Gondwanan Glacial Events and their Influence on Petroleum Systems in Arabia*

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Introduction

Throughout the period from the Late Proterozoic to the end of the Palaeozoic, the Arabian Peninsula was part of Gondwana and lay at moderate to high latitudes in the southern hemisphere. Several glacial episodes are identified during this time across Gondwana, and four distinct glacial events are recorded in the sedimentary record of the Arabian Peninsula (Figure 1). Three of these glacial events can be clearly linked to petroleum systems, not only in the deposition of reservoirs, but also in the deposition of source rock facies.

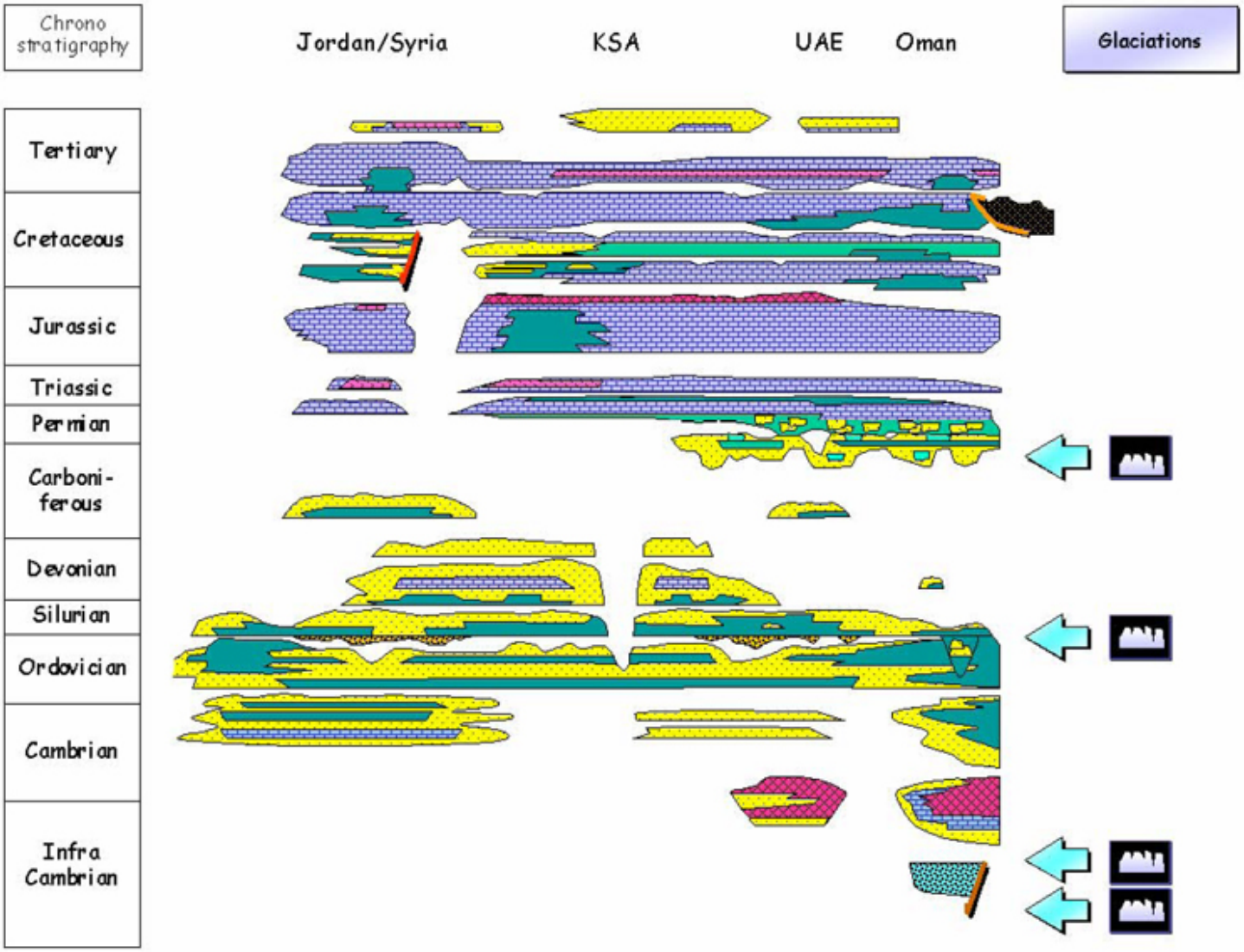

Figure 1: Stratigraphic synopsis across Arabia showing glacial events.

