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EDITED BY
Yaowu Hu,
Fudan University, China

REVIEWED BY
Yimin Yang,
University of Chinese Academy of Sciences, China
Xingxiang Zhang,
University of Science and Technology of China, China

*CORRESPONDENCE
Zihua Tang,
tangzihua@mail.iggcas.ac.cn

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A score of bioavailable strontium isotope archaeology in China: Retrospective and prospective

Zihua Tang[1,2]* and Xueye Wang[3]

[1]Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, [2]CAS Center for Excellence in Life and Paleoenvironment, Beijing, China, [3]Anthropology Department, University of California, Santa Cruz, CA, United States

Bioavailable strontium isotope analysis was proposed for prehistoric human ecology almost 40 years ago and rapidly became one of the most important tools to trace past migratory behaviours. Since its first introduction to China in 2003, this method has greatly improved our understanding of migrations on individual- and community-scales over the past 20 years. This paper summarizes the current state of knowledge regarding identifying non-locals, utilizing animal resources, and strontium isoscapes for China based on empirical data. By incorporating additional baseline data, we updated and extended the current bioavailable strontium isoscape for China and Southeast and South Asia. These data will shed new light on intercultural communications and the spread of customs and technologies. In the future, strontium isotope analysis will involve an integrated provenancing system along with multiple approaches such as various isotopes and different modellings. Correspondingly, the existing isoscape needs to improve its spatial resolution and predictive accuracy to source the non-local archaeological biological remains. Furthermore, advances in analytical techniques allow us to reconstruct lifetime mobility of animals and humans at high temporal resolution.

KEYWORDS

bioavailable strontium isotope, migration, animal resource utilizations, isoscape, Chinese archaeology

Introduction

Migrations are closely related to almost all aspects of archaeology, including but not limited to the dispersals of Homo sapiens, the origin of civilizations, and intercultural connections. In 1985, Jonathon E. Ericson first introduced strontium isotope analysis into archaeology as a methodological approach to characterize specific catchment areas and trace the sources of various materials. He noticed that significant variation in strontium isotope depends on age and type of rock and, characteristic of local geology, strontium isotopes pass through the food chain with negligible fractionation, thus providing a promising method to reconstruct migration/residence pattern for ancient individuals (Ericson, 1985).

In the following several years, the methods for removal of non-biological strontium (Sillen, 1986, 1989; Price et al., 1992), evaluation of preservation condition (Price et al., 1992), and determination of local range (Price et al., 2002; Bentley et al., 2004), were gradually established by different groups, making strontium isotope analysis practicable in the geochemical lab around the world. Over the past several decades, strontium isotope analysis has become the most fundamental approach to understand past migratory behaviours and the connections between different communities.

In 2003, ZHANG Xuelian first introduced the principle of strontium isotope analysis in archaeology in China (Zhang, 2003). Since then, Chinese scholars have released strontium isotopic data from more than 40 sites and discussed topics from the identification of non-local individuals and subsistence strategies to the potential provenance of biomaterials in broader contexts. Partly because most results were published in our native Chinese, little international attention was paid to this rapidly developing subject in China, in contrast to the incredible achievements of strontium isotope and the promising future of Chinese archaeology.

This paper reviews the main achievements in strontium isotope archaeology across China. There are several parts to our article. The first section presents an overview of the early stage of strontium isotopic analysis in China, spanning from 2003 to 2007. The second section details the advances of bioavailable strontium isotope archaeology in three themes. A third section concludes with recommendations for applying this method in future investigations.

Pioneering introductions and pilot studies in China

It is worth mentioning that Jonathon E. Ericson reported the earliest bioavailable strontium isotopic analysis to Chinese samples. In 1986, he submitted an abstract to the Geological Society of America (Ericson, 1989), in which he compared the $^{87}Sr/^{86}Sr$ values of Pleistocene *Gigantopithecus* (extinct) tooth enamel and cave bear femur both collected from the *Gigantopithecus* Cave, Liucheng County, Guangxi, South China. He found significant differences between them and tentatively attributed the difference to diagenesis or diets. Unfortunately, this work was ignored by Chinese academic communities. Even before we wrote this, the first author personally communicated with several potentially relevant researchers and failed to get more details.

