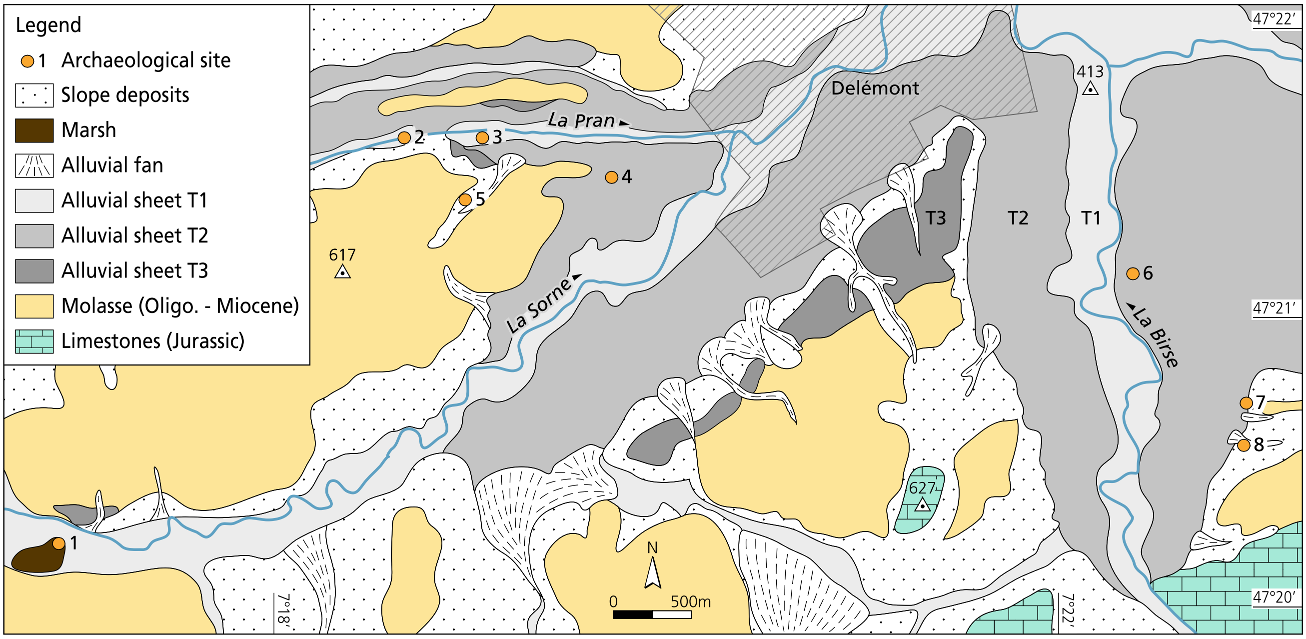


Fig. 2 Geological map of the central part of the Delémont valley (location: see Fig. 1). Quaternary formations consist primarily of fluvial sediments, slope deposits and peat (marsh deposits). Modified from Keller and Liniger (1930). The built-up area of the town of Delémont is shown with a *diagonal shading*

measured with Müller's calcimeter; the percentage of organic matter by combustion after burning at 1,000 °C; the total percentages in phosphates and in humus obtained by colorimetry; the pH, measured with a pH-meter in a potassium chloride solution (KCl).

2.2 Palynology

The sediments were taken directly from the sections prepared by one of the authors (MG) after a precise stratigraphical description. The sediments were extracted in metal boxes and conserved in plastic film in a cold room. The sampling was done in the laboratory. Two cubic-centimeter of sediments were taken from every layer, with a sampling step which was more or less dense depending on the site. When the layers were thin, the quantity taken could drop to 1 cm^3. All the samples were prepared following a concentration method with a dense solution of zinc chloride ZnCl_2 (Björck et al. 1978). Most often, the entire residue obtained after the preparation was read under a microscope (Zeiss, 200× or 400×). Determinations were made using the reference collection of the Chrono-Environment Laboratory of Besançon, the determination keys of Faegri and Iversen (1989), and the works of Reille (1992, 1995, 1999). Non-pollinic microfossils were also determined in the more recent samples, mainly by consulting the works of Van Geel (2001) and Van Geel et al. (2006). The pollen diagram was done in a classic way using Tilia and TiliaGraph software (Grimm 1991).

2.3 Dating

The following nomenclature is used in the chronology (Online Resources 2–8):

- The uncalibrated ^{14}C dates are given in years Before Present (BP).
- The ^{14}C dates calibrated with a probability of 95.4 % are indicated in years cal BC/cal AD (Before Christ/Anno Domini); calibration was done with Oxcal 4.2 [74] software, using the Intcal04 curve for most of dates (issued from the database of the cantonal Section of Archaeology), and the Intcal09 curve for those older than 10,000 cal BC, according to Reimer et al. (2009).
- The dates based on archaeological data, or obtained by dendrochronological analyses, or referring to historical regional chronology, are given in years BC/AD.

Moreover, two optically stimulated luminescence (OSL) dates were acquired from the site of Courrendlin-En Solé (Online Resource 7) by the laboratory of the Geographical Institute of Cologne University. In the field, OSL samples were extracted by planting PVC tubes to core sediment without exposing it to light. The extremities of the tubes, partly exposed to light, were sawed off and used for the dosage of radionuclides (U, Th and K). The sediment contained in the central part of the tubes, and specifically the 4–11 µm fraction, was used to determine the palaeo-doses on multiple aliquots according to the regenerative method (Wintle 1997). The luminescence ages are given in ka.

2.4 Other studies

In some of the summary tables (see Online Resources), the results from other scientific analysis are briefly mentioned. These data are the result of work carried out by the following colleagues: Ch. Brombacher (University of Basel) for the analysis of vegetal macro-remains or carpology, N. Thew (Neuchâtel) for malacology, and L. Chaix (University of Geneva) for the determination of fauna remains.

3 Results

3.1 The peat deposits of Courfaivre-La Faverge (Site 1)

3.1.1 Samples and radiocarbon dates

The two palynology samples taken from the vertical section of a sedimentary sequence of 74 cm, beginning at a depth of 22 cm below the surface (Fig. 3). Thirty-eight samples were taken from this sequence for pollen analysis (Fig. 4). They involve all the layers described, including the gravel at the bottom (layer 4) and the overbank deposits near the surface (layer 2). Vegetal macro-remains taken from the following sediments provided three ^{14}C dates (Fig. 3):

- bottom of layer 3.3 (90.5 cm): 10,035 ± 50 BP, or 9,820–9,330 cal BC (ref.: Ly-8301);
- top of layer 3.3 (60.5 cm): 8,760 ± 45 BP, or 8,000–7,600 cal BC (ref.: Ly-8300);
- top of layer 3.1 (30.5 cm): 3,860 ± 30 BP, or 2,470–2,200 cal BC (ref.: Ly-8299).

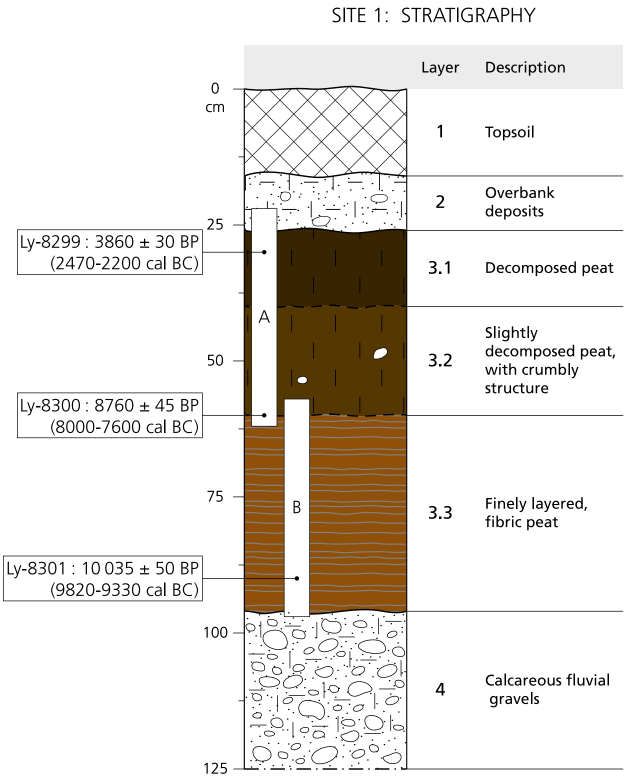


Fig. 3 Stratigraphy at Site 1 (Courfaivre-La Faverge). Samples for pollen analysis (*A* and *B*) were extracted from the peat where three ^{14}C dates were acquired

If we assume a very hypothetical continuity of sedimentation, the bottom of the sequence (sample 97 cm) would date back to 10,900–10,800 cal BC and the top (sample 23 cm) would date to about 100–300 cal AD. Five local pollen zones, the main zones C1–C5, were distinguished; the most recent (C5) is divided into four subzones, C5a–C5d (Fig. 4). In the following, the vegetation history of the peat deposits at Site 1 is reconstructed on the basis of these palynological and radiocarbon dating results.

3.1.2 Zone C1 (97–89 cm)

This first local pollen zone is dominated by pine (*Pinus*), which accounts for about 80 % of the total pollen sum but is nevertheless less well represented than in the following zone (C2). Pine is very discreetly associated with birch (*Betula*), willow (*Salix*) and juniper (*Juniperus*). C1 is distinguished from C2 by a greater representation of herbaceous plants in C1 (Fig. 4, centre). In addition to the peak of *Cyperaceae*, the presence of herbaceous plants with a rather heliophilic character, such as *Artemisia* and *Chenopodiaceae*, as well as *Poaceae* and *Apiaceae*, marks this zone.

