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Review article

The palaeobiology and geochemistry of Precambrian hydrocarbon source rocks

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ABSTRACT

Organic carbon productivity and formation of hydrocarbon source rocks during the Early Precambrian was almost exclusively the product of the growth of microbial mats. Indirect evidence of microbial mats can be traced back to at least 2.6–2.7 Ga (Neoarchaean), with the earliest evidence of mat development in siliciclastic sediments coming from the 2.9 Ga (Mesoarchaean), predominantly marine sedimentary rocks of the Mozaan Group in South Africa. The earliest direct evidence for terrestrial microbial mats in siliciclastic sediments comes from the 2.75 Ga (Palaeoproterozoic) fluviolacustrine sediments of the Hardey Formation of the Pilbara craton in Western Australia. Well-preserved Proterozoic hydrocarbons provide valuable information about the early evolution of the biosphere. Eukaryotic steranes (biomarker for eukaryotic cells and, therefore, evolved forms of life) are present in the geological record from about 2.7 Ga, but they are not abundant or diverse within Archaean communities, which tend to be dominated by Archaea isoprenoids. Some hydrocarbons have been generated and migrated from Archaean organic-rich shales, but they were probably not of sufficient volume to be of commercial interest. The world's oldest significant hydrocarbon source rocks are Palaeoproterozoic in age and include the shungite deposits (2.0 Ga) in the Lake Onega region of Arctic Russia.

There is strong evidence of a global biospheric oxygenation event at c. 1300–1250 Ma (Mesoproterozoic) in conjunction with a first-order positive shift in the marine carbon isotope record. This is supported by the appearance of the oldest bedded marine gypsum deposits and of the earliest, unambiguously multicellular eukaryotes at this time. This oxygenation event probably played a significant role in supporting the more diverse eukaryotic communities preserved in the Neoproterozoic molecular record and provided the volume of organic material required to generate commercial volumes of hydrocarbons. Hydrocarbon source rocks of late Mesoproterozoic and Early Neoproterozoic age are widespread and include highly organic-rich shales deposited in restricted basinal settings adjacent to stromatolitic carbonate banks. By c. 850 Ma, the Neoproterozoic molecular record is dominated by hopanes from cyanobacteria with a significant abundance and diversity of eukaryotic steranes, including those of multicellular eukaryotes (red and green algae), as well as molecular evidence for heterotrophic protists. The most widespread hydrocarbon source rocks of mid to late Neoproterozoic age are commonly transgressive organic-rich black shales associated with inter-glacial and post-glacial phases of the Neoproterozoic global scale glaciations. The relative dominance of microbial mats in the contribution of organic matter as a source for hydrocarbon generation probably decreased significantly during the late Neoproterozoic and earliest Cambrian, perhaps as a result of the rapid growth of grazing metazoan communities or possibly as a result of changes in seawater chemistry and/or nutrient supply.

Precambrian and 'Infracambrian' petroleum systems are relatively abundant and widespread. The oldest live oil recovered to date is sourced from Mesoproterozoic rocks within the Velkerri Formation (Roper Group) of the McArthur Basin of northern Australia, dated at 1361 ± 21 Ma and 1417 ± 29 Ma (Re–Os dates) with at least the initial phase of oil generation and migration having taken place before 1280 Ma. However, the geologically oldest commercial production is currently from the somewhat

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younger mid to Late Neoproterozoic (Cryogenian–Ediacaran) petroleum systems of the Lena-Tunguska province in East Siberia and in southern China, from the latest Neoproterozoic to Early Cambrian Huqf Supergroup in Oman and, potentially in the near future, from the age-equivalent Mawar Supergroup in western India.

1. Introduction

Interest in Precambrian petroleum systems has gathered pace over the past decade as they have become increasingly recognised as a potentially large and relatively untapped resource. The vast potential of these systems has been demonstrated by the discovery and exploitation of giant oil and gas fields in China, Russia and Oman. This has resulted in increasing interest in exploration for both conventional and unconventional hydrocarbon resources in Precambrian successions in many areas of the world, particularly in West Africa, Brazil, North America and Australia (Craig et al. 2009; Bhat et al., 2012).

True Precambrian Petroleum Systems (as opposed to 'hybrid' systems) require the existence of source rocks of Precambrian age that are of sufficient quality and volume to generate hydrocarbons that, through the processes of thermal maturation and migration, are subsequently trapped in reservoirs of Precambrian age by seals that are either of Precambrian or younger in age. In 'hybrid' Precambrian Petroleum systems either the source or reservoir is generally younger than Precambrian in age. Most commonly these involve hydrocarbons generated from Precambrian source rocks that are trapped in Phanerozoic reservoirs or, alternatively Precambrian reservoirs that are charged by Phanerozoic source rocks.

