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Short Communication

Humans as the third evolutionary stage of biosphere engineering of rivers

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ABSTRACT

We examine three fundamental changes in river systems induced by innovations of the biosphere, these being: (1) the evolution of oxygenic photosynthesis; (2) the development of vascular plants with root systems; and (3) the evolution of humans. The first two innovations provide context for the degree of human-induced river change. Early river systems of the Precambrian Archean Eon developed in an atmosphere with no free oxygen, and fluvial sediments accumulated 'reduced detrital' minerals. By 2.4 Ga the evolution of oxygenic photosynthesis produced an oxygenated atmosphere and 'reduced detrital' minerals mostly disappeared from rivers, affording a distinct mineralogical difference from subsequent fluvial deposits. Rivers of the Precambrian and early Phanerozoic were dominantly braided, but from 0.416 Ga, the evolution of vascular plants with roots bound floodplain sediments and fostered fine-grained meandering rivers. Early meandering river deposits show extensive animal activity including fish and arthropod tracks and burrows. *Homo sapiens*, appearing about 150 ka BP, has, in recent millennia, profoundly modified river systems, altering their mineralogical, morphological and sedimentary state. Changes in sediment fluxes caused by human 'reverse engineering' of the terrestrial biosphere include deforestation, irrigation and agriculture. Sediment retention has been encouraged by the construction of dams. Modern river systems are associated with extensive human trace fossils that show a developing complexity from ancient civilizations through to megacities. Changes induced by humans rank in scale with those caused by earlier biosphere innovations at 2.4 and 0.416 Ga, but would geologically soon revert to a "pre-human" state were humans to become extinct.

Introduction

Water may have been delivered to the surface of Earth largely by comets and hydrous carbonaceous chondrite meteorites in the Hadean Eon (e.g. Albarède, 2009) after the planet's accretion at 4.54 Ga (4.54 billion years ago). However, early oceans and rivers were likely vaporized by the continued influx of large asteroids (Kasting and Ono, 2006). After the 'late heavy bombardment' of Earth (finishing about 3.9 Ga), water oceans have persisted at the surface, to provide water vapour for rainfall (Fig. 1). From then until the present, rivers have flowed across the evolving landscape of Earth (with the possible exception of the most severe 'Snowball' glaciations of the Proterozoic Eon: see Hoffman et al., 1998). Rivers were and remain a key component of the silicate rock weathering cycle and thus a control on the atmospheric level of carbon dioxide (see, for example, Dessert et al., 2003), and they also provide a source of nutrients from weathered terrestrial minerals to supply the ocean biosphere with biologically important materials (e.g. see Meybeck, 2003). There is an extensive geological record of sedimentary deposits formed from rivers, extending back in time to the Archean Eon of the Precambrian (Fig. 1). Examination of river systems in the geological and archaeological record suggests three major step changes in river evolution produced by innovations of the biosphere, involving the evolution of oxygenic photosynthesis at 2.4 Ga (Blankenship, 2010), the development of a terrestrial biosphere with vascular plants, beginning about 0.416 Ga (Davies and Gibling, 2010, 2013), and the geologically recent evolution of *Homo sapiens* (Fig. 1). In this

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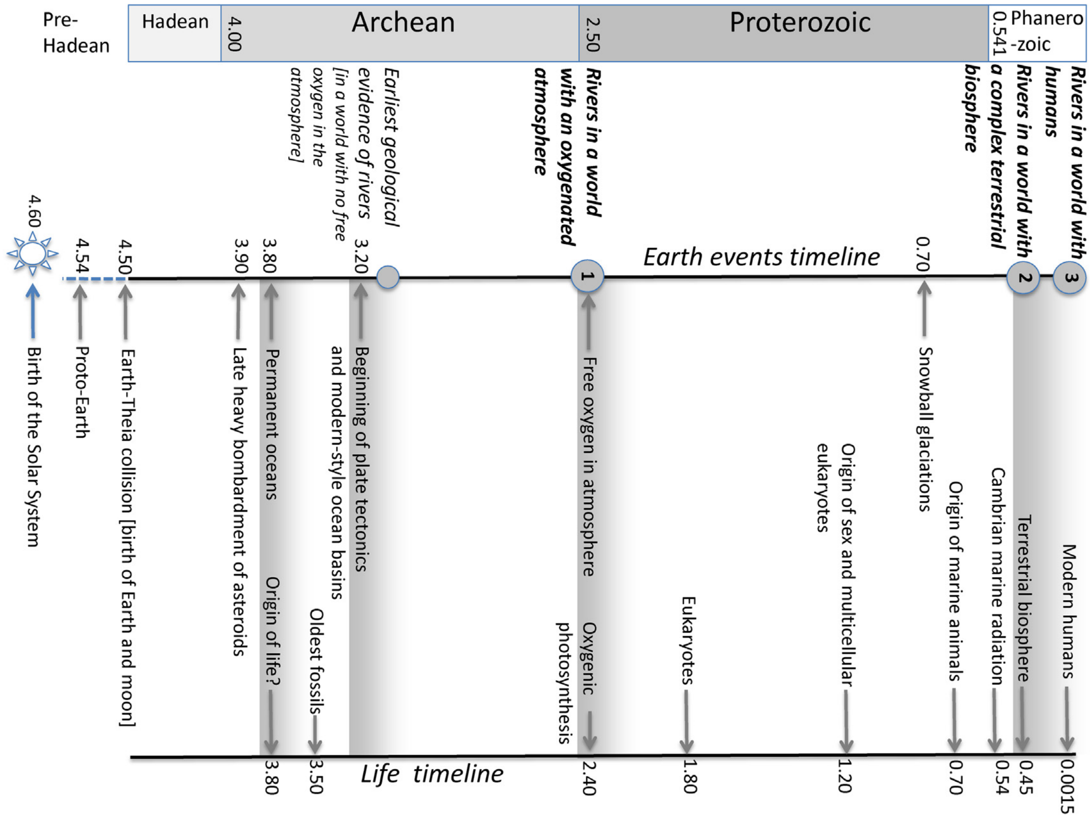

