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Palaeoenvironmental and palaeoclimatic reconstructions for the impact-crater lake of the Steinheim Basin, Middle Miocene, SW Germany: a multi-proxy stable isotope approach on phosphatic and carbonaceous fossil skeletal remains

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The Steinheim Basin is a 3.5 km wide Middle Miocene meteorite crater in the Upper Jurassic limestone plateau of the Swabian Alp, SW Germany. It formed contemporaneous with the neighbouring but larger Nördlinger Ries crater at 14.3±0.2 Ma (Buchner et al., 2003). With the basin being closed and sealed by an impact breccia, it was successively filled by meteoric water, forming a long-term freshwater lake existing for several 100 ka up to 1 Ma (Reif, 1988). The abundant mammal remains date the Steinheim Basin lake deposits to the European Neogene mammal zone MN 7 for which it is the reference locality. The aragonite-bearing calcareous lake sediments contain sympatric skeletal remains of a well-preserved invertebrate and vertebrate fauna (Heizmann & Reiff, 2002). Especially the fresh water snail *Gyraulus multiformis* is well-known for its intra-lacustrine speciation into 7 distinct morphospecies, (Hilgendorf, 1867; Mensink et al., 1984), that allow for a biostratigraphic separation of the otherwise lithostratigraphically uniform lake sediments into 7 snail beds.

In a multi-species multi-proxy approach, fossilized teeth of large and small mammals as well as freshwater snails, ostracods, fish teeth and otoliths from the lake sediments of the Steinheim Basin have been analysed for their oxygen, carbon and strontium isotope composition to determine the evolution of the water chemistry and temperature of the Miocene lake setting.

Results for oxygen and carbon isotope compositions (both versus VPDB) have been obtained for the calcitic ostracod carapaces (*Ilyocypris binocularis:* $\delta^{18}O_{CO3}$= 1.7±1.2 per mille, $\delta^{13}C$ = –0.5±0.9 per mille, n = 67), aragonitic shells of the freshwater snails (*Gyraulus* spp.: $\delta^{18}O_{CO3}$= 1.6±1.2 per mille, $\delta^{13}C$= –1.2±1.6 per mille, n = 34) and phosphatic fish teeth (*Barbus steinheimensis* + *Tinca micropygoptera*: $\delta^{18}O_{CO3}$= –1.8 ±0.4 per mille, $\delta^{13}C$= –6.5±0.6 per mille, n = 17) as well as for the aragonitic fish otoliths (*Tinca micropygoptera*: $\delta^{18}O_{CO3}$= 1.0±0.3 per mille, $\delta^{13}C$= –11.8±1 per mille, n = 10). The $\delta^{18}O$values of the skeletal tissues of all freshwater organisms are high, except for the early lake stage, and similar to marine but not freshwater biogenic carbonates or phosphates. This indicates a strong ^{18}O enrichment of the lake water due to intense evaporation of this long-term lake, which is known from the lake in the Nördlinger Ries as well (Wolff & Füchtbauer, 1976). The high $\delta^{13}C$ values of the biogenic carbonate indicate little input of recycled organic carbon into the lake water, with the dissolved inorganic carbon possibly being largely controlled by exchange with atmospheric CO_2 and/or dissolution of the underlying marine Jurassic limestone.

From the tooth enamel of large mammals ($\delta^{18}O_{PO4}$= 18.4±2.0 per mille VSMOW, n = 33, equids, proboscids, suids, cervids, rhinocerotids) a $\delta^{18}O_{H2O}$ (VSMOW) value of –5.9±1.7 per mille can be calculated using species-specific calibrations for extant taxa. This value is similar to $\delta^{18}O_{H2O}$ values calculated for mammal teeth from other Middle Miocene localities of the nearby Molasse Basin and is taken to be representative of the isotopic composition of the meteoric water at that time. Perhaps because of the poor water quality as a result of extensive evaporation large mammals did not use the ^{18}O-enriched water of the Steinheim basin as a principal drinking water source, even though other surface water sources may have been scarce on the karstic limestone plateau. Possible migration and thus potential use of other food and water sources of the large mammals is also supported by preliminary results for tooth enamel strontium isotope compositions that are elevated above the expected $^{87}Sr/^{86}Sr$ ratio of the Swabian Alp plateau carbonates.

In contrast, small mammal teeth have higher $\delta^{18}O_{PO4}$values ($\delta^{18}O_{PO4}$= 20.4±2.9 per mille VSMOW, n = 14, *Galerix socialis, Prolagus oeningensis, rodents indet.*) and a larger standard deviation compared to the large mammals. This is possibly because of a stronger evaporative influence on the ingested water and thus body water due to: (1) drinking water from the ^{18}O-enriched lake Steinheim, (2) a larger fraction of ^{18}O-enriched water intake by the food, or (3) small body mass and high metabolic rate. The teeth from the Pike *Prolagus oeningensis* have similar $\delta^{18}O_{PO4}$values and standard deviations (δ^{18}O$_{PO4}$= 17.9±1.6 per mille VSMOW, n = 6) compared to the large mammals. The Pikes thus ingested the majority of their body water oxygen from a more homogeneous and less evaporated water source than the rodents and hairy hedgehogs, perhaps from the Steinheim lake. Using the equation for small mammals of Grimes et al. (2003), a δ^{18}O$_{H2O}$ (VSMOW) value of 1.8±4.2 per mille can be calculated for the Steinheim lake from the δ^{18}O value of the Pike.

This δ^{18}O$_{H2O}$ value for the lake water in which all the sympatric fresh water organisms mineralised their skeletal tissue, can be used to calculate ambient water temperatures during their respective growing seasons from skeletal δ^{18}Ovalues of fish, snails, ostracods and otoliths (Grimes et al., 2003). The lowest calculated lake water temperature is that of the benthic ostracod *Ilyocypris binocularis* (T$_{H2O}$ = 13.8±4.1˚C), while that of the snails *Gyraulus spp.* (T$_{H2O}$ = 15.9±4.7˚C) living in the littoral zone is about 2˚C warmer. The teeth of both pelagic fishes *Barbus steinheimensis* and *Tinca micropygoptera* (T$_{H2O}$ = 14.4±3.5˚C) give intermediate temperatures between the bottom and surface water of the lake while the *Tinca micropygoptera* otoliths give the highest water temperature (T$_{H2O}$ = 20.5±1.6˚C), representing the warmest month of the growing season (Grimes et al., 2003).

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