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3. Mobility, migration and provenance

"Are you suggesting that coconuts migrate?"

Monty Python (1974)
Monty Python and the Holy Grail

The perception of prehistoric migration and mobility within sedentary societies has fundamentally changed in the last decades. While migration had been a "lazy person's explanation for culture change" in archaeology (comment by Anthony in Burmeister 2000: 554), the theoretical framework has been intensively discussed (Anthony 1990; Anthony 1992), and scientific methods to trace human movement have been developed (Ericson 1985; White *et al.* 1998). In theory, migration is defined as the spatial movement of people, which is expected to leave traces in the social and physical milieu (Albrecht 1972). In the archaeological record, these people will mainly appear as foreign or exotic due to their foreign material culture. However, it remains difficult to differentiate between the presence of immigrants and cultural diffusion or trade (Burmeister 2000). Also the underlying mechanism of cultural diffusion is most likely human mobility, not necessarily migration. The presence of exotic grave goods at the sites of Magdalenenberg and Singen suggest the presence of 'foreign' or at least highly mobile individuals at the sites. Metal objects and raw materials could be associated with distant regions like the Atlantic coast, the Baltic Sea or the Hungarian Plain. But did the transfer of these exotic goods and objects require long distant mobility or even replacement of single individuals, or even groups of people? Or could objects 'migrate' via exchange and trade without the necessity of single humans actually migrating from one group to the other? As only the destination and not the journey of artefacts can be identified in the archaeological record, this question remains largely unanswered. While chemical analysis of metal can detect the origin of certain metal ores (Rehren and Pernicka 2008), comparable techniques are also available for human tissues. The analysis of strontium and oxygen isotopes in teeth, and of sulphur in bone collagen, can provide information of not only exotic objects, but also if 'exotic people' are present within a burial community.

3.1. Strontium

The analysis of strontium isotopes ($^{87}Sr/^{86}Sr$) in skeletal tissues allow the tracing of human mobility, as each location has a characteristic $^{87}Sr/^{86}Sr$ signature, depending on its geology and formation history (Price *et al.* 2004; Bentley 2006). The $^{87}Sr/^{86}Sr$ signature of a given location is determined by the age and rubidium (Rb) content of the underlying bedrock, as the radiogenic isotope ^{87}Sr forms through radioactive decay of ^{87}Rb. Older geological formations like granite and gneiss have more radiogenic $^{87}Sr/^{86}Sr$ values than e.g. younger volcanic rocks. Unlike many other isotope systems, strontium enters the biosphere without fractionation and is incorporated by plants and animals (Faure and Powell 1972; Graustein 1989). In areas with a heterogeneous geological substrate, the analysis of the $^{87}Sr/^{86}Sr$ ratios in skeletal material can provide information whether an individual lived locally or derived from a different geological context. As different geological formation of similar age may produce similar values, $^{87}Sr/^{86}Sr$ analysis is most reliably applied in combination with other isotope systems like oxygen, sulphur or lead. The sample material of choice for $^{87}Sr/^{86}Sr$ analysis is tooth enamel due to its highly mineralized structure which reliably locks the *in vivo* $^{87}Sr/^{86}Sr$ signal while the tooth is formed (Budd *et al.* 2000; Hoppe *et al.* 2003). As strontium has chemical properties similar to calcium, it is mainly ingested as a trace element in calcium rich foodstuffs like plants and is deposited in the mineral fraction of body tissues including bones and teeth (Bentley 2006). In humans, tooth enamel forms and matures in the first years of life and does not change its composition once mineralized (Humphrey *et al.* 2008). Therefore, dietary signatures of $^{87}Sr/^{86}Sr$ in enamel represent the geological background of an individual's diet during tooth formation in early life history. Depending on the position of the tooth in the dentition, this can record adolescence (third molars), early infancy (anterior dentition) or even the mother's diet (i.e. *in utero* development of the child's deciduous teeth). On the other hand, the porous structures of bone and tooth dentine are more prone to chemical alteration from soil derived strontium (Budd *et al.* 2000). Therefore, $^{87}Sr/^{86}Sr$ data obtained from bone or dentine may be used as a proxy for the soil derived strontium to determine the specific $^{87}Sr/^{86}Sr$ ratios of the burial site. While concerns regarding diagenesis are largely resolved for the analysis of $^{87}Sr/^{86}Sr$ ratios in enamel (Chiaradia *et al.* 2003; Hoppe *et al.* 2003), the main challenge in strontium biogeochemistry is determining which signatures can be considered local and non-local.

