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Strontium isotopes in faunal remains: Evidence of the strategies for land use at the Iron Age site Eberdingen-Hochdorf (Baden-Württemberg, Germany)

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Abstract
This paper presents the results of an investigation into the process of centralization that took place north of the Alps during the Late Hallstatt and Early Latène Culture, conducted within the framework of a special research program. The focus of the archaeozoological project was on investigating livestock farming and the supply of Early Celtic hillfort sites and their rural environs. The Early Latène site Hochdorf in southwestern Germany, near the princely seat Hohenasperg, was a wealthy settlement characterized by crop farming, stock breeding, wool production, and weaving.

The $^{87}Sr/^{86}Sr$ ratios in Iron Age livestock teeth from Hochdorf indicate that predominantly areas above the geologic unit Keuper were used for pasture, and that some portion of the livestock were probably kept at a distance of about 15–30 km from the site or were imported from further away. The intra-species, intra-individual, and intra-tooth variations reflect movements and non-permanent pastures for cattle, caprines, and even pigs. The high variations among the $^{87}Sr/^{86}Sr$ values found in livestock render domestic animals not always suited for use in determining the local strontium signature for the region of Hochdorf. Modern snail shell and water samples reflect the local geology nicely; though they too yield highly variable values, too, reflecting the varied geology of the region.

Keywords
Iron Age, Hochdorf, animal teeth and bones, pasture, strontium isotopes

Introduction

Isotopic proveniencing of human and animal remains has been employed in archaeology for approximately 20 years. Investigations have focused predominantly on the mobility of prehistoric human populations or that of single individuals (e.g. Grupe et al., 1997; Price et al., 1998, 2003; Bentley et al., 2003; Schweissing, 2004). For the most part, researchers have used analyses of animal remains from archaeological sites to define the local range (Price et al., 2002; Bentley et al., 2003; 2004; Bentley and Knipper, 2005a; Giblin, 2009; Gillmaier et al., 2009). Knipper (2004) discussed the mobility of humans and animals in detail, but few investigations have dealt with the provenance and the transport of animals (Horn et al., 1997; Schweissing and Grupe, 2003; Bentley and Knipper, 2005b; Poll et al., 2005; Sykes et al., 2006; Bendrey et al., 2009). A combination of strontium, carbon, and oxygen isotope ratios in teeth has been used to investigate the seasonal mobility of sheep and cattle in South Africa, to document herd movement patterns of modern caribou, and those of cattle and horses in Bronze Age Georgia and Germany (Balasse et al., 2002; Britton et al., 2009; Knipper et al., 2008; Knipper, in press). Brubaker and colleagues (2006) have begun studies tracking seasonal and longer-term Bronze Age horse migration in the Botai region in Kazakhstan. Viner and colleagues (2010) found evidence of cattle movement over significant distances during the Late Neolithic period in Britain, probably connected with large-scale feasting activities.

This study uses strontium isotopes in Iron Age animal teeth to explore herd movement and the mobility habits of livestock, and to acquire knowledge about pasture grounds in the environs of the settle-

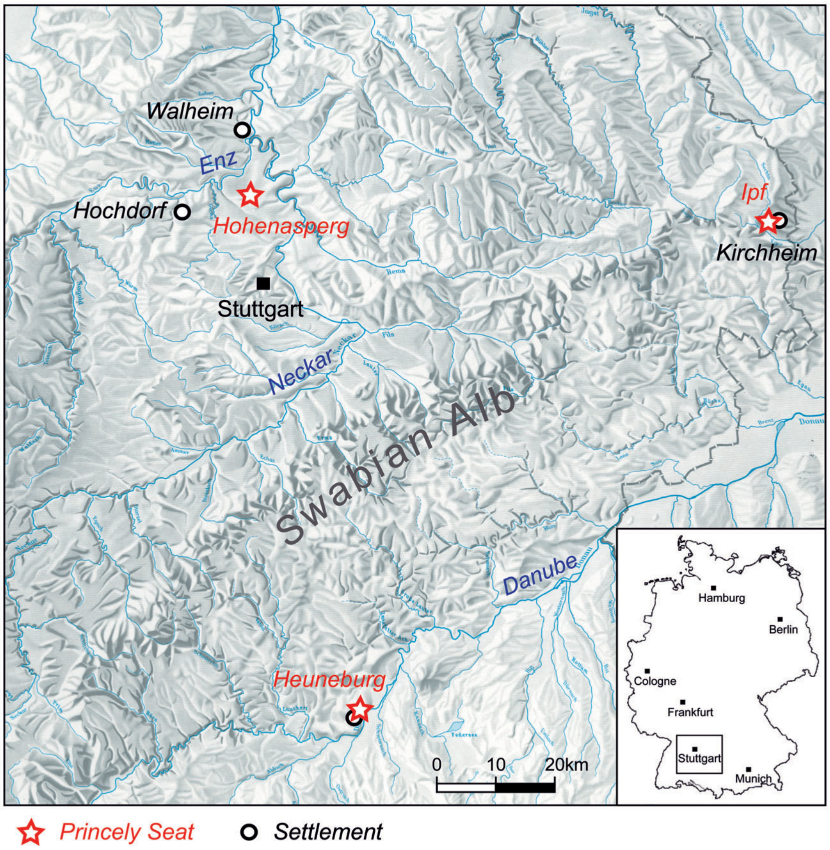

Fig. 1 | Relief map of southwest Germany and the location of the Iron Age princely seats Hohenasperg, Ipf, and Heuneburg and the surrounding settlements

ments. It was conducted as part of the special research program "Early Processes of Centralisation and Urbanisation – Studies on the Development of Early Celtic Princely Seats and Their Hinterland", which was funded by the German Research Council (DFG). The aim of the program was to investigate the processes of centralisation that took place north of the Alps during the Late Hallstatt (ca. 650 to 450 B.C.) and Early Latène cultures (ca. 450 to 300 B.C.). Princely seats, the German *Fürstensitze*, are defined as rich fortified settlements, mainly situated on hilltops that have large and rich burial mounds in their vicinity and are associated with finds of imported goods, mainly ceramics from the Mediterranean. The Fürstensitze seem to be the result of a social and maybe even cultural change or transformation in the Protoceltic societies, one that we still do not fully understand. Among the better known, important princely seats are the Heuneburg, the Hohenasperg, and the Ipf (Fig. 1). Other sites, such as Hochdorf, Walheim, and Kirchheim, represent open rural settlements or farmsteads located in the area surrounding the *Fürstensitze*. About 20 projects were conducted, with researchers in the fields of history, geography, palaeobotany, and archaeozoology, as well as archaeology, participating. The goal of the project "The Archaeozoology of Early Celtic Faunal Remains" was to reconstruct the subsistence strategies and hunting behaviours of the Iron Age populations during the processes of centralization. The archaeozoological and isotopic work involved faunal remains from about 20 sites of different size, function, and age in southwest and western Germany (Schatz and Stephan, 2008).

The rationale of strontium isotope analyses

The isotope ^{87}Sr is formed over time through the radioactive decay of the isotope ^{87}Rb. It comprises approximately 7.04 % of total strontium in nature (Faure, 1986). Other isotopes of strontium are nonradiogenic and include ^{84}Sr (~ 0.56 %), ^{86}Sr (~ 9.87 %), and ^{88}Sr (~ 82.53 %). Variations in the strontium isotope composition found in natural materials are generally expressed as $^{87}Sr/^{86}Sr$ ratios. $^{87}Sr/^{86}Sr$ ratios vary depending on the age and composition of the rocks forming the earth's crust. The value of the $^{87}Sr/^{86}Sr$ ratios in fossils is a function of the Rb/Sr ratio in the basement rocks (and in the soils derived from them) and the time that elapsed since the basement rocks were formed. So-called inherited $^{87}Sr/^{86}Sr$ is negligible in crustal rocks and soil. Strontium is easily mobilized in rocks through weathering and is transported into soil and ground water, finally ending up in plants and the food chain. Due to the small difference in the relative masses of the ^{87}Sr and ^{86}Sr isotopes, only minute fractionation takes place during the intake of the biologically available strontium in plants and animals, its metabolism, and incorporation in bones and teeth. It is possible to correct for the fractionation that does occur, though, by normalizing the isotope ratios to an internal standard, which is the $^{86}Sr/^{88}Sr$ isotope ratio, with an assumed value of 0.1194. Thus, the strontium isotope composition in groundwater, soil, plants, and animals is closely related to local geology (discussed in detail by Price and colleagues [2002]) and it can be used as a tracer to characterize the provenance of fossil animals and humans.

The settlement of Eberdingen-Hochdorf

The settlement of Eberdingen-Hochdorf "Reps" is located northwest of the city of Stuttgart is one of a group of sites in the environs of the Early Celtic princely seat "Hohenasperg" (Fig. 1). The site is located in a fertile region of the Neckar River, an area with a hilly landscape and soils of high quality (Küster, 1985; Balzer and Biel, 2008). The excavation of the entire settlement area, 1989–1993, uncovered about 40 pit houses, several granaries, earth cellars, small ditches and large amounts of ceramics, loom weights, spindle whorls, metal objects, and faunal remains (Biel, 1995). The archaeological finds demonstrated that Hochdorf was a wealthy settlement characterized by crop farming, stockbreeding, wool production, and handicraft activities, particularly weaving.

Most of the animal remains were found in pit houses or cellars and have been dated to the Early Latène period, from about 450 to 300 B.C. Some few finds came from pits that represent the remnants of a settlement of the Early Neolithic Linear Pottery Culture (Linearbandkeramik, LBK). Almost all Iron Age bones are from domestic cattle, sheep, goat, and pig (Schatz, 2009). Finds include a few horse, dog and chicken remains and, very rarely, remains of wild animals like red deer, roe deer, wild boar, wolf, fox, and beaver. Cattle were predominantly used as draught animals for fieldwork. Sheep were bred for meat and wool production, and pig served as source for meat and fat. Dog and chicken were also consumed. Different methods of dismembering and preparing the slaughtered animals produced differences in the quality of the meat and point to social differences among the inhabitants.

