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Passports from the Past: Investigating Human Dispersals using Strontium Isotope Analysis of Tooth Enamel

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Abstract

Strontium isotopes are a powerful tool which provide information about provenance directly from the tissues of humans rather than the grave context and burial goods. Geographical variation in strontium isotopes is primarily controlled by the underlying geology but there are many other factors that need to be considered before migratory individuals can be identified. Consequently, despite many studies which have shown that the method works well, it is clear that much remains to be clarified and it will not work for every question or in every place. It rests on the assumption that people were sourcing their food locally and that there is a measurable strontium isotope difference between the place the person migrated from and the place they migrated to. As migrants may deliberately seek out familiar soil types and terrains in their new homeland, some questions surrounding major migration events may prove intractable for this technique. Other factors that can create heterogeneity or homogeneity leading to false positives or false negatives, such as human choices or coastal subsistence, are explored and the metabolism of strontium into human tooth enamel is discussed. Several models of land use choices by humans are presented to highlight the subtleties inherent in the isotope data and these are used to interpret archaeological human isotope ratios from three studies.

Introduction

In 1985, Jonathon Ericson (1985) floated the idea that measuring the strontium isotope ratios of human skeletal tissue could allow archaeologists to unravel information about the geographic mobility and origins of individuals. Previously, prehistoric and proto-historic human dispersals had been identified by indirect inference from sudden changes in material culture or burial practices, or directly from skeletal traits such as cranial shape, stature and build. None are straightforward to read: skeletal traits are difficult to interpret and can vary more within than between populations; and how the burial was arranged may say more about the beliefs and needs of the survivors, who, for a variety of reasons, may make choices that do not relate in any direct way to the geographic origins of the deceased. Even in the case of historically documented migrations, such as the Anglo-Saxon settlement of England, the scale and nature is often difficult to grasp from written records which often have an agenda or were written many years after the event (Hamerow 1997). For the *adventus Saxonum*, scholars have long argued over how many people came, whether it was an elite migration of male warriors or if women and children were involved (Adams et al. 1978, Arnold 1984, Härke 1998, Hawkes and Dunning 1961, Higham 1992, Hills 1999, Hines 1984, Lucy 2000, Welch 1992).

Extracting information from elements such as strontium that have been locked away since childhood in the tooth enamel of ancient people provides another strand of evidence archaeologists can use to compare and characterise a cemetery population and identify people who did not originate from the local region. Enamel is an acellular, avascular tissue which can neither regenerate nor remodel and thus represents an archive of childhood diet and geographic origins, an ancient passport that people carry with them wherever they travel. Permanent teeth commence mineralization in a well established sequence starting with the first mandibular and maxillary molars approximately ten weeks before birth and permanent crowns (with the exception of the highly variable third molar) are normally completed before the age of nine (Hillson 1996, Gustafson and Koch 1974). There is variation in timing between individuals but dental traits, genesis and eruption are considered to be unaffected by function and relatively immune to non-genetic developmental factors both *in utero* and *in vivo* (Scott and Turner 1997, Tyrrell 2000). By targeting specific teeth with shorter periods of mineralization, or less variability in the age at which mineralization occurs, archaeologists can focus on a specific periods of lif or construct longer sequences from sequentially mineralizing teeth. Unlike DNA, which would struggle to distinguish the migrant from their descendants, strontium isotope analysis will identify only first generation settlers and thus permits an assessment of their age and sex profile.

Following Ericson's landmark paper, two main research groups at the University of Cape Town under Professor N. van der Merwe and the University of Wisconsin Madison led by Professor T.D. Price started to investigate the possibilities of using strontium isotopes to address archaeological questions of mobility, transhumance and migration in Africa, North America and Europe (Ezzo et al. 1997, Grupe et al. 1997, Price et al. 1994b, Sealy 1989, Sealy et al. 1995, Sealy et al. 1991, Sillen et al. 1995). More recently, two substantial review papers specifically pertaining to the use of strontium isotopes in studies of archaeological residential mobility have been published by Price et al. (2002) and latterly by Bentley (2006) and the reader is referred to these for further detail on the underlying geochemical principles. The aim of this paper is to unpick some of the sources and mechanisms that cause variation in humans and illustrate how these impact on the identification of prehistoric migration and mobility.

Background

The possibilities for exploiting strontium isotopes to investigate environmental processes in ecosystems were first proposed by Graustein and Armstrong (1983) and the large number of subsequent studies enabled two major review papers to be published within fifteen years (Åberg 1995, Capo et al. 1998). The technique rests on the principal that rocks of different types and ages have characteristic strontium isotope ratios (conventionally $^{87}Sr/^{86}Sr$) and these ratios do not alter (fractionate) in any measurable way as the element is transferred from the source rocks through the biosphere (Graustein 1989). This lack of mass-dependent fractionation in low-temperature biogeochemical processes results from the comparatively small differences between the isotope masses of heavy elements and contrasts with the ready fractionation that occurs in lighter elements such as oxygen, carbon and nitrogen. Increasing numbers of neutrons can depress chemical reaction rates (Hoefs 1997) and there is, for example, a much greater relative difference between ^{16}O and ^{18}O than between ^{87}Sr and ^{86}Sr. Consequently, an overlying soil, or water flowing over or through the rock, will contain strontium from that rock as will any plants growing in the soil or water. Animals eating those plants will thus be linked through the strontium isotope ratio of their tissues to the source rock type. As the underlying geological terrain changes, so will the isotope ratio of the strontium released from the rocks into the biosphere above. ^{90}Sr is an artificial radionuclide (half-life: 28 years) produced by nuclear reactions. It has little relevance to archaeological studies but concern since the 1950s over ^{90}Sr fallout and exposure, coupled with its long residence time in bone (Comar et al. 1957, Eckelmann et al. 1957, Hodges et al.1950, Kulp et al. 1957, MacDonald et al. 1951, Turekian and Kulp 1956) initiated a large corpus of work on strontium movement through the biosphere and incorporation into skeletal tissues (e.g. Blanchard 1966, Leggett et al. 1982, Mangano et al. 2003, Odum 1957, Papworth and Vennart 1984, Rickard 1964, Tolstykh et al. 2003, Vose and Koontz 1959, Yamaguchi et al. 2007). These studies provide much of the fundamental knowledge necessary for archaeological investigations of human mobility using strontium isotopes.

Strontium metabolism into bone

Strontium is classified as a lithophile (silicate "loving") element along with calcium which it often replaces in many minerals such as apatite: the predominant mineral from which the mammalian skeleton is composed is a carbonated hydroxyapatite or dahllite (McConnell 1973). Archaeologists wishing to use this technique to provenance humans are fortunate therefore that, as a result of the very similar chemical and physical properties of strontium and calcium, most of the body's strontium burden is, like calcium, found in the skeleton and this is the part of the body that most frequently survives burial. Strontium is a non-nutrient trace element that is ingested and metabolised into mammalian tissues principally from food and drink. The mechanism of incorporation is a passive and apparently benign substitution between two alkali earth divalent cations, i.e. Sr^{2+} for Ca^{2+}, during nutrient uptake, internal distribution and excretion. During active ion movement across cell membranes in both plants and animals Sr^{2+} is actively transported in place of Ca^{2+} (Bowen 1979, Storey and Leigh 2004) enabling strontium to be successfully used as a tracer in calcium-related clinical studies (e.g. Rokita et al. 1996). It is incorporated into the carbonate hydroxyapatite lattice at four-fold Ca^{2+} sites (Rokita et al. 1993, Vukovic et al. 1998) and also by adsorption onto the crystal surface (Dahl et al. 2001, Parker and Toots 1980). In laboratory studies, the amount of strontium incorporated into the skeleton of animals is believed to directly reflect the amount available from the diet and environment, i.e. it is dose-dependent (Boivin et al. 1996, Dahl et al. 2001, Pan et al. 2009, Price et al. 1986), as there are no known homeostatic mechanisms that specifically regulate levels of such non-nutrients (Parker and Toots 1980).

Strontium is distributed relatively homogeneously in the skeleton and concentrations of strontium in skeletal tissues from a single individual are very similar, with bone and dentine containing slightly more than enamel (Aufderheide 1989, Montgomery 2002, Parker and Toots 1980, Turekian and Kulp 1956, Underwood 1977). *In vivo* strontium concentrations in bone and teeth appear, like isotope ratios, to vary geographically (Brudevold and Söremark 1967, Turekian and Kulp 1956, Underwood 1977). This could be due to regional variations in bedrock geology, water and food, or cultural differences in subsistence strategies and the types of diet, but the sources of variation have not been extensively researched or fully characterised. Reported values for modern human skeletal and dental tissues are typically 50-300ppm (Brudevold and Söremark 1967, Elliott and Grime 1993, Hancock et al. 1989, Underwood 1977). Animal tissues exhibit a similar range, although herbivores tend to have higher concentrations than carnivores in the same locality and foodchain because plants are strontium-rich and meat strontium-poor, with most of the body's strontium residing in the bones which are rarely eaten (Bocherens et al. 1994, Tuross et al. 1989).

Nevertheless, it is extremely rare for any mammalian tissues to exceed 1000 ppm (Radosevich 1993) and a concentration plateau effect in bone has been observed in clinical studies where high levels of strontium are administered (Dahl et al. 2001).

