Bivalve shells: ultra high-resolution paleoclimate archives
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Shells of bivalve mollusks provide time-constrained, multi-proxy records of climate change in any aquatic setting with unprecedented temporal resolution ranging from years to individual days. We explain why this archive is unique and list current research foci.

Climate proxy-data are crucial to better understand natural environmental variability prior to the instrumental era (Jones et al. 2001). In particular, there is a need for more sub-seasonal to annual resolutions of well-constrained and quantifiable proxy data from environmental settings for which only limited data are available, e.g. in coastal marine regions and mid- to high-latitude oceans (Solomon et al. 2007). Sclerochronology describes the investigation of the growth patterns and geo-chemical properties of the skeletal hard parts of bivalve shells. During the last decade, many sclerochronological studies (e.g. Schöne and Gillikin 2013) have confirmed that bivalve shells can record climate at sub-seasonal time scales (Butler et al. 2013; Schöne et al. 2003; Wanamaker et al. 2012).

Bivalve shells as paleoclimate archives

Bivalve shells can provide a precise chronology because calcium carbonate is periodically accreted to all growing shell margins (Barker 1964; Clark 1974; Jones 1980; Schöne and Surge 2012; Fig. 1). Regularly changing rates of skeletal formation are controlled and maintained by so-called biological clocks, which are constantly reset by environmental pacemakers (light, tides, food availability, etc.; Kim et al. 2003; Williams and Pilditch 1997). These internal time-keeping mechanisms ensure that the shell growth pattern is divided into time slices of approximately equal duration (Dunca and Mutvei 2001; Witbaard et al. 1997), which produce growth increments and growth lines. Growth increments represent periods of fast growth and growth lines periods of slow growth. Together, they are prerequisite for sclerochronological analyses because they can be used to measure time, and place each shell portion into a precise temporal context. Periodic growth patterns in bivalves include annual cycles (Jones and Quitmyer 1996; Pulteney 1781; Weymouth 1922), fortnightly cycles (15 and 13.5 lunar days; Evans 1972; House and Farrow 1968; Ohno 1989), as well as circadian (ca. 24 hours; Schwartzmann et al. 2011), circalunidian (lunar-daily, ca. 24.8 hours; Richardson 1987), circatidal (semidiurnal, ca. 12.4 hours, ebb/neap tide cycle; Beentjes and Williams 1986) and ultradian cycles (periods of minutes to hours; Rodiand et al. 2006). This makes shells unrivaled archives for measuring time in the geological past at high resolution.

Bivalve shells also function as faithful and sensitive recorders of environmental change (Fig. 2). Like other cold-blooded animals, bivalve growth is largely controlled by external energy input in the form of temperature, and food quantity and quality. As a result, relative changes in shell growth, expressed through varying increment widths, can provide information on changes in these environmental variables (Kennish and Olsson 1975). Furthermore, the ambient physicochemical conditions (salinity, water quality and temperature, food availability, etc.) that prevailed during its growth are also preserved in the shell as geo-chemical and crystallographic properties. For example, shell oxygen isotope ratios ($\delta^{18}O_{\text{shell}}$) provide an ideal means to estimate past water temperature and salinity because almost all bivalve species form their shells very close to...
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Schöne BR, Surge DM (2012) In: Selden PA (Ed) Treatise of Invertebrate Paleontology, Part N (Mollusca, Bivalvia), Treatise Online 44, 1-24

Wanamaker AD et al. (2012) Nat Commun 3, doi: 10.1038/ncomms1901

**THE FUTURE OF BIVALVE SCLEROCHRONOLOGY**

The potential of bivalve sclerochronology in the fields of archeology and anthropology, evolution, retrospective environmental monitoring, and ecology is still waiting to be fully exploited; however, it will likely have a significant impact on paleoclimate and paleoenvironmental studies. Linking different high-resolution paleoclimate archives advances our knowledge of coupled climate systems, which will further improve predictive numerical climate models. The ubiquitous occurrence of bivalves in shallow-marine settings, especially longer-lived species, makes them suitable candidates for the construction of long master chronologies in both hemispheres. This would, for example,

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