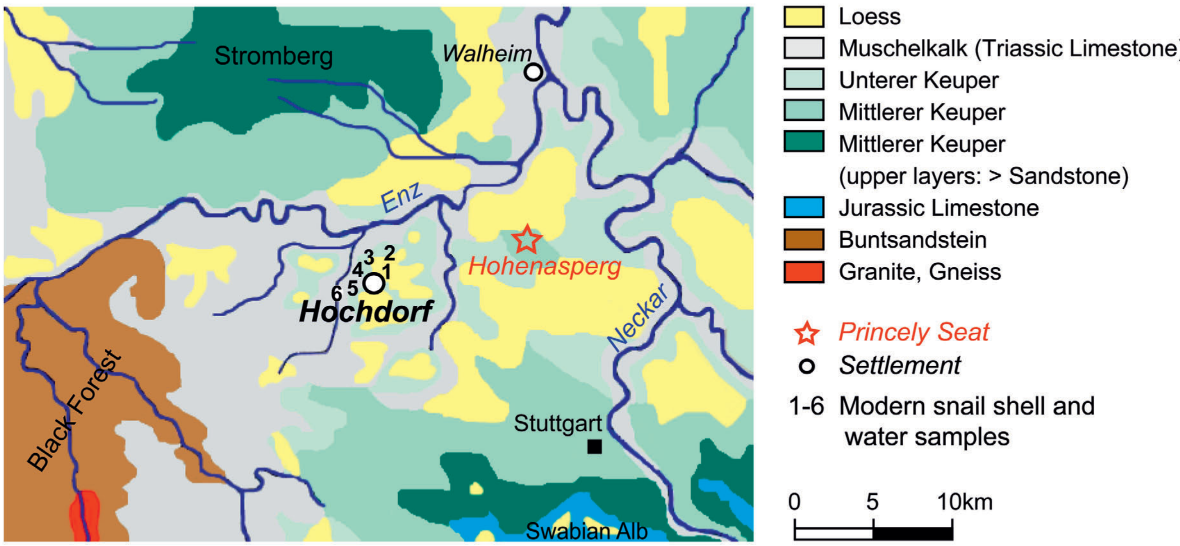

Fig. 2 | Schematic geological map of the middle Neckar region and the location of the site Eberdingen-Hochdorf. Numbers 1–6 indicate the location of modern snail shell and water samples from different geologic units in the surroundings of the site

The geological setting of the study area

The environment of Hochdorf is geologically heterogeneous and characterized by extended glacial loess deposits as well as Triassic Keuper and Muschelkalk formations (Fig. 2). Keuper sandstones and Muschelkalk (limestone) are visible where loess is eroded. Muschelkalk is present in the areas southwest of Hochdorf and is exposed predominantly along the valley slopes. The Keuper formation characterizes the hilly landscape of the Löwenstein and Stromberg mountains and larger areas of the lowlands northwest of the Swabian Alb (Jurassic limestone). Alluvial sediments exist in the river valleys, i.e. those of the Neckar and the Enz. The site itself is located on loess.

Comparatively low strontium isotope ratios predominate in most of these regions. The strontium isotope signatures of Muschelkalk and loess vary between 0.7080 and 0.7097 and 0.7085 and 0.7100 (Table 1), respectively. More detailed investigations of modern and archaeological faunal and human remains of the Early Neolithic (LBK) sites of Vaihingen and Stuttgart-Mühlhausen near Hochdorf have yielded $^{87}Sr/^{86}Sr$ values ranging from 0.7091 to 0.7098 (Price et al., 2003; Bentley et al., 2003, 2004). Isotopic ratios determined for the water and a freshwater mollusc of the Neckar and for modern mice bone from Schwetzingen near Heidelberg in the Neckar valley are slightly lower (0.7086 and 0.70883±0.00015, resp.; Buhl et al., 1991; Bentley et al., 2003). The analyses of human and animal bones and teeth from the LBK site of Schwetzingen yielded slightly higher ratios (0.7095±0.0003; Bentley et al., 2002, 2003).

The petrographic diversity of the Keuper sediments is reflected in their highly variable strontium isotope ratios (Table 1). Some of the Keuper ratios, in particular those for groundwater and the soluble fractions of the rocks from the middle and upper formations, overlap with the values for loess and Muschelkalk, but values for the lower Keuper formation in the close vicinity of Hochdorf almost all fall above 0.710 (Ufrecht and Hölzl, 2006). Comparatively radiogenic ratios were also well represented in the samples of tree leaves from the middle Keuper layers of the Stromberg hills, ca. 15 km north of

Table 1 | $^{87}Sr/^{86}Sr$ values of modern and archaeological samples from different geologic units in southwest Germany

Geologic unit	Material	n	$^{87}Sr/^{86}Sr$ range	References
Loess	Sediment; modern snail shells, mice; LBK cattle, sheep/goat, pig, dog, red deer enamel, human bone and enamel	178	0.7085–0.7100	Taylor 1983; Price et al. 2003; 2006; Bentley et al. 2003; 2004
Neckar valley	Rock, sediment, river water; modern molluscs, mice; LBK: human & pig bone and enamel	43	0.7085–0.7100	Buhl et al. 1991; Horn et al. 1994; 1997; Bentley et al. 2002; 2003; Bentley & Knipper 2005a
Muschelkalk	Muschelkalk (limestone), groundwater	33	0.7080–0.7097	Price et al. 2004; Ufrecht & Hölzl 2006
Keuper	Keuper (sandstone), groundwater; modern roe deer bone	28	0.7080–0.7115 (–0.7170)	Tütken 2003; Ufrecht & Hölzl 2006; Knipper 2009
Jurassic (limestone; Swabian Alb)	Jurassic (limestone); modern horse & roe deer bone; IA pig enamel	div. 5	0.7070–0.7095	Veizer et al. 1997; Tütken 2003; Bentley & Knipper 2005a
Buntsandstein (Black Forest & Odenwald)	Groundwater; modern snail shells; Middle Ages pig enamel	29	0.7090–0.7210	Bentley et al. 2003; Bentley & Knipper 2005a; Ufrecht & Hölzl 2006
Crystalline Basement (granite, gneiss; Black Forest & Odenwald)	Rocks, groundwater; modern snail shells, fish; Middle Ages pig enamel	133	0.7090–2.9270	Hofmann & Köhler 1973; Drach et al. 1974; Brewer & Lippolt 1974; Kalt et al. 1994; Altherr et al. 1999; Bentley et al. 2003; Bentley & Knipper 2005a; Ufrecht & Hölzl 2006

Hochdorf (Knipper, 2009). In the case of Hochdorf, the lower isotope values should represent exclusively Muschelkalk and loess. In contrast, the crystalline basement rocks, granite and gneiss, as well as the sandstones (Buntsandstein) of the Black Forest and the Odenwald, exhibit substantially higher values (Table 1).

Samples and procedure

Samples

Tooth enamel from the main Iron Age domestic species – horse, cattle, pig, sheep and goat – were chosen for the analyses (Table 2). Enamel is very resistant to post-mortem diagenesis and thus better suited for isotope analysis than are bone finds (e.g. Chiaradia et al., 2003; Richards et al., 2008). Unlike

Table 2 | $^{87}Sr/^{86}Sr$ values of Iron Age domestic animal tooth samples from Eberdingen-Hochdorf

Sample N°.	Feature	Species	Sample	$^{87}Sr/^{86}Sr$ ± 2 s.e. (last digits)		
				Top	Middle	Bottom
Eq-Ho 1[a]	Cellar 1605/1	Horse	Maxilla M1/2	0.709129 ± 11	0.708932 ± 10	0.709819 ± 10
Eq-Ho 2[a]	Cellar 1902/3	Horse	Mandible M3	0.709684 ± 07	0.709010 ± 09	0.709611 ± 10
Eq-Ho 3[a]	Cellar 1906/3	Horse	Mandible P2	0.710336 ± 07	0.710634 ± 10	0.709374 ± 11
Eq-Ho 4[a]	Cellar 2106/1	Horse	Mandible P3	0.711403 ± 11	0.711404 ± 10	0.710526 ± 11
Eq-Ho 5[a]	Cellar 2106/1	Horse	Mandible P4	0.711485 ± 11	0.711424 ± 38	0.708871 ± 13
Bo-Ho 6[a]	Pit house 1303/12	Cattle	Maxilla M3	0.709809 ± 09	0.709947 ± 21	0.709952 ± 11
Bo-Ho 7.1[b]	Pit house 2000/1	Cattle	Mandible M1		0.709652 ± 15	0.709499 ± 10
Bo-Ho 7.2[b]	Pit house 2000/1	Cattle	Mandible M2	0.709278 ± 24	0.709375 ± 27	0.709286 ± 34
Bo-Ho 7[a]	Pit house 2000/1	Cattle	Mandible P4	0.709353 ± 11	0.709337 ± 14	0.709526 ± 11
Bo-Ho 8[a]	Pit house 2002/1	Cattle	Maxilla M3	0.710191 ± 10	0.710366 ± 11	0.710525 ± 09
Bo-Ho 9[a]	Pit house 2002/1	Cattle	Mandible M3	0.710009 ± 09	0.709977 ± 10	0.710121 ± 09
Bo-Ho 10.1[b]	Cellar 1605/1	Cattle	Mandible M1	0.710505 ± 16	0.710342 ± 24	0.710327 ± 12
Bo-Ho 10.2[b]	Cellar 1605/1	Cattle	Mandible M2	0.710754 ± 22	0.711162 ± 18	0.711277 ± 26
Bo-Ho 10[a]	Cellar 1605/1	Cattle	Mandible M3	0.711171 ± 10	0.711620 ± 10	0.710937 ± 11
Bo-Ho 11[a]	Cellar 1608/2	Cattle	Mandible M3	0.710166 ± 10	0.709711 ± 32	0.710403 ± 18
OC-Ho 12[a]	Pit house 1303/12	Sheep/Goat	Mandible M3	0.709624 ± 10	0.709338 ± 10	0.709741 ± 10
OC-Ho 13.1[b]	Pit house 2002/1	Sheep/Goat	Mandible M1	0.710471 ± 16	0.710595 ± 28	0.710644 ± 15
OC-Ho 13.2[b]	Pit house 2002/1	Sheep/Goat	Mandible M2	0.710760 ± 11	0.710779 ± 17	0.710880 ± 30
OC-Ho 13[a]	Pit house 2002/1	Sheep/Goat	Mandible M3	0.710865 ± 14	0.710179 ± 09	0.710933 ± 10
OC-Ho 14[a]	Pit house 2409/1	Sheep/Goat	Mandible M3	0.712106 ± 11	0.712308 ± 13	0.710161 ± 10
OC-Ho 15[a]	Cellar 1608/2	Sheep/Goat	Mandible M3	0.710035 ± 09	0.710634 ± 11	0.710891 ± 10
OC-Ho 16[a]	Cellar 1707/6	Sheep/Goat	Mandible M3	0.709892 ± 10	0.710036 ± 11	0.710268 ± 10
OC-Ho 17.1[b]	Cellar 2004/2	Sheep/Goat	Maxilla M1	0.708615 ± 25	0.708692 ± 22	0.708606 ± 15
OC-Ho 17[a]	Cellar 2004/2	Sheep/Goat	Maxilla M2	0.708509 ± 10	0.708538 ± 13	0.708551 ± 13
Su-Ho 18[a]	Pit house 1303/12	Pig	Maxilla P4	0.710334 ± 09	0.710599 ± 13	0.710569 ± 11
Su-Ho 19[a]	Pit house 1505/1	Pig	Maxilla M3	0.710161 ± 10	0.710212 ± 10	0.710494 ± 14
Su-Ho 20.2[b]	Pit house 1603/1	Pig	Mandible M2		0.710971 ± 13	0.711539 ± 13
Su-Ho 20.1[b]	Pit house 1603/1	Pig	Mandible P4		0.710971 ± 10	0.711539 ± 13
Su-Ho 20[a]	Pit house 1603/1	Pig	Mandible M3	0.710898 ± 23	0.710549 ± 10	0.710282 ± 09
Su-Ho 21[a]	Cellar 1805/3	Pig	Mandible M3	0.710302 ± 09	0.710371 ± 10	0.711093 ± 10
Su-Ho 22[a]	Cellar 1902/3	Pig	Mandible M3	0.710579 ± 11	0.710632 ± 11	0.710327 ± 10

[a] Universtity of North Carolina; [b] University of Munich

bone tissue, enamel, once formed, is not remodelled, preserving instead the original isotope signatures associated with the place of residence during its formation. Because enamel is formed in incremental layers over a period lasting from several months to several years (Hillson, 1986, 113pp; Passey and Cerling, 2002), the sequential sampling of enamel at different locations along the tooth height offers the possibility of detecting a chronological record of the strontium isotopic composition.