Precambrian Glacial Sediments

The oldest two glaciations are known only from Oman where Infracambrian basins are preserved, and glacial sediments are known both from outcrop (Le Guerroué et al., 2005) and the subsurface. The oldest of these glaciations is Sturtian in age and is unequivocally exposed in the Oman Mountains, where it has been dated by U-Pb radiometric dating of volcanically derived zircons (723+16/-10 Ma; Brasier et al., 2000). Glacial sediments are also exposed in the area of Murbat, 70 km east of the city of Salalah in south Oman. Diamictites have been penetrated on many occasions in the subsurface of Oman, and there is evidence that these are in part derived form the Marinoan glaciations. An unpublished U-Pb age in diamictites from the subsurface has been measured at 635 Ma. It is likely that the Fiq Formation of the Oman Mountains, as well as many of the glacial sections penetrated in the subsurface, are related to this younger, Marinoan glaciation. Many wells show that this sequence is terminated by a cap carbonate, which in turn is overlain by organic rich shales.

In the outcrops of Murbat, the top few metres of the glacial diamictite unit show sedimentary features consistent with reworking, including clast-supported conglomerates and cross-bedded sandstones. Conformably overlying the diamictites is a 2-m-thick dolomite unit with domal stromatolites at the top. The stromatolites are abruptly overlain by several metres of laminated, fissile shales. Although this shale has no measured TOC, possibly through surface oxidation, the lamination is consistent with organic-rich shales that are found to overlie the cap carbonates in the subsurface. Hydrocarbon fluid inclusions are also seen in the cap carbonate at this location.

In the subsurface there are no commercial hydrocarbons reservoired in the glacial sediments; however, the organic-rich shales above the cap carbonate have been shown to be of source-rock quality. They are believed to be the source for low-gravity oils and oil stains found in Infracambrian-aged turbiditic sediments above the glacial sediments in central Oman. Although, by far not the most prolific of the Infracambrian source rocks of Oman, they have made contributions to some Oman fields.

The Ashgillian Glaciation (Figure 2)

In the Arabian Peninsula there is widespread evidence of the latest Ordovician Hirnantian Glaciation. In McClure (1978) the evidence from outcrop sections can be seen, while McGillivray and Husseini (1992) show evidence of glacially scoured channels in the subsurface. This glacial event is described from many locations in North Africa. The South Pole was positioned at this time in the west of North Africa in present-day Mauritania. The position of channels and tunnel valleys at the surface and from the subsurface in Arabia suggest that the glaciated area was to the west in the region of the Nubian and Arabian shield and that sediment transport was toward the present-day east and northeast. The abrupt end to glaciation in the Ordovician is marked by an extensive marine flood that deposited organic-rich “hot shale” across large parts of the Arabian Plate.

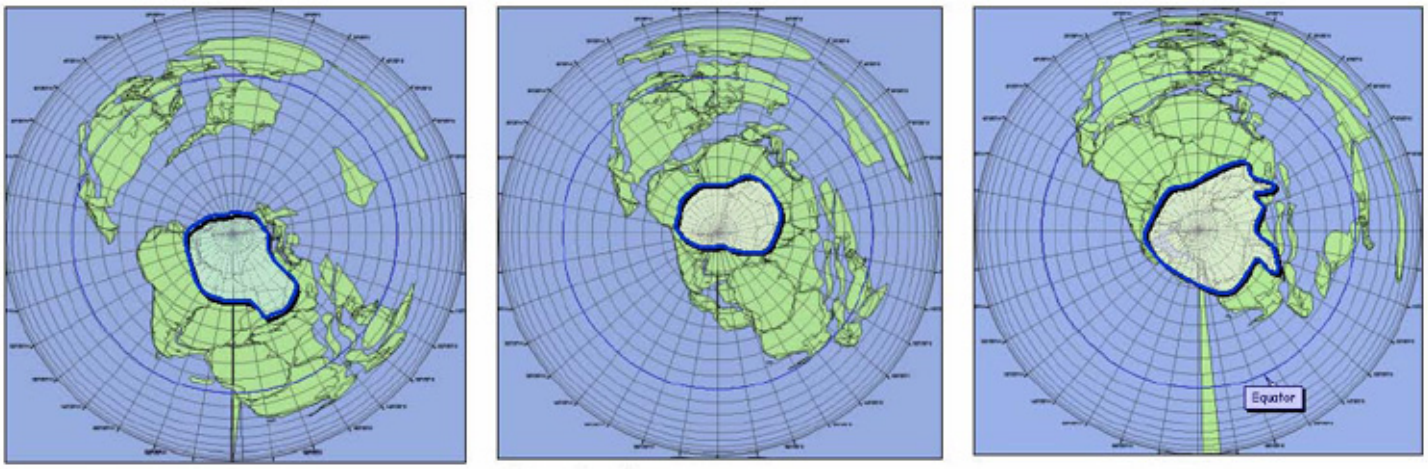

Figure 2: Position of glaciated areas through the Palaeozoic. Left: Ashgillian latest Ordovician; Center: Frasnian Late Devonian; Right: Late Carboniferous / Early Permian.