The ratio of Sr/Ca is widely used in archaeological and modern food chain studies to identify the trophic level, and hence types of food, that an individual exploited (Blum et al. 2000, Burton and Price 1999, Burton et al. 1999, Burton and Wright 1995, Elias et al. 1982, Sealy and Sillen 1988, Sillen et al. 1995). There is a progressive biopurification, i.e. discrimination against Sr^{2+} in favour of Ca^{2+}, at each successive trophic level in both marine and terrestrial environments (Burton and Price 1999, Comar et al. 1957, Elias et al. 1982, 2561). This works well with single-component diets but, in practice, has proved difficult with multi-component diets (Burton and Wright 1995). Mineral metabolism is an extremely complex interaction between many variables that affect trace element bioavailability. Some are physiological and intrinsic to the individual such as health status and age and some are intrinsic to the particular composition of ingested foods. Individual strontium metabolism is, therefore, dependent upon many factors and synergisms/antagonisms, only one of which is the amount of calcium in the diet. For example, strontium-uptake is suppressed in high-calcium or protein-rich diets (Aufderheide 1989, Burton and Wright 1995, Lambert and Weydert-Homeyer 1993, Underwood 1977), and due to the low levels in milk, by consumption of dairy produce (Ezzo 1994). Strontium-uptake is increased in high phytate and fibre diets which actively reduce calcium absorption (Lambert and Weydert-Homeyer 1993) and accordingly, herbivorous diets (Alexander and Nusbaum 1959, Underwood 1977). Consequently, the strontium concentration measured not only reflects the amount of strontium that is ingested but, if calcium levels are not constant, it is sensitive to the amount of calcium.

These factors may result in dietary components contributing disproportionate amounts of strontium that are unrelated to how much of the food is consumed. On balance, it would appear that, in omnivores such as humans, the plant part of the diet is likely to be the dominant contributor to skeletal strontium signatures with a comparatively negligible input being derived from animal sources (Burton and Price 2000, Elias 1980). This is perhaps fortunate given the ease with which wild and live domestic animals can move around the landscape (Bentley and Knipper 2005, Pellegrini et al. 2008, Towers et al. 2010).

Assessing the biogenic integrity of excavated skeletal tissue

Clearly, there is an *a priori* assumption in archaeological trace element and isotope studies that *in vivo* signatures can be retrieved and any exchange, substitution or equilibration between the biogenic tissue and the burial medium has been negligible. For the vast majority of archaeological remains the burial medium is soil and preservation (or survival) is a result of the physical, chemical and biological interaction between soil and skeleton. As many researchers have pointed out this can vary on both large and small scales, from cemetery to cemetery and between two teeth from the same jaw (Henderson 1987, Radosevich 1993, Sponheimer and Lee-Thorp 1999). Preservation does not appear to be directly related to the length of time that skeletal remains have been buried: *"diagenesis is only incidentally a time-dependent* *process."* (Parker and Toots 1980). However, several studies have concluded that chemical alteration can occur remarkably quickly and then remain relatively stable thereafter (Koch et al. 1997, Sponheimer and Lee-Thorp 1999, Trueman et al. 2004).

Mature enamel has considerably higher density and much lower porosity than any other skeletal tissue and is kinetically more stable. At the point of burial it is virtually entirely mineral, in effect already *"a living fossil"* (Robinson et al. 1986). During burial, it retains the micro-morphology created during matrix formation over millions of years and is normally indistinguishable microscopically from modern tissue (Boyde et al. 1988, Kolodny et al. 1996).

In a large number of biochemical and isotope studies, enamel is considered to be stable and resistant to structural and chemical change over geological (Bocherens et al. 1994, Glimcher et al. 1990, Horn et al. 1994, Kolodny et al. 1996, Michel et al. 1995, Michel et al. 1996, Rink and Schwarcz 1995, Wang and Cerling 1994) as well as archaeological time scales (Budd et al. 2000, Elias et al. 1982, Ericson 1993, Koch et al. 1997, Lee-Thorp and van der Merwe 1991, Montgomery et al. 2000, Nielsen-Marsh and Hedges 2000, Price et al. 2002, Price et al. 1994a, Robinson et al. 1986, Trickett et al. 2003, Vernois et al. 1987). Enamel and dentine contain the same carbonate hydroxyapatite mineral phase but their structure, formation process, crystal size and organic content are very different. These differences reflect the specific functions for which each tissue is created and as a consequence dentine bears far more similarities to cortical bone than to enamel. It should, therefore, be expected that enamel would also react in dissimilar ways to dentine and bone when subjected to post-mortem taphonomic and diagenetic processes. Consequently, although it would be very useful to use bone and dentine to extend the period of life for which strontium isotope data can be obtained, and methods have been suggested for the removal of diagenetic strontium from bone and dentine (e.g. Sillen and Legeros 1991, Sillen and Sealy 1995), there are still major concerns over such data unless it is used simply to provide information about the burial soil or local biosphere strontium ratios (Evans et al. 2010, Montgomery 2002, Montgomery et al. 2007b).

What time of life does enamel represent?

Strontium is incorporated into enamel and primary dentine during mineralisation of the two tissues and neither tissue reforms nor remodels (Brudevold et al. 1977, Veis 1989, 189). Thus, the strontium isotope ratio and concentration will derive from those circulating in the plasma during the period of mineralisation, irrespective of the age of death of the human under investigation (Koch et al. 1997, Underwood 1977, Wieser et al. 1996). The period of life represented by individual teeth will vary with tooth type but for the permanent dentition it ranges from the peri-natal period (first molar crown initiation) to about eight years of age when all but the third molar crowns should be complete (Gustafson and Koch 1974, Hillson 1996). Third molar crown mineralization is highly variable but the period represented is predominantly the adolescent years up to approximately 16 years of age (Hillson 1996). The enamel of a human tooth may take months to years to mature (Boyde 1989) and may thus be incorporating strontium throughout this period. There is an incremental structure to the initial organic matrix, e.g. the brown lines of Retzius which is subsequently "fossilized" during maturation when the majority of mineral ions are deposited in the tissue. However, maturation does not appear to necessarily proceed along the same trajectory as matrix deposition, on one front only, or at a regular pace (Boyde 1989, Suga 1982, Suga 1989).

Although there are concerns over the biogenic integrity of any strontium measured in excavated archaeological bone and dentine, the role of bone in mineral homeostasis during the individual's lifetime may impact on the resolution of any dietary signal that can be retrieved from enamel. Bone is a living tissue and subject to modelling (formation) and remodelling (turnover) processes throughout its lifetime. Both processes are functionally different and proceed at different rates and at different times in the skeleton (Priest and Van de Vyver 1990). Remodelling processes result in the release of previously incorporated strontium and the incorporation of new, or reincorporation of old strontium (Priest and Van de Vyver 1990). As a result, bone isotope ratios may change gradually throughout life and so offer the prospect of comparing enamel formed during childhood with bone formed mainly in later life. Although this may suggest that enamel represents a discrete time-slice of diet at the time the tissue was mineralizing and bone a long-term average over many years, it rests on the assumption that only recently ingested strontium is circulating in plasma and available for incorporation in the tissue. This may not be the case: enamel will not represent short-term diet, even if a very small sample is used, if the strontium is already an average of several months or even years of strontium ingestion *before* it is incorporated into the enamel. Such a reservoir effect has been postulated to explain intra-enamel gradients in hypsodont bovine molars even when the sample size is reduced to a shallow 100 μm laser ablation craters (Balasse 2002, Montgomery et al. 2009). Data from studies of human exposure to heavy metals demonstrates long-term residence of heavy "bone-seeking" elements, possibly as a result of storage and recycling by the skeleton through such processes as calcium homeostasis. Residence times of different elements in the body can vary considerably and will be dependent on bone turnover rates, calcium intake, age and health status (Papworth and Vennart 1984, Rabinowitz 1991, Rabinowitz et al. 1973). For example, Gulson et al. (1999) showed that 50% of the lead circulating in the blood of pregnant women resident in Australia had been remobilised from old skeletal stores deposited prior to their migration to Australia. Strontium, like calcium, has a long residence time in the body of 800 to 1600 days and studies suggest retention after 400 days, most likely as a result of buffering from skeletal stores, can still exceed 10% of the original dose (Barenholdt et al. 2009, Bowen 1979, Dahl et al. 2001). Elimination rates from bone can be age and sex dependent but studies of Sr^{90} in humans suggest they rarely exceed 6% per year (Degteva and Kozheurov, 1994; Tolstykh et al., 1997). Moreover, strontium incorporated by heteroionic substitution into deep cortical bone during modelling will have a longer residency time than strontium in exchangeable pools of bone that participate in calcium homeostasis, e.g. bone surfaces, and will take longer to remobilise than that incorporated by a fully grown adult subject only to the processes of remodelling and surface exchange. Data obtained from tooth enamel that formed in infancy may thus represent a shorter period of time as the skeleton itself is very young and the residence time of strontium in the skeleton of growing children may be shorter due to a highly vascular and chemically active skeleton (Leggett et al., 1982; Dahl et al., 2001).

These factors highlight the complexity of heavy metal uptake and residence in the skeleton and its dependence on multiple physiological and environmental factors, most of which will not be known with certainty for the majority of archaeological skeletons.

How do we establish the local signature?

Despite the myriad opportunities for geologically and physiologically induced variation, many of which have not yet been fully characterised or explored, it is usually possible to establish whether the strontium isotope ratio obtained from a skeleton can be obtained from the locality in which it was buried or not. Strontium isotope ratios can only vary between the available strontium end-members: in the improbable scenario that there is only one source of strontium available locally and it provided a ratio of 0.7075, everybody would have a ratio of 0.7075, there would be no normally distributed range of ratios amongst the population because the strontium isotope ratio cannot be altered measurably in low temperature biological processes. If two sources were available, for example 0.7075 and 0.7092, everyone's strontium isotope ratio would fall between these two values (Figure 1). Consequently, an individual with a ratio of 0.7097 could not have eaten locally sourced food as child.