The ^{14}C sample from the upper part of zone C1 (9,820–9,330 cal BC) date it to the last episode of the Late Glacial, the Younger Dryas. All of zone C1 could be attributed to this cold period whose pollen picture at Courfaivre, with a dominant pine forest, is different from what is generally the case in the Jura Mountains (see Bégeot et al. 2000; Magny et al. 2006), where the pollen diagrams from an altitude of 700–800 m show instead a Younger Dryas in which pine is less present and where the open areas are the domain of heliophile plants, particularly *Artemisia*. On the sites closest to the Swiss plateau, forests of pine and birch seem sparser, interspaced by clearings or glades favourable to heliophile taxa (see Schwalb et al. 1998; Richoz and Magny 2000).

3.1.3 Zone C2 (87–75 cm)

This phase is mainly dominated by pine which varies around 90 %. Few other trees and shrubs are present: birch, willow and some juniper occur, and at the end of the phase, hazel (*Corylus*) becomes important. Among the herbaceous plants, only the *Poaceae* and the *Cyperaceae* are constantly present. These characteristics, and particularly the

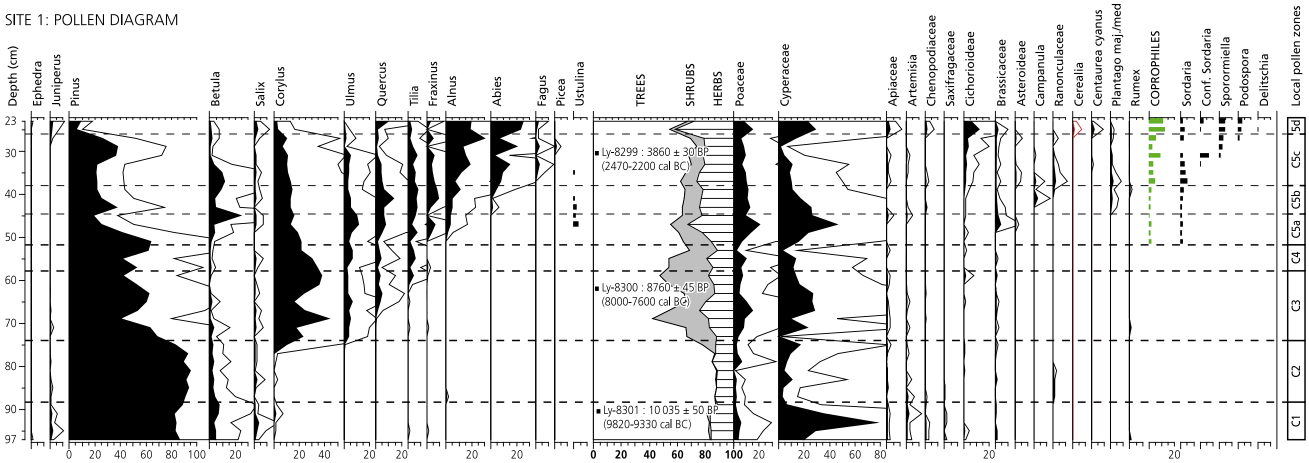


Fig. 4 Pollen diagram of Site 1 (Courfaivre-La Faverge). Analysis: H. Richard, E. Gauthier and M. Boucheron. For sample location and stratigraphic framework, see Fig. 3. The diagram was drawn using Tilia and TiliaGraph software (Grimm 1991). The percentages were calculated by excluding spores and *Cyperaceae* pollen grains from the total pollen count. The *left side of the diagram* contains the tree and shrub pollen, the *right one* herbaceous pollen and spores; the *central part* summarizes the proportion of tree, shrub and grass pollen, and the radiocarbon dates. The *column at the far right of the diagram* corresponds to the local pollen zones (LPZ). Five main zones (*C1–C5*, oldest to most recent) were distinguished; the most recent (*C5*) is divided into four subzones (*C5a–C5d*)

predominant position of pine, mean that zone C2 can be attributed entirely to the beginning of the Holocene, approximately between 9,500 and 8,200 cal BC.

3.1.4 Zone C3 (73–59 cm)

In zone C3, there is a clear decrease in pine which varies between 40 and 50 %, with very irregular percentages. Other taxa in zone C3 are also marked by this irregularity: hazel and some herbaceous plants, for example. This zone covers a part of the sequence in which spore and pollen material is poorly preserved and this can affect the regularity of the percentages of some taxa. After pine, hazel characterizes this zone. These two species are accompanied by elm (*Ulmus*) and, in the upper part, by oak (*Quercus*) and lime (*Tilia*). The pollen grains of herbaceous plants show little taxonomic diversity, they are still dominated by *Poaceae* and *Cyperaceae*.

The second ^{14}C date (8,000–7,600 cal BC) is obtained from zone C3. The association of hazel and pine is characteristic of this period but, at this altitude, pine seems to persist for a long time and thus slows down the development of hazel. The persistence of pine is also confirmed at the site of Boécourt-Les Montoyes located 4.5 km west of Courfaivre, at an altitude of 490 m (Guélat et al. 1993; Fig. 1, Site 9). A similar situation has been observed in the western part of the Jura Mountains and on the Burgundy plains, such as at Molesme, at an altitude of 185 m, where pine continues to dominate until about 3,500–3,000 cal BC (Gauthier et al. 2005). This dominance of pine also seems to affect the first representations of the mixed oak grove, such as elm and oak, which are much more present at higher altitudes during the same period (for example: Magny et al. 1998). It should be pointed out that the ^{14}C date from the top of layer 3.3 (8,760 ± 45 BP) is somewhat too old in comparison to the regional pollen stratigraphy (Wegmüller 1966; Matthey 1971; Beaulieu et al. 1994).

3.1.5 Zone C4 (57–53 cm)

Pine still dominates this short phase, characterized by the progressive decline of hazel and the stabilization of elm, oak and lime. The taxonomic diversity of herbaceous plants is poorest in zone C4. The three samples from C4 are undoubtedly part of the Early Atlantic. But due to very poor sedimentation or the presence of lacunae, this pollen zone, which nevertheless lasts for two millennia, is poorly represented in this sequence. The Early Atlantic at the site of Boécourt-Les Montoyes is also very incomplete, with a hiatus at about 6,000 cal BC.

3.1.6 Zone C5 (51–23 cm) divided into subzones C5a, C5b, C5c, C5d

Unlike the four preceding zones, zone C5 is defined by the presence of pollen indicating a human impact in the vicinity. These indicators are however very discreet. Some spores of a group of coprophilic fungi belonging to the family of Sordariales appear in a modest but regular manner in C5a. Some herbaceous plants also seem favoured in this zone, such as *Poaceae*, *Cyperaceae* and *Brassicaceae*, particularly in sample 47 cm. The pollen grains of trees and shrubs from this phase indicate the decrease of pine and the arrival of ash (*Fraxinus*) and alder (*Alnus*); the presence of *Ustulina* ascospores, parasites of wood in decomposition, at the end of this phase is noteworthy. It indicates a discreet human influence during phase C5a. However, no direct evidence of deforestation is visible; livestock may have only used forest pastures. It is also difficult to situate this phase chronologically. By extrapolation based on the two upper ^{14}C dates (Fig. 3), this first trace of human presence could date back to the Middle Neolithic (around 3,500 cal BC). Neolithic markers of pastoralism in this sequence are a novelty in this region that, until now, was assumed to be colonized by farmers during the Early/Middle Bronze Age. At Delémont-En La Pran, located at about 4 km northeast of Courfaivre, the first cereal pollens only appear at about 2,000 cal BC, during the Early Bronze Age (Pousaz et al. 2009).

The following subzone, C5b, records the same phenomena but this time with more indicators of open spaces devoted to meadows, particularly with the presence of *Plantago major/media*, as well as the *Campanulaceae* and several layers of *Chenopodiaceae* and *Rumex*. As for trees, this phase is marked by the appearance of fir (*Abies*). The indications of human presence increase in C5c. The herbaceous taxa are more diversified and better represented. *Sordaria* spores are very common along with *Sporormiella* ascospores at the end of the phase and, in the last sample, *Podospora*, two coprophiles, which reinforces the evidence of livestock in the vicinity of the site. In the middle of this subzone, the discovery of a pollen grain of *Centaurea cyanus* (cornflower), a messicole plant, self-propagating in cereal fields, is noteworthy as a tenuous indication of crops. The most notable change among trees is the appearance of beech and, to a very modest degree, spruce. The upper ^{14}C date (2,470–2,200 cal BC) was provided by a sample from the centre of subzone C5c, which would place it in a range covering the end of the Neolithic and perhaps the very beginning of the Early Bronze Age. The last subzone, C5d, corresponds to the two uppermost samples analysed (25 and 23 cm). In this subzone, the presence of livestock is marked by coprophilic fungi (*Sordaria, Sporormiella, Podospora, Delitschia*). Meadows are also shown by an increase in herbaceous plants such as *Poaceae*, *Cyperaceae*, *Chenopodiaceae* and *Cichorioideae*; juniper could also be present in these open spaces. For the first time, pollen grains of cereal were found in these two samples, they are accompanied by *C. cyanus*, attesting to the presence of crops near the site. It is difficult to date this last subzone, but by extrapolation of the ^{14}C date made at a depth of 30.5 cm, subzone C5d could be placed in the Early Bronze Age (2,200–1,550 cal BC).

3.1.7 *Nine millennia of history of the vegetal cover*

This sequence of only 74 cm of sediments recorded the history of the lowland vegetation of this part of the Swiss Jura over a period of roughly 9,000 years. The first samples date to the end of the Late Glacial while the more recent ones are contemporary with the Early Bronze Age. However, all the periods are not equally represented due to variable and at times absent sedimentation. This is to be expected in such an oxbow environment. Moreover, some layers show rather poorly preserved spore and pollen material. In spite of these reservations, this sequence gives a detailed picture of the evolution of the vegetal cover, particularly of interest because of its relatively low altitude. Thus, the cold period of the Younger Dryas, very little marked by the usual steppe environment, is dominated by pine forests which persist for a considerable span of time during the first half of the Holocene, limiting the expansion of hazel and the first elements of a mixed oak grove. There is a limited development of fir in the more recent layers, with a discreet presence of beech and the quasi-absence of spruce, while the areas near the waterways are covered with alder. The first very discreet indications of the presence of livestock around this site could be dated to the Middle Neolithic: this could involve only limited pasturing in the forest. These practices will become more and more important, although the cultivation of cereals remains almost imperceptible before the topmost layers, which could belong to the Early Bronze Age.