The permanent third molar (M3) and fourth premolar (P4) were selected for this study in most cases. These last teeth to erupt are formed mainly during the second and third year of life (Silver, 1969; Habermehl, 1975; Wilson et al., 1982; Hillson, 1986; Amorosi, 1989). The first and second molars (M1, M2), and second and third premolars (P2, P3), which form earlier on, were also analyzed, when available, in order to provide additional information about the animals' place of residence during their infancy.

Mineralization time varies with type of the tooth and species and only very limited data relating to the timing and process of crown formation in different species have been published (e.g. Brown et al., 1960; McCance et al., 1961; Hillson, 1986; Bryant et al., 1996; Hoppe et al., 2004; Niven et al., 2004). Estimations of the rates of enamel mineralization are complicated by the maturation processes that follow the initial deposition of enamel (Passey and Cerling, 2002) and by the fact that original tooth height is often unknown. Furthermore one has to keep in mind that the growth patterns and the homogenizing influence of transverse sampling result in attenuating effects (Balasse et al., 2002; Passey and Cerling, 2002; Balasse, 2003; Hoppe et al., 2004).

Skeletal remains of wild and small domestic animals found at the site, and modern snail shells and river water of the immediate vicinity were used to define the strontium isotope characteristics of the local environment (Tables 3–4). Teeth were preferred for these analyses, too, but bones were used when teeth were not available. Figure 2 shows the locations at which the modern snail shells (multiple species) and river water were sampled in the north and northwest of the Iron Age settlement. To avoid contamination from modern fertilizers, no samples were collected from fields (cf. Wolff-Boenisch, 1999; Probst et al., 2000; Price et al., 2002). Location 1 consists of shrubbery grassland, Locations 2 and 3 are small forested areas, and Locations 4 and 5 are abandoned Muschelkalk quarries. The forested areas are characterized by a good and stable nutrient supply and have not been chalked in the past (Official information of the Forest Administration 2010, Landratsamt Ludwigsburg, Fachbereich Forsten, Forstamt, Vaihingen/Enz). The exact positions of the sampling locations and the underlying geology were determined using topographical and geological maps with a scale of 1:25,000 and 1:50,000, respectively.

Analytical procedures

Before sampling, tooth surfaces were cleaned with a diamond abrasive drill bit and the cementum of horse teeth was removed. The enamel samples were taken as powder with a diamond-coated dental drill. All of the teeth were sampled at three locations from cusp to cervix: close to the top, in the middle, and close to the cervix at the bottom (Fig. 3). In cases where only teeth with a severe abrasion were available, the drill sampling was only done at the middle and bottom location. The enamel powders weighed between 10 to 20 mg. The snail shell samples were cleaned ultrasonically in distilled water and ground, and about 5 mg were processed for isotopic analyses.

The samples were analysed at the laboratory for Archaeological Chemistry at the University of Wisconsin in Madison; the Department of Geological Sciences at the University of North Carolina, Chapel

Table 3 | ^{87}Sr/^{86}Sr values of Iron Age domestic and wild animal tooth samples including snail shells from Eberdingen-Hochdorf (University of Munich)

Sample No.	Feature	Species	Sample	^{87}Sr/^{86}Sr ± 2 s.e. (last digits)		
Gg-Ho 125	Cellar 1504/1	Chicken	Humerus		0.710004 ± 14	
Gg-Ho 126	Cellar 2408/2	Chicken	Humerus		0.710027 ± 20	
Gg-Ho 127	Cellar 2007/3	Chicken	Femur		0.709518 ± 13	
Cn-Ho 123.2	Cellar 397/2	Dog	Mandible		0.710137 ± 19	
Cn-Ho 124.2	Cellar 397/2	Dog	Mandible		0.709916 ± 11	
				Top	Middle	Bottom
Cn-Ho 123.1	Cellar 397/2	Dog	Mandible M1	0.710413 ± 13		0.710087 ± 14
Cn-Ho 124.1	Cellar 397/2	Dog	Mandible M1	0.710473 ± 19		0.710078 ± 12
Fe-Ho 128	Pit house 1707/7	Wild cat	Maxilla Canine		0.708118 ± 15	
Bo-Ho 144	Pit house 1505/1	Bison	Mandible M3		0.710723 ± 16	0.710819 ± 17
Ce-Ho 145	Cellar 1103/5	Red deer	Mandible M3		0.709765 ± 13	0.709908 ± 15
Od-Ho 146	Pit house 1704/1	Roe deer	Mandible M3		0.710248 ± 14	0.710311 ± 12
Ss-Ho 147	Pit house 1302/7	Wild boar	Mandible M3		0.712659 ± 15	0.712382 ± 13
Cn-Ho 148	Cellar 1302/4	Wolf	Maxilla M1	0.712416 ± 19		0.711585 ± 13
Le-Ho 149	Pit house 1707/7	Hare	Mandible P3		0.710091 ± 14	
Cs-Ho 150	Pit house 1707/7	Beaver	Mandible M3		0.708557 ± 14	
Ml-Ho 129	Pit house 1704/1	*Unio crassus*	Snail shell		0.708540 ± 11	
Ml-Ho 130	Pit house 1704/1	*Cepaea hortensis*	Snail shell		0.709410 ± 20	
Ml-Ho 131	Cellar 397/2	*Cepaea nemoralis*	Snail shell		0.708831 ± 16	
Ml-Ho 132	Cellar 397/2	*Helix pomatia*	Snail shell		0.709385 ± 19	
Ml-Ho 133	Cellar 397/2	*Bradybaena fruticum*	Snail shell		0.709773 ± 19	

Table 4 | ^{87}Sr/^{86}Sr values of modern snail shell and water samples from different geologic units in the surroundings of Eberdingen-Hochdorf (University of Munich; locations see Fig. 2)

No.	Field name	Geologic unit	Sample No.	Sample	^{87}Sr/^{86}Sr ± 2 s.e. (last digits)
1	Hölle	Loess	Ml-Ho 134	*Fruticicola fruticum*	0.709363 ± 19
1	Hölle	Loess	Ml-Ho 135	*Cepaea hortensis*	0.709056 ± 20
2	Pulverdinger Holz	Loess / Keuper	Ml-Ho 136	*Helix pomatia*	0.709712 ± 16
3	Rubholz	Keuper	Ml-Ho 137	*Helicodonta obvoluta*	0.711457 ± 18
4	Rieter Tal, quarry northeast of Riet	Muschelkalk	Ml-Ho 139	*Perforatella incarnata*	0.709320 ± 18
5	Heulenberg, quarry east of Riet	Muschelkalk	Ml-Ho 140	*Helix pomatia*	0.709191 ± 16
5	Heulenberg, quarry east of Riet	Muschelkalk	Ml-Ho 141	*Cepaea nemoralis*	0.708861 ± 18
5	Heulenberg, quarry east of Riet	Muschelkalk	Ml-Ho 142	*Cepaea nemoralis/hortensis*	0.708441 ± 13
6	Strudelbach, Riet	Muschelkalk	W-Ho 143	Stream water	0.708455 ± 14

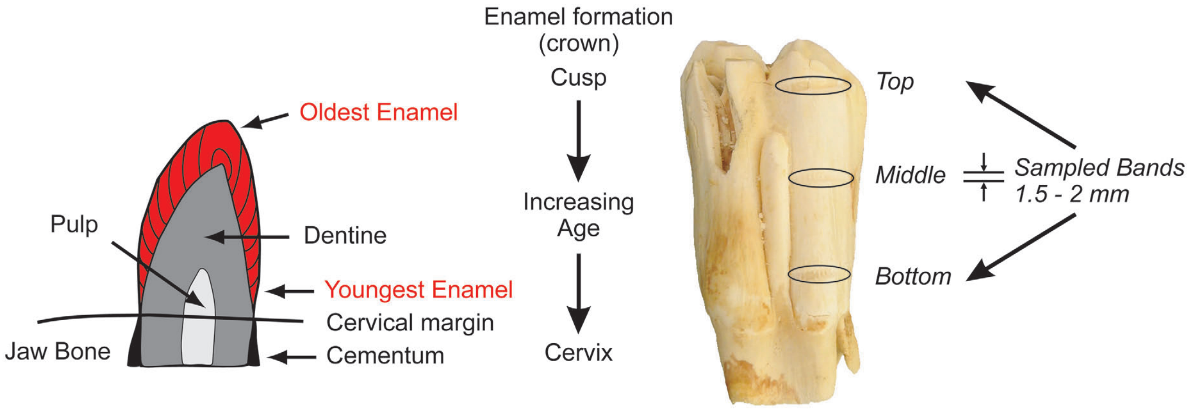

Fig. 3 | Schematic figure of the enamel formation (left; mod. from Fricke and O'Neil, 1996, Fig. 2A) and the sampling of animal cheek teeth shown for a cattle molar

Hill (Table 2); and the Department of Earth and Environmental Sciences at the University of Munich (Table 2–4).

At the University of Wisconsin, the enamel samples were dissolved in 5 M HNO_3. Strontium was separated using EiChrom Sr-Spec resin and the strontium isotopic compositions were analyzed on a VG Sector 54 thermal ionization mass spectrometer (TIMS) at the Department of Geological Sciences, University of North Carolina at Chapel Hill (UNC-CH). At Chapel Hill strontium was loaded on a single Re filaments and analyzed with a dynamic quintuple-collector data-collection mode. Within-run precision of the $^{87}Sr/^{86}Sr$ ratios in the Iron Age samples is ≤ ±0.000038 (2 s.e.). Analyses of the strontium reference material NIST 987 yielded a $^{87}Sr/^{86}Sr$ ratio of 0.710260 ± 0.000010 (2 s.d., N = 30). The $^{87}Sr/^{86}Sr$ ratios were corrected for thermal fractionation using $^{86}Sr/^{88}Sr$ = 0.1194. Total procedural blanks for strontium are <100 picograms, which is not significant for the amounts of strontium processed.

In Munich the enamel, bone and snail shell sample powders were dissolved in 2 ml 4 M HNO_3 in PFA beakers over a period of 1 day at 80°C. Strontium was separated on quartz columns with a 5 ml resin bed of AG 50W-X12 of 200–400 mesh (Hegner et al., 1995). The carbonate samples were dissolved in 2.5 M HCl. Strontium was loaded on a single W-filament using TaF_5 as emitter and the isotopic composition was measured on an upgraded MAT 261 mass spectrometer employing a dynamic double collector routine. $^{87}Sr/^{86}Sr$ ratios are normalized to $^{86}Sr/^{88}Sr$ = 0.1194. Within-run precision of the $^{87}Sr/^{86}Sr$ ratios in the Iron Age samples is ≤ ±0.000036 (2 s.e.). Over the course of the study the NIST SRM 987 strontium reference material yielded $^{87}Sr/^{86}Sr$ = 0.710244 ± 0.000008 (2 s.d., N = 15). Total procedural blanks are <500 pg Sr and not significant for the samples analyzed.