However, isotopes cannot reveal whether the food was brought to the person, or the person went to the food. This is a major problem if the study involves modern people. In the West, a meal can involve food from not only different countries but different continents: sugar snap peas from Zimbabwe; sweetcorn from the United States; beef from Argentina; butter from New Zealand; wine from Italy; and mineral water from Fiji. Even within a single country, food may be mass produced and distributed widely leading to homogenisation of the regional isotope signatures as was found in a study of modern inhabitants of Norway who bore no relation to the ancient, granitic rocks from which the country is predominantly composed (Åberg et al. 1998). Mass produced feed for cattle in a society eating a large amount of meat and diary products was proposed as the reason. In developing countries, where the link between people and the land may be assumed intact, food aid produced many thousands of miles away from where it is consumed, may swamp any locally derived strontium isotope ratio and sever the link between the person and the place of origin. Transport of food over long distances may also be a problem for archaeological studies in certain periods or places. During the Viking settlement of Iceland for example, grain production on Orkney increased dramatically (Bond et al. 2004). If this grain was shipped to Iceland, its inhabitants would have isotope signatures that would identify them as Orcadians rather than Icelanders. Nonetheless, for most archaeological studies, sustained and successful transportation of food or water was probably unlikely and the assumption is thus made when a ratio is inconsistent with local strontium values that the individual was living elsewhere during the time the tooth in question mineralized. For sedentary farming communities, this may indeed be a valid assumption, but there are food procurement strategies that may have involved a wholly mobile subsistence regime or seasonal mobility such as transhumance. Equally, the exploitation of different local environmental niches, for example, if they grazed animals on the hills and grew crops in the valleys, may be reflected in the strontium isotope ratios of a mixed farming community if they contributed different strontium ratios. In some places, there may be several sources of strontium from which foods can be obtained (Figure 2). However, this may not be the hopelessly complex situation it first appears: given the observations that meat and milk do not contribute strongly to metabolised strontium if plants are also eaten, would the exploitation of the hill-land for grazing leave any trace in the human strontium isotope ratios? Furthermore, if the community under investigation lived near the sea they may have exploited coastal resources but again, eating fish and marine mammals may not be visible in their strontium isotope ratios whilst eating seaweed or foods preserved with sea-salt might (Burton and Price 1999, Montgomery et al. 2007b).

How different strontium sources contribute to human isotope ratios

The strontium isotope ratio of a piece of tooth enamel is a single figure: a weighted average derived from all the food and drink ingested, absorbed through the gut, released from the skeleton and finally deposited in the mineral lattice structure of the enamel over the period of mineralization. In itself and out of context, the resulting number may not signify a specific geographic location. For example, imagine a small community living on the Isle of Skye who sourced their food from two places: the Red Cuillins (granite) and the adjacent Black Cuillins (basalt). The granite will supply a strontium isotope ratio of approximately 0.720, the basalt a ratio of 0.705 (Evans et al. 2009). If the individuals in the community had differential access to food produced from these two end-members whilst their enamel was mineralizing, for example, some individuals ate little or no grain due to a preference for meat or as a result of harvest failure at the time of enamel mineralization, their strontium isotope ratios would fall on a mixing line somewhere between the two sources (Figure 3). However, if the contribution to plasma strontium from these two sources was very similar and everyone ate more or less the same diet, the weighted averaged ratios in the tooth enamel of the community exploiting them may be very similar, for example, 0.712 (Figure 4). On its own, 0.712 would be indicative of people originating from a region of Old Red Sandstone (Evans et al. 2010); but they are not. They do not live on any terrain that would provide such a value but have obtained it simply because it is the result of mixing of strontium from two food types sourced from very different rocks. If they grew their crops (strontium-rich) on the basalt and grazed the animals (strontium-poor) on the granite, it is likely their strontium isotope ratios would be nearer the basalt than the granite, say for example 0.708 (Figure 5). Co-incidentally, this is also a value that would indicate food sourced on marine carbonates such as chalks and limestone (Evans et al. 2010, Montgomery et al. 2000, Montgomery et al. 2007a). If such a value were obtained from the inhabitants of Skye, it could be attributed to the Durness limestone valley to the south of the Cuillins which is sheltered and fertile (Evans et al. 2009). Should choice be the only factor controlling land-use in prehistory, this valley would be the most productive place to cultivate crops, on what is otherwise a marginal island for agriculture. Thus, a variety of geological terrains may be available and may be occasionally exploited for food, but in sedentary farming communities, people are far more likely to have strontium isotope ratios that reflect the rocks underlying the good arable land.

Transported atmospheric dust and aerosols may be a major consideration when working in arid or continental regions (Andersson et al. 1990, Benson et al. 2008, Negrel and Roy 1998), but is less of a problem in temperate, maritime islands such as the British Isles where rainfall is the major source of atmospheric deposition. The Isle of Skye, like much of the western Atlantic seaboard of Britain, has high rainfall throughout the year and increasing rainfall has been shown to gradually shift the ratios of strontium available to plants away from the rock toward that of rainwater (Figure 6) (Capo et al. 1998, Raiber et al. 2009), which in coastal regions is close to seawater, i.e. ~0.7092 (McArthur et al. 2001, Veizer 1989). The logical extension of this, is that two communities occupying the same type of geology but one subject to high and one to low rainfall, may be characterised by quite different strontium isotope values. Similarly, the ratios that characterise a particular locality may change over time during periods of increased wetness or aridity. More research is needed to clarify these issues.

In addition to the marine-derived strontium deposited in rain, the crops grown by communities living in coastal regions will be subject to marine sea-splash and sea-spray (Figure 7) which is a significant source of both nutrients and labile soil strontium (Whipkey et al. 2000). Seawater and brines have considerably higher strontium concentrations than freshwaters (Odum 1957) and increased salt intake either by deliberate direct ingestion or indirectly through aerial deposition into the local environment has been suggested as the reason that geologically-derived strontium is swamped in coastal dwellers who have marine-dominated strontium isotope ratios coupled with the high strontium concentrations modelled in Figure 7 (Montgomery et al. 2007b).

High enamel strontium concentrations have also been found in other island populations and prehistoric salt miners inland (Brudevold and Söremark 1967, Jay et al. 2007). Nonetheless, it should be stressed that although increased dietary sodium can result in a decrease in metabolised calcium, changes in absorbed strontium with increased salt intake have not been found in clinical studies of pre- and post-menopausal women (Evans et al. 1997, McParland et al. 1989). However, enamel is mineralized in early childhood when metabolism, efficiency of the gut, growth, bone formation and bone turnover rates may be very different: for example, children absorb lead much more efficiently across the gut wall than do adults and as a result are far more susceptible to lead poisoning (Bowen 1979). This question needs further investigation.

The Isle of Skye is an unusual case because this small island is a microcosm containing rocks dating from almost every geological period from the PreCambrian through to the Tertiary (British Geological Survey 2001). Hence, its inhabitants could be exposed to as wide a range of strontium isotope ratios as are present in the whole of the British Isles (Evans et al. 2009). The opposite is true of many regions of the world where the geology can be extremely homogeneous over vast regions and the isotope signatures of people from a wide geographic area may be very similar; in such regions long-distance immigrants are liable to be rare but remarkably easy to identify. However, in a region of considerable variability such as Skye, whatever the ratio obtained from an archaeological burial, it would be difficult to say, using strontium isotopes alone, that an individual did *not* originate from the Isle of Skye. If every skeleton excavated from the island had a strontium isotope ratio indicative of limestone, it might be reasonable to assume that it would be difficult to survive there in the past without cultivating the limestone valley and an individual who had not done this was unlikely to originate from Skye. Unfortunately, there are only handful of extant archaeological burials because basalts and granites host acidic soils and peat, which in temperate, high rainfall regions are not conducive to bone survival. Consequently, there is a bias in the comparative data available because the vast majority comes from archaeological humans excavated from regions of alkaline rocks such as chalks and limestones; granite-dwellers are only likely to be found if they have left their homeland and been buried in a place where bone survival is good.

If not local - then where?

Establishing whether a skeleton is of local origin is rarely the ultimate goal of strontium isotope analysis. The vast majority of research questions focus on the identification of immigrants amongst cemetery populations as these may illuminate major changes in material culture (Price et al. 2004), the primary colonisation of islands (Bentley et al. 2007a, Price and Gestsdottir 2006), invasions, slavery and warfare (Bentley et al. 2007b, Cox and Sealy 1997, Evans et al. 2006, Price et al. 2006, Schroeder et al. 2009). Once immigrants are identified, the next question is inevitably, if they are not from here, where did they come from? This is rarely simple because isotope analysis is an exclusive technique: it can only rule out places of origin and a strontium isotope ratio is rarely unique. In addition, as previously explained, some rock types simply do not preserve archaeological remains. Occam's Razor may dictate the nearest overland route may be the most likely place of origin but given the archaeological period under investigation, migration theory about how and to where people migrate, this may not be a valid assumption. Recently, papers that specifically address the need for large scale maps of the geographic variation of biosphere strontium isotope ratios and including regions where bone does not survive have been published for use in archaeological or forensic provenancing studies, by measuring geographic variation in waters and plants (Evans et al. 2009, Evans et al. 2010, Hodell et al. 2004, Montgomery et al. 2006) but these are still few and coverage remains thin and uneven in many regions.

Studies of archaeological humans

Many of the dietary regime models presented in Figures 1 and 3 to 7 are visible in Figure 8, which shows archaeological human enamel data from Hebridean islands off the northwestern seaboard of Scotland (Montgomery et al. 2007b). Although complex, the plot can be teased apart into groups of individuals occupying different places in isotope space and, hence, different subsistence strategies. Non-local origins can be proposed for several individuals on various counts and supports the frequent use of sea travel in this region in the past. In situations such as this, strontium isotope data may not be suitable for statistical analysis to identify the population range because the data is unlikely to be normally distributed and would for example result for the coastal dwellers in a standard deviation that fell below the marine end-member which is clearly wrong.