Two ^{14}C dates recently obtained from the Boécourt-Les Montoyes site (Site 9 on Fig. 1) are of importance here (Demarez et al. 2013; Fig. 5). One was obtained from a charred wind-blown tree (Ua-4368: 3,017 ± 31 BP, or 1,390–1,130 cal BC) and the other on a fir stump, which was also carbonized (Ua-43681: 2,758 ± 30 BP, or 1,000–820 cal BC), confirming that extensive forest clearing only occurred from the second half of the Bronze Age onwards, as indicated by the pollen spectra.

3.2 The Pran floodplain (Fig. 2: Sites 2–5)

3.2.1 *Site 2 (Online Resource 2)*

Palaeo-environmental studies on this Early Middle Age archaeological site were the subject of a monograph by Guélat et al. (2008). Situated at a mean altitude of 450 m, it is in the western part of the alluvial plain of the Pran. With a total surface of 3.5 ha (1 ha = 10,000 m^2), its stratigraphic sequence goes from the upper Würmian Pleniglacial to the recent Holocene (Fig. 6). The Quaternary sediments, with a thickness of 2–4 m, mainly consist of fluviatile formations and buried soils, and more rarely organic deposits. Chronostratigraphic and sedimentological approaches result in a palaeo-geographic and

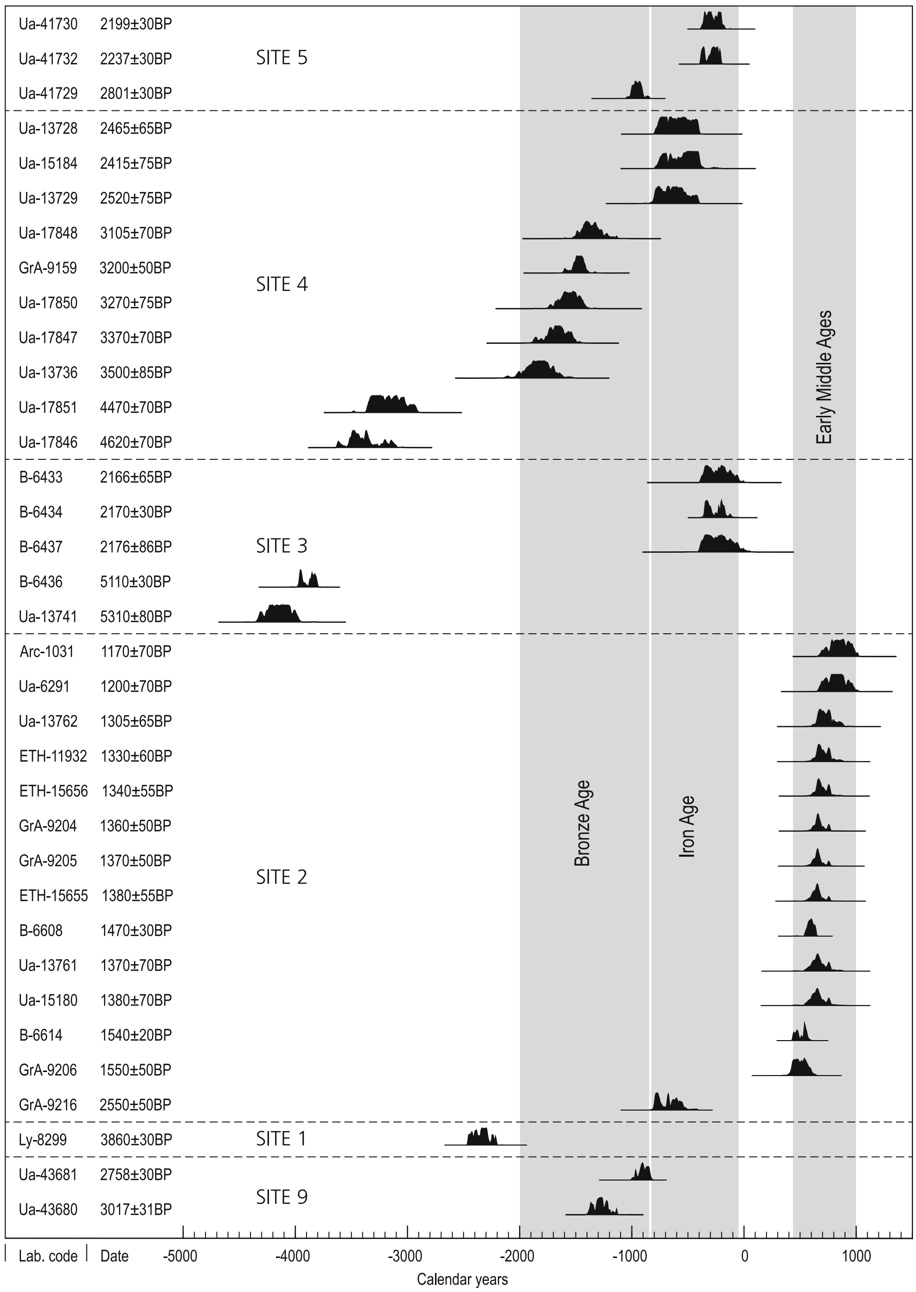


Fig. 5 Radiocarbon dates of the Pran floodplain (Sites 2–5) between 5,000 cal BC and 1,500 cal AD. This compilation highlights the successive phases of human occupation (for full references, see Online Resources 2–5). For comparison, the radiocarbon dates obtained from Sites 1 and 9 (see Fig. 1) are added

palaeohydrological reconstruction, mainly from the period from about 500–800 cal AD. This period, contemporary to the Merovingian hamlet occupied between 575 and 750 cal AD (Fellner et al. 2007), generated abundant deposits; in addition, it provided numerous radiocarbon dates (Fig. 5).

3.2.2 *Site 3 (Online Resource 3)*

Although of a very small size (140 m^2), this site occupied during the Late Iron Age (400–30 cal BC) is of interest because of its central position in the Pran floodplain, at an altitude of 440 m. Its environmental analysis was partly integrated in publications of neighbouring sites (Guélat et al. 2008; Pousaz et al. 2009). Archaeological excavations showed a thickening of deposits in the form of a succession of filled palaeochannels, which show a migration of the stream toward the north side of the plain (Fig. 7). The transition between the Iron Age and the Roman period (about 150 cal BC–100 cal AD) is also recorded.

3.2.3 *Site 4 (Online Resource 4)*

This large prehistoric site covering a surface of 4 ha also generated palaeo-environmental analyses, leading to multidisciplinary publications (Pousaz et al. 2009; Guélat et al. 2011). It is located at the opening of the valley of the Pran

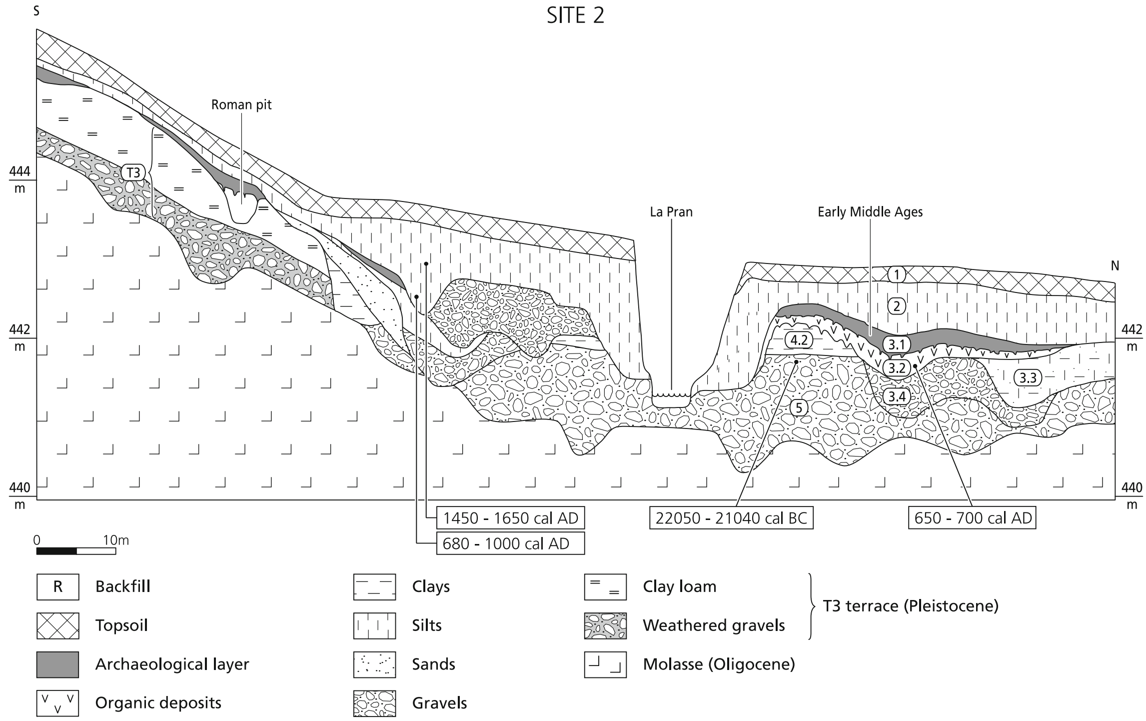


Fig. 6 Compiled cross-section through Site 2 (Develier-Courtételle), constructed from the field and laboratory data collected from the site area. Holocene deposits are mainly palaeochannels with partly organic fills and flood loam. The upper Pleistocene alluvial sheet (T3) forms here the southern edge of the valley (height exaggerated by a factor of 10). The local stratigraphy and sedimentology (*ringed numbers*) is described in detail in Online Resource 2