For inter-laboratory comparison, duplicate analyses were performed on five Iron Age teeth samples. Two replicates yielded almost identical results, two replicates correspond to the within-run precisions (differences of the $^{87}Sr/^{86}Sr$ ratios: 0.000010; 0.000038), and one replicate exhibits a slightly higher difference of 0.000059.

Results and discussion

Modern samples

The strontium isotope ratios of modern snail shells and river water of the immediate vicinity are consistent with the values published for the different geological formations of the region (Table 4; Fig. 4). Values of shells from soils above loess and Muschelkalk, including the Strudelbach water, vary over a range of 0.7084 to 0.7097. The ratio determined for one shell from a small forested area on Keuper is considerably higher and corresponds with the high signatures of the lower Keuper formations of the region. The signature of the snail from Location 2 is more radiogenic than those of the other loess samples. According to the geological map, Location 2 should represent pure loess, but the vegetation points to only a thin layer of loess that covers the underlying Keuper. Therefore, the strontium ratio represents a mixture of the Keuper and loess signals.

Strontium-rich snail shells have been suggested as representing samples well-suited for use in characterizing the strontium signatures of a particular location (e.g. Price et al., 2002). Snails have a small home range and it is assumed that the strontium isotope signatures in their shells represent the average of the values of the food they have consumed. However, Evans and colleagues (2009, 2010) reported that modern snail shells in Scotland and Britain do not reflect the average biosphere values obtained from plants, but instead yield a rainwater-muted signature. According to those authors this may be caused by the snails' need for relatively large amounts of water to sustain their body fluid levels, which results in a much stronger contribution by rainwater to their isotope composition.

The carbonate necessary to form the shell of pulmonate land snail is chiefly ingested with the food and water from the upper layers of the soil (air-soil water and dew). Where there is a shortage of calcium capable of contributing to the carbonate of the shell, the mollusc is generally able to compensate by increasing the input from other sources, incorporating external water through the skin and feeding upon soil and shells of other molluscs (Heller and Magaritz, 1983; Leng et al., 1998; Yates et al., 2002). The effect of soil carbonate and external water on the strontium isotope signatures is expected to be small, because several studies have demonstrated that $^{13}C/^{12}C$ ratios in snail shell carbonate are influenced primarily by diet with little to no influence from ingested carbonate (e.g. Stott, 2002; Metref et al., 2003; McConnaughey and Gillikin, 2008). Nevertheless, varying contributions of carbon from local limestone carbonate and external water may contribute to scatter in the relationship (e.g. Goodfriend and Hood, 1983; Yanes et al., 2008). No shortages of calcium have been determined for the area of Hochdorf and the strontium isotope ratios in modern snail shells reflect what one would expect based on the local geology.

Archaeological samples

The $^{87}Sr/^{86}Sr$ ratios of the archaeological snail shells vary within the range of loess, Muschelkalk, and the modern shells (Fig. 4, Table 3). However, the strontium values of the wild animals found at the site of Hochdorf show a large variation (Fig. 4, Table 3). The ratios of the wildcat and beaver samples fall within the Muschelkalk and loess range. Their habitats could have been the river valleys. Wolf and wild boar samples exhibit very radiogenic values in the range of Buntsandstein, granite and gneiss. These animals probably originated from the Black Forest or the Odenwald. The variation of the isotope signatures determined for hare, roe deer, red deer, and bison lie within the range of the values of the livestock teeth.

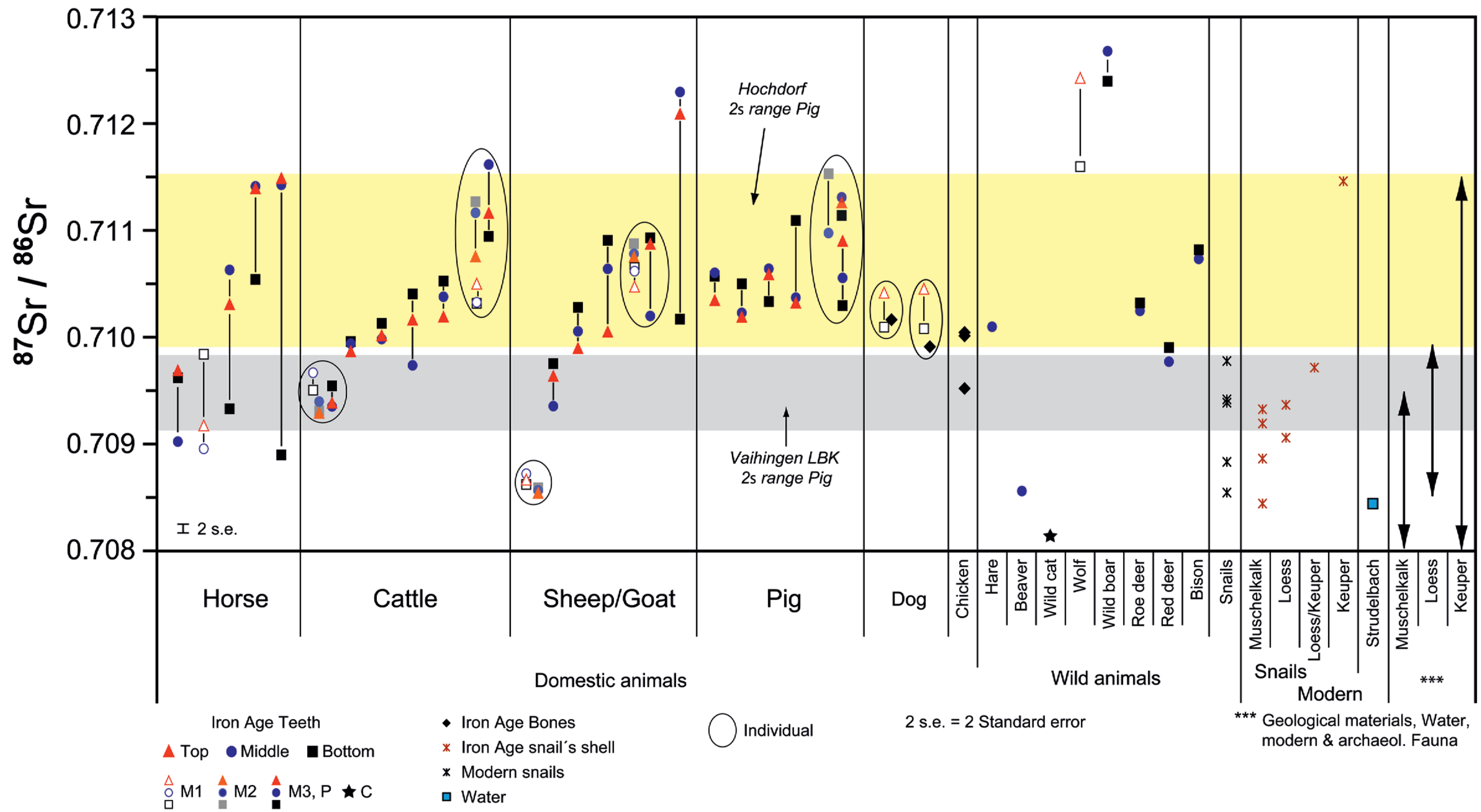

Fig. 4 | $^{87}Sr/^{86}Sr$ values in Iron Age teeth and bone samples of domestic and wild animals from Eberdingen-Hochdorf and of modern snail shell and water samples from the surroundings compared with Sr isotope signatures of the geological formations of the region (data of the LBK site of Vaihingen from Bentley et al. 2004) The typical analytical error (±2 sigma s.e.) is smaller than symbol size

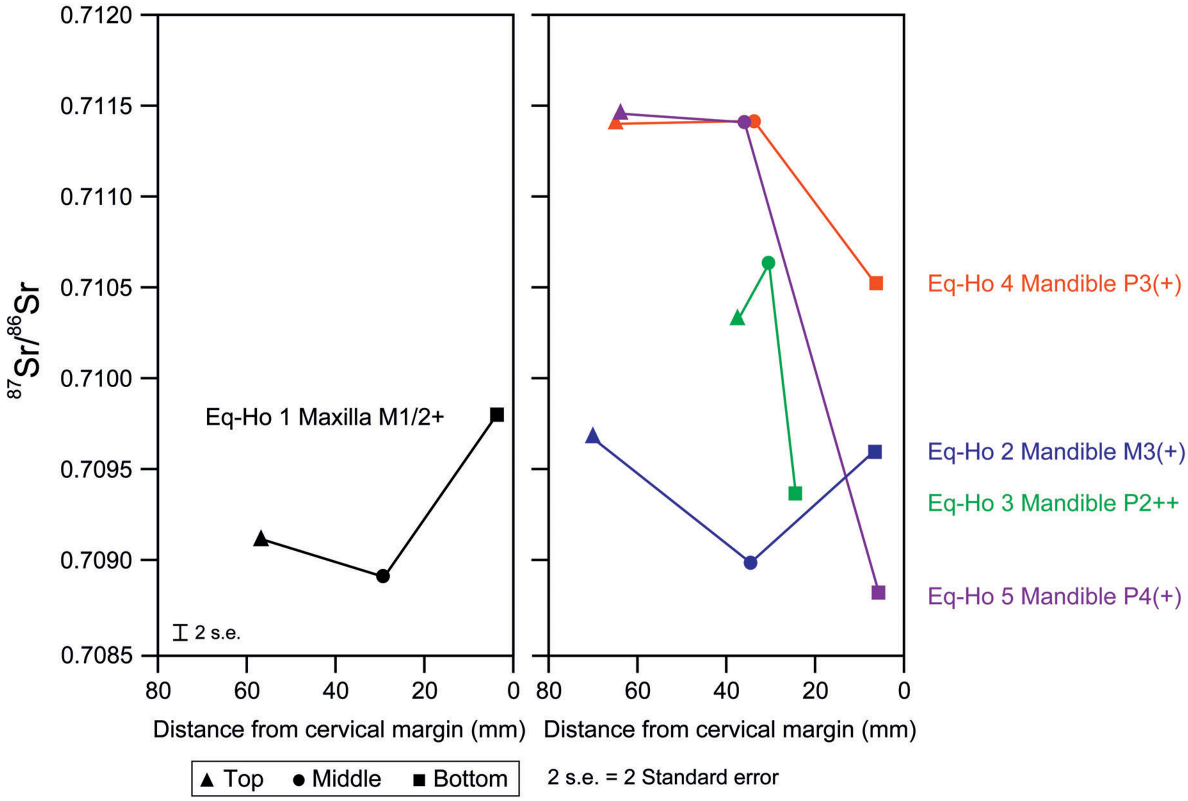

Fig. 5 | Intra-tooth variation of $^{87}Sr/^{86}Sr$ values in Iron Age horse teeth of different individuals from Eberdingen-Hochdorf. M1/2/3: first/second/third molar; P2/3/4: second/third/fourth premolar; (+): in line but not or slightly worn; +: slightly worn; +(+): slightly to moderately worn; ++: moderately worn; +++: heavily worn. The typical analytical error (±2 sigma s.e.) is smaller than symbol size

Therefore, the wild ruminants used areas for grazing and/or browsing that were isotopically similar to those used by domestic animals. The values recovered from cattle, pig, and caprine teeth are highly variable and the datasets of these species overlap widely (Table 2, Fig. 4). Very few values for horse, cattle, and caprines reflect Muschelkalk and/or loess. The majority of the values are considerably higher, ranging from 0.710 on up to 0.7115. They correspond with the strontium signatures of Keuper. There are smaller Keuper areas close to the site. The Stromberg and Löwenstein mountains represent large Keuper areas located in the north and east of the settlement in a distance of about 15 to 30 km, the foreland of the Swabian Alb is another, further away (Fig. 2). These could also have been used for pasturing. Furthermore, pasturing in the Buntsandstein areas of the Black Forest in a distance of about 20 km west of the site cannot be ruled out. The isotope signatures of dog and chicken lie well within the range of the values of the livestock teeth. No significant differences could be observed between bone and tooth samples.