Figure 9 is a group of prehistoric burials from the Yorkshire Wolds, a region of intense ritual activity with henges, cursus and hundreds of burial barrows, but little evidence for settlement in the Neolithic and Bronze Age (Manby et al. 2003). The mobile, eclectic subsistence strategy of the Neolithic population is evidenced from the diffuse cloud of enamel compositions. In contrast, the Bronze Age individuals show a much reduced variability and separate into two groups, one apparently living locally on the Chalk, and the other utilising foods sourced elsewhere but all were ultimately brought to the Wolds for burial.

Finally, Figure 10, illustrates a study of early Neolithic people buried at the site of Niedermörlen in Germany. The aim of this study was to use isotopes to investigate the initial expansion of farming across Europe and address the question of whether it spread as a result of farmers moving into new territories or local hunter-gatherers adopting a new, settled lifestyle (Nehlich et al. 2009). A group of individuals were present at the site who had high strontium ratios indicative, not of the easy to cultivate, loess filled valleys targeted by the early Neolithic famers, but of the granitic uplands.

These people had clearly come some distance to the site but perhaps the most poignant observation is that they were all children. No adults with such origins were found. One possible explanation may be because the community was transhumant, sending the children with the animals to upland summer pastures. If so, none survived to adulthood and all of the teeth that were measured in the study must have co-incidentally mineralized during those summer months, which is somewhat implausible. Why these children were buried at Niedermörlen, why an upland origin resulted in early death, and where the adults that might have brought them to the site had gone may never be ascertained but this study may constitute evidence for the exploitation of child labour amongst early farmers (Taylor 2005).

Conclusions

Geographical variation in strontium isotopes is controlled by the underlying geology. However, there are many other factors that need to be considered before migratory individuals can be identified. The swamping of labile soil strontium by marine strontium in people living on or near the coast means that, although their coastal origins will be clear, precisely which coast they hail from may be impossible to determine using strontium alone. False positive differences in populations inhabiting the same type of rock may be found if the level of rainfall varies considerably either through time or space and it is vital to consider these issues when making interpretations. Although it is unlikely that the entire diets of archaeological people will ever be known for sure, the averaging processes that occur both in the body pool and in strontium deposition in tooth enamel should remove short-term seasonal dietary anomalies. The strontium ratios of omnivores such as humans should be dominated by the plant component of the diet; whilst it was possible in prehistory to move animals long-distances, it is unlikely that sustained large-scale transport of grains and vegetables occurred in most periods.

Communities can define a cluster of strontium isotope ratios or a line, depending on their access to and exploitation of different strontium sources. This can make statistical analysis difficult but can provide information not only on their origins but on their food procurement strategies and indeed, changes through time through choice or necessity.

Strontium isotope analysis is a powerful technique that supplies information about provenance directly from the human skeleton rather than how, and with what accompanying artefacts, the individual was buried. Despite many studies which have shown that the method works well, it is clear that much remains to be clarified and it will not work for every question or in every place. To work at all, it requires that there is a measurable strontium isotope difference between the place the person migrated from and the place they migrated to. Given the predilection for people to seek out similar soil types and terrains in their new homeland, there may be some questions that will remain forever unanswered by strontium isotope analysis, such as the Anglo-Saxon settlement of England and the spread of early Neolithic farmers across the loess of Europe.

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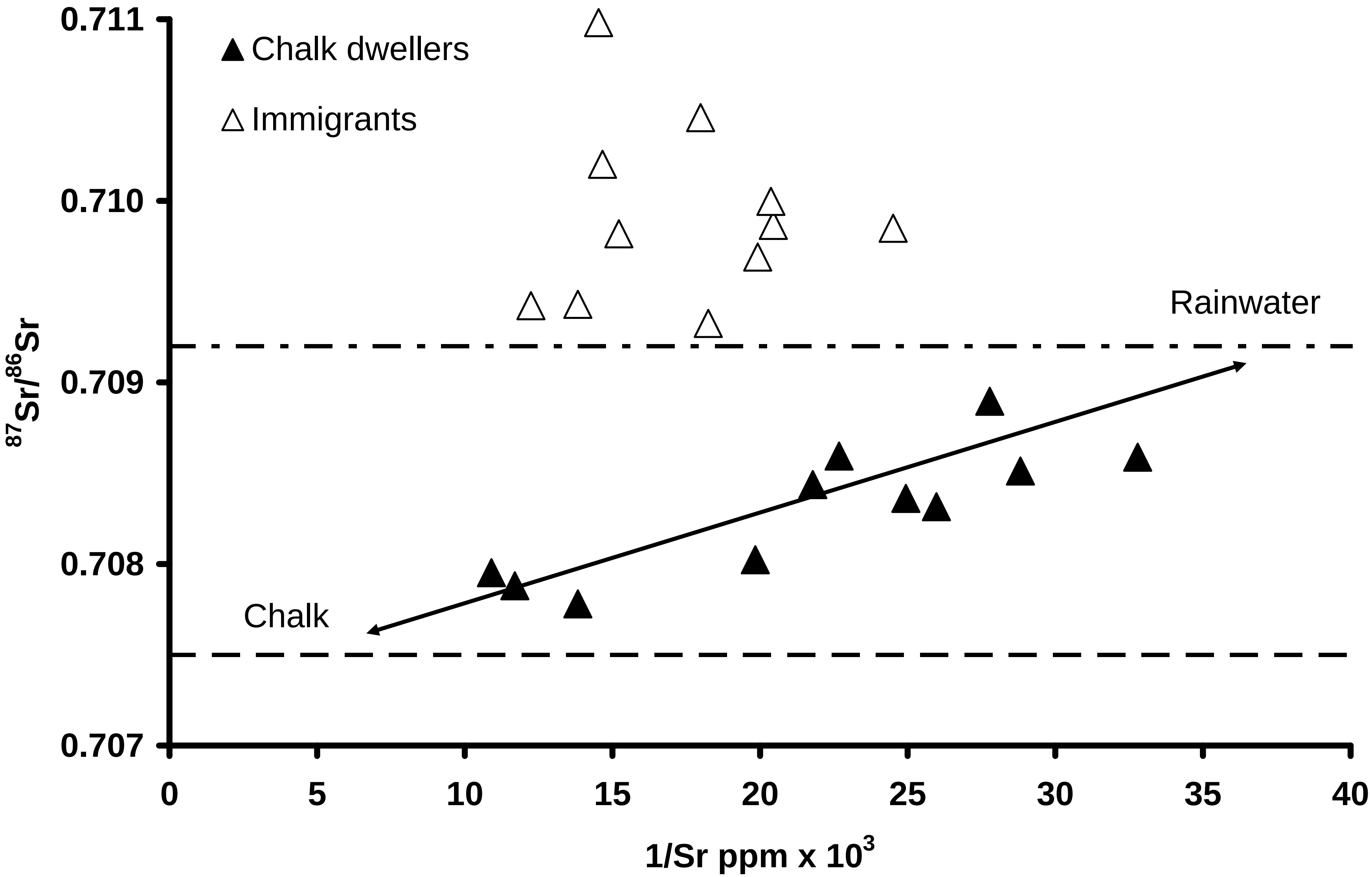
Figure 1

A plot of model enamel strontium compositions for humans who sourced their food from an homogenous rock type (chalk) and who drank and watered their crops with rainwater (black symbols). This provides two sources (end-members) of strontium and local inhabitants will fall on a mixing line between the two ratios if 1/Sr ppm is plotted (this transforms a mixing curve into a straight line with high concentrations are on the left, low concentrations on the right). Individuals who have ratios below 0.7075 or above 0.7092 are inconsistent with this subsistence regime and must be accessing alternative sources elsewhere (white symbols).



Chalk dwellers
Immigrants
Rainwater
Chalk
$^{87}Sr/^{86}Sr$
0.711
0.710
0.709
0.708
0.707
0
5
10
15
20
25
30
35
40
1/Sr ppm x 10^3

Figure 2

Schematic model illustrating the sources of strontium that, if exploited for food and drink, could contribute to the weighted average ratio of enamel from humans inhabitants. Whether a food source is visible will depend on if it is exploited, how much is eaten and how much strontium is metabolised from it. Drinking from rivers may result in the ingestion of strontium from distant rock sources. Atmospheric sources such as dust may provide an additional input in arid regions.