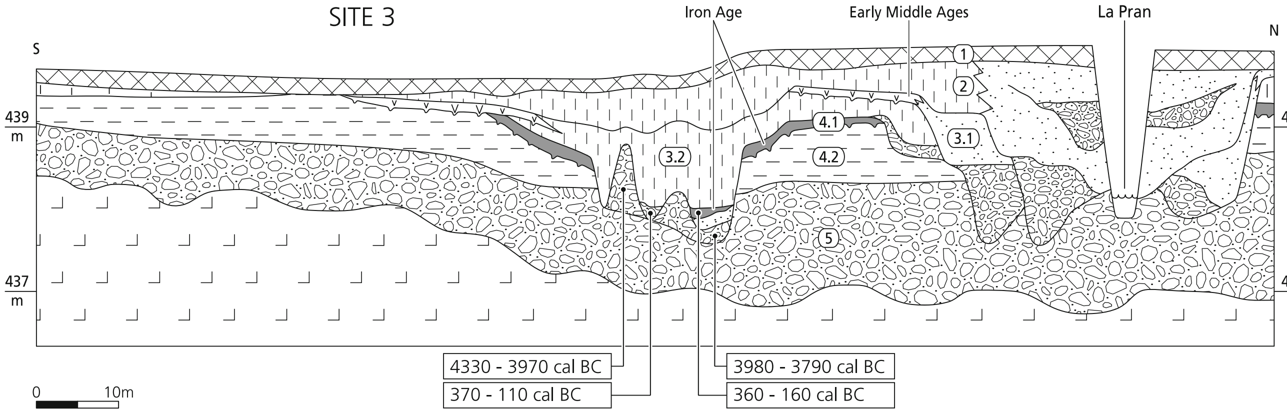


Fig. 7 Compiled cross-section through Site 3 (Courtételle-Tivila), constructed from the field and laboratory data collected from the site area (legend in Fig. 6; height exaggerated by a factor of 10). The local stratigraphy and sedimentology (*ringed numbers*) is described in detail in Online Resource 3

in the central part of the Delémont basin, at an altitude of 430 m. Its sequence mainly has an alluvial character, which is similar to that of the other sites of the plain, but with several particularities. First, it includes deposits from the Late Glacial containing charcoal from which ^{14}C dates can be obtained (Fig. 8). It offers a better resolution for the period between 2,000 and 400 cal BC, during which an evolution of the landscape and of the settlement can be observed.

Carpological and palynological studies by C. Brombacher and A.-M. Rachoud-Schneider (in Pousaz et al. 2009) document the period between roughly 2,000 cal BC and the Iron Age. The beginning of this period, corresponding to the Early Bronze Age, is dominated by a grove of beech-fir in which hazel, and some oak and lime are found; the bottom of the valley, more humid, is the domain of the alder. Human impact on the vegetal cover is still limited, but it becomes more and more important,

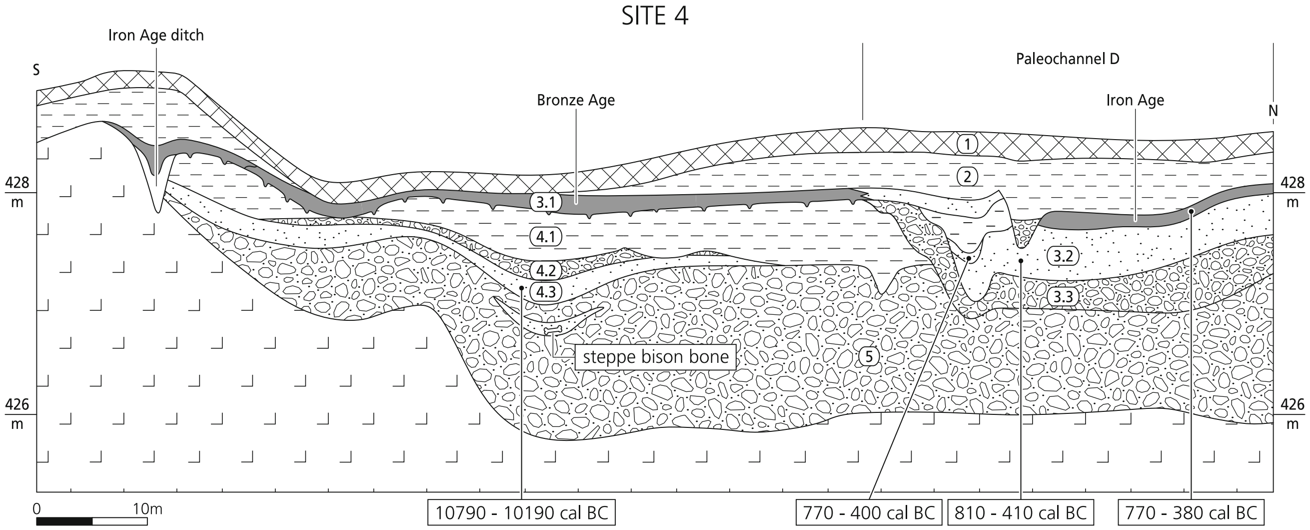


Fig. 8 Compiled cross-section through Site 4 (Delémont-En La Pran), constructed from the field and laboratory data collected from the site area. The sedimentary sequence includes Late Glacial and Early Holocene deposits and also palaeochannels filled between about 2,000 and 400 cal BC (legend in Fig. 6). The archaeological layer was formed during the Bronze and Iron Ages and constitutes a marker horizon all along the A16 motorway (height exaggerated by a factor of 10). The local stratigraphy and sedimentology (*ringed numbers*) is described in detail in Online Resource 4

and the first cereals appear. This impact is increasingly marked toward the end of the Middle Bronze Age. The forest diminishes, the ecosystems diversity has increased and the landscape is more complex. Cultivated plants (i.e. cereals, millet, lentil, broad beans) are very present at this site and confirm sustained agricultural activities in the vicinity. This activity is accelerated in the Late Bronze Age during which the forested surfaces recede, and meadows and farming expand. Carpology shows the diversity of these crops, as well as sustained gathering activities.

The environment of the Iron Age is partially recognized at Delémont-En La Pran and at the site of Courtételle-Tivila (Frei Paroz et al. 2012). After a limited reforestation at the beginning of the Iron Age, observed in numerous Jura sites (e.g. Gauthier 2004; Gauthier and Richard 2007), and thought to be of climatic origin (Van Geel and Magny 2000), clearings expand during the Late Iron Age. Crops are diversified and the wet meadows are farmed.

3.2.4 Site 5 (Online Resource 5)

Located in a small lateral valley at an altitude of 460 m, this unpublished site was the subject of a geological expertise. Spread over an area of 2,600 m^2, the site produced Bronze and Iron Age remains and is complementary to the other sites of the alluvial plain. The site stratigraphy, between 0.5 and 3.6 m thick, represents an incomplete succession of buried soils and slope sediments, of which debris flow deposits at the base are related to the Late Glacial (Fig. 9). However, some ^{14}C dates and archaeological remains allow us to determine the principal pedo-sedimentary phases. The slopes, or at least their lower part, underwent a first impact of human activities at the beginning of the Late Bronze Age, at about 1,300 cal BC. The stratigraphic record shows an increasing instability of the terrain overlying the molasse and subsequent gullying. In the Late Iron Age, between about 150–50 cal BC, a charcoal-rich occupation layer is formed, which is stratigraphically positioned above the soil developed during the first half of the Holocene and under the more recent colluvia: this palaeosol constitutes a real marker horizon appearing in the Holocene sequences all along the A16 motorway (Guélat 2006).

3.3 The Birse floodplain (Fig. 2: Sites 6–8)

Sites 6–8 provided a large number of radiocarbon dates, which are summarized on Fig. 10. In the following, the results from the individual sites are briefly described (for details, consult Online Resources 6–8).

3.3.1 Site 6 (Online Resource 6)

This site, located centrally in the eastern part of the Delémont basin at an altitude of 425 m, was recently published in a multidisciplinary study (Demarez et al. 2011). It is located on the right bank of the Birse river near the western erosional limit of the T2 alluvial sheet, about 10 m above the valley bottom T1 (Fig. 11). The Quaternary sediments reach a maximal thickness of 2.9 m in this area. Spread over 1,750 m^2, the excavations revealed a