The Chinese debut of strontium isotope analysis was a review of dietary research authored by ZHANG Xuelian, who works for the Institute of Archaeology, Chinese Academy of Social Sciences (IA-CASS). In the paper on *Acta Anthropologica Sinica*人类学学报, for the first time in China, the emerging strontium isotope analysis was described as "a tracer of human habitats which is playing an increasing role in archaeology" (Zhang, 2003).

Later that year, QIAN Junlong translated and published an abstract of a case study (Freestone et al., 2003), in which strontium isotope was used to investigate Near East glass production. The strontium isotope technique was then applied to source traded ceramics in China (Li et al., 2005, 2006), in cooperation with geochemists from Queensland University, Australia.

Strontium isotope analysis is an instrument-dependent laboratory technology. As early as 2004, a team from the University of Science and Technology of China (USTC) established an analytical method for $^{87}Sr/^{86}Sr$ analysis to discriminate the production site of ancient pottery in their lab (Zhang et al., 2004). Slightly later, geochemists at Jilin University independently developed a pretreatment method for analyzing the strontium isotopic composition of ancient human bones (Zhou et al., 2005). These efforts demonstrated the accessibility of $^{87}Sr/^{86}Sr$ analysis for archaeological remains in China.

In 2007 a doctoral candidate YIN Ruochun from USTC made a thorough and detailed review on the application of isotopic strontium in archaeology (Yin and Zhang, 2007), covering strontium geochemistry, principles of strontium isotopes as a geologic tracer, cases for identifying the local range and for migration in Americas and European. Besides, they paid sufficient attention to sample pretreatment; for example, the chemical treatments should be processed in an ultraclean lab.

Progresses over the latest twenty years

Since YIN Ruochun reported the first bioavailable strontium isotopic data for Chinese archaeology in 2008 (Yin et al., 2008), bioavailable $^{87}Sr/^{86}Sr$ analyses have been conducted for more than 40 sites across the country in the past 15 years (Figure 1). These works covered various topics with the foci on immigratory behaviours of populations and individuals, exploitations of faunal resources, and the development of strontium isoscape.

Identification of non-local individuals

The Jiahu site, situated at the south Central Plains, is one of China's most critical early Neolithic sites. Here, YIN Ruochun opened the door of strontium isotope archaeology in China. During his doctoral studies at USTC, Yin and his supervisors first established the local range using five teeth enamel $^{87}Sr/^{86}Sr$ values of archaeological pigs. They successfully identified five non-locals from 14 human individuals (Yin et al., 2008). This is the first time for Chinese scholars to analyze strontium isotopic signals for archaeological biological remains following the protocols