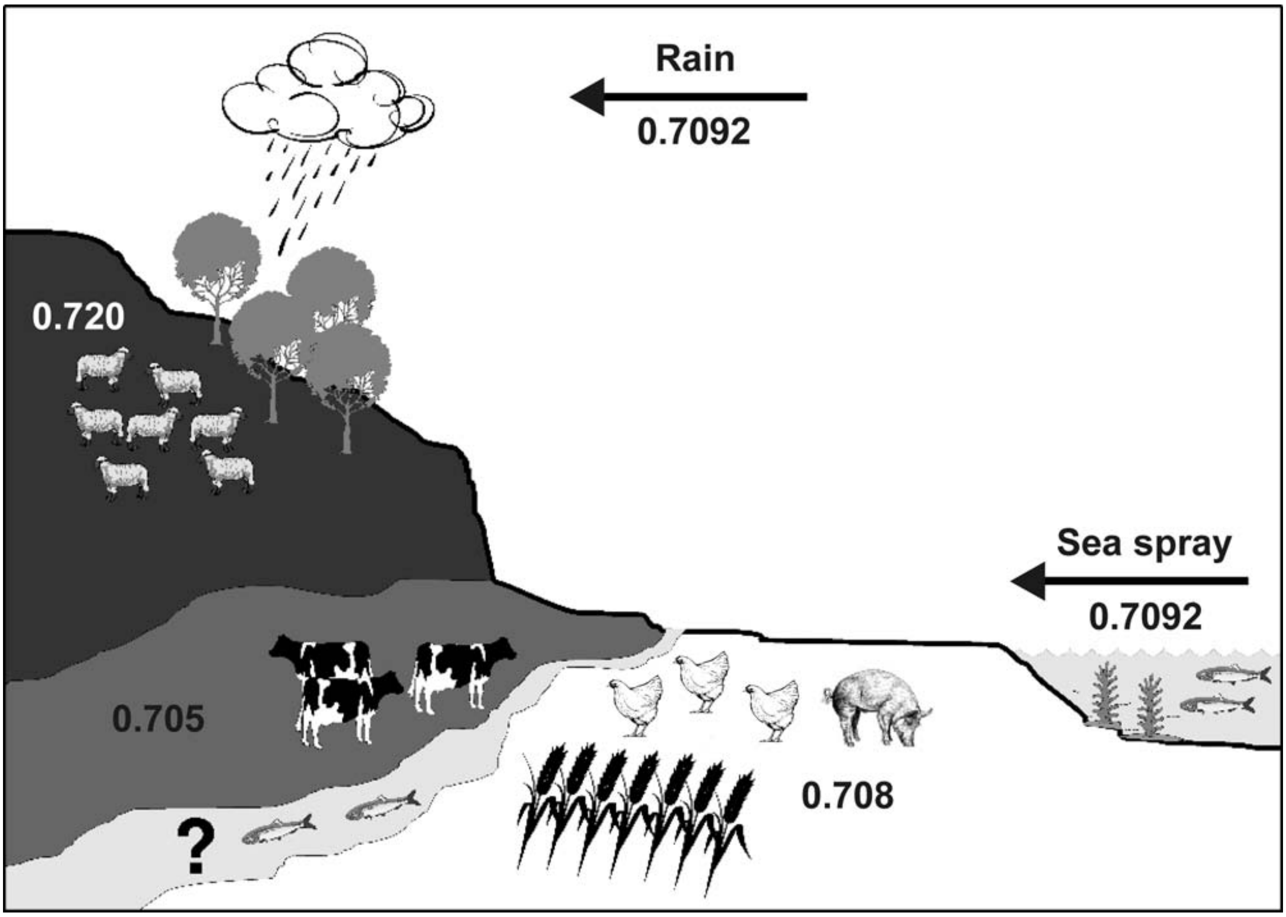

Rain
0.7092
0.720
Sea spray
0.7092
0.705
0.708
?

Figure 3

A plot to illustrate how the enamel strontium compositions of a human community on the Isle of Skye exploiting two food sources: one from the basalt of the Black Cuillins; and one from the granite of the Red Cuillins, might reflect differential access to foods. Where the individuals fell on the mixing line would be dependant on which rock type dominated their dietary intake at the time of enamel mineralization.

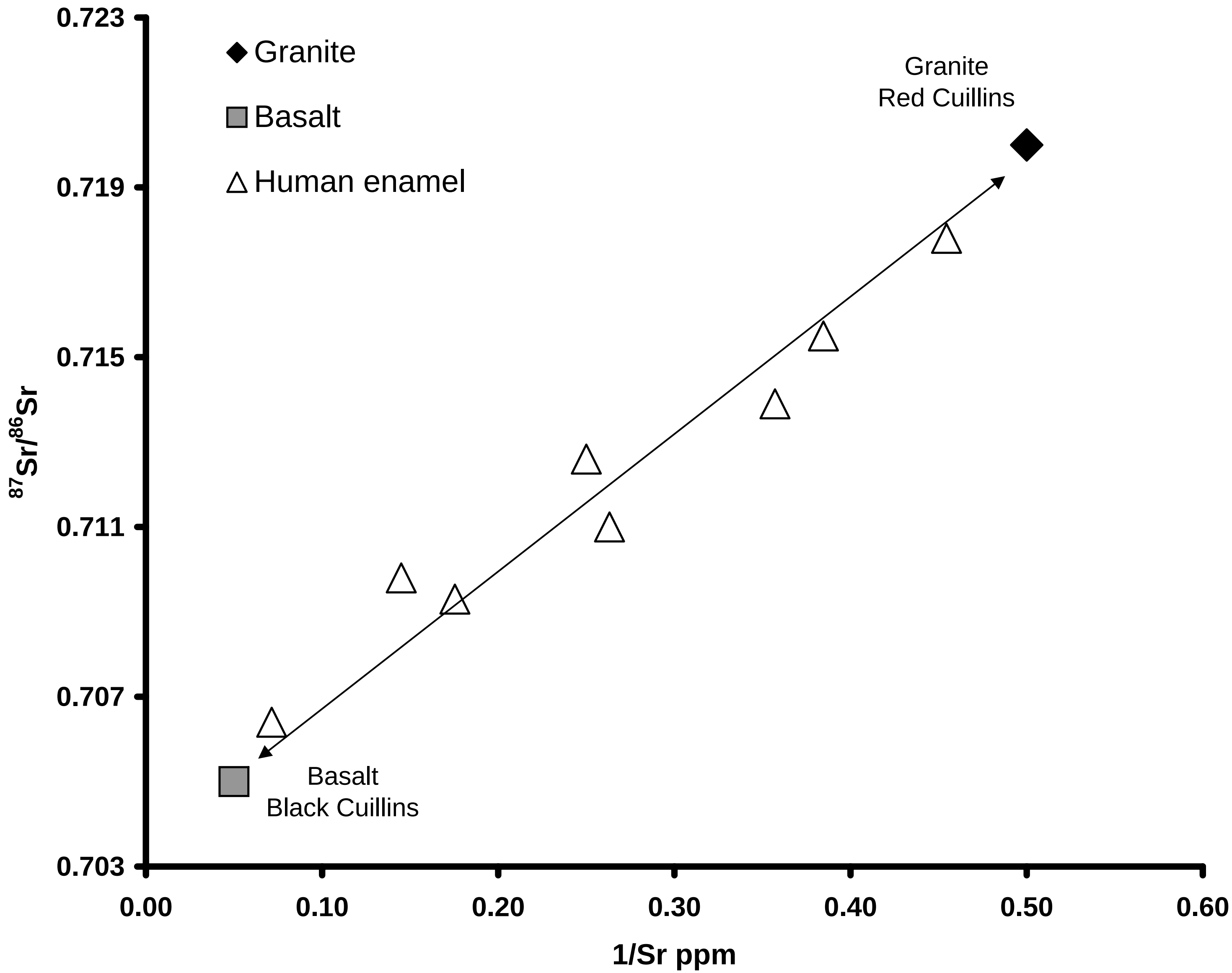
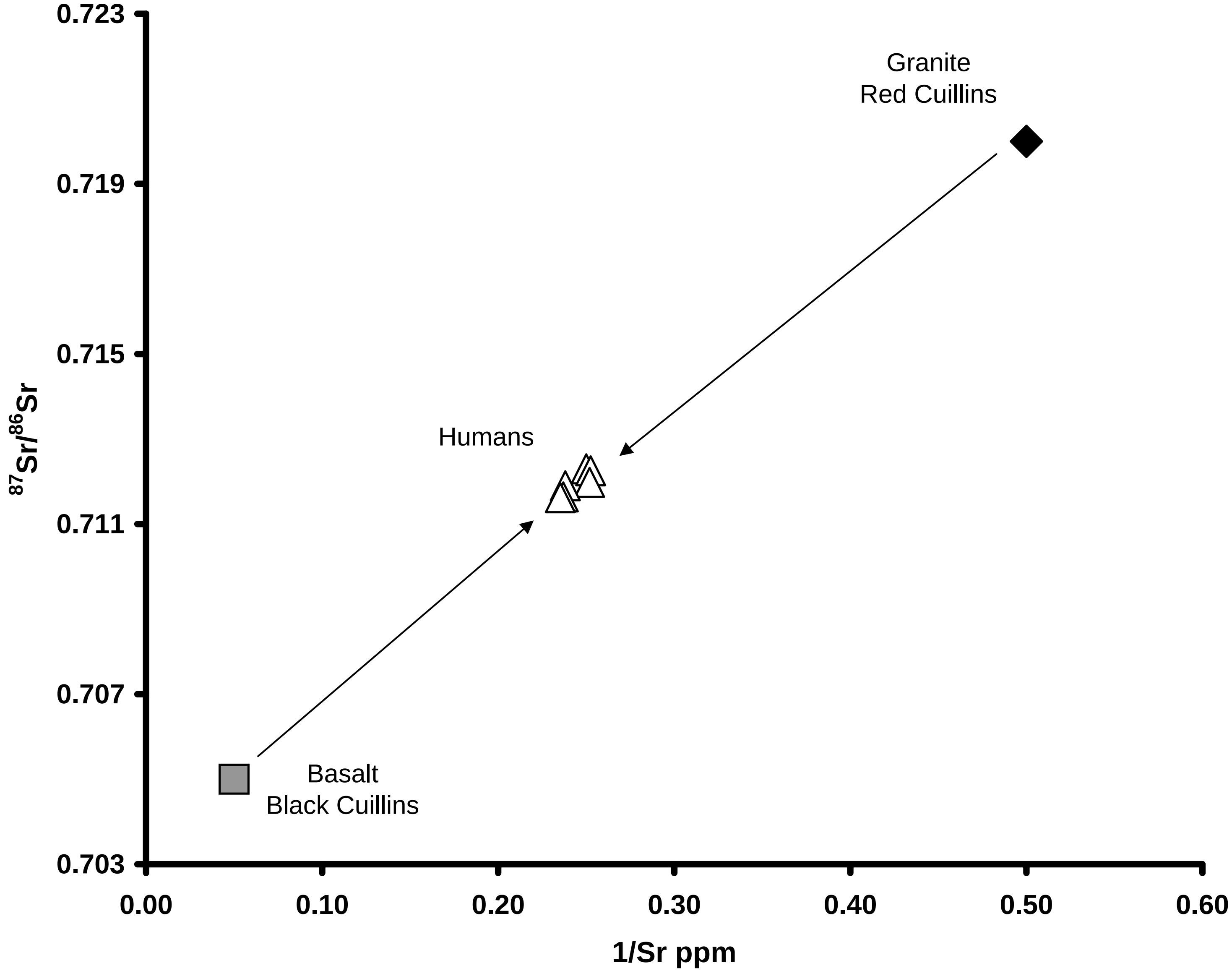