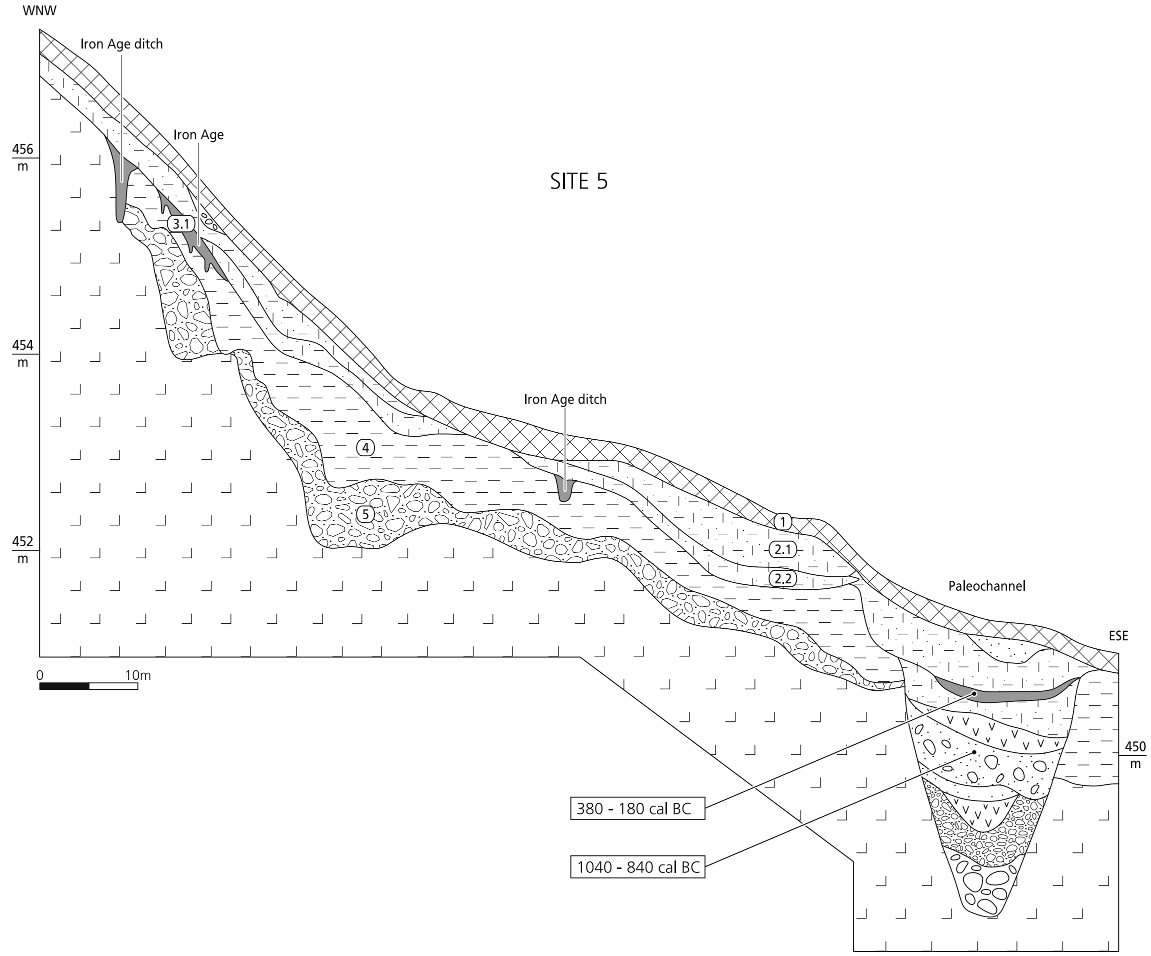


Fig. 9 Compiled cross-section through Site 5 (Courtételle-La Rintche), constructed from the field and laboratory data collected from the site area located in a small lateral valley cut into the Oligocene molasse. At the foot of the slope, a deep palaeochannel was filled with partly organic deposits (legend in Fig. 6; height exaggerated by a factor of 10). The local stratigraphy and sedimentology (*ringed numbers*) is described in detail in Online Resource 5

Roman occupation situated along an ancient roadway. These traces were preserved within an abandoned meander that was still active before roughly 800 cal BC, during the Late Bronze Age (Fig. 10). From the Early Iron Age onwards, this backwater functioned as a sediment trap and was progressively filled until disappearing in the Middle Ages. The sedimentary sequence was dated up to about 400 cal AD by dendrochronology and ^{14}C samples. Altitude variations of the bed of the Birse make it likely that downcutting of the river accelerated at a later date, after about 1,000 cal AD.

Two series of samples were taken at the Site 6 for palynological analysis. The results and dates are given in Online Resource 6. The samples of the first series, dating between 900–770 cal BC and 70–250 cal AD, are very poor in pollen grains and spores. In addition, the high percentage of *Cichorioideae* and indeterminable grains underlines an obvious problem of differential conservation which affects the accuracy of the results. This series can therefore not be exploited. Although cereal pollen grains are absent, these samples contain relatively large amounts of microcharcoal, which confirms human activity near the river. Several hearths and ovens dating to the Roman period have in fact been discovered in the palaeochannel. The samples of the second series, obtained from silt rich in organic material, contain an acceptable number of pollen grains and spores, although their conservation is often mediocre. These paludal formations are dated to the Late Iron Age and represent the final deposits in the evolution of the abandoned meander before it silted up. A Roman fill covers these deposits.

3.3.2 Site 7 (Online Resource 7)

This still unpublished site, <1 km distant from the preceding one, is also located on the right bank of the Birse,

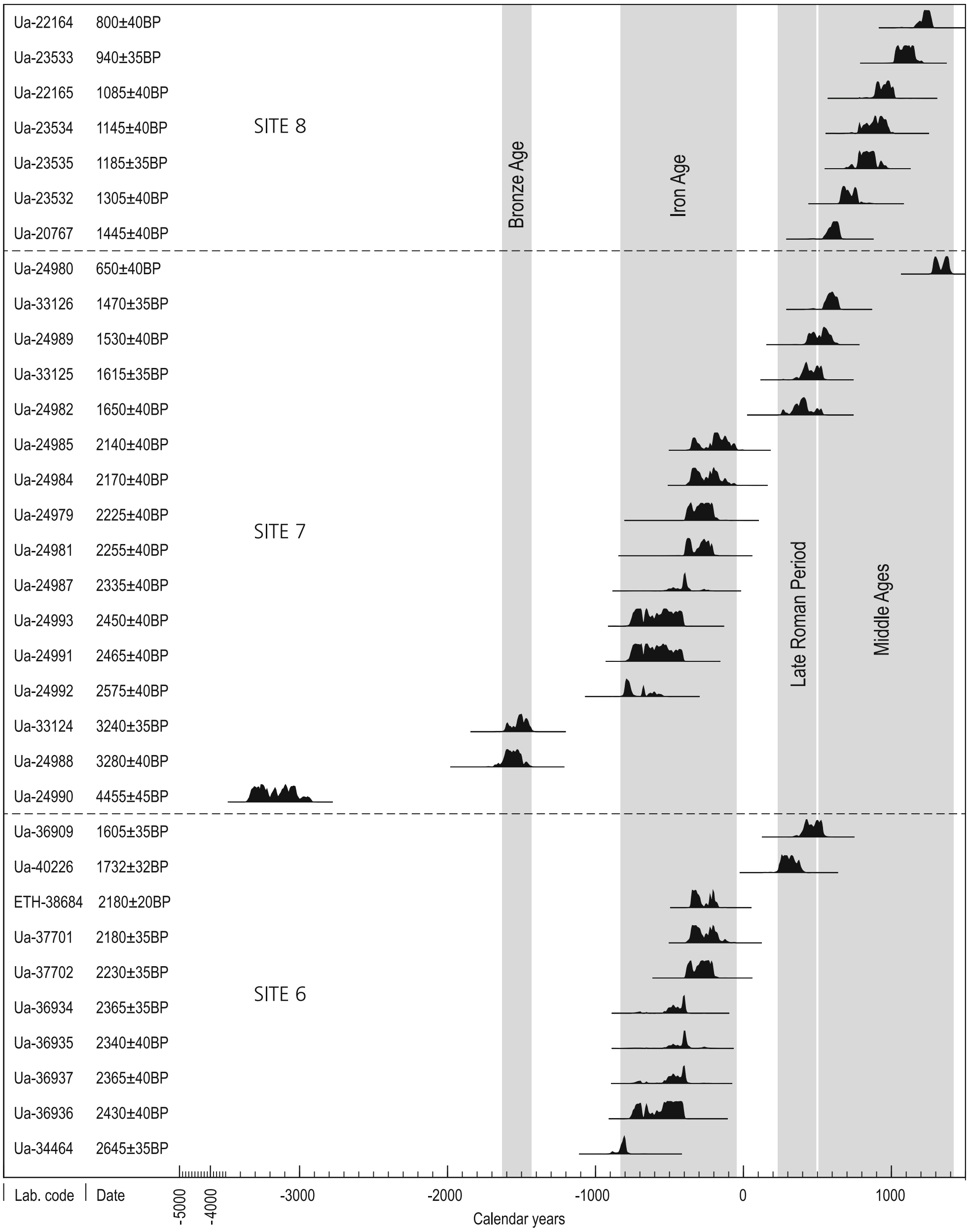


Fig. 10 Radiocarbon dates of the Birse floodplain (Sites 6–8) between 5,000 cal BC and 1,500 cal AD. No date is available for the interval 5,000–3,500 cal BC (for full references, see Online Resources 6–8)

on the south-eastern edge of the floodplain, at an altitude of 435 m. The excavated surface of 6,000 m^2 was divided into three morphosedimentary units. The northern section is located at the foot of a molasse hill. The central area includes a depression on the side of the hill. The remaining site surface is relatively flat and corresponds to the Birse floodplain; the southern limit of the site is formed by the fossil bed of a stream active during the protohistoric period. The sequence of the Quaternary deposits is up to 4 m thick and mostly consists of the alluvial sheet T2, a layer of fluviatile gravel which could be dated by OSL to the upper Würmian Pleniglacial (28 ± 2 and 25 ± 2 ka: Fig. 12). Loam of alluvial or colluvial origin covering this gravel terrace dates from the Late Glacial to the historic periods. Man occupied the site repeatedly, leaving behind numerous dated finds. The synthesis of the sedimentological and the chronostratigraphic data of the three morphosedimentary units allow us to reconstruct the sequence of events which formed these deposits, particularly during the Metal Ages, between 1,500 and 50 cal BC. A limited palynological analysis of the organic deposits dating from the end of the Roman period was carried out.