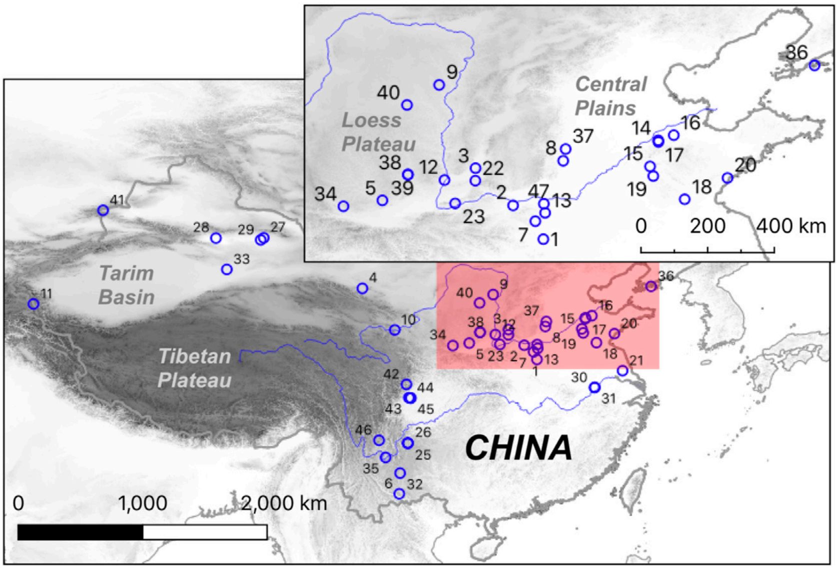

FIGURE 1
Archaeological sites with bioavailable strontium isotope data in China and the sites were presented in the order of year of publication. 1 Jiahu (Yin et al., 2008); 2 Erlitou (Zhao et al., 2011a; 2012b); 3 Taosi (Zhao et al., 2011b; Zhao and He, 2014); 4 Heishuiguo (Zhao, 2012); 5 Zaoshugounao (Lan, 2017); 6 Mayutian (Zhang et al., 2014); 7 Wadian (Zhao et al., 2012a; Zhao and Fang, 2014); 8 Yinxu (Zhao et al., 2015); 9 Shimao (Zhao et al., 2016a); 10 Lajia (Zhao et al., 2016b; Zhao et al., 2018); 11 Jirzankal (Wang et al., 2016); 12 Liangdaicun (Chen, 2012); 13 Wangjinglou (Zhao et al., 2018); 14 Jiaojia; 15 Dawenkou (Fang, 2018); 16 Dinggong; 17 Chengziya; 18 Guangzhuang; 19 Yinjiacheng; 20 Liangchengzhen; 21 Jiangzhuang; 22 Zhoujiazhuang; 23 Qingliangsi (Wu, 2018; Wu et al., 2019b; Zhang et al., 2021); 24 Hongyingpan; 25 Yinzitan; 26 Jigongshan (Zhang et al., 2018; Zhang et al., 2022a); 28 Wubu; 28 Jiayi; 29 Aisikexia'ernan (Li, 2019; Wu et al., 2021); 30 Lingjiatan; 31 Weigang (Zhao et al., 2019); 32 Shamaoshan (Wu et al., 2019a); 33 Lop2015 cemetery 1 (Wang et al., 2020); 34 Xuechi (Tang et al., 2020, 2022); 35 Houzidong (Wang, 2020); 36 Xiaozhushan (Zhao et al., 2021); 37 Nancheng (Hou et al., 2021); 38 Shijiahe; 39 Zhaitouhe (Liu, 2021); 40 Jiadamao (Zhao et al., 2022); 41 Adunqiaolu (Cong et al., 2021); 42 Yingpanshan; 43 Hongqiaocun; 44 Jinsha; 45 Shi'erqiao; 46 Guijiabu (Lin et al., 2022); 47 Zhengzhou Shang City (Fang et al., 2022).

recommended by T. Douglas Price et al., 2002. These results showed the potential of strontium isotope research on migration and greatly encouraged subsequent research.

A latest Neolithic site, Taosi, was situated in south Shanxi Province. At the site, an internal rammed-earth wall separated the elite's residential and ceremonial areas from those inhabited by commoners, signifying a stratified society that occurred during the interval of 4,500–3900 BP. An archaeometry team led by ZHAO Chunyan from IA-CASS established the local $^{87}Sr/^{86}Sr$ range using the signals of archaeological domestic pigs and primarily concluded that a part of domesticated sheep (two out of five) and cattle (two out of four) were imported into the site (Zhao et al., 2011b). Similar conclusions also arrived from a contemporary Wadian site located at the upper reaches of the Huaihe River. Referring to the local range inferred from the signals of mice, Zhao et al. (2012a) identified several non-local pigs, sheep and cattle. Combined with zooarchaeological evidence, the authors argued that Wadian occupants imported sheep and cattle from outside and hunted wild pigs nearby. Based on faunal isotopic analysis, the authors also worked on the human remains and revealed high proportions of immigrants at the two sites. Specifically, 14 out of 21 analyzed Taosi human individuals (Zhao and He, 2014) and all five analyzed Wadian individuals (Zhao and Fang, 2014) fell out of the local range determined by pig and mouse, respectively.