The deglaciation flood at the base of the Llandovery provides the ideal conditions for the deposition of source rocks. The availability of extensive flooded shelves with restricted circulation and high productivity results in the formation of an extensive source rock. The reducing conditions at the seabed were sufficient to produce extensive framboidal pyrite and organic matter rich in radioactive elements. This gives the distinctive "hot" response on gamma ray logs. This base Silurian source rock is a proven source for hydrocarbons throughout the margin of the Gondwana continent, from Algeria in the west to Oman in the east. It is believed to be one of the main source rocks for the North Field in Qatar as well as a source for accumulations such as Hawtah (oil in the Unayzah) and Ghawar (gas in Khuff and Unayzah) in Saudi Arabia, as well as the Sahmah oilfield in Oman. In these fields, the Silurian is the source for stratigraphically younger reservoirs; however, there is evidence that the Silurian source rock can also expel downward into older formations, in particular the glacial-related sediments that underlie the source rock. The Risha field in Jordan and the Akkas field in Iraq fall in this category.

The Late Carboniferous Glaciation (Figure 2)

After the Silurian flooding event in Arabia and the subsequent deposition of a sequence dominated by fluvial and marine sandstones, the plate was affected by a series of uplift events culminating in the Carboniferous-aged Hercynian event. This resulted in the peneplanation of a large part of the Arabian Plate, combined with the discrete re-activation and inversion of some older structural features. This unconformity surface was then sculpted by a series of glacial valleys and the widespread deposition of glacial sediments in the Late Carboniferous. These are described by Levell et al. (1988) from Oman and Al-Husseini (2004) from Saudi Arabia. The sediments of the glacial Al Khlata Formation in Oman and Unayzah C in Saudi Arabia are characterised by diamictites and interbedded shales and sandstones, representing a series of glacial and peri-glacial environments. In places in central Saudi Arabia, deposition of Carboniferous glacial sediment immediately above the Hercynian unconformity has resulted in the juxtaposition with Silurian shales associated with the deglaciation after the Ordovician glaciation.

Above the glacial sediments there are laterally extensive lacustrine shales that in Oman are termed the Rahab Member. Diamictites are essentially absent from units above these shales, and as such these may represent the deglaciation event. Unlike the base Silurian deglaciation event, the deglaciation in the Late Carboniferous did not result immediately in a marine flood, but instead in a rise in base level, the formation of bodies of standing water, and extensive root-bed horizons. Above the Rahab Member, the fluvial and marine sandstones and siltstones of the Gharif Formation (Oman) and Unayzah A (Saudi Arabia) are deposited.

The glacial and peri-glacial sandstones of the Unayzah and Al Khlata (as well as the post-glacial sands of the Gharif Formation) are proven reservoirs for both oil and gas in Arabia. In Oman this results mainly from charge from Infracambrian source rocks, whereas in Saudi Arabia these are charged almost exclusively from the Silurian source rock. The Rahab shales, representing the end of glaciation, are responsible for seals in many of these reservoirs. Hakami et al. (2005) have presented that there is potential for these lacustrine shales to be source rocks in Saudi Arabia. Oils have been discovered with a waxy lacustrine character, and the de-glaciation lakes are the prime candidates as the source.

Discussion

The glacial events that have affected the Arabian Plate have had a major impact on the petroleum systems in this region. Three of these glaciations have resulted in the deposition of source rocks, all in the de-glaciation phase immediately following the final glaciation. The oldest two of these, the Marinoan and Ordovician glacial events, have resulted in marine source rocks associated with the original post-glacial flood, while the younger Carboniferous glaciation has a probable lacustrine source rock associated with a rise in base level. The reason why the Carboniferous is not associated with a marine flood source rock is not completely understood; however, the rise in land plants causing greater soil stability and possibly more common floodplain lakes may have played a role. In addition the fact that the Carboniferous glaciation is also associated with the first extensional events leading to the opening of Neo-Tethys may also have been a control on sedimentation.

The younger two glacial events (Carboniferous and Ordovician) are both associated with glacial sandstone reservoirs, while this is not true of the Marinoan. The presence of hydrocarbon fluid inclusions in the cap carbonate of Murbat suggests that similar-style downward migration is possible, and the clast-supported and reworked sediments at the top of the diamictite package show that reservoirs are possible. The absence of accumulations could be a result of charge-timing issues, the effectiveness of Precambrian cap carbonates as seals to downward migration, or, most intriguingly, the stage of exploration in that these hydrocarbons have not yet been discovered.

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