Evolution of Lake Basins in Northeast Tibet from Strontium Isotope Studies of Carbonates

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The Tibetan Plateau is the Earth’s largest geologic anomaly, composed of the highest mountain range on Earth with an average elevation of five km (16,400 feet). This vast high-elevation region sits north of the tectonic collision zone between Asia and the Indian subcontinent (Figure 2). The plateau consists of a series of small crustal blocks that were accreted to the southern margin of Asia. India represents the most recent accretion event, colliding with Asia around 50 million years ago. Although this region has a complex structural history related to each crustal block’s accretion, the Indian collision and subsequent subduction under Tibet has caused the most recent deformation. This has raised some parts of the plateau from near sea level to their current elevations. Geologists continue to study this region to determine the processes that form broad, high, and uniformly elevated plateaus. One of the current issues of interest is how the margins of the plateau have evolved over the past 14 million years and what this tells us about surface uplift processes on the plateau. This study is focused on the tectonic evolution of the northeastern margin of Tibet to explore the nature of deformation and basin formation over the past 12 million years.

This study employs strontium (Sr) isotope analysis of carbonates collected in sub-basins in northeast Tibet to determine whether sedimentary basins were formed in one large basin that was later segmented by the growth of large mountain ranges. Sedimentary deposits in this area indicate the presence of ancient lakes that existed roughly 7 to 12 million years ago (Ma). These paleolake deposits record information about the paleo-hydrology of the lake system and the sources of water and sediments to the lake basins. Lake deposits contain a Sr isotope fingerprint that is recorded in carbonate rocks formed throughout the lifespan of the lakes. This fingerprint is the ratio of the two major isotopes of Sr, $^{87}$Sr, and $^{86}$Sr. Sr is ideal for studying basin histories because the trace element Sr readily substitutes for calcium sites in carbonate rocks. This substitution occurs without any noticeable fractionation, or preference for one isotope over another. This means that the ratio of $^{87}$Sr to $^{86}$Sr in the water will be the same as the ratio of $^{87}$Sr to $^{86}$Sr in the precipitated carbonate.

If the source area feeding the lakes evolves over time, then the Sr isotope fingerprint of those source regions will also change. That change is recorded in the carbonate precipitated from the lake water. By comparing these fingerprints recorded in different paleolakes at the same time, we can better understand if the lakes occupied separate basins or if they were part of one large basin. If intervening mountain ranges rose in response to deformation from the collision of India and split a large basin into smaller sub-basins, then the Sr isotope fingerprint should also reflect this.

An application of this type was used for looking at the history of the Bonneville paleolake system whose modern analogue is now known as the Great Salt Lake. During the Pleistocene (1.8 - 0.01 Ma), this was a vast basin that extended over 50,000 km, an area much larger than the present-day Great Salt Lake, which covers 4,400 km. The study of its strontium isotope record helped to explain the evolution from...

Figure 1: Author standing by the Yellow River, China in June 2006.
Lake Bonneville to the Great Salt Lake by interpreting changes in Sr isotopic compositions through time. Analysis of the Sr in carbonates from this lake showed an initial common Sr isotopic composition that diverged over time into two separate signatures. Hart et al. (2004) interpreted this pattern as a decreasing lake level which lowered to the height of an intra-basin ridge, splitting Bonneville into two separate lakes. One of these lakes eventually shallowed to nonexistence as the water level continued to drop. The other survives today as the Great Salt Lake. Similarly, our study hopes to show the evolution of paleolakes that existed in northeast Tibet in order to deduce whether or not they were initially linked. This will give us insight into the growth of mountain ranges on the northeast margin of Tibet that currently segment these basins.

**Background Geology**

Currently there are many small basins within northeast Tibet which are isolated by mountain ranges that rise 1 to 2 km above the basin floors. Several locations of similar ages have exposed sedimentary sequences containing lake deposits. These sequences have been dated using magnetostratigraphy, a technique based on periodic reversals of the magnetic poles recorded in the orientations of magnetic minerals in rocks. By correlating the pattern of magnetic reversals in the sedimentary rock sequence with published precisely dated magnetic reversal patterns, the ages of the sedimentary rocks can be inferred.