On the Chinese Loess Plateau, the latest Neolithic Shimao site, contemporary with the sites of Taosi and Wadian, showed a different scenario of livestock provenance. Compared with the archaeological pigs, strontium isotopic signals identified a single non-local sheep from the 19 analyzed individuals of cattle and sheep. The differences in livestock provenances between Shimao and Taosi/Wadian are partly related to their locations. The former was situated in the steppe zone, making it much easier to access herds. This explanation was reconfirmed by another slightly older site, Jiadamao (4,500–4,300 yrBP (Zhao et al., 2022), from the Loess Plateau.

The Erlitou Site marked the earliest Bronze Age urban society, and the archaeological culture existed in the Yellow River valley from approximately 3,900 to 1,500 yrBP. Zhao and her colleagues determined the local $^{87}Sr/^{86}Sr$ range of 0.71190–0.71226 using ten pigs' enamel signals, and further identified seven out of 14 sheep and two out of seven cattle non-locals (Zhao et al., 2011a). For the Wangjinglou site of the Erlitou period, $^{87}Sr/^{86}Sr$ signals identified five non-local cattle out of nine analyzed individuals (Zhao, 2018). Both Erlitou and

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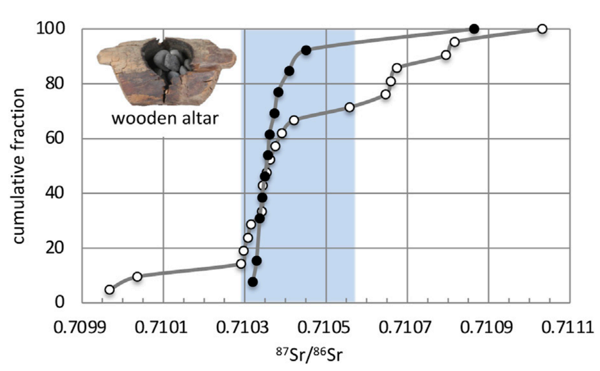

FIGURE 2
Cumulative distribution plot of ^{87}Sr/^{86}Sr in human enamel from Jirzankal individuals.

The shadow represents the local range of ^{87}Sr/^{86}Sr for the site. Black dots denote individuals buried with altars, and circles show individuals without an altar. The variance in ^{87}Sr/^{86}Sr is significantly larger for the individuals without altar (n = 21) than for individuals with altar (n =13), by an F test ($p < 0.001$ without outliers M50, and $p < 0.05$ adding the outliers).

Wangjinglou would imply an extensive exchange network of livestock during the very early stage of Chinese Bronze Age.

Yinxu, ca. 1,300–1,046 yrBP, was the site of the first well-documented capital in ancient China, famous for the earliest records of Chinese writing systems and the earliest domestic horses in China (Kikuchi et al., 2019). Among the horses, five individuals (5/10) fall outside the local range of ^{87}Sr/^{86}Sr (0.71132–0.71174) defined by nine archaeological cattle bones from the cemetery, strongly suggesting imported horses to the Central Plains during the late Shang period.

Besides these critical sites mentioned above, several sites from the Chinese frontiers also revealed valuable information about the ancient migratory pattern. In the southwest corner of China, the highest-status individual from Mayutian showed a significantly lower ^{87}Sr/^{86}Sr value than others, suggesting a distinct geographic origin (Zhang et al., 2014). This is the very first archaeological paper about Chinese bioavailable strontium isotope in international journals.