Precambrian hydrocarbon source rocks differ from most 'conventional' Phanerozoic source rocks in that the organic matter they contain is predominantly, if not exclusively, of bacterial or algal origin. Exploration for Precambrian Petroleum Plays requires a thorough understanding of the both the spatial and temporal distribution of organic-rich horizons within Precambrian successions and the progressive evolution of the mix of organic components within these through geological time. It is the purpose of this paper to provide a comprehensive review of the palaeobiology and geochemistry of Precambrian source rocks using a combination of published information and some new research and analysis and to track the progressive changes in these through Precambrian time.

1.1. Precambrian stratigraphy and time scale

'Precambrian' is an informal stratigraphic term that encompasses all geologic time from the beginning of the Cambrian Period (542 Ma) back to the early stages in the formation of Earth. It is preceded by the informal time unit of the 'Hadean' (Ogg et al. 2008). The 'Precambrian' is generally subdivided into the Archaean (4000–2500 Ma) and Proterozoic (2500–542 Ma) Eons (e.g. International Commission on Stratigraphy, 2009, Chart), although there is a proposal to redefine the age ranges of these to 4030–2430 Ma and 2430–542 Ma, respectively (Ogg et al., 2008; Fig. 1). The Archaean Eon is further subdivided into four Era. The transition to the Proterozoic is considered to be diachronous in all cratons and the formalization of a 'Transition Eon' (Eoproterozoic) is under discussion by the Precambrian sub-commission of IUGS (Fig. 1). For the present, the Proterozoic Eon conventionally begins at 2500 Ma; a time of major change in the evolution of the crust, atmosphere and of life on Earth. The Proterozoic Eon is subdivided into three Era (Palaeoproterozoic, Mesoproterozoic and Neoproterozoic) and further subdivided in 10 Periods, the names of which broadly reflect large scale tectonic or sedimentary events.

The term 'Infracambrian' has, historically, been used in the oil and gas industry to define the Neoproterozoic to earliest Cambrian time interval (Smith, 2009). It can also be regarded as including the Vendian and later Riphean stages of the Russian Neoproterozoic nomenclature. It was originally proposed as 'Infracambrien' by Menchikoff (1949) in a paper on the stratigraphy of the Western Sahara. Subsequently, the term 'Système Infracambrien' was used by Pruvost (1951) to include Precambrian sediments underlying known Cambrian rocks and unconformably overlying generally metamorphosed strata. 'Infracambrian' remains an informal term, and is not synonymous with 'Precambrian'. Use of the defined stratigraphic Periods of Tonian, Cryogenian and Ediacaran is preferred when stratigraphic dating is robust enough to allow this. Use of the term 'Infracambrian' is now generally discouraged (e.g. Craig et al., 2009). For simplicity, the chronostratigraphic divisions of 'Precambrian' time into Eon, Era and Period are used in this paper without their relevant suffixes.

Precambrian and 'Infracambrian' (Neoproterozoic–Early Cambrian) petroleum systems can be classified as either 'producing or proven' (those that either do, or could soon, produce commercial volumes of hydrocarbons) or 'potential' (those where all the elements of a play are known to exist, but where there is, as yet, no commercial production). They are relatively abundant and widespread (Craig et al., 2009; Ghori et al., 2009; Bhat et al., 2012).

1.2. The origin of life on Earth

The fact that life was established on the Earth almost as soon as conditions permitted the development of a liquid water ocean, has led to the suggestion that life may have begun in the gas and dust cloud from which the solar system formed (King, 2009). The Earth was probably heavily bombarded with meteors until at least 3.85–3.82 Ga and probably until 3.5–3.0 Ga (Johnson and Melosh, 2012; Garde et al., 2012) while further periodic heavy bombardments may have occurred until at least 1.7 Ga (Bottke et al., 2012). Many of these bolides probably carried complex organic molecules formed in space (e.g. Cohen, 1996). Apatite grains from the 3.82 billion year old Isua Formation of Greenland (Brooks, 2011) have $_{12}C_{+}-_{13}C_{+}$ ratios that are consistent with them having been derived from living matter (Mojzsis et al., 1996; Mojzsis and Harrison, 2000) and these chemical signatures may be the earliest signs of biological life on Earth. The chemical origins of life and the process by which the earliest 'life-like' molecules were synthesized remain hotly debated, but one popular theory invokes a 'transitional phase' involving ribonucleic acid (RNA) – a polymer that is simpler than, but possibly a precursor to deoxyribonucleic acid (DNA), the primary molecular 'building block' of life. RNA is considered to be a potential early-life molecule because it can store information in its molecular structure, replicate, catalyse the necessary chemical reactions and because at least one of its major building blocks can be synthesized from simpler molecules under conditions that could plausibly have existed on the early Earth (Powner et al., 2009; Van Noorden, 2009). It is generally, but not universally, accepted that life existed on Earth as early as 3.5 billion years ago, based on morphological evidence combined with detailed geochemical and palaeoecological studies (Czaja, 2010 and references therein). Sequencing of DNA suggests that the earliest organisms on Earth