Granite
Basalt
Human enamel
Granite
Red Cuillins
Basalt
Black Cuillins
0.723
0.719
0.715
0.711
0.707
0.703
$^{87}Sr/^{86}Sr$
0.00
0.10
0.20
0.30
0.40
0.50
0.60
1/Sr ppm

Figure 4

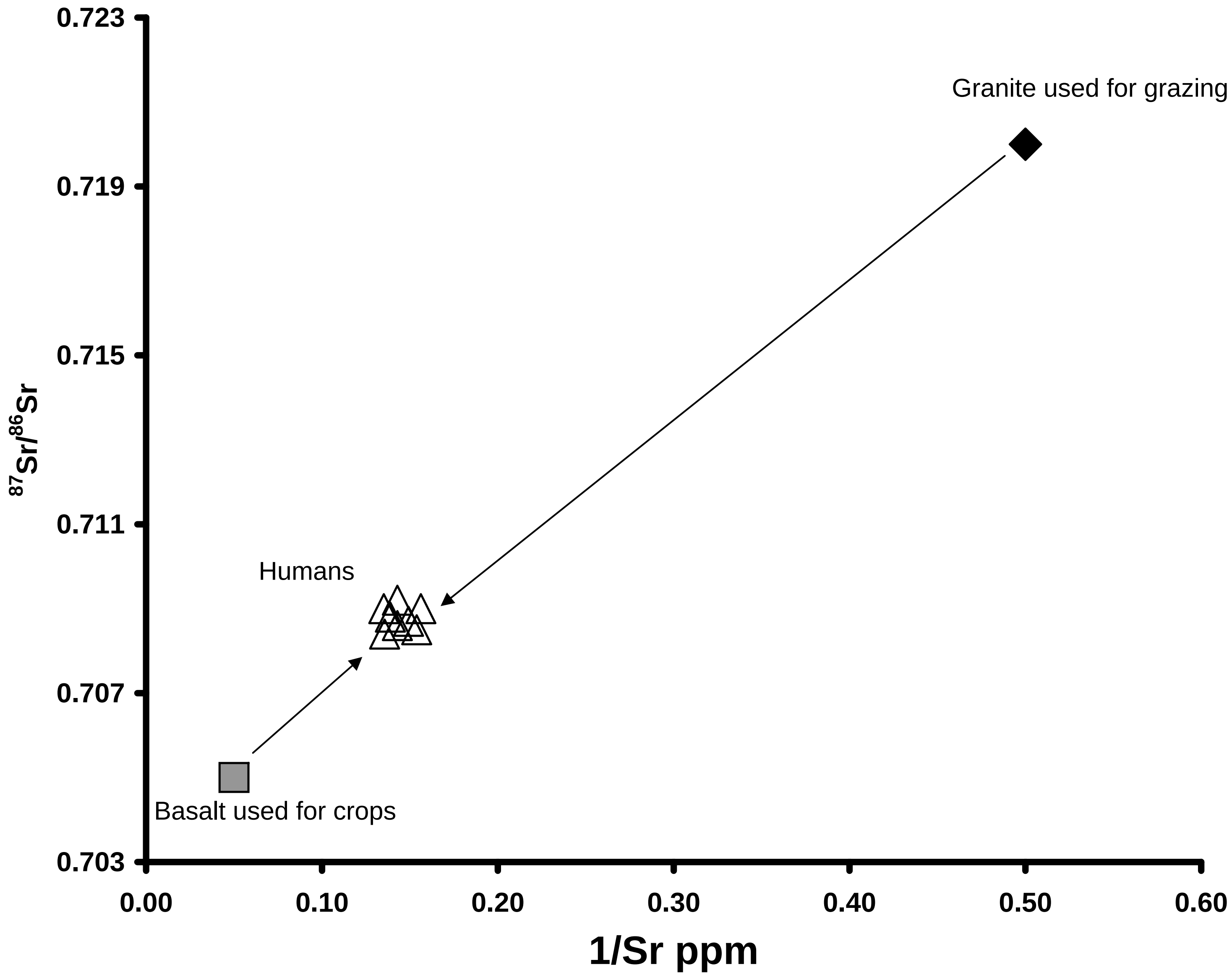
A plot to illustrate how the enamel strontium compositions would cluster if all members of the community had eaten very similar diets sourced from both types of rock. In this scenario, a strontium ratio of 0.712 is not attributable to a specific rock type but is simply a result of mixing between two very different rock types.



Granite
Red Cuillins
Humans
Basalt
Black Cuillins
0.723
0.719
0.715
0.711
0.707
0.703
$^{87}Sr/^{86}Sr$
0.00
0.10
0.20
0.30
0.40
0.50
0.60
1/Sr ppm

Figure 5

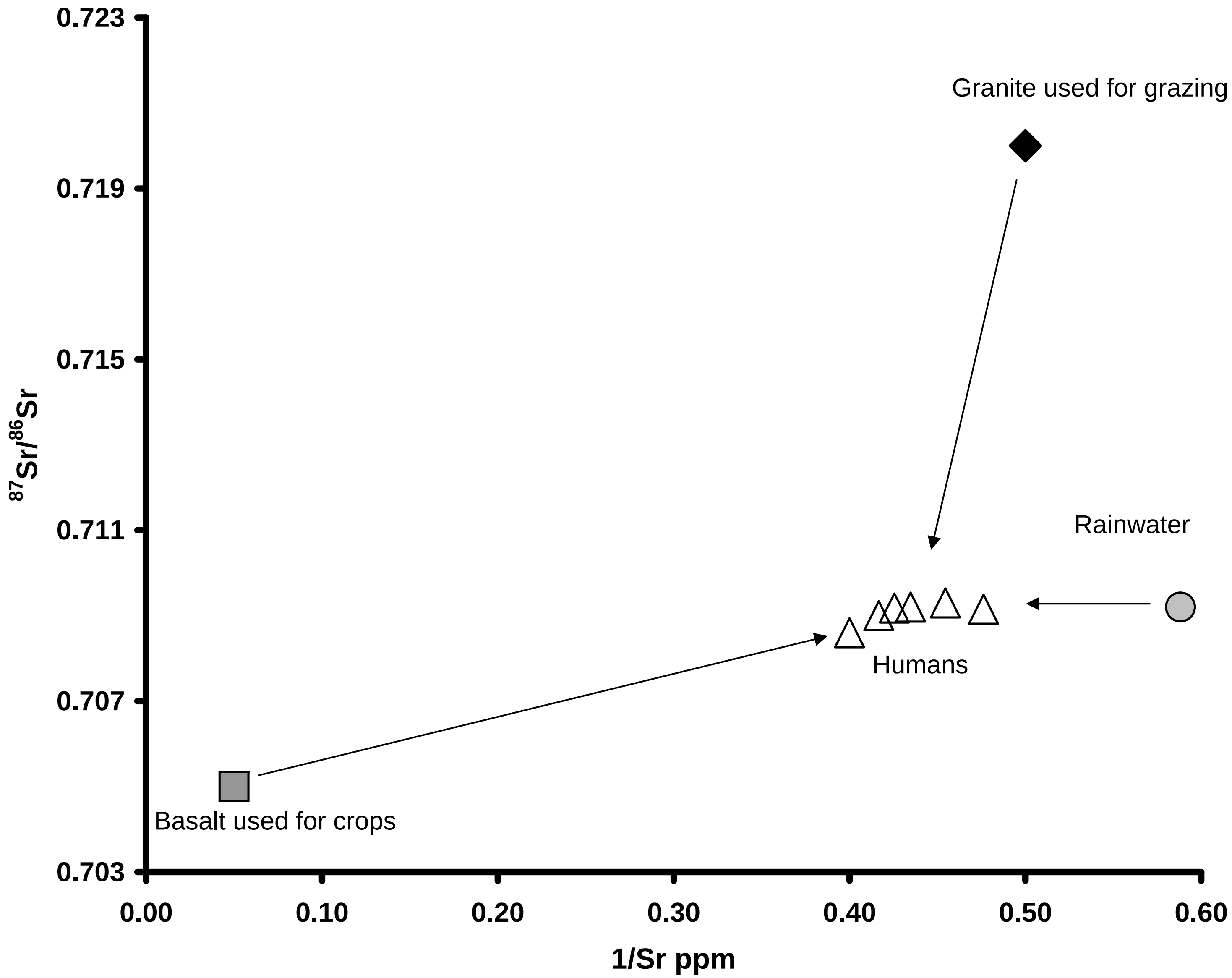
A plot to illustrate how the strontium derived from arable crops might dominate the enamel strontium compositions of humans. A strontium ratio of 0.708 is also indicative of limestone terrains and if such a ratio was obtained it would be difficult to tell from the isotope data alone whether such ratios derived from a mixing scenario or if humans were cultivating only the fertile limestone valleys rather than the inhospitable granite hills.



Granite used for grazing
Humans
Basalt used for crops
0.723
0.719
0.715
0.711
0.707
0.703
87Sr/86Sr
0.00
0.10
0.20
0.30
0.40
0.50
0.60
1/Sr ppm

Figure 6

A plot to illustrate how the addition of a third end-member may affect the enamel strontium compositions. In regions of very high rainfall, such as the Hebrides, rainwater can dilute the soil pore fluids and dampen the plant strontium ratios towards those of rain whose source is seawater (~ 0.7092).