Close to the China-Tajik border, ten immigrants out of 34 individuals from the Jirzankal cemetery, ~2,500 yrBP, were identified using strontium isotopic approach, where the local range was constrained by 12 ovicaprine bones. The immigrants were partly accompanied by exotic musical instruments, harps, and oriental silk textiles, suggesting active long-distance exchanges across the Eurasian continent (Wang et al., 2016). Besides, the Jirzankal cemetery attracted considerable attention partly due to the unique wooden altars (Wu and Tang, 2016), which were once used for inhaling cannabis fumes (Ren et al., 2019). When placing the 13 individuals buried with the altar into the context of strontium isotopic signals, we found that only one individual from the grave M50 fell out of the local range, suggesting that the practice of inhaling cannabis more likely rooted in the local settlers on the Pamir Plateau, instead of the exotic convention (Figure 2).

Exploitations of faunal resources

As a consistent and essential part of the subsistence of ancient society, the circulation networks of domestic animals are one of the critical aspects. Strontium isotopic analysis can identify and source non-local animals in ancient zooarchaeological assemblages, providing valuable information on mobility across China.

At the lower reaches of the Yellow River, animal remains from the Dinggong site were subjected to strontium isotope analysis to detect their potential provenances (Wu et al., 2018). The data indicated that the ^{87}Sr/^{86}Sr values of the animals were different on taxa, i.e., freshwater bivalves had highly variable ^{87}Sr/^{86}Sr values. In contrast, freshwater fishes showed more uniform ^{87}Sr/^{86}Sr signals, and the terrestrial mammals and reptiles had the variability in between. Taking the regional geological background, the authors argued that the residents of the Dinggong Site obtained freshwater fish nearby the site and fetched bivalves from the mountainous area.

More importantly, the authors got a similar ^{87}Sr/^{86}Sr value from an osteoderm of Chinese alligator found in the site and made a preliminary discussion about indigenous or extraneous alligators (Wu et al., 2018). Recently the authors conducted multiple isotope analyses of the alligator remains from three sites in the Yellow River basin (Zhang et al., 2021), including Qingliangsi, Dinggong, and Yinjiacheng sites. Both ^{87}Sr/^{86}Sr and δ^{18}O values of the alligator osteoderms were consistent with the background signals where the site was situated. These data further supported the indigenous alligators during the Late Longshan Period, appealing more attention to the paleoenvironment reconstruction and the relationship between humans and the Chinese alligator. Using a similar approach, ZHAO Chunyan worked on the livestock supply during the Erlitou period (Zhao, 2018). Based on the local range defined by pigs, high proportions of immigratory sheep were found from the Erlitou site, while more immigratory cattle were supplied to the contemporary Wangjinglou site. Those results suggested complicated livestock supply networks for different sites during the early Chinese Bronze Age.

On the Yunnan-Guizhou Plateau, the sites of Jigongshan, Hongyingpan, and Yinzitan established an integrated chronology of the Yelang, a minority monarchy in ancient southwest China, from the Bronze Age to the Early Iron Age (Zhang, 2014). Horse remains were excavated from the Jigongshan and Yinzitan sites, allowing for understanding horse trading of the Yelang civilization using strontium isotope analysis (Zhang et al., 2018). The Jigongshan site, the earliest Bronze Age remains (1,300–800 BC) in the area, is parallel with the period of the Late Shang to the Early western Zhou dynasties in central China, when horses were just being used extensively in war and transportation. There are three out of seven horse tooth samples with the $^{87}Sr/^{86}Sr$ ratios outside of the range of regional geological background. Among the three outliers, two values are significantly higher, possibly indicating that the horses come from places outside the karst areas. The Yinzitan site covers the Later Warring States to the former Han period when domestic horses were used extensively in China. Three out of four horses from the site showed $^{87}Sr/^{86}Sr$ ratios outside of the regional signals. The authors noted that the outlying horses from Jigongshan and Yinzitan sites shared similar $^{87}Sr/^{86}Sr$ values and proposed that the ancient people obtained the horses through trade with the Dian and Zuo tribes. This work shed lights on the interregional horse trade in Southwest China (Zhang et al., 2018; Zhang and Zhang, 2021).