3.1.1. Local or non-local? Solving the resolution problem by biosphere $^{86}Sr/^{87}Sr$ mapping

Numerous geochemical studies on strontium isotopes in bedrock and sediments of different ages and formation histories are available in the literature and can provide initial estimates of the local $^{87}Sr/^{86}Sr$ signature. However, these direct measures of geological substrates are not necessarily representative of what actually enters the biosphere and the food chain due to leaching and weathering (Bentley *et al.* 2004; Evans *et al.* 2010). Therefore, reference data from archaeological or modern materials are needed to serve as a proxy for the soluble and therefore bioavailable strontium fraction at a given location. Some scholars have used a 2σ standard deviation from the mean $^{87}Sr/^{86}Sr$ recovery in archaeological samples to define the local $^{87}Sr/^{86}Sr$ signature (Price *et al.* 1994; Grupe *et al.* 1997). However, this approach does not account for the specific geological conditions at a given location and its surroundings.

Today, most researchers studying $^{87}Sr/^{86}Sr$ ratios in archaeological remains follow the recommendations by Bentley, Price and colleagues (Price *et al.* 2002; Bentley *et al.* 2004) by analysing modern environmental samples (plants and animals) or tooth enamel of contemporary domestics and presumably local fauna. However, acquiring reference material with either method has shown to have both advantages and pitfalls. Modern environmental samples should be collected from plants which grow on the targeted geological substrate, which requires detailed geological background information. More importantly, these plants should not be exposed to modern pollutants and fertilizers from traffic, industry or agriculture to avoid biasing with modern strontium. Collections of modern faunal reference materials should be limited to animals which live relatively exclusively on the targeted geological unit e.g. due to small body size and low levels of mobility (snails, rodents). Conveniently, these animals should provide strontium rich mineralized body tissues sufficient for analysis (teeth, bone, shell), and should be easy to catch or collect in a field survey (snail shells). Strontium reference data from archaeological fauna has the disadvantage that either teeth of locally living animals are simply not available at a site or the reference fauna is less local then expected; this has been documented for prehistoric pigs and other domestics (Bentley and Knipper 2005; Stephan 2009). In summary, the sampling strategy to assess the bioavailability of $^{87}Sr/^{86}Sr$ in a given location or region largely depends on the material available at the archaeological site and the environmental and geological conditions of its surroundings.

No suitable animal teeth were available to be used as a reference for the local $^{87}Sr/^{86}Sr$ values at the Bronze Age and Iron Age sites used for this thesis. Therefore, modern plants and snails (n=96) were collected in unfertilized forest patches between Lake Constance and the Black Forest in southwest Germany during the summer 2009. A total of 14 sites in the federal state of Baden-Württemberg were visited for sampling. Each site corresponds to a predominant geological unit in the landscape around the archaeological sites of Singen and Magdalenenberg. By mapping the local variability in bioavailable $^{87}Sr/^{86}Sr$, the geological terrains surrounding the sites were characterized by means of strontium isotopes. The complete dataset is made available including GPS coordinates to provide a high degree of reproducibility in future isotope studies in this region.

Other problems arise with the analysis of lead isotopes in archaeological tissue, which is not outlined in detail in this chapter. While the *in vivo* lead isotope signature may be recorded in tooth enamel (Chiaradia *et al.* 2003), it is difficult to find references for lead isotope variation in the modern environment which is imperative if no archaeological faunal specimens are available. Since industrialization and the emission of lead from fossil fuels, modern lead isotope ratios are abundant in nature (Rummel *et al.* 2007). As reference data from archaeological tooth enamel is not available for localizing authentic geological signatures in southern Germany, this methodological approach was considered, but finally not applied in the work of this thesis.