The basins chosen for this study are Linxia ("ling-shah"), Xunhua ("shun-wah"), Tongren ("tong-wren"), and Guide ("gwe-dugh") (Figure 3). All of these basins have stratigraphic sections with lake deposits ranging from 7 to 12 Ma. If some of these basins were connected in the past as one large foreland basin, then we would expect the sub-basins to have the same isotopic signatures during this time period (Figure 4).

A foreland basin (Figure 5) forms in front of a growing mountain belt due to crustal thickening within the mountain belt. This thickened crust causes elastic deformation (bending) of the adjacent lithosphere. The oldest documented fault motion in northeast Tibet comes from the West Qinling ("shin-ling") fault, which led to a linear mountain belt to the south of the Linxia and Xunhua basins. Crustal thickening associated with this fault's motions might have been sufficient enough to cause the subsidence in the foreland. If Linxia and Xunhua basins were part of a large integrated foreland basin, then their lake carbonate deposits would have produced uniform Sr isotopic compositions. As later ranges rose during further deformation in northeast Tibet, the Linxia and Xunhua basins would have been separated, and their Sr isotopic ratios would have diverged to reflect their present-day morphology (Figure 3).

Guide and Tongren basins, which are both south of the West Qinling fault, are piggy-back basins (Figure 5). Piggy-back basins form within zones of folding and faulting and are transported passively on active faults (such as the West Qinling fault) that are deforming beneath the piggy-back basins. If Guide and Tongren basins were unique piggy-back basins, then they should have unique isotopic compositions that reflect this separation.

**Sr Isotopes**

Sr is ideal for studying lake histories because the ratio of the isotopes is unique for each body of water and is clearly recorded in the lake's deposits of carbonates. Sr (atomic number 38) is a member of the alkaline earth metals, as is calcium. Although alkaline earth metals have some differences in electronegativity and atomic radius, they behave similarly due to their t2 oxidation, which makes them very reactive. Because of their reactivity, the alkaline metals precipitate from water as compounds such as CaCO3 and SrCO3 (carbonate rocks). Through hydrolysis and dissolution reactions, water and groundwater leach Sr from silicate minerals and dissolve.
carbonate, which contains Sr as a trace element. This dissolved Sr is transported to lakes by rivers and groundwater.

The isotope \(^{87}\text{Sr}/^{86}\text{Sr}\) is produced from the radioactive beta decay (loss of an electron) of rubidium (\(^{87}\text{Rb}\)), which leads to different ratios of the radiogenic \(^{87}\text{Sr}\) to the stable \(^{86}\text{Sr}\) isotope. Source rocks in the drainage areas have varying ratios of radiogenic and stable Sr, and therefore the dissolved strontium derived from these regions reflects their different isotopic compositions. A lake will obtain its dissolved isotopic composition from the mixing of all the water flowing into it.

Methods

To analyze the \(^{87}\text{Sr}/^{86}\text{Sr}\) recorded in carbonates, a small piece of the carbonate rock was separated. Because carbonates can be altered in the millions of years following original deposition, veins, diagenetic crystals, and weathered surfaces were avoided during sampling to remove the effects of alteration of the original strontium isotopic signature of the lake. The unaltered samples were dissolved in 0.5 M acetic acid solution. This extremely mild solvent was used so that the Sr from lake carbonate minerals could be dissolved out without leaching the Sr from other silicate minerals deposited in the lake.

Sr has a moderate solubility and a long residence (about 10\(^4\) years) in freshwater and ocean basins compared to its mixing time (10\(^5\) to 10\(^7\) years). This long residence time allows for mixing of all theSr sources to give a uniform signature for interconnected basins at one time. For example, in the oceans, Sr resides for approximately 4 to 5 million years but only takes 1000 years to mix. In lakes, these times are not as well defined due to varying rates of outflow. However, there is evidence from some of the basins in northeast Tibet indicating that the outflow was minimal, allowing the water to stay within the reservoir and mix thoroughly. Also, due to lower salinity, carbonates precipitate more slowly than in ocean water. Thus, we assume a similar relationship of long residence and rapid mixing time for these lakes.