From the Early Neolithic to the early historical periods, the pattern of animal exchanges evidenced by strontium isotopes offered detailed insights into circulation networks. As a preliminary analysis, Wang and her colleagues employed previously reported strontium isotopes measured in tooth enamel from domesticated animals (cattle, sheep/goats, horses, and dogs) in 13 sites to investigate animal movement and circulation across the Yellow River Basin over extended periods (Wang et al., 2021). They found that a few strontium isotope ratios outliers for animals from large Late Neolithic sites, suggesting the initial expansion of animal circulation systems and an increase in the proportion of animals originating from various regions from the Late Shang period until the Western Zhou Dynasty, accompanying an increasing degree of social complexity.

Most recently, we reported 29 sacrificial animal enamel $^{87}Sr/^{86}Sr$ values from a Chinese imperial ritual site, Xuechi, and clearly demonstrated that no sacrificial animals were raised in the vicinity of the site (Tang et al., 2022). Comparison of $^{87}Sr/^{86}Sr$ values from Xuechi with other six sites on the Chinese Loess Plateau showed an increasing trend in variation of faunal $^{87}Sr/^{86}Sr$ values from the latest Neolithic to imperial periods, in concordance with the territorial expansion model for state formation (Spencer, 1998, 2010). These tentative attempts were broadening the reach of strontium isotope archaeology.

Strontium isoscape for China

The field of isotope sourcing is rapidly expanding and forming the realm of data science and community efforts to make modelling products widely accessible (Bowen and West, 2019). To estimate the geographic origins of immigrants, a pre-requisite is a bioavailable isoscape of the region. Like the global practices, the development of strontium isoscape in China has lagged behind hydrogen, oxygen, or carbon isotopic systems, partly due to the challenging, relatively expensive, instrument-dependent $^{87}Sr/^{86}Sr$ analysis.

Until recently, the first regional bioavailable strontium isoscape was generated for the Tarim Basin, the hub on the Silk Roads connecting eastern and western civilizations. Using 73 river samples, the bioavailable strontium isoscape across the Tarim Basin and the neighbouring area was established by the kriging interpolation method (Wang et al., 2018). The basin exhibits a strong south-north gradient in $^{87}Sr/^{86}Sr$ values. The rivers draining the northern regions are less radiogenic than the rivers south of the basin. The rivers from the north have a mean value of 0.7105 ± 0.0007 (n=25), whereas the rivers south of the Tarim Basin have a mean value of 0.7118 ± 0.0008 (n = 29). Besides, an overlap exists in between. Using this map, seven out of 27 individuals were successfully identified as the non-locals from a Han-Jin cemetery in the Lop Nur (Wang et al., 2020).

Collected from previous publications and supplemented by a targeted collection in China, the authors (Wang and Tang, 2020) compiled a bioavailable $^{87}Sr/^{86}Sr$ dataset for China. After internal normalization for instrumental mass-dependent isotopic fractionation and removal of outliers using the Anselin's Local Moran's I statistic, the very first large-scale bioavailable strontium isotope map of China was generated using the kriging interpolation based on 1872 samples. The $^{87}Sr/^{86}Sr$ dataset shows considerable heterogeneity and has a distinct strontium isotope distribution based on the characteristics of geological and isotope data in China. Evidenced by integrated geochemical data, the biosphere $^{87}Sr/^{86}Sr$ ratios are primarily consistent with the underlying geological bedrocks. Besides, poor matches are also observed in regions with high relief, eolian deposits and complex geology, mainly due to the insufficient sampling density. This strontium isoscape laid a solid ground for studying past migrations in China.

Based on the detailed $^{87}Sr/^{86}Sr$ baseline map, strontium isotope analysis on ancient human and animal remains will improve our understanding the role of human and animal migrations in shaping history. Reassessment of spatial variability of the bioavailable strontium isotopes for China using the geographic detector model (GDM) (Zhang et al., 2022b) revealed that the watershed factor explains 50.35% of the spatial variation of bioavailable strontium isotopes, while, in a descending order, the climate, terrain, geology, and soil in China explained much less. Furthermore, the GDM suggested that the non-linear interactions between watershed and geology explained 59.90% of spatial variation in bioavailable Sr isotopes. These results indicated that the natural processes still dominate the bioavailability of strontium isotopes in China and required a proper proxy to establish the local range of $^{87}Sr/^{86}Sr$ for a specific site.