Intra-tooth variation

Intra-tooth variations in the individual teeth are shown in Figures 5 to 8. Variation in the analytical data for one tooth reflects a situation in which the pasture areas of the animals in question were not restricted to a single geological unit: mobility sometimes played a significant role in domestic animal

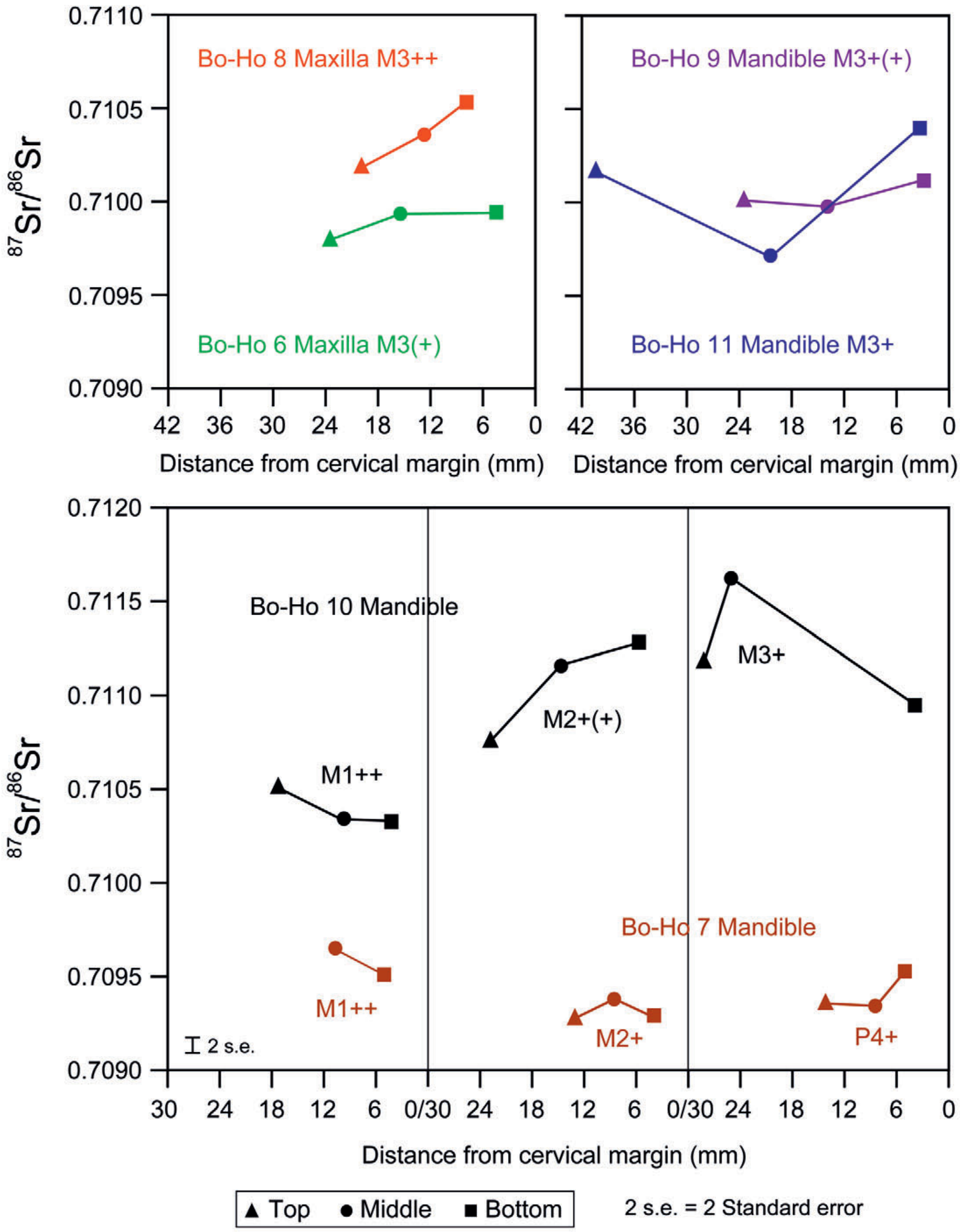

Fig. 6 | Intra-tooth variation of $^{87}Sr/^{86}Sr$ values in Iron Age cattle teeth of different individuals from Eberdingen-Hochdorf. Types of teeth and abrasion see Figure 5. The typical analytical error (±2 sigma s.e.) is smaller than symbol size husbandry. The ratios of the top, middle, and bottom of the teeth are arranged according to the distance, in mm, between the sampling location and the cervical margin. The time span which is represented ranges from a few months to more than a year, depending on the species, tooth type, and the stage of abrasion. The high variations of the strontium ratios in individual horse teeth point to a greater mobility of those animals and possibly the use of horses for transport, i.e. riding (Fig. 5). Judging by size and degree of abrasion, Eq-Ho 1, 2, and 3 originate from three different individuals. Both of the first two, Eq-Ho 1 and 2, seemed to have lived predominantly in loess and Muschelkalk regions: Eq-Ho 1 during the first six month of its life and Eq-Ho 2 between ca. the 18th and 40th month of its life. Eq-Ho 3 reveals a higher degree of mobility on the part of this individual in the beginning of the 3rd year of its life. Samples Eq-Ho 4 and 5 probably belong to one individual. The crown of the third and fourth premolar starts to mineralize at about the same time and the strontium signatures for these samples show a similar pattern. High $^{87}Sr/^{86}Sr$ ratios associated with the end of the second year reflect Keuper areas (top and middle ratios of both teeth), but during the third year, the horse moved to a Muschelkalk and/or loess region (bottom ratio Eq-Ho 5). The bottom ratio of the third premolar is higher, due to the shorter mineralization time of the P3 compared to that of the fourth premolar.

The intra-tooth variation found in cattle, pig, and caprine samples is generally lower (Fig. 6, 7, 8). Judging by body side, tooth size, and abrasion, all single premolars and molars originate from different individuals. More individuals are represented in rows of maxillary or mandible premolars and molars. Figure 6 shows the individual strontium profiles of the cattle teeth Bo-Ho 6, 8, and 9. The isotope ratios indicate that these cattle consumed an isotopically homogeneous diet and remained in a geologically homogeneous loess or Muschelkalk area during tooth crown formation. The data from the first and second molar and forth premolar of sample Bo-Ho 7 are comparable. Nevertheless, their interpretation is difficult because of the considerable abrasion of the teeth, which results in a gap in the isotope record. The $^{87}Sr/^{86}Sr$ ratios of the slightly worn M3 (sample Bo-Ho 11) reflect a greater mobility during the second year of life. The greatest mobility is revealed by the molars of sample Bo-Ho 10 (0.7094 to 0.71162). During the first half year of its life, the individual stayed in more or less isotopically homogeneous areas, but afterwards it moved to pasture grounds associated with higher Keuper signals, probably situated at some distance in the Löwenstein and Stromberg mountains.

The strontium signatures in molar rows of caprines provide evidence that almost no changes in the isotopic features of the pasture land occurred during the eight or nine months of the animals' lives (Fig. 7). Individual OC-Ho 17 seems to have been fed exclusively in a Muschelkalk area. Although the maxilla teeth could not be identified to the species level, it is conceivable that this individual was a goat, feeding on the steep Muschelkalk slopes of the Strudelbach. Individual OC-Ho 13 initially lived in Keuper regions. Its diet during the first half of its second year of life, reflected in the third molar, was more heterogeneous and shows what was probably an "excursion" to loess areas. The signatures in the third molars of Individuals 12, 15, and 16 reflect mainly Keuper, and based on the relatively large variations, the animals grazed in isotopically different Keuper areas. The more radiogenic ratios in the top and middle location of the third molar of Individual 14 point to pasture land above Buntsandstein or granite and gneiss. The individual may have been raised, up to an age of about 12 months, in the Black Forest. Evidence of such a practice has been obtained from animal finds from the princely seat Heuneburg in southwest Germany (Stephan, 2009). The $^{87}Sr/^{86}Sr$ values at the end of the mineralization of the M3 of Individual 14, at about 1.5 years, demonstrate that the animal moved or was brought to the site of Hochdorf within a relatively short time.

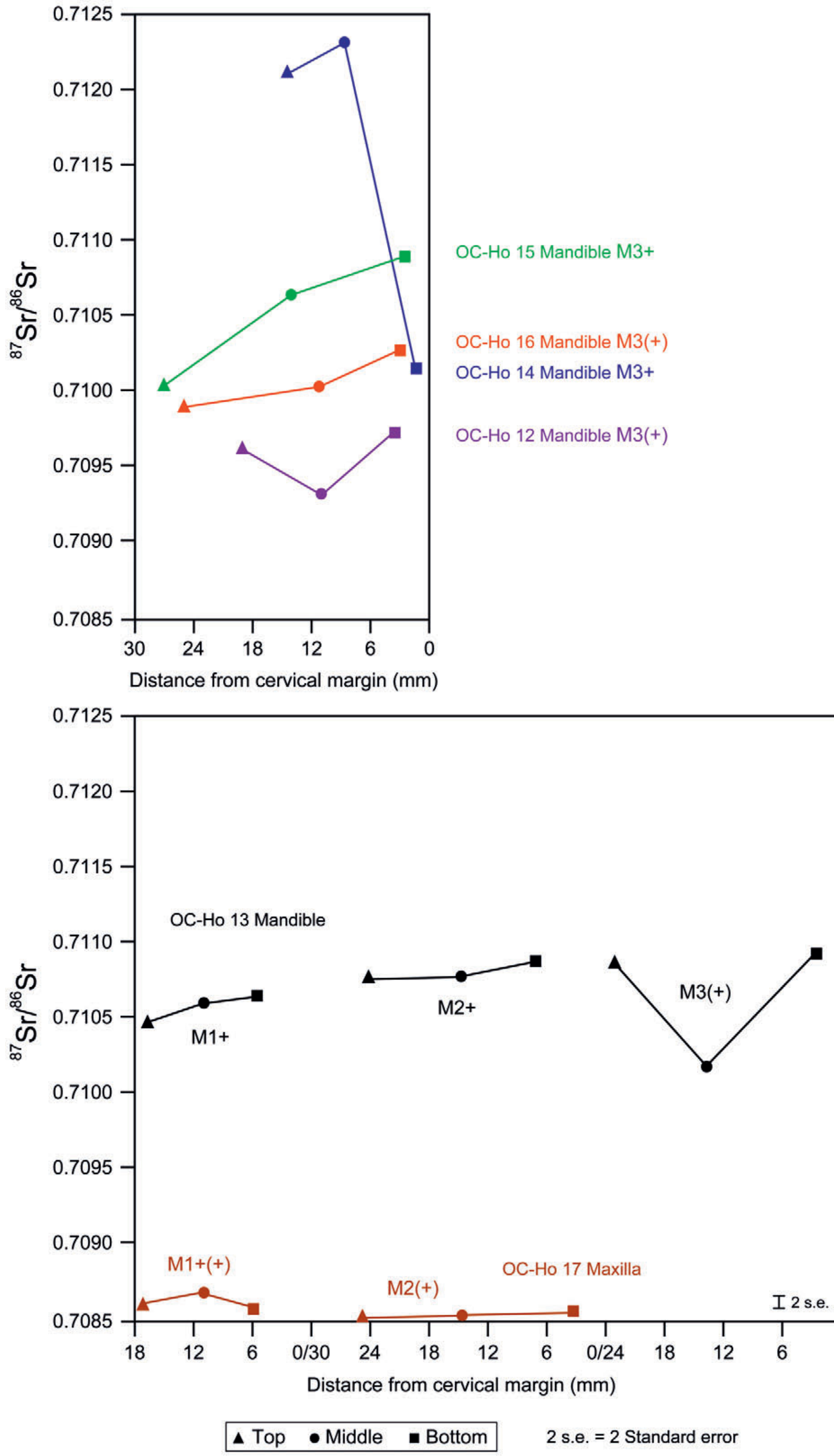

Fig. 7 | Intra-tooth variation of $^{87}Sr/^{86}Sr$ values in Iron Age caprine teeth of different individuals from Eberdingen-Hochdorf. Types of teeth and abrasion see Figure 5. The typical analytical error (±2 sigma s.e.) is smaller than symbol size