Granite used for grazing
Rainwater
Humans
Basalt used for crops
0.723
0.719
0.715
0.711
0.707
0.703
$^{87}Sr/^{86}Sr$
0.00
0.10
0.20
0.30
0.40
0.50
0.60
1/Sr ppm

Figure 7

A plot to illustrate the effect of marine-derived strontium on a coastal dwelling population. The concentration of strontium in seawater, brines and salt is high (Odum 1957) and coastal communities cultivating crops subject to salt deposition through sea-splash and spray have increased enamel strontium concentrations. In addition, some use strontium-rich seaweed as fodder, fertilizer and food. Eating meat from marine fish and mammals is unlikely to cause this effect as even meat from marine sources is a poor source of strontium (Burton and Price 1999); however, the addition of salt as a preservative may greatly enhance the strontium content of the flesh.

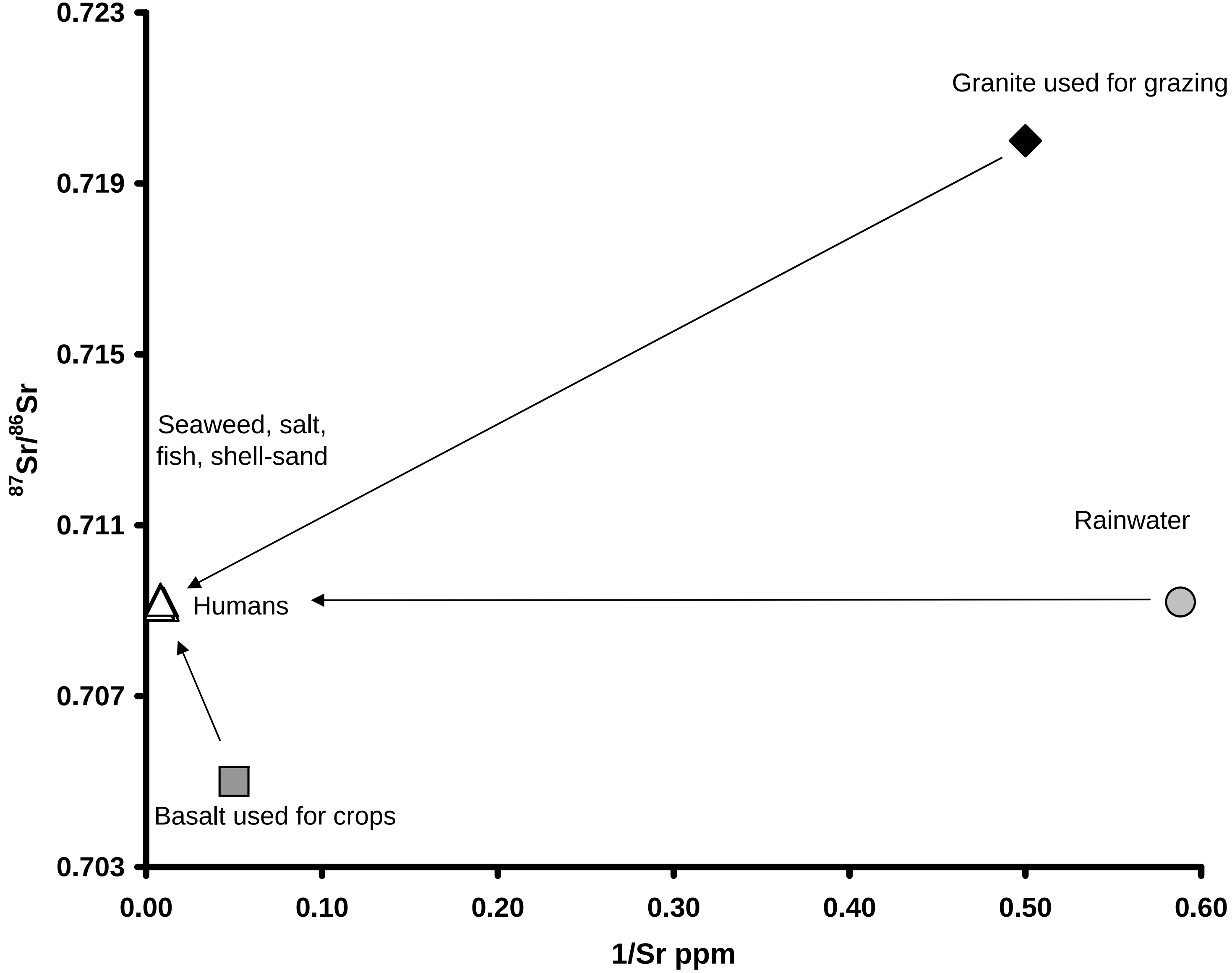
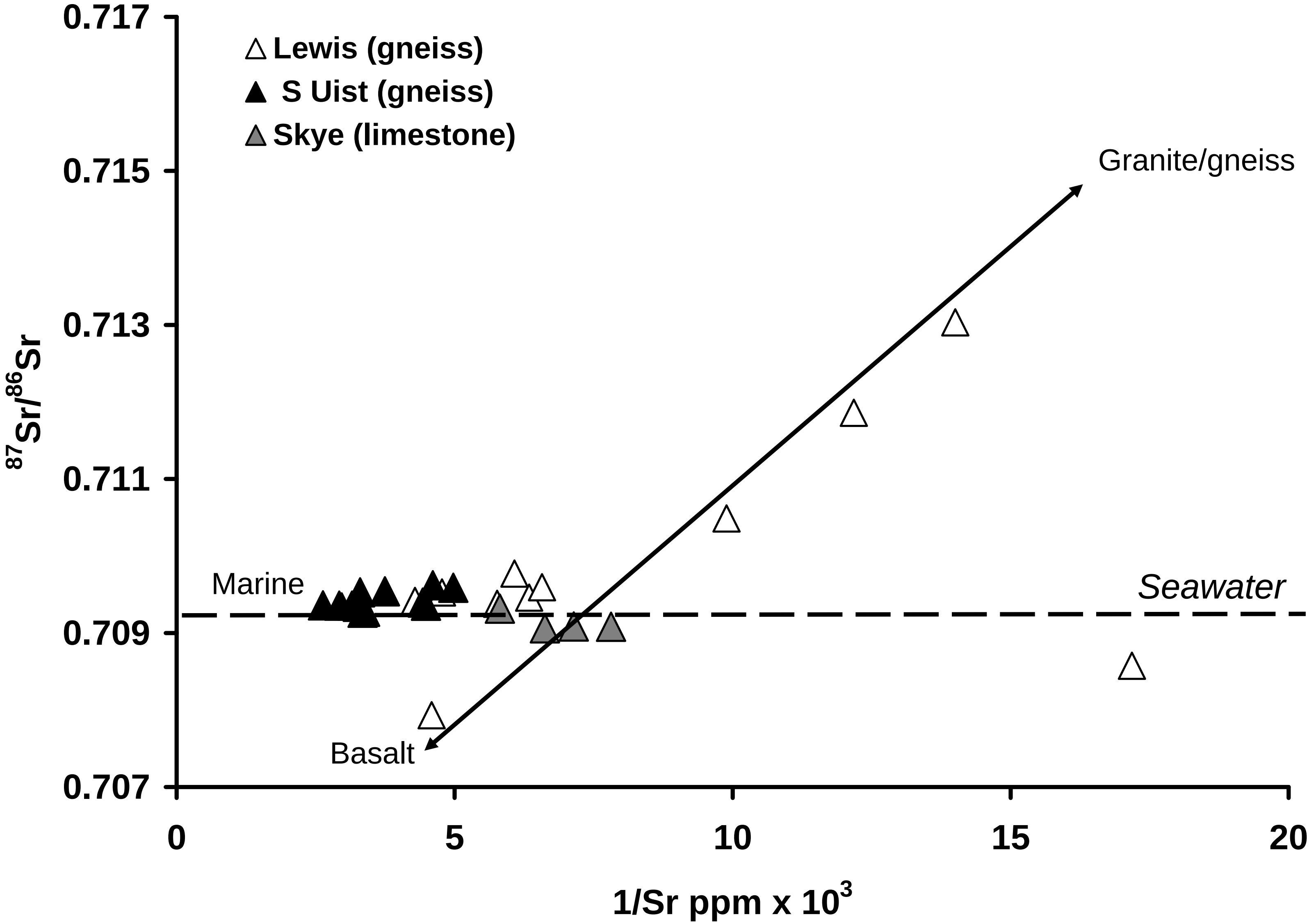

Granite used for grazing
Seaweed, salt, fish, shell-sand
Rainwater
Humans
Basalt used for crops
0.723
0.719
0.715
0.711
0.707
0.703
87Sr/86Sr
0.00
0.10
0.20
0.30
0.40
0.50
0.60
1/Sr ppm

Figure 8

A plot of multi-period human enamel data from the Hebrides, NW Scotland. Individuals fall into four possible groups: 1. on the lower left, a coastal community from South Uist (black symbols) and Lewis (white symbols) with high strontium concentrations and marine-dominated strontium ratios with very little contribution from the gneiss (as per the model in Figure 7); 2. An immigrant group (white symbols) who do not originate from Lewis, have not exploited coastal resources, but fall on a mixing line between basalt and granite (as per the model in Figure 3); 3. Four teeth from a single individual from the Isle of Skye (grey symbols) who exhibits a strontium composition consistent with limestone (as per the model in Figure 5); 4. On the lower right, a lone individual exhibiting the low strontium concentrations and ratios consistent with inland populations living on Chalk (see Figure 9). Data source: Montgomery et al. 2003, Montgomery et al. 2007, Evans et al. 2009. 2σ errors are within the symbols.