It must be pointed out that past migratory behaviours were not limited to modern administrative boundaries. The

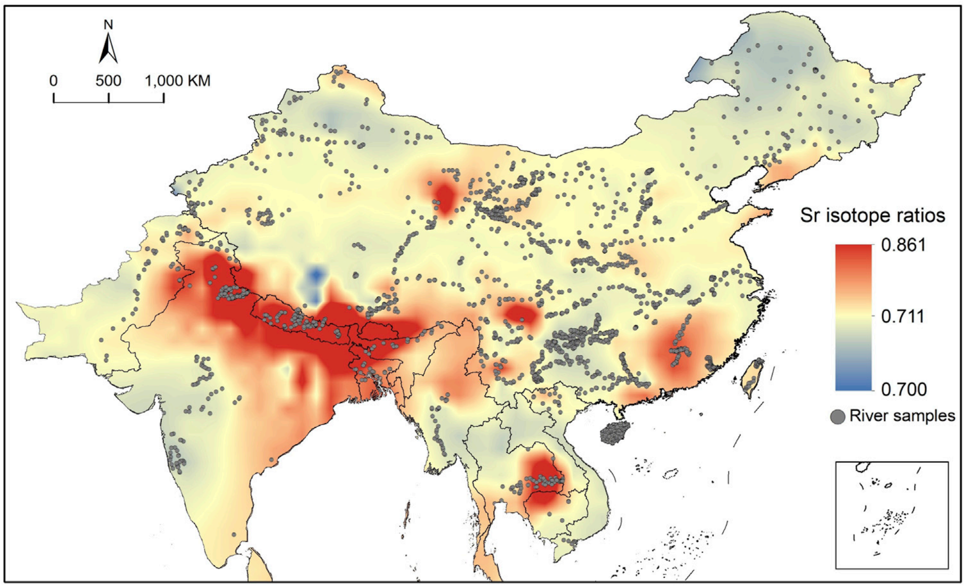

FIGURE 3
The updated bioavailable strontium isoscape for China and its neighbouring area. The dataset consists of 3,158 water samples, and details can be available from the Supplementary File.

bioavailable strontium isoscape presented above mainly resulted from the ease of data collection rather than the actual ancient migration. Based on the compilation of newly released river water $^{87}Sr/^{86}Sr$ data and previous datasets (Bataille et al., 2020; Wang and Tang, 2020), we update the current bioavailable strontium isoscape for China and neighbouring regions using the kriging interpolation (Figure 3). These data will provide a helpful reference set for archaeological, forensic and environmental studies, especially for studying the interconnections among east, south, and southeast Asia.

Summary and prospects

Strontium is an element in rocks and is released into water and soils by weathering, then incorporated into the mineralized tissue of organisms as substitution of calcium. Due to the ratio $^{87}Sr/^{86}Sr$ independent to physiochemical and biological processes, this bioavailable strontium isotopic ratio reflects the local geologic background, making it the most helpful tracer of provenances. The surge in bioavailable strontium isotope research over the past 20 years is yielding new insights into Chinese archaeological and historical studies. For the first time, it enabled direct estimation of individual migration and laid the ground for evaluating mobility through geospecific isotope ranges. Our present work provides an overview of the outstanding achievements of bioavailable strontium isotopes in Chinese archaeology, ranging from migratory individuals, and animal resource exploitation, to strontium isoscape for China.

As an emerging and promising field in China, several critical issues for bioavailable strontium isotope study remain open and need more consideration in the future.