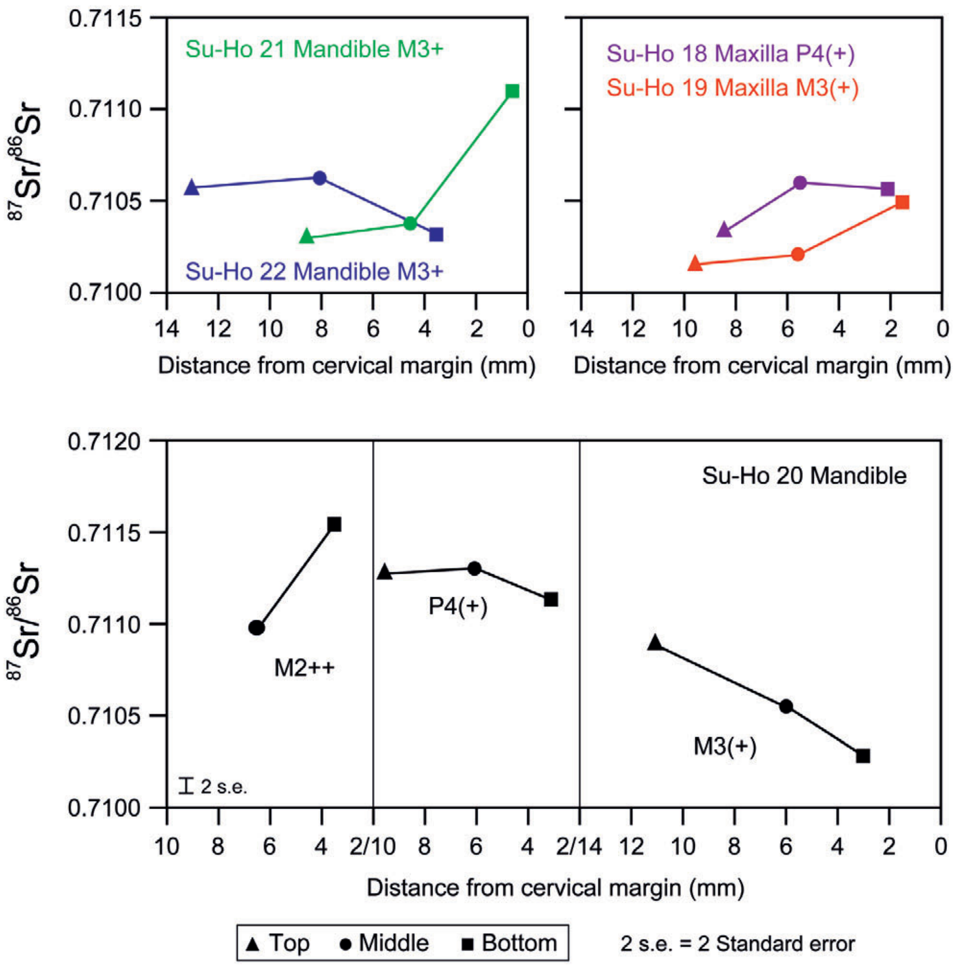

Fig. 8 | Intra-tooth variation of $^{87}Sr/^{86}Sr$ values in Iron Age pig teeth of different individuals from Eberdingen-Hochdorf. Types of teeth and abrasion see Figure 5. The typical analytical error (±2 sigma s.e.) is smaller than symbol size

Strontium signatures in pig teeth show less marked variation than those of the samples of horse and the large and small ruminants (Fig. 8). All data reflect Keuper and as was the case for the other animals, the variations suggest that the pigs were fed in isotopically different Keuper areas. We assume that pigs fed predominantly in forests during the Iron Age (Stephan et al., 2010), as they are known to done in medieval times (e.g. Regnath, 2008). Because soils suitable for crop farming were formed above loess, forests are expected predominantly in Keuper regions. Pig pasture may for that reason have been restricted to Keuper regions.

Local range and spatial organization of domestic animal husbandry

In studies of human mobility, the definition of the "local range" of biologically available strontium isotope ratios is usually based either on human bones or dentine from archaeological contexts (Grupe et al., 1997; Price et al., 2002; Bentley et al., 2004; Schweissing, 2004; Nehlich et al., 2009) or on tooth enamel from domestic animals that are considered to have been raised locally, primarily pigs (Price et al., 2002; Bentley et al., 2004; Bentley and Knipper, 2005a). Due to diagenesis, bones usually reflect the strontium in the immediate burial environment: biogenic values that once differed are often overprinted (Horn and Müller-Sohnius, 1999; Price et al., 2002; Schweissing and Grupe, 2003; Viner et al., 2010). The use of pig teeth is based on the assumption that pigs were kept near the human settlements and reflect an average of the biologically available strontium of the cultivated plots of land.

The strontium isotope data from animal teeth from the Early Latène period are very variable and reflect larger areas with diverse geological conditions (Fig. 4; Tables 3–4). The loess in the immediate vicinity of Hochdorf is represented only in some few teeth and bones of horse, cattle, sheep/goat, and chicken, as well as in modern and some archaeological snail shells. This raises questions concerning the practice of basing the definition of the "local range" on domestic animal teeth. For instance, the arithmetic mean ± 2σ of the pig teeth (0.709861–0.711500; Fig. 4 yellow bar) does not primarily represent the local loess, but rather is consistent with more radiogenic values, such as have been reported for Keuper (cf. Ufrecht and Hölzl, 2006; Knipper, 2009; modern snail shell, this study). Taking the ratios of archaeological snails and most of the modern snails, the 2 sigma range includes only lower values and overlaps only slightly with the pig local range. This underlines the importance of a comparison with a range of independent data from soils, meteoric and ground water and modern sympatric plants and fauna (cf. Price et al., 2002; Bentley et al., 2004; Evans and Tatham, 2004; Evans et al., 2009; 2010; Knipper et al., this volume). Furthermore, it seems appropriate to locate the pasture grounds based on already published and newly created data for the biologically available strontium of the different geological units.

In contrast, the strontium isotope ratios in teeth of cattle, sheep and/or goat from Linearbandkeramik pits in Hochdorf, which were analyzed in the scope of the NSF-Project "*Pastures, Chert Sources, and Upland-Lowland Mobility in Neolithic Southwest Germany*" (Award BCS – 0316125), vary in a small range between about 0.7091 and 0.710 and fall well within the loess range (Knipper, unpublished data). The values are consistent with the 2 sigma local range based on pig teeth from the LBK settlement of Vaihingen, which is situated about 6 km to the north, in similar geological conditions dominated by loess and Keuper (Bentley et al., 2004: 0.709130–0.709794; Fig. 4 grey bar). For the Early Neolithic the $^{87}Sr/^{86}Sr$ values in domestic animal teeth represent a preference of pasture grounds on loess in the immediate vicinity of the sites and a rather small-scale husbandry system (cf. Knipper, 2009).

The large variations of the Iron Age strontium isotope data also provide insights into changes in husbandry practises and land use from the Neolithic to the Early Latène period. None of the Iron Age livestock species seem to have been kept solely on loess in the immediate vicinity of the site. Investigations of the faunal and botanical remains from the Early Latène site of Hochdorf and in the Neckar region gave evidence for an open landscape intensively used for crop farming and a decreasing stock of wild animals (Schatz, 2009; Stika, 2009). The high quality of the soils in the surroundings of Hochdorf (6 km radius) suggests that most of this area was permanently cultivated for barley, wheat, and legumes (Fischer et al., 2010.). The land exploited for livestock production could have been located in the meadows along the valley slopes (Muschelkalk), the fields during the fallow (loess and partly Keuper), and the forested areas (mainly above Keuper) in the immediate vicinity and at some distance from the site.

Due to their dietary requirements, different species need different pasture grounds and it is suggested that horses and the large and small domestic ruminants grazed in open landscape i.e. grass- and meadowland and that pigs were predominantly fed in forests, although cattle can browse in forested areas and pig can collect their fodder in meadows with humid conditions, i.e. flood plains. Clear separations of the pasture areas for different species are not evident in the strontium isotope ratios. The intra-tooth and intra-individual variations reflect movements and non-permanent pastures but no obvious seasonal herding practice. This kind of livestock management required access to adequate pasture areas, and communication between the inhabitants of Hochdorf and the population of the contemporary settlements and farmsteads in the surrounding area (Balzer and Biel, 2008). It can be suggested that different kinds of exchange and trade occurred between the settlements of the regions and that the inhabitants might have managed the livestock pasturing in common.

Conclusions

The site of Eberdingen-Hochdorf "Reps" in southwestern Germany belongs to a group of Iron Age settlements in the vicinity of the princely seat Hohenasperg. The site lies in a fertile region of the Neckar River, which is characterized by a hilly landscape and areas of varied geology. During the Early Latène period Hochdorf was a wealthy settlement characterized by crop farming, stock breeding of cattle, sheep, goat, and pig, wool production, and weaving. Some features provided evidence of a settlement of the Early Neolithic Linear Pottery Culture (LBK), which also yielded animal bone finds.

Strontium isotope ratios in animal teeth were used to explore the herd movements and the mobility habits of livestock, and to obtain information about the pasture grounds in the environs of the settlements. The values recovered from the teeth of the livestock from the Early Latène settlement of Hochdorf are highly variable and the data overlap widely. The $^{87}Sr/^{86}Sr$ values in pig teeth as well as in cattle and caprine teeth are not suited for use in determining the local strontium signature for the region of Hochdorf. Modern snail shell and water samples reflect the local geology nicely; though they too yield highly variable values, too, reflecting the varied geology of the region. For the most part, areas above the geologic unit Keuper were used for pasture, and part of the livestock was probably kept in the Stromberg and/or Löwenstein mountains at a distance of about 15–30 km from the site. Nevertheless the possibility that animals were imported from further away cannot be ruled out. The intra-tooth and intra-individual variations in cattle, sheep/goat, and pig samples reflect movements and non-permanent pastures, but no obvious seasonal herding practice. The high variations of the strontium ratios in single horse teeth point to a greater mobility and possibly the use of horses for transport i.e. riding. In contrast to the Iron Age finds, the isotope signatures of the Early Neolithic livestock from Hochdorf and the Linearbandkeramik settlement of Vaihingen, a site situated near Hochdorf, indicate that animal herding concentrated in loess areas close to the settlements and that seasonal movements to geologically different areas, including Keuper, were exceptions (Bentley and Knipper, 2005b; Knipper, 2009).