Lewis (gneiss)
S Uist (gneiss)
Skye (limestone)
Granite/gneiss
Marine
Seawater
Basalt
0.717
0.715
0.713
0.711
0.709
0.707
87Sr/86Sr
0
5
10
15
20
1/Sr ppm x 10³

Figure 9

A plot of Neolithic and Early Bronze Age human enamel compositions from the Yorkshire Wolds, England. All individuals were excavated from barrows on the Cretaceous Chalk of the Wolds. The Neolithic humans (white symbols) form a diffuse cluster of data suggesting they are exploiting a variety of sources. The Early Bronze Age individuals (black symbols) fall on two mixing lines: the lower line is indicative of origins on the Chalk and four of these individuals were excavated from the same barrow (Aldro 116) suggesting a family group: the upper mixing line indicates a group who did not originate solely on the Wolds but exploited a terrain with higher strontium ratios elsewhere. Data source: Montgomery et al. 2007. 2σ errors are within the symbols.

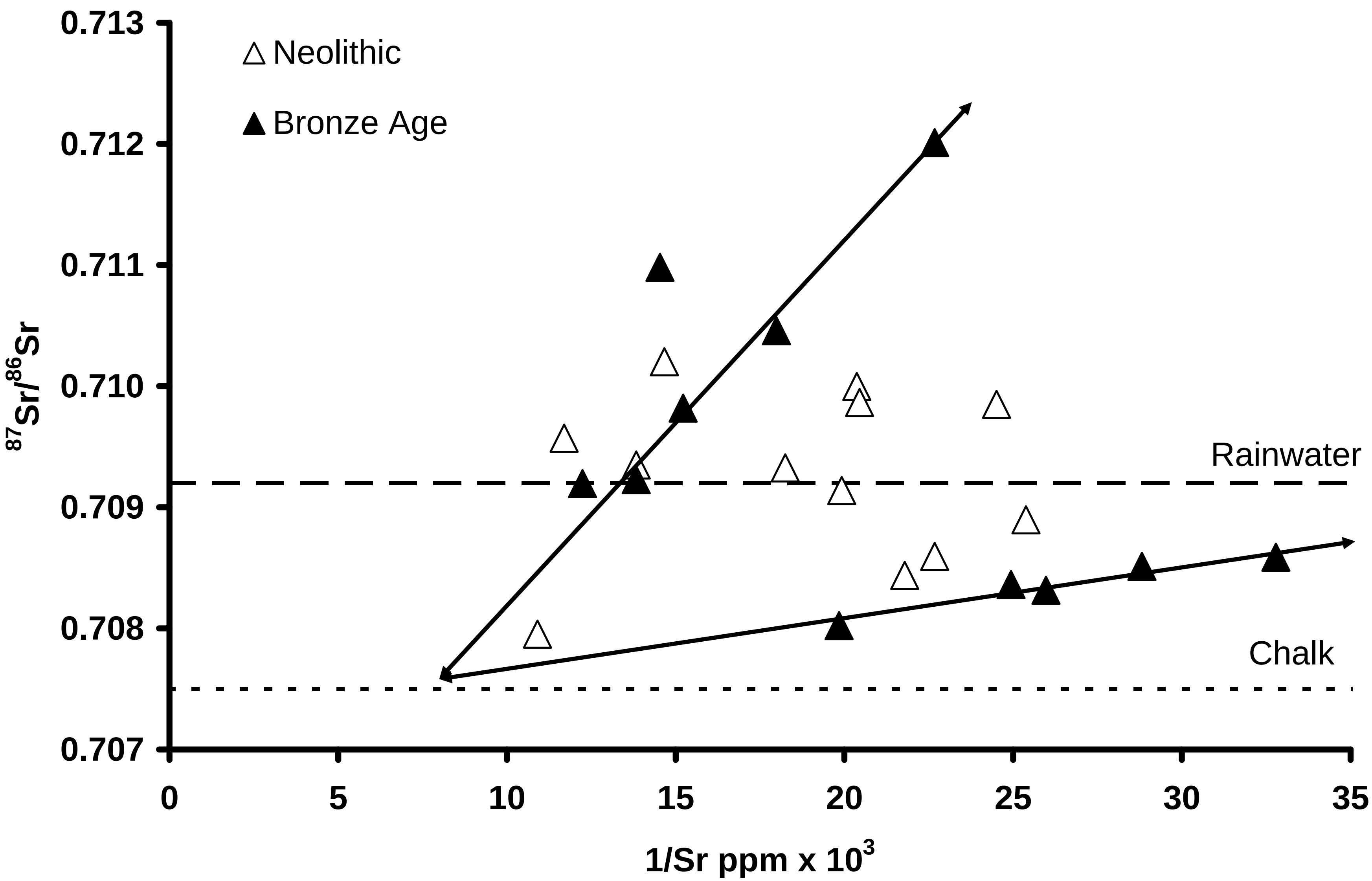
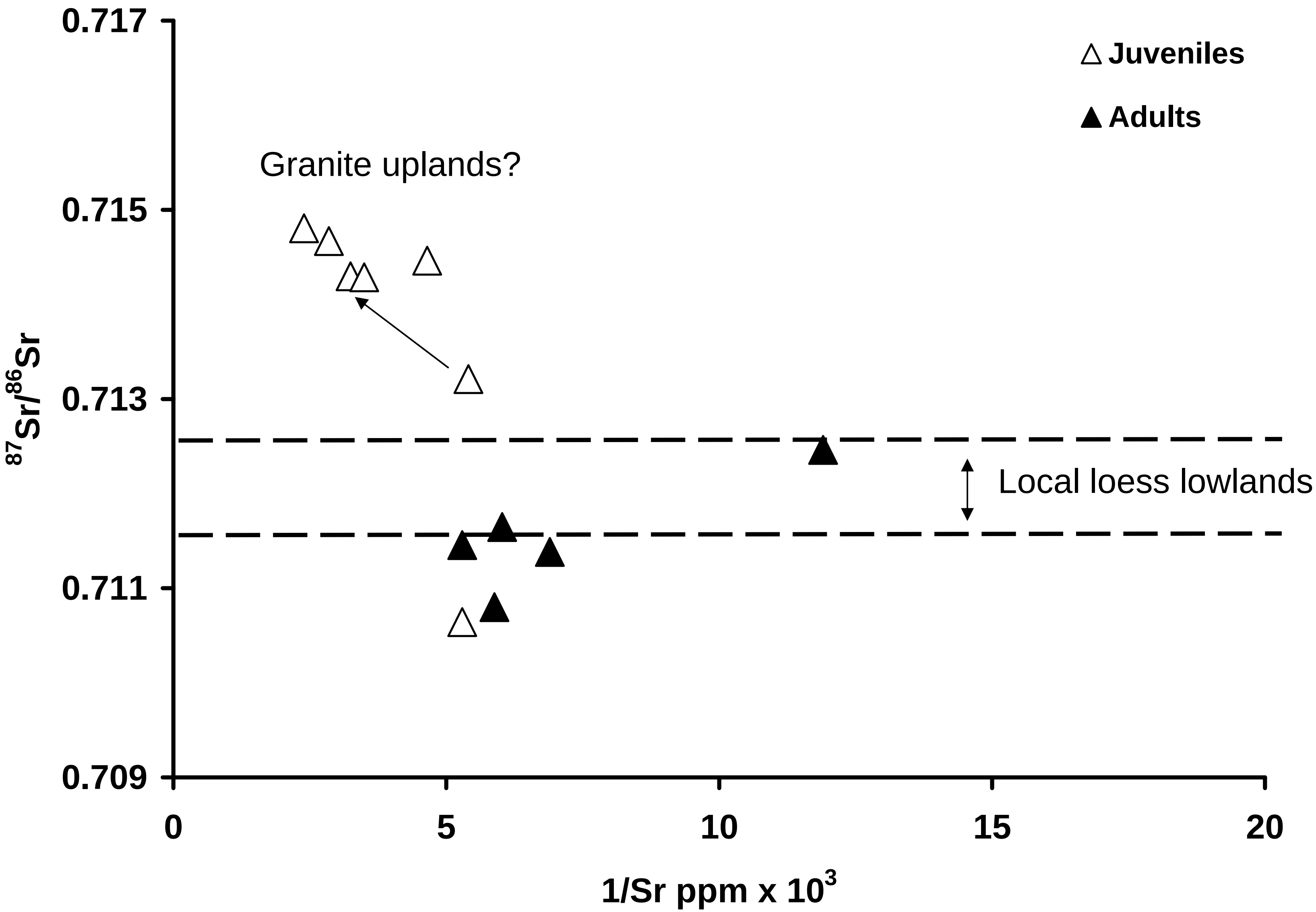

0.713
0.712
0.711
0.710
0.709
0.708
0.707
87Sr/86Sr
△ Neolithic
▲ Bronze Age
Rainwater
Chalk
0
5
10
15
20
25
30
35
1/Sr ppm x 10^3

Figure 10

A plot of Early Neolithic (Linearbandkeramic and Flomborn) human enamel compositions from the site of Niedermörlen, Germany. The group of juveniles have high strontium concentrations and ratios that are not consistent with the loess-filled valley where they were buried. Such ratios suggest origins on the granite uplands. No adults at the site had such values. The two symbols joined by the arrow are deciduous and permanent teeth from the same individual: the arrow points from the deciduous to the permanent tooth. Data source: Nehlich et al. 2009. 2σ errors are within the symbols.


0.717
0.715
0.713
0.711
0.709
87Sr/86Sr
Juveniles
Adults
Granite uplands?
Local loess lowlands
0
5
10
15
20
1/Sr ppm x 103