Fig. 1. Time-line of major events in the evolution of river systems from the Precambrian to present: data for the development of the terrestrial plant biosphere is taken from Davies and Gibling (2010, 2013). Steps 1–3 on the Earth events timeline signify the three stages of evolution of rivers identified here. Dates on the vertical axes are in Ga (billions of years).

paper we examine human impacts on global river system change using the context of major global changes of the past.

Rivers in a world with an oxygenated atmosphere

The geological record of fossil rivers extends to the Mesoarchean (3.2–2.8 Ga) part of the Precambrian (e.g. Rasmussen and Buick, 1999; see Fig. 1). The dearth of river deposits from yet older rocks may reflect the absence of large continental areas on which extensive rivers could flow; or, it may reflect the very incomplete record of sedimentary deposits from Paleo- and Eoarchean rocks. Earth's Archean atmosphere likely comprised nitrogen, hydrogen, water vapour, methane, ammonia and carbon dioxide, with traces of other gases, but no free oxygen (Kasting and Ono, 2006). Under this atmosphere rivers flowed but accumulated a different suite of minerals to those that formed in the post-Archean, oxygenated atmosphere. These 'reduced' minerals include the uranium ore uraninite, the iron mineral pyrite, and the nickel–arsenic mineral gersdorffite (see Rasmussen and Buick, 1999). These minerals occur as detrital grains within sedimentary deposits of ancient Archean braided river systems from as far afield as Australia (Rasmussen and Buick, 1999), South Africa (e.g. Frimmel, 2005) and North America (Koglin et al., 2010). They are important sources of uranium ore. The minerals were sourced from the weathering of yet more ancient Archean granitic intrusions or the pegmatitic mineralization associated with them (Depiné et al., 2013). After 2.4 Ga, these detrital minerals largely disappear from river deposits, reflecting a fundamental change in Earth's biosphere caused by the evolution of oxygenic photosynthesis and the accumulation of free oxygen in the atmosphere (Blankenship, 2010). A mineralogical distinction thus exists between the river deposits of the Archean and those of the later geological record. This distinction is pertinent to Anthropocene changes to fluvial systems, which have likewise accumulated a distinctive suite of human-induced mineral and chemical changes not found in the earlier record of rivers. This includes signatures of novel organic compounds (e.g., see Vane et al., 2011) and novel minerals and rocks. The minerals include metals rare or non-existent in nature such as aluminium fragments (Zalasiewicz et al., 2014a) and 'mineraloids' such as plastics, both only present as a distinctive and common component of many river sediments (Morritt et al., 2014; Rech et al., 2014) in significant amounts from the mid-20th century. There are also novel rock types including ceramic, brick and concrete fragments entering the sedimentary system in large and increasing amounts. In small amounts, versions of these have been present for millennia, but in recent decades they show rapid growth in quantity (>95% of the circa half-trillion tonnes of concrete made to date is post mid-20th century) and novel petrographies (such as the addition of fly ash from power stations as a major filler in concrete). Anthropocene river strata in the future will be as petrographically distinctive as we find Archean fluvial lithotypes to be today.

Rivers in a world with a complex terrestrial biosphere

The signatures of the coeval evolution of the terrestrial plant biosphere and its sedimentological and geomorphological impact on river systems have been summarized by Davies and Gibling (2010, 2013). The preserved sedimentary record suggests that many rivers of the Precambrian and Early Palaeozoic adopted a 'sheet-braided' style formed by rapid channel switching and lateral migration of channels over kilometres of floodplain (Davies and Gibling, 2010). Precambrian meandering rivers have left a rare sedimentary record, with only a few known examples of sand-bed