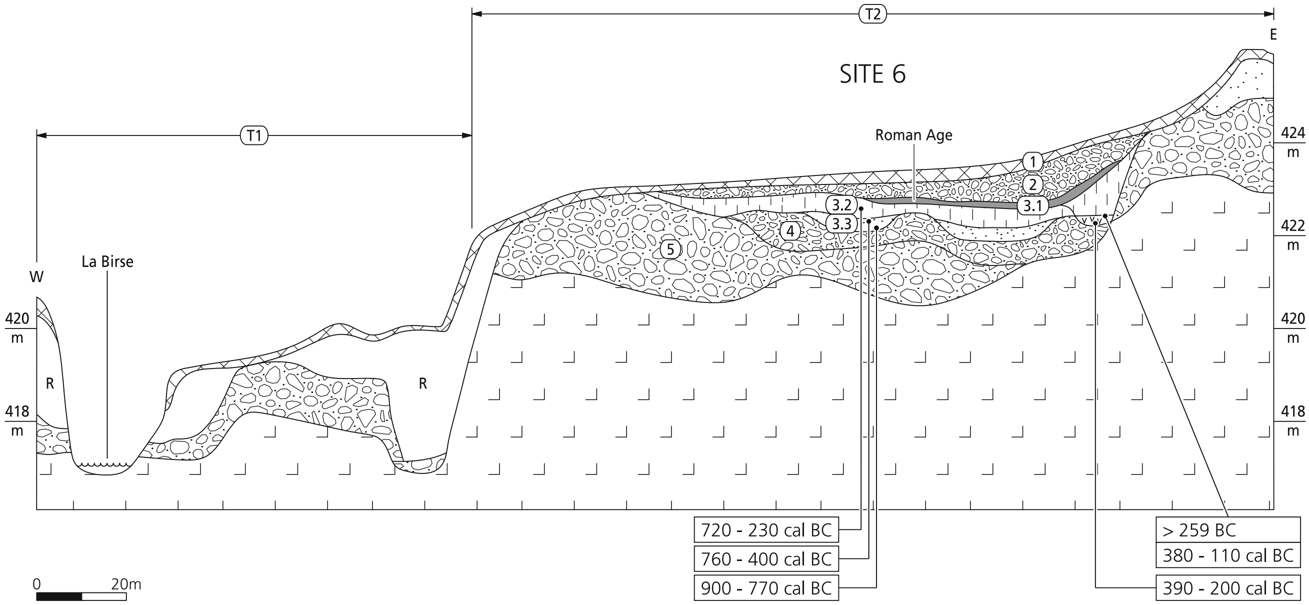


Fig. 11 Compiled cross-section through Site 6 (Courrendlin-Vers La Vieille Eglise), constructed from the field and laboratory data collected from the site area located at the border of terrace T2 formed during the Würmian Upper Pleniglacial (legend in Fig. 6). Between the Bronze Age onwards and the early Middle Ages sediment accumulated in an abandoned meander of the Birse (height exaggerated by a factor of 10). The local stratigraphy and sedimentology (*ringed numbers*) is described in detail in Online Resource 6

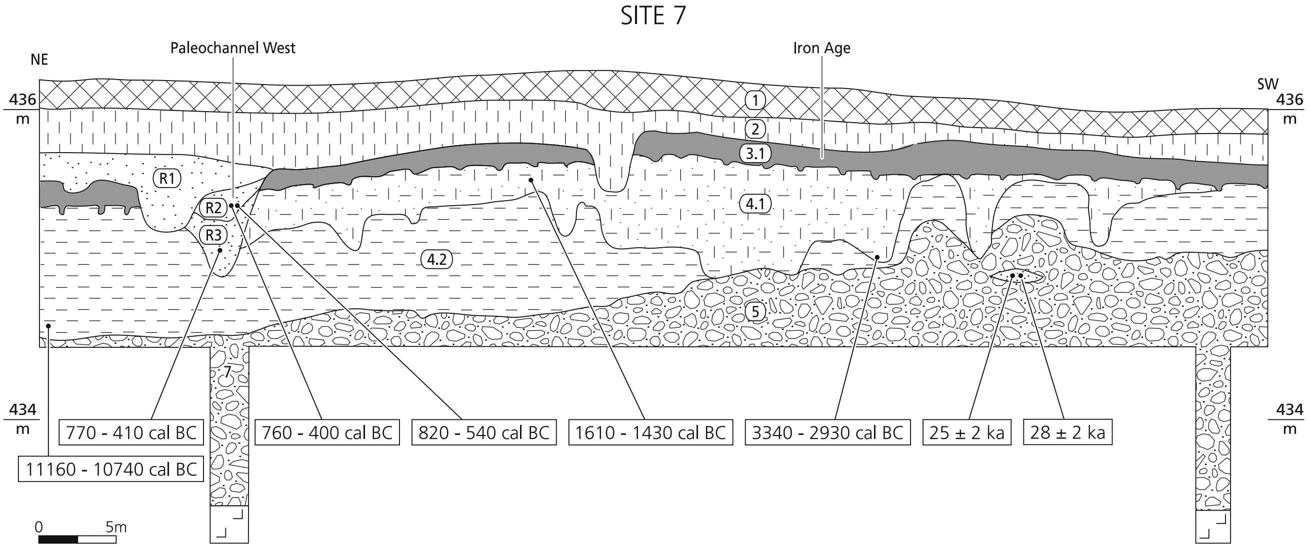


Fig. 12 Compiled cross-section through Site 7 (Courrendlin-En Solé), constructed from the field and laboratory data collected from the site area. OSL dates confirm that the fluvial gravels at the base of the sequence (layer 5) were deposited during the last glacial maximum. During the Iron Age, sediments accumulated in a palaeochannel (legend in Fig. 6; height exaggerated by a factor of 10). The local stratigraphy and sedimentology (*ringed numbers*) is described in detail in Online Resource 7

3.3.3 Site 8 (Online Resource 8)

More unpublished data comes from a series of test trenches located in a palaeochannel on the slope adjacent to the Birse floodplain, at an altitude of 440 m, on the northern foot of the anticline delimiting the Delémont basin. Incised in an Oligocene molasse, this ancient streambed contained a 2.7 m high sequence of fine sediments, often rich in organic matter (Fig. 13). These phases of accretion are explained by the sporadic flow of the ancient stream, a regime already documented on the neighbouring site of En Solé, 150 m to the south. The palaeochannel was filled in after 331 AD according to the dendrochronological analysis of a fir trunk discovered in contact with the molasse.

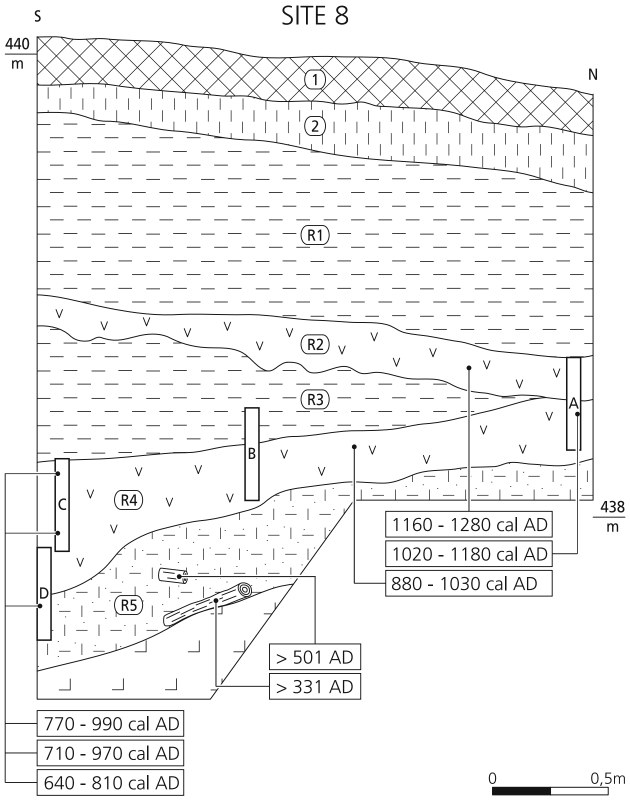


Fig. 13 Compiled cross-section through Site 8 (Courrendlin-Les Pécas), constructed from the field and laboratory data collected from the site area. A palaeochannel cut into the Oligocene molasse was episodically active between about 550–1,300 cal AD. Its fill is constituted of clayey silts alternating with organic deposits (legend in Fig. 6). Some pieces of driftwood were dated by dendrochronology and others by ^{14}C (full reference, see Online Resource 8)

However, this only gives a lower chronological limit (Kalicki and Krapiec 1995). Wood extracted from the sediment fill suggests that the lower part of the sequence developed at about 550 cal AD. A succession of stratigraphically coherent dates, ending around 1,300 cal AD, overly these early deposits. The palynological analysis of the organic layers provided solid data on the evolution of the vegetal cover (Fig. 13: samples A–D). The Pécas sequence provides thus an extremely valuable record of the Middle Ages.

4 Discussion

4.1 Holocene evolution of the Pran valley

The synthesis on the scale of the Pran floodplain (Fig. 14a), like that of the left bank of the Birse (Fig. 14b), is based on a chronological schema going from the Late Glacial to the end of the Middle Ages. In the plains, the change from braided to meandering fluvial systems is dated to the beginning of the Late Glacial. This is indicated by the ^{14}C dates from the loam covering the Würmian Pleniglacial gravels. A recurrence of cold and dry conditions during this period, which could correspond to the Younger Dryas, is signalled by the deposit of gravelly material: this covered the valley of the Pran with a system of many shallow channels.

At the beginning of the Holocene, vertical erosion first affects the earlier fluviatile formations and gravel is deposited on the channel bottoms. This meandering system lasted for more than four millennia (about 8,000–4,000 cal BC) with the waterway remaining relatively stable. Because of this slow sedimentation, the deposits were greatly affected by pedogenesis. The discovery of lithic industries dating to the 6th and 5th millennium BC at the site of En La Pran (Site 4; Pousaz et al. 2009), at the top of these weathered flood deposits, confirms that the sedimentation rate was very low at this period. At the same time, a readjustment took place on the slopes, first by the accumulation of loam-covered, debris-flow deposits then through pedogenesis: a developed brown forest soil, or a hydromorphic soil in poorly drained areas, forms at the top of these colluvia.

Following an increase in hydric activity after 4,000 cal BC, gravels deposited during this period frequently enclose driftwood. The streams cut the weathered alluvial substratum and reach the glacial gravels and even the bedrock. Radiocarbon analyses of some of the enclosed tree trunks give dates between 4,000 and 3,800 cal BC for the central part of the valley, and after 3,400 cal BC further downstream. The phenomenon of vertical incision is intensified by the fact that the banks are stabilized by vegetation, which is confirmed by archaeo-botanical data indicating a wooded environment, represented by a beech-fir type of forest, to which alder, lime and hazel are associated (Fig. 14c, see Sect. 3.1). Dated about 3,600 cal BC by palynology, this vegetal spectrum shows no trace of human impact.