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References

Altherr, R., Henjes-Kunst, F., Langer, C., Otto, J., 1999. Interaction between crustal-derived felsic and mantle-derived mafic magmas in the Oberkirch Pluton (European Variscides, Schwarzwald, Germany). Contribution to Mineralogy and Petrology 137, 304–322.

Amorosi, T., 1989. A Postcranial Guide to Domestic Neo-Natal and Juvenile Mammals. The Identification and Aging of Old World Species. BAR International Series 533. Archaeopress, Oxford.

Balasse, M., 2003. Potential biases in sampling design and interpretation of intra-tooth isotope analysis. International Journal of Osteoarchaeology 13, 3–10.

Balasse, M., Ambrose, S., Smith, A.B., Price, T.D., 2002. The seasonal mobility model for prehistoric herdes in the south-western Cape of South Africa assessed by isotopic analysis of sheep tooth enamel. Journal of Archaeological Science 29, 917–932.

Balzer, I., Biel, J., 2008. Die Erforschung der Siedlungsdynamik im Umfeld des frühkeltischen Fürstensitzes Hohenasperg, Kr. Ludwigsburg, auf archäologischen und naturwissenschaftlichen Grundlagen, in: Krausse, D. (Ed.), Frühe Zentralisierungs- und Urbanisierungsprozesse. Zur Genese und Entwicklung frühkeltischer Fürstensitze und ihres territorialen Umlandes. Kolloquium des DFG-Schwerpunktprogramms 1171 (Blaubeuren, 9.–11. Oktober 2006). Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg 101, Theiss, Stuttgart, pp. 143–161.

Bendrey, R., Hayes, T. E., Palmer, M. R., 2009. Patterns of Iron Age horse supply: an analysis of strontium isotope ratios in teeth. Archaeometry 51, 140–150.

Bentley, R.A., Knipper, C., 2005a. Geographical patterns in biologically available strontium, carbon and oxygen isotope signatures in prehistoric SW Germany. Archaeometry 47, 629–644.

Bentley, R.A., Knipper, C., 2005b. Transhumance at the early Neolithic settlement at Vaihingen (Germany). Antiquity 70 (306), 1–4.

Bentley, R.A., Krause, R., Price, T.D., Kaufmann, B., 2003. Human mobility at the Early Neolithic settlement of Vaihingen, Germany: Evidence from strontium isotope analysis. Archaeometry 45, 471–486.

Bentley, R.A., Price, T.D., Lüning, J., Gronenborn, D., Wahl, J., Fullagar, P.D., 2002. Prehistoric human migration in Europe: strontium isotope analysis of early Neolithic skeletons. Current Anthropology 43, 799–804.

Bentley, R.A., Price, T.D., Stephan, E., 2004. Determining the "local" ^{87}Sr, ^{86}Sr range for archaeological skeletons: a case study from the Neolithic Europe. Journal of Archaeological Science 31, 365–375.

Biel, J., 1995. Die Siedlung der Späthallstatt-/Frühlatènezeit von Hochdorf/Enz, Kreis Ludwigsburg. In: Fürstensitze – Höhensiedlungen – Talsiedlungen. Bemerkungen zum frühkeltischen Siedlungswesen in Baden-Württemberg. Archäologische Informationen aus Baden-Württemberg 28, Stuttgart, 30–37.

Brewer, M.S., Lippolt, H.J., 1974. Rb-Sr age determinations of pre-tectonic granites from the Southern Schwarzwald. SW Germany. Neues Jahrbuch für Mineralogie, Monatshefte 1974, 28–41.

Britton, K., Grimes, V., Dau, J., Richards, M., 2009. Reconstructing faunal migrations using intra-tooth sampling and strontium and oxygen isotope analyses: a case study of modern caribou (*Rangifer tarandus granti*). Journal of Archaeological Science 36, 1163–1172.

Brown, W.A.B., Christofferson, P.V., Massler, M., Weiss, M.B., 1960. Postnatal tooth development in cattle. American Journal of Veterinary Research 21/80, 7–34.

Brubaker, T.M., Fidler, E.C., Capo, R.C., Olsen, S.L., Hynicka, J.D., Sikorka, M T., Rosenmeier, M.F., 2006. Strontium isotopic investigation of horse pastoralism at Eneolithic Botai settlements in northern Kazakhstan. Geological Society of America, Annual Meeting 2006, Paper 83–14, Abstracts with Programs 38, 215.

Bryant, J.D., Froelich, P.N., Showers, W.J., Genna, B.J., 1996. Biologic and climatic signals in the oxygen isotopic composition of Eocene-Oligocene equid enamel phosphate. Paleogeography, Paleoclimatology, Paleoecology 126, 75–89.

Buhl, D., Neuser, R.D., Richter, D.K., Riedel, D., Roberts, B., Strauss, H., Veizer, J., 1991. Nature and nurture: environmental isotope story of the river Rhine. Naturwissenschaften 78, 337–346.

Chiaradia, M., Gallay, A., Todt, W., 2003. Different contamination styles of prehistoric human teeth at a Swiss necropolis (Sion, Valais) inferred from lead and strontium isotopes. Applied Geochemistry 18, 353–370.

Drach, V.v., Lippolt, H.J., Brewer, M.S., 1974. Rb-Sr-Altersbestimmungen an Graniten des Nordschwarzwaldes. Neues Jahrbuch für Mineralogie, Abhandlungen 123, 38–62.

Evans, J.A., Tatham, S., 2004. Defining "local signature" in terms of Sr isotope composition using a tenth- to twelth-century Anglo-Saxon population living on a Jurassic clay-carbonate terrain, Rutland, UK. in: Pye, K., Croft, D.J. (Eds.), Forensic Geoscience: Principles, Techniques and Applications. Geological Society, London, Special Publications 232, pp. 237–248.

Evans, J.A., Montgomery, J., Wildman, G., 2009. Isotope domain mapping of $^{87}Sr/^{86}Sr$ biosphere variation on the Isle of Skye, Scotland. Journal of the Geological Society, London 166, 617–631.

Evans, J.A., Montgomery, J., Wildman, G., Boulton, N., 2010. Spatial variations in biosphere $^{87}Sr/^{86}Sr$ in Britain. Journal of the Geological Society, London 167, 1–4, including Supplementary Publications No. SUP18388.

Faure, G., 1986. Principles of isotope geology. 2nd ed. Wiley, New York.

Fischer, E., Rösch, M., Sillmann, M., Ehrmann, O., Liese-Kleiber, H., Vogt, R., 2010. Landnutzung im Umkreis der Zentralorte Hohenasperg, Heuneburg und Ipf. Archäobotanische Untersuchungen und Modellberechnungen zum Ertragspotential des Ackerbaus. in: Krausse, D., Beilharz, D. (Eds.), "Fürstensitze" und Zentralorte der frühen Kelten. Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg 120/2, Theiss, Stuttgart, pp. 195–265.

Fricke, H.C., O'Neil, J.R., 1996. Inter- and intra-tooth variation in the oxygen isotope composition of mammalian tooth enamel phosphate: implications for palaeoclimatological and palaeobiological research. Paleogeography, Paleoclimatology, Paleoecology 126, 91–99.

Giblin, J.I., 2009. Strontium isotope analysis of Neolithic and Copper Age populations on the Great Hungarian Plain. Journal of Archaeological Science 36, 491–497.

Gillmaier, N., 2009. The Strontium Isotope Project of the International Sachsensymposion. Beiträge zur Archäozoologie und Prähistorischen Anthropologie VII, Beier and Beran, Langenweißbach, 133–142.

Goodfriend, G.A., Hood, D.G., 1983. Carbon isotope analysis of land snail shells: Implications for carbon sources and radiocarbon dating. Radiocarbon 25, 810–830.

Grupe, G., Price, T.D., Schröter, P., Söllner, F., Johnson, C.M., Beard, B.L., 1997. Mobility of Bell Beaker people revealed by strontium isotope ratios of tooth and bone: a study of southern Bavarian skeletal remains. Applied Geochemistry 12, 517–525.

Habermehl, K.H., 1975. Altersbestimmung bei Haus- und Labortieren. 2nd ed. Parey, Hamburg/Berlin.

Hegner, E., Walter, H.J., Satir, M., 1995. Pb-Sr-Nd isotopic compositions and trace element geochemistry of megacrysts and melilitites from the Tertiary Urach volcanic field: source composition of small volume melts under SW Germany. Contributions to Mineralogy and Petrology 122, 322–335.

Heller, J., Magaritz, M., 1983. From where do land snails obtain the chemicals to build their shells? Journal of Molluscan Studies 49, 116–121.

Hillson, S., 1986. Teeth. Cambridge Univ. Press, Cambridge.

Hofmann, A., Köhler, H., 1973. Whole rock Rb-Sr ages of anatectic gneisses from the Schwarzwald, SW Germany. Neues Jahrbuch für Mineralogie, Abhandlungen 119, 163–187.

Hoppe, K.A., Stover, H.M., Pascoe, J.R., Amundson, R., 2004. Tooth enamel biomineralization in extant horses: implications for isotopic microsampling. Palaeogeography, Palaeoclimatology, Palaeoecology 206, 355–365.

Horn, P., Hölzl, S., Fehr, T., 1997. Spurenelemente und Isotopenverhältnisse in fossilen Knochen und Zähnen. in: Wagner, G. A., Beinhauer, K. W. (Eds.), Homo heidelbergensis von Mauer. Das Auftreten des Menschen in Europa. Winter, Heidelberg, pp. 144–166.

Horn, P., Hölzl, S., Storzer, D., 1994. Habitat determination on a fossil stag's mandible from the site of Homo erectus heidelbergensis at Mauer by use of ^{87}Sr, ^{86}Sr. Naturwissenschaften 81, 360–362.

Horn, P., Müller-Sohnius, D., 1999. Comment on "Mobility of Bell Beaker people revealed by strontium isotope ratios of tooth and bone: a study of southern Bavarian skeletal remains" by Grupe, G., Price, T.D., Schröter, P., Söllner, F., Johnson, C.M., Beard, B.L. Applied Geochemistry 14, 263–269.

Kalt, A., Grauert, B., Baumann, A., 1994. Rb-Sr and U-Pb isotope studies on migmatites from the Schwarzwald (Germany): constraints on isotopic resetting during Variscan high-temperature metamorphism. Journal of Metamorphic Geology 12, 667–680.

Knipper, C., 2004. Die Strontiumisotopenanalyse: Eine naturwissenschaftliche Methode zur Erfassung von Mobilität in der Ur- und Frühgeschichte. Jahrbuch Römisch Germanisches Zentralmuseum 51, 589–685.