Quality control of measurement

Thermal ionization mass spectrometry (TIMS) and multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) have been widely used to determine strontium isotopic composition in China. To determine accurate and precise $^{87}Sr/^{86}Sr$ values, utmost care must be practiced from sampling, sample pretreatment, and optimization of the instrument, to mass bias correction during measurements. Correspondingly, the protocol of pretreatment, the reference material and its reproducibility during the measurements, as well as the correction method of mass fractionation, need to be clarified in data reports. For the burgeoning laser ablation MC-ICP-MS (LA-MC-ICP-MS) technique, matrix-matched calibration standards are essential to generate results comparable to TIMS and MC-ICP-MS, especially for samples with low-strontium concentration, such as teeth enamel of humans and mammals (Wang and Tang, 2019). If effective, the LA-MC-ICP-MS method can generate $^{87}Sr/^{86}Sr$ data with a spatial resolution data better than 50μm, allowing for reconstruction of high temporal resolved life history (e.g., Wooller et al., 2021; Miller et al., 2022).

Better isoscapes

The potential for precise tracking of migratory behaviour largely depends on the accuracy of the isoscape produced using empirical data and/or geostatistical models. Like other places around the world, these models and data are always imperfect; thus, continued improvements in data and models are needed to improve the scope and quality of isoscape. Even in the updated version presented above, bioavailable strontium isoscape for China and the neighbouring areas is still to be improved continuously. Furthermore, the isoscape for China generated mainly on water samples from streams and lakes does not meet the demand for high-resolution tracking; various materials (e.g. plants and low-mobility animal skeletons) and robust models are required for an isoscape of higher spatial resolution. Recently, researchers combined the sampling data and machine learning methods such as random forest regression models to draft the large-scale biaoavailable sotontium isoscape for Europe (Bataille et al., 2018; Hoogewerff et al., 2019) and even the gobal scale (Bataille et al., 2020), which greatly improved the predictive power of isoscapes. However, the acuracy of these models is highly reled on the sampling data and the global Sr isoscape shows extremely poor performances in China due to the lack of baseline data in that study. In addition, a web-based portal to bioavailable strontium isoscape is convenient for relevant researchers.

Whether "local" or "non-local" according to strontium isotope method is a relative concept. When tracing animal and human migrations, researchers should give a clear description of the migration scale that they discuss, i.e. a local scale or a large scale (how large?). In this case, the choice of baseline types and the extent of sampling becomes particularly important. For example, the selection of the baseline samples must take into account the research questions and research objects. Deep ground water, for example, is not suitable to establish baselines as it is not likely to form a significant part of strontium intake by humans and terrestrial animals.

Individual history of migration

A great tradition of "through remains, into humans 透物见人" in Chinese archaeology calls for care to personal experiences of the past individual, besides the whole scheme of contemporary societies. Since not all teeth formed simultaneously, high-resolution isotope ratios of the enamel from different teeth allow reconstructing different life snapshots. The combination of strontium isotopes with others of distinctly spatial heterogeneity, such as oxygen, hydrogen, and lead, will produce quantitative results at various spatial resolutions and offer the potential for understanding mobility information at individual and community scales.

Integrated sourcing methodology and beyond

There are great desires for sourcing various materials, inorganic and organic, in Chinese archaeology. For instance, archaeological plant remains, such as seeds, leaves, and stems, hold great potentials of provenancing their past movements (Styring et al., 2019) and, at this stage, practicable protocol for extracting their original $^{87}Sr/^{86}Sr$ signals are imperative, although the approach has been applied for determining geographical authenticity of modern agriculture products (e.g., Lagad et al., 2017; Liu et al., 2020). Furthermore, cross-discipline collaborations of petrology, geochemistry, immunomics, proteomics and ancient genomics, as well as statistics and modelling, are a promising approach to establish an integrated sourcing methodology for different materials. A most recent pilot study, in which strontium isotopes were used to track cocoons (Liu et al., 2022), is a positive signal for broadening the reach of strontium isotope tracer. Along with the emphasis on individual life and specific material, the structures, identities and collective action are also the foci of bioavailable strontium isotope, especially to the transition in the developments of Chinese civilization and history.

Author contributions

ZT and XW designed the research, collected and visualised the data, and wrote the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.1094424/full#supplementary-material

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