3.2. Oxygen

Complementary to strontium isotopes, stable oxygen isotopes ($\delta^{18}O$) can be used as a geographic indicator that reflects geographical and climatic parameters (White *et al.* 1998). $\delta^{18}O$ is the ratio between light and heavy oxygen isotopes ($^{18}O/^{16}O$) and can be standardized to the values of standard mean ocean water (SMOW) or PDB (see 2.1). While strontium and sulphur are ingested mainly with food, the $\delta^{18}O$ ratio of body water and skeletal tissue relates to the $\delta^{18}O$ ratios in drinking water (Longinelli and Peretti Padalino 1980). The dynamics of $\delta^{18}O$ fractionation are largely driven by the water cycle (e.g. evaporation, condensation and precipitation). Any isotopic input through rainwater is thereby related to temperature, altitude and the distance to the coastline. This generates a gradient of signatures which is reflected in local groundwater, lakes and streams (Longinelli 1984). For southwest Germany, proxies for $\delta^{18}O$ variation have been developed using data from modern precipitation and archaeological fauna (Bentley and Knipper 2005). As in strontium isotope analysis, $\delta^{18}O$ ratios are most reliably measured in tooth enamel, which is largely resistant to diagenesis and isotopic contamination in the burial environment (Kohn *et al.* 1999). However, for the analysis of $\delta^{18}O$, differences in tooth formation times have to be taken into account, as a significant fractionation of $\delta^{18}O$ can be observed during breastfeeding (Wright and Schwarcz 1998). While the measures of strontium and sulphur isotopes are fairly comparable between laboratories, the comparison of $\delta^{18}O$ values obtained with different methods (extraction from phosphate or carbonate) and scaled against different international standards (SMOW or PDB) is prone to miscalculation. By means of reproducibility, it has been suggested to convert enamel $\delta^{18}O$ values to drinking water $\delta^{18}O$ values. However, despite the linear relationship between drinking water and human body tissue, calculations of drinking water $\delta^{18}O$ values from tooth enamel may vary depending on the equations used (Daux *et al.* 2008; Chenery *et al.* 2010; Pollard *et al.* 2011). Keeping these limitations in mind, geographical attributions should not be estimated solely using $\delta^{18}O$ ratios, but supported by other isotopic evidence, e.g. more robust strontium isotope data (Pollard *et al.* 2011).

3.3. Sulphur

The analysis of $\delta^{34}S$ in bone does not only have the potential to detect dietary signals from aquatic ecosystems, but can also provide information on the geological or geographical background of terrestrial foods. In terrestrial ecosystems, the isotopic composition of sulphur in a given locality is mainly determined by the geological substrate and its formation history (Sakai 1957). Due to the fact that fractionation (<1‰) of sulphur in the biosphere is negligibly low, $\delta^{34}S$ values of food sources directly correspond to the local signal and are reflected in body tissues like bone collagen (Richards *et al.* 2001). Furthermore, coastal environments are dominated by marine sulphur isotope ratios due to sea spray effects, which are detectable several kilometres inland (O'Dowd *et al.* 1997). $\delta^{34}S$ ratios therefore provide information if ancient food sources derive from coastal environments (Craig *et al.* 2006). Although the application of sulphur isotopes in mobility studies is still in its infancy, an initial study has illustrated the potential in identifying immigrant individuals (Vika 2009). The analysis of $\delta^{34}S$ in bone collagen is especially useful where teeth (enamel) cannot be sampled for $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ measurements.

Moreover, the combination of isotope analysis in collagen and tooth enamel can provide information on different episodes in an individual's life history. Bone collagen is a living tissue which remodels constantly during life and different bones appear to remodel variably. Therefore, depending on the particular skeletal element, complete turnover of its isotopic composition may never occur (Wild *et al.* 2000; Geyh 2001). The isotopic ratios of carbon, nitrogen and sulphur measured in collagen reflect the diet in the last decades of an individual's life, while the strontium and oxygen isotope ratios measured in tooth enamel provide information on the earliest life stages when the tooth is formed (Humphrey et al. 2008). Combining the analysis of both tissues holds the potential to explore the approximate timing of mobility and migratory events.