The period 2,500–1,450 cal BC corresponds to a hydrological lull, although more active episodes of relatively short duration occur. After a slow migration of the stream, secondary branches are filled in by organic sediments, also containing fallen trees. Archaeo-botanical and malacological analyses show that this still occurs in a forested environment; in the alluvial plain, the glutinous alder constitutes the most frequent species. The average level of the water table tends to lower, which favours the deterioration of superficial deposits. After 2,000 cal BC, in the Early Bronze Age, human influence on the surrounding vegetation is identified by palynology: the beech grove recedes, open area plants develop, and the presence of cereals attest to the practice of limited agriculture in the valley. It is noteworthy that, in the Tavannes valley,

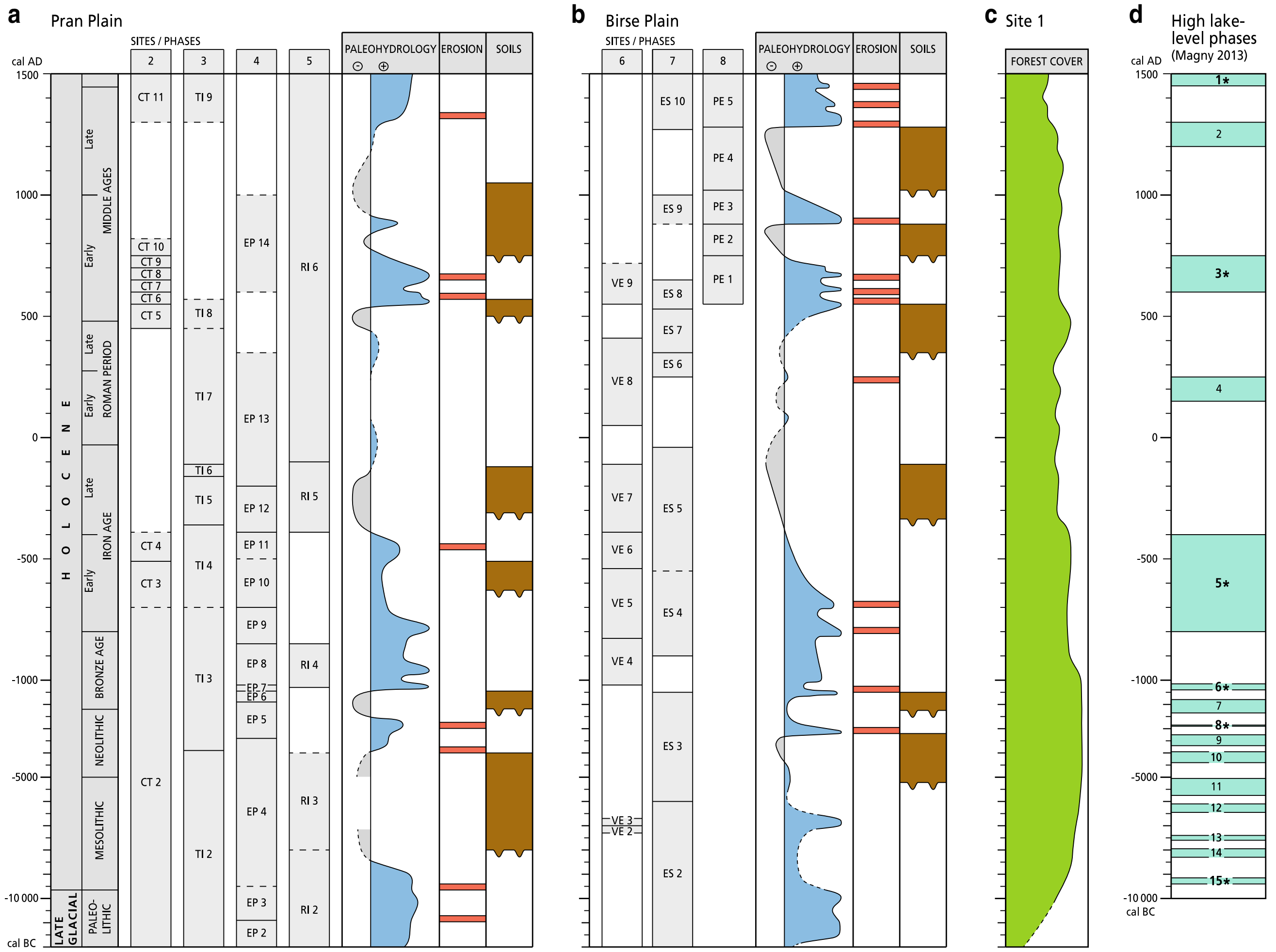


Fig. 14 Synthetic diagram for the Holocene of the Delémont valley (12,000 cal BC–1,500 cal AD). **a** Evolution of the Pran floodplain. Change of time scale at 1,000 cal BC is due to abundant data for the period up to 1,500 cal AD. Parallel to sites phasing, palaeohydrological curve points rises (+) and lulls (−) of hydrological flow. Erosion includes episodes of floodplain downcutting and gully formation on slopes. Soil genesis on the contrary indicates relative landscape stability. **b** Evolution of the Birse floodplain. **c** Evolution of the vegetal cover results from pollen analysis realised at Site 1 (Courfaivre-La Faverge). **d** Comparison with the high lake-level periods from France and Switzerland (Magny 2013). Six episodes (Nos. *15**, *8**, *6**, *5**, *3** and *1**) can clearly be correlated to hydrological rises and erosion phases in the study area

parallel to that of Delémont and about 15 km to the south, the first traces of cereal agriculture are much older, appearing between 4,500–4,000 cal BC (Wick 2010).

A marked resumption of hydrological activity occurs in the second half of the Bronze Age, after about 1,450 cal BC, with an increase in alluviation as a consequence: coarse deposits containing potsherds accumulate in the active bed of the stream. The latter becomes destabilized, secondary channels form, and the stream migrates to several places in the plain. Little by little, cutoffs are filled in by fine sediment containing charcoal. Conditions appear hydromorphic with a relatively high level of the water table. The streambed widens at the beginning of the Iron Age, around 800 cal BC, but the hydrodynamism does not weaken. Human occupation is marked more clearly and archaeological features colonize the abandoned channels. The influence of human activity on the vegetation, shown by the decline of forest species, distinctly increased after about 1,400 cal BC, from the end of the Middle Bronze Age onwards. The landscape also includes forest edges, hedges and alluvial forests. This evolution is accompanied by an increasing influence of crops and the appearance of other cultivated plants. The gathering of wild fruit still plays an important role in the diet. The impact of human activities is also marked on the neighbouring slopes, which were progressively cleared: the soil is exposed to erosion and landslides occurs (Guélat 1994).

After about 700 cal BC, hydrological activity decreases and sedimentation occurs at a slower rate. In some places, deposits containing archaeological remains undergo pedogenesis. Sedimentation starts again temporarily between about 500–400 cal BC, at the end of the Early Iron Age:

new channels are incised, then filled in by coarse alluvia and minor channels are reactivated.

The hydrological lull is confirmed after about 400 cal BC. Slow currents fill the secondary channels with silt which then undergoes weathering. One of these wet depressions in the median section of the valley serves as a dump for a Late Iron Age settlement, certainly close to the stream, and several ditches were dug in the alluvial plain, perhaps to aid drainage. Some farmsteads were also installed on the neighbouring slopes in an open environment. Little by little, the stream begins migrating which, from the Roman period and in the more downstream section, will lead to the development of a new meander belt on the northern border of the plain, that is, on the opposite side of its former location.

During the Roman period (30 cal BC–480 cal AD), pedo-sedimentary phenomena are limited to an accumulation of colluvia at the foot of the slopes and reworked during rare flooding. At the same time, in the valley bottom, the water table remains at a rather low level. Between roughly 350–550 cal AD, the hydric flow is again reduced and a soil begins to develop on the abandoned channel fill. Intermittent human activities, such as wood cutting in the forest along the stream, reappear with the onset of the Early Middle Ages in the 6th century AD. Hydrodynamism increases again: coarse alluvia accumulate and the banks of the stream, which tends to migrate, are subject to erosion.

A hamlet of craftsmen is established between 575 and 600 cal AD. The villagers make new cuttings in the forest and exploit the waterway. In the bottom of the valley, the level of the water table rises on a long-term basis, requiring the building and maintenance of a drainage network in order to reduce the water level. The height of hydric activity is reached between 650 and 700 cal AD, and then a hydric decrease starts. Human activities have a strong impact on the local environment and the deforestation of the slopes becomes more and more important. After about 750 cal AD, the hamlet is abandoned. A hydrological lull begins but is interspersed with occasional but important floods, particularly around 900 cal AD. The alluvia deposited in the previous interval are subject to pedogenesis. This evolution in the area lasts beyond 1,000 cal AD. Then, from about 1,300 cal AD, large amounts of loam washed down by the erosion of the soil on the slopes, cover the whole floodplain. The waterway migrates only little and even these changes will stop at about 1,750 cal AD when it is canalized.

4.2 Holocene evolution of the Birse floodplain

The Birse, such as we know it today, begins its existence as a braided river during the Late Glacial period (Guélat 2006). The T2 gravel sheet, dating mostly to the last glacial maximum, is covered by a continuous layer of loam which began to accumulate before 11,000 cal BC, during the temperate Bølling-Allerød interstadial. The limit between these two formations marks the passage from a braided to a meandering channel system.