Knipper, C., 2009. Die räumliche Organisation der Tierhaltung in der Linearbandkeramik: Naturwissenschaftliche und archäologische Untersuchungen. PhD thesis, University Tübingen.

Knipper, C., Paulus, S., Uerpmann, M., Uerpmann, H.-P., 2008. Seasonality and land use in Iron Age Kachetia (Georgia). Oxygen and strontium isotope analyses on horse and cattle teeth. Archäologische Mitteilungen aus Iran und Turan 40, 149–168.

Knipper, C., in press. Strontium-Isotopenanalysen an Pferde- und Schweinezähnen von der Hünenburg bei Watenstedt. Ein Vorbericht. in: K.-H. Willroth (Ed.), Die Bronzezeit im nördlichen Harzvorland. Eine bronze- und früheisenzeitliche Befestigung nördlich des Harzes und ihr Umfeld. Göttinger Forschungen zur Ur- und Frühgeschichte 2. Wachholtz, Neumünster.

Küster, H., 1985. Hochdorf I. Neolithische Pflanzenreste aus Hochdorf, Gemeinde Eberdingen (Kreis Ludwigsburg). in: Körber-Grohne, U. Hochdorf I. Die biologischen Reste aus dem hallstattzeitlichen Fürstengrab von Hochdorf, Gemeinde Eberdingen (Kreis Ludwigsburg). Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg 19, Theiss, Stuttgart, pp. 13–83.

Leng, M.J., Heaton, T.H.E., Lamb, H.F., Naggs, F., 1998. Carbon and oxygen isotope variations within the shell of an African land snail (*Limicoloaria kambeul chudeaui* germain): a high-resolution record of climate seasonality. The Holocene 8 (4), 407–412.

McCance, R.A., Ford, E.H.R., Brown, W.A.B., 1961. Severe undernutrition in growing and adult animals. The British Journal of Nutrition 15, 213–224.

McConnaughey, T.A., Gillikin, D.P., 2008. Carbon isotopes in mollusk shell carbonates. Geo-Marine Letters 28, 287–299.

Metref, S., Rousseau, D.-D., Bentaleb, I., Labonne, M., Vianey-Liaud, M., 2003. Study of the diet effect on $\delta^{13}C$ of shell carbonate of the land snail *Helix aspersa* in experimental conditions. Earth and Planetary Science Letters 211, 381–393.

Nehlich, O., Montgomery, J., Evans, J., Schade-Lindig, S., Pichler, S.L., Richards, M.P., Alt, K., 2009. Mobility or migration: a case study from the Neolithic settlement of Nieder-Mörlen (Hessen, Germany). Journal of Archaeological Science 36, 1791–1799.

Niven, L.B., Egeland, C.P., Todd, L.C., 2004. An intersite comparison of enamel hypoplasia in bison: implications for paleoecology and modeling Late Plains Archaic subsistence. Journal of Archaeological Science 31, 1783–1794.

Passey, B.H., Cerling, T.E., 2002. Tooth enamel mineralization in ungulates: Implications for recovering a primary isotopic time-series. Geochimica et Cosmochimica Acta 66, 3225–3234.

Poll, S., Wagenstaller, J., Schweissing, M.M., Driesch, A.v.d., Grupe, G., Peters, J., 2005. Sr isotopes in horn cores provide information on early modern cattle trade. Archaeofauna 14, 243–251.

Price, T.D., Burton, J.H., Bentley, R.A., 2002. The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. Archaeometry 44, 117–135.

Price, T.D., Grupe, G., Schröter, P., 1998. Migration in the Bell Beaker period of central Europe. Antiquity 72, 405–412.

Price, T.D., Knipper, C., Grupe, G., Smrcka, V., 2004. Strontium isotopes and prehistoric human migration: the Bell Beaker period in Central Europe. European Journal of Archaeology 7, 9–40.

Price, T.D., Wahl, J., Bentley, R.A., 2006. Isotopic evidence for mobility and group organization among Neolithic farmers at Talheim, Germany, 5000 BC. European Journal of Archaeology 9, 259–284.

Price, T.D., Wahl, J., Knipper, C., Burger-Heinrich, E., Kurz, G., Bentley, R.A., 2003. Das bandkeramische Gräberfeld vom 'Viesenhäuserhof' bei Stuttgart-Mühlhausen: Neue Untersuchungsergebnisse zum Migrationsverhalten im frühen Neolithikum. Fundberichte aus Baden-Württemberg 27, 23–57.

Probst, A., Gh'Mari, A.E., Aubert, D., Fritz, B., McNutt, R., 2000. Strontium as a tracer of weathering processes in a silicate catchment polluted by acid atmospheric inputs, Strengbach, France. Chemical Geology 170, 203–219.

Regnath, R.J., 2008. Das Schwein im Wald. Vormoderne Schweinehaltung zwischen Herrschaftsstrukturen, ständischer Ordnung und Subsistenzökonomie. Schriften zur Südwestdeutschen Landeskunde 64. Thorbecke, Ostfildern.

Richards, M., Harvati, K., Grimes, V., Smith, C., Smith, T., Hublin, J.-J., Karkanas, P., Panagopoulou, E., 2008. Strontium isotope evidence of Neanderthal mobility at the site of Lakonis, Greece using laser-ablation PIMMS. Journal of Archaeological Science 35, 1251–1256.

Schatz, K., 2009. Die Tierknochenfunde aus der frühlatènezeitlichen Siedlung Eberdingen-Hochdorf "Reps" – Archäozoologische Untersuchungen zur Wirtschaftsweise, Ernährung und Landnutzung der frühen Kelten im mittleren Neckarraum. In: Schatz, K., Stika, H.-P., Hochdorf VII. Archäobiologische Untersuchungen zur frühen Eisenzeit im mittleren Neckarraum. Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg 107, Theiss, Stuttgart, pp. 17–123.

Schatz, K., Stephan, E., 2008. Archäozoologie frühkeltischer Faunenfunde – Studien zur Wirtschaftsgeschichte im Umfeld frühkeltischer Fürstensitze. in:

Krausse, D. (Ed.), Frühe Zentralisierungs- und Urbanisierungsprozesse. Zur Genese und Entwicklung frühkeltischer Fürstensitze und ihres territorialen Umlandes. Kolloquium des DFG-Schwerpunktprogramms 1171 in Blaubeuren, 9.–11. Oktober 2006. Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg 101, Theiss, Stuttgart, pp. 349–366.

Schweissing, M.M., 2004. Strontium-Isotopenanalyse (^{87}Sr, ^{86}Sr). Eine archäometrische Applikation zur Klärung anthropologischer und archäologischer Fragestellungen in Bezug auf Migration und Handel. Münchner Geologische Hefte, A 31, München.

Schweissing, M.M., Grupe, G., 2003. Tracing migration events in man and cattle by stable strontium isotope analysis of appositionally grown mineralized tissue. International Journal of Osteoarchaeology 13, 96–103.

Silver I.A., 1969. The ageing of domestic animals. in: D.R. Brothwell, E. Higgs (Eds.), Science in Archaeology. Thames and Hudson, London, pp. 283–302.

Stephan, E., 2009. Rekonstruktion eisenzeitlicher Weidewirtschaft anhand archäozoologischer und isotopenchemischer Untersuchungen. in: Benecke, N. (Ed.), Beiträge zur Archäozoologie und Prähistorischen Anthropologie VII, Beier and Beran, Langenweißbach, pp. 65–79.

Stephan, E., Schatz, K., Posluschny, A., 2010. Archäozoologische Untersuchungen und Modellberechnungen zu Viehhaltung, Landnutzung und Ertragspotential im Umkreis der Zentralorte Hohenasperg, Heuneburg und Ipf. in: Krausse, D., Beilharz, D. (Eds.), "Fürstensitze" und Zentralorte der frühen Kelten. Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg 120/2, Theiss, Stuttgart, pp. 232–253.

Stika, H.-P., 2009. Stika, Landwirtschaft der späten Hallstatt- und frühen Latènezeit im mittleren Neckarland – Ergebnisse von pflanzlichen Großrestuntersuchungen. In: Schatz, K., Stika, H.-P. Hochdorf VII, Archäobiologische Untersuchungen zur frühen Eisenzeit im mittleren Neckarraum. Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg 107, Theiss, Stuttgart, pp. 125–295.

Stott, L.D., 2002. The influence of diet on the δ^{13}C of shell carbon in the pulmonate snail Helix aspersa. Earth and Planetary Science Letters 195, 249–259.

Sykes, N.J., White, J., Hayes, T.E., Palmer, M.R., 2006. Tracking animals using strontium isotopes in teeth: the role of fallow deer (*Dama dama*) in Roman Britain. Antiquity 80, 948–959.

Taylor, S.R., McLennan, S.M., McCulloch, M.T., 1983. Geochemistry of loess, continental crustal composition and crustal model ages. Geochimica et Cosmochimica Acta 47, 1897–1905.

Tütken, T., 2003. Die Bedeutung der Knochenfrühdiagenese für die Erhaltungsfähigkeit in vivo erworbener Element- und Isotopenzusammensetzungen in fossilen Knochen. PhD thesis, University Tübingen. URN: urn:nbn:de:bsz:21-opus-9629; URL:http://w210.ub.uni-tuebingen.de/dbt/volltexte/2003/962/

Ufrecht, W., Hölzl, S., 2006. Salinare Mineral- und Thermalwässer im Oberen Muschelkalk (Trias) im Großraum Stuttgart – Rückschlüsse auf Herkunft und Entstehung mit Hilfe der ^{87}Sr, ^{86}Sr-Strontium-Isotopie. Zeitschrift der deutschen Gesellschaft für Geowissenschaften 157, 299–316.

Veizer, J., Buhl, D., Diener, A., Ebneth, S., Podlaha, O.G., Bruckschen, P., Jasper, T., Korte, C., Schaaf, M., Ala, D., Azmy, K., 1997. Strontium isotope stratigraphy: potential resolution and event correlation. Palaeogeography, Palaeoclimatology, Palaeoecology 132, 65–77.

Viner, S., Evans, J., Albarella, U., Parker Pearson, M., 2010. Cattle mobility in prehistoric Britain: Strontium isotope analysis of cattle teeth from Durrington Walls (Wiltshire, Britain). Journal of Archaeological Science 37, 2812–2080.

Wilson, B., Grigson, C., Payne, S. (Eds.), 1982. Ageing and Sexing Animal Bones from Archaeological Sites. BAR British Series 109, Oxford.

Wolff-Boenisch, B., 1999. Sr-Isotope und Multielement-Analysen zur Herkunftsbestimmung von Wein. PhD thesis University Mainz. Reihe Geowissenschaften 58. Edition Wissenschaft. Marburg.

Yanes, Y., Delgado, A., Castillo, C., Alonso, M.R., Ibanez, M., Nuez, J. de la, Kowalewski, M., 2008. Stable isotope (δ^{18}O, δ^{13}C, and δD) signatures of recent terrestrial communities from a low-latitude, oceanic setting: Endemic land snails, plants, rain, and carbonate sediments from the eastern Canary Islands. Chemical Geology 249, 377–392.

Yates, T.J.S., Spiro, B.F., Vita-Finzi, C., 2002. Stable isotope variability and the selection of terrestrial mollusc shell samples for ^{14}C dating. Quaternary International 87, 87–100.