Results and Discussion

Sixteen lake carbonate samples (five from Linxia basin, four from Tongren and Guide, and three from Xunhua) were analyzed for their \(^{87}\text{Sr}/^{86}\text{Sr}\) composition. The samples were selected to span the approximately 5 million years of lake deposition. There are three main observations of the data (Figure 6), which can be interpreted as the connections between these basins. The most obvious is that the Guide basin deposits are very distinct, having a minimum separation of 0.003 \(^{87}\text{Sr}/^{86}\text{Sr}\) from any of the other data points. This variation in the third decimal place indicates significant alteration in Sr isotopic composition, with a source of Sr for Guide that is either much older or much more felsic (silica rich). The second observation is that Tongren also has a distinct and increasingly radiogenic signal. The oldest sample from Tongren has the lowest \(^{87}\text{Sr}/^{86}\text{Sr}\) value, which suggests its waters sourced from either younger and/or more mafic (iron and magnesium rich) sources. Although Tongren lake deposits overlap the ranges of Linxia and Xunhua, the lake’s slope shows a significantly different pattern that suggests changing sources over time. The last observation is that the Linxia and Xunhua samples all fall within the range of 0.710769 to 0.710990 and thus are within \pm 0.000121 of each other. They also share a very similar trend, especially in the older part of the record (11.5 to 8.5 Ma).

The interpretation of these observations is that the West Qinling fault was active by 12 Ma, separating Guide and Tongren from the basins on the north side of the fault. This is made clear from Guide’s discrete Sr composition as well as Tongren’s distinct trend. These basins’ unique isotopic signatures and position to the south of the West Qinling fault
define them as piggy-back basins.

During the comparable age range of 11.5 to 8.5 Ma, Linxia and Xunhua’s similarity in range and trend does not preclude the possibility that they were part of the same basin. Carbonates that fall within a range of $^{87}\text{Sr}/^{86}\text{Sr}$ up to $0.00027$ are considered invariant (Hart et al. 2004), and therefore variability within this range is considered negligible. The variability in Linxia and Xunhua’s record is less than half of this (Figure 7), and so it can be assumed that their signatures were derived from the same body of water. Furthermore, the proximity of these ancient lakes to the West Qinling fault is consistent with the idea that these basins were part of a large, foreland basin.

Sr isotopic evidence does not rule out a foreland basin setting for basins north of the West Qinling fault, but additional tests would be required to demonstrate the validity of this interpretation. Some uncertainty arises from the dating of the Xunhua record. Although there are tight magnetostratigraphic correlations for the Linxia and Guide basins, Xunhua’s magnetostratigraphy is less well resolved. Therefore the ages could be off by several million years. If the Xunhua samples are younger than assumed for this study, their values would show overlap of the basins post-8.5 Ma. If they are older, then the records for Linxia and Xunhua may not overlap in time and thus would be incomparable. The integrated foreland basin hypothesis could be further tested with detailed mapping along the eastern and western flanks of the mountain range that separates the Xunhua and Linxia basins, as well as stable oxygen isotope ($\delta^{18}\text{O}$) studies of lake deposits to determine whether they reflect hydrologic connections between Xunhua and Linxia basins.

Conclusions

The study of strontium isotopes in northeast Tibet paleolakes has shown that the topography and geography changed over the last 12 million years and were different from the present configuration. Guide and Tongren basins show distinct Sr isotopic compositions from Xunhua and Linxia basins that are north of the West Qinling fault. The most likely explanation for this is that they were isolated basins. Linxia and Xunhua’s records show striking similarity in the range of $^{87}\text{Sr}/^{86}\text{Sr}$, and therefore support the hypothesis that they were interconnected during the period of 11.5 to 8.5 Ma. The later records cannot be compared due to a lack of lake carbonates. Studies using stable oxygen isotopes ($\delta^{18}\text{O}$) and mapping along the boundary of the mountain range that separates Linxia and Xunhua basins may be able to further track the evolution and inevitable divergence of these basins to their present day separation.

The possibility that Linxia and Xunhua basins sourced a similar combination of rock types for Sr isotopes cannot be ruled out. Future work to clarify this issue would be to characterize both paleocurrents and the probable source areas for dissolved Sr to determine whether similar source areas can explain Sr isotopes in the basins through time. This would help differentiate similarities in their signatures that were caused by some similar sources in age and rock type from more precise similarities that indicate the basins were one and the same. Based on knowledge about the variability in Sr isotopes, the simplest interpretation remains that Linxia and Xunhua were part of a large, integrated foreland basin, and Guide and Tongren were separate, piggy-back basins. Their progression to the present day (Figures 3 and 4) has shown how the northeast Tibetan margin has evolved over the past 12 million years, and insinuates how this region will continue to change.

References