At the beginning of the Holocene, river downcutting progresses at a relatively high rate (about 3 mm/year), but this decreases with time and the fluvial system remains generally stable during the following periods. Sedimentation is mostly restricted to deposits accumulated in the waterway itself (gravel and sand in the channels and loam on the floodplain). Around 7,000 cal BC, the vegetation surrounding the site of La Vieille Eglise (Site 6) is quite open; it is composed of broad-leaved trees, bushes and high grasses. The process of vertical accretion continues sporadically until at least 6,000 cal BC. It is locally accompanied by the intermittent accumulation of colluvia on the slopes. The discovery of reworked flint artefacts indicates an occasional human presence on the floodplain. After 6,000 cal BC, sedimentation slows following a hydrological lull and the alluvial deposits are greatly affected by pedogenetic processes.

At En Solé (Site 7), the opening and filling of several channels indicate a resumption of hydrological activity between 3,200 and 2,200 cal BC. At the same time, deposits of colluvia accumulate at the foot of the slope, a possible consequence of localized deforestation. Floodplain deposits, whether of colluvial or alluvial origin, then again undergo pedogenesis in a generally hydromorphic environment. Between about 1,500–900 cal BC, in the second half of the Bronze Age, a clearly marked erosive phase occurs, leading to episodic loam deposits on the plain. Intensified agricultural activity leads to increased deforestation. At Site 6 (La Vieille Eglise), the Birse forms a progressively migrating meander, whereas at Site 7 (En Solé), a humified horizon, enriched with charcoal and artefacts develops.

From the end of the Late Bronze Age to the Early Iron Age (about 830–550 cal BC), the meander of La Vieille Eglise undergoes a secondary stage, while further to the south, a stream wanders across the plain. The tendency of the waterways to migrate is indicative of very active hydric flows during this period. A lull appears only around 550 cal BC, indicated by the overbank deposits undergoing weathering. During the Late Iron Age (400–30 cal BC), hydrological activity decreases further, sedimentation clearly decreases, and pedogenesis becomes predominant. The intersected meander at La Vieille Eglise (Site 6) fills with organic silt. The vegetation cover is very open, organized into meadows and cultivated fields. The forest, now apparently at some distance from the alluvial plain, is composed of conifers, especially fir. The rarity of beech is surprising in such an environment and at this altitude. A few areas might have been richer in oak, unless this species only exists here and there in open spaces, in hedges, for example, where it would be associated with hazel and ash. The rather strong presence of oak could signify that the surrounding territories are being exploited as wooded pastures, as is still the case today. It is also possible that the forests were managed in a way similar to coppiced forests. This type of production increases the yield of wood, and the palaeo-metallurgical activities observed at several sites made particularly intense use of this resource (Richard and Eschenlohr 1998). This particular form of forest management has been observed at several sites in the Jura (Brombacher et al. 2013a). The wet meadows become important during the same period. Finally, the apparition of a pollen grain of rye (*Secale*), a plant usually identified with more recent periods (i.e. the Early Middle ages: Gauthier 2004), could be due to the fact that this plant acts as a messicole for other cereal cultures.

The interval 40 cal BC–50 cal AD is not recorded in the sequences. During the first centuries of the Roman period, flooding occurs only rarely on the plain, where soil tends to erode as a result of more intensive ploughing. A roadway is constructed along the plain and artisanal activity takes place at La Vieille Eglise. The vegetation cover is characterized by a dominance of meadows over fields (cereals and lentil). Very little activity takes place between 350 and 550 cal AD, as far as sedimentation and hydric flows are concerned. This period is characterized by the development of soils, which regain stability on slopes. In the vicinity of En Solé, reforestation occurs (alder being particularly frequent), and the impact of human activity is nearly imperceptible.

Sedimentation in the Pécas palaeochannel (Site 8) at the foot of the southern flank of the Delémont valley begins around 550 cal AD. A first detrital deposit accumulates after a deep downcutting by a tributary of the Birse. Likewise, at Site 7 (En Solé), slope run-off increases. Floods at La Vieille Eglise (Site 6) lead to the formation of a gravel layer sealing the abandoned meander containing the Roman features and finds. This resumption of hydrological activity is confirmed by local palynological data, which show a high level of humidity in an open and cleared environment, with a strong impact of human activity.

A clear decrease in sedimentation occurring after 750 cal AD results in an accumulation of organic material, marking the aggradation of the Pécas sequence. The palynological data also indicates a drying trend. After a marked episode of incision around 900 cal AD, loam is again deposited as a consequence of a resumption of hydrological activity. After about 1,000 cal AD, organic matter accumulates again in the palaeochannel of the Pécas. The nearby vegetation remains open, with a marked human impact (cereals). At about 1,300 cal AD, the sequences of En Solé and the Pécas channel record renewed erosion, while flood deposits seal the plain. The Birse shows a strong downcutting tendency (about 7 mm/year) towards the centre of the basin, and its right bank, above alluvial terrace T2, is no longer subject to flooding after this period.

Finally, lake-level fluctuations defined from 26 sites in the Jura Mountains (France/Switzerland), the Swiss Plateau, and the northern French Pre-Alps (Magny 2013) allow an inter-regional comparison with the data collected in the Delémont valley (Fig. 14d). Six high lake-level episodes (15, 8, 6, 5, 3 and 1) can clearly be correlated to hydrological rises and erosion phases in the study area. Between about 8,000–5,000 cal BC, only the Birse river shows some significant activity. Additionally, an erosion phase occurring around 250 cal AD, in the Roman period, is attributed to increased agricultural activity.

5 Conclusions

The compilation of data from the Pran floodplain (Sites 2–5) and the Birse floodplain (Sites 6–8) shows a clear convergence of evolutionary tendencies which, for the vegetation cover, are completed by the Courfaivre-La Faverge sequence (Site 1).

Processes can be traced back to the end of the Late Glacial or the Younger Dryas, when intense hydrological activity leads to marked sedimentary dynamic and superficial erosion. During this cold stage, unfavourable for pedogenesis, the development of the steppe could not be completely confirmed, though it is documented in other areas within the Jura mountain range. Pine forests dominate, a situation which will continue for a long time and will also limit the expansion of the first elements of the mixed oak grove during the first half of the Holocene. At the beginning of this same period, the alluvial environment is characterized by downcutting in the older fluviatile formations, a typical consequence of the thermal change (Bridgland et al. 2009). Subsequently, the meandering river system remains stable for more than four millennia (about 8,000–4,000 cal BC), during which sedimentation progressively decreases and pedogenesis affects deposits. In this balanced environment, climate fluctuations play a determinant role and the influence of human activity is absent, although archaeological finds indicate a sporadic occupation of the valley bottom from the Late Mesolithic to Early Neolithic (6th–5th millennium BC) onwards.

The first indication of human impact in the palynological record is very modest. From the Middle Neolithic on, this consists of indications of herding in the forest, while the cultivation of cereals remains imperceptible. An increase in hydrological activity occurred between the

Middle and Late Neolithic, from about 3,600–2,500 cal BC, based on dates obtained from several fir trunks discovered in the alluvial plain; they show no trace of human activity. The Delémont basin remains forested, dominated by a beech-fir grove, while alder occupies the valley bottom. It is only around 2,000 cal BC, during the Early Bronze Age, that cereal cultivation can be clearly identified. The influence of man, still very limited at this period, will become more and more important from this time on. However, extensive agricultural colonization only occurs during the second half of the Bronze Age, after 1,400 cal BC. Deforestation marks the pollen diagrams through a strong decline of forest species together with the emergence of open spaces and cultivated plants. The soil degrades on the progressively cleared valley flanks causing instability, and colluvia accumulate at the foot of the slope. After about 1,200 cal BC, during the Late Bronze Age, increased settlement activity contributes indirectly to the destabilization of the alluvial environment, already very dynamic at this stage, and this continues until about 650 cal BC, the beginning of the Iron Age.

A characteristic soil develops outside the zones of activity along the waterways. For the first time in the history of the region, the environment is strongly marked by human impact, linked in particular to the Late Iron Age. Identified all along the A16 motorway, this palaeosol constitutes a marker horizon in the stratigraphy of Holocene deposits in the Delémont valley. Indeed, between about 400–100 cal BC, deforestation intensifies and crops become diversified, while hydrological activity decreases. Settlements are situated within a very open landscape made up of intermittently wet meadows and cultivated areas. The forest is now at a considerable distance from the valley bottom. The marked presence of oak could be the sign of an exploitation of wooded pastures, while the discreet appearance of rye among the cultivars would be typical of this period in the Jura (Brombacher et al. 2013a).

During the first centuries of our era, in the Roman period, pedo-sedimentary phenomena are very limited. This phase is characterized by the continuity of landscapes created during the Late Iron Age. However, during Late Roman period, from about 350 cal AD onwards, human activity decreases, leaving room for reforestation, particularly for alder. The slopes are stabilized and soils tend to develop in various geomorphological contexts.

At the beginning of the Early Middle Ages, after 550 cal AD, a new rupture can be observed. A marked resumption of hydrological activity occurs, probably due to a change in the climate towards greater humidity (Magny 2004). In the alluvial plain, recurring floods lead to alluvial deposits containing a great deal of driftwood, covering Roman deposits and features. The water table rises for a long period, between about 550–750 cal AD. At the same time, the landscape becomes open and is again strongly marked by human impact, concretised in the pollen spectra by a strong decline of fir, a tree that reacts quickly to forest cutting (Brombacher et al. 2013b). Deforestation, driven by the need for open spaces and timber, leads to erosion and the incision of slope gullies. Between about 750–1,250 cal AD, in the Middle Ages, drier conditions set in and the sequences record pedogenesis. However, human impact remains strong, as is exemplified by increased pine pollen, a sign of a manifest degradation of the forests. This phase of relative stability includes occasional floods on the plains, especially around 900 cal AD. After 1,300 cal AD, hydrological activity and the corresponding erosion increase again. Downcutting occurs in the main waterways in the centre of the valley, a probable consequence of the climate deterioration of the Little Ice Age (Mann et al. 2008; Guélat in Demarez et al. 2011), combined with the local upsurge of human activity, such as agriculture and ironworking.

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