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Challenges of Sequence Stratigraphy in the Siluro-Devonian Succession of the Sahara Craton

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The aim of this paper is to review different parameters which interfered during the sedimentation of the Siluro-Devonian succession in the Sahara craton, and controlled the peculiar architecture of the sequences. The classic sequence stratigraphy models have to be adapted to the subsidence pattern, which characterised the cratonic Sahara basins. Sahara basin morphology during Silurian and Devonian was also characterised by low topographic gradients between the continental and marine areas. No well-defined shelf break existed between the platform and the deeper basin. Finally, Palaeozoic was the site of peculiar sedimentation conditions, both in the continental and marine domains, in relation with the climatic conditions and the rarity of vegetation. The sequence nomenclature, the unconformity and system tract definition has to be adapted to take into account the peculiar tectonic setting and morphological configuration of these Gondwana cratonic basins.
The presentation will be illustrated with outcrop, subsurface regional transects and stratigraphic simulations in different basins in the Algerian Sahara.

Arches and sub-basins of the Saharan craton
Cratonic basins are characterised by relatively low subsidence and uplift rates. The Gondwana margin in Algeria formed a wide and low relief platform, gently dipping north and opened to the Hiapetus Ocean. The platform itself consisted of sub-basins separated by tectonic arches which dynamic is still poorly understood. The wavelength between the arches reached hundreds of kilometres, and their uplift was associated to a large amplitude flexure rather than to horst and graben tectonics. The deformation was probably associated to intra-plate stresses and lithosphere buckling. The arches present a positive morphological relief and separated more subsident sub-basins. They were inundated during periods of relatively high sea levels, and are emerged and eroded during relative sea-level fall. Arches formed most of the time a positive relief, which induced subtle facies and thickness variations during most of the Palaeozoic. The basin and arch configuration for example controlled the anoxic conditions during the deposition of the Lower Silurian source rock. The arch uplift accelerated during specific periods of the Sahara history. For example, the boundary between Silurian and Devonian was marked by a major reorganisation of the sedimentary systems, associated with the Caledonian unconformity. From this time onward, the arches such as the Ahara arch in Algeria or the Gargaff arches in Libya

were emerged and eroded, and progressive unconformity were formed above and around these highs.
The sub-basins, and « a fortiori » the arches, are characterised by a low subsidence rate. The thickness of the whole Siluro-Devonian succession in the centre of the Illizi basin is less than 1000 m for a 75 Ma duration).

A sediment flux largely controlled by climate
From Cambrian to Upper Devonian, the Gondwana super-continent progressively shifted North from the South Pole location towards temperate latitudes. Dry, periglacial (?) conditions prevailed during Cambro-Ordovician, and, apart from the Upper Ordovician glacial event, the climate progressively warmed during the Silurian and the Devonian. Water was warm enough to make possible carbonate precipitation during the upper Devonian. In the continental domain, the progressive climate warming was probably associated to an increase of the water fluxes in the river systems. Cambro-ordovician fluvial systems do not show large-scale bedforms or channel incisions, which suggest that the water flux was relatively low. On the contrary, Devonian fluvial systems show well preserved large-scale bedforms evidencing deep channels with high permanent water discharges.

Specificity of the sedimentation pattern during Siluro-Devonian.
In fluvial systems, vegetation colonisation began during Late Silurian, which profoundly modified the dynamic of the fluvial systems. Generally speaking, vegetation fixes the finer portion of the sediments is fixed in the floodplain during stages of overflow. Vegetation in floodplain also fixes the channel margins, and then controls channel lateral migration. Floodplain sediments in the pre-Devonian fluvial systems were poorly preserved. Channel lateral migration was easy and sand-rich braided-plain covered basin-wide areas. The Palaeozoic fluvial systems generally make sand-rich units with a very important lateral extension. For the first time, during Lower Devonian, floodplain aggradation was made possible and ribbon channels were preserved and alternated with the braided fluvial units.
In marine environments, Silurian and Devonian shallow marine successions were characterised by mixed wave and tidal ramps, which formed progradational units with very low angle clinoforms and with a very wide lateral continuity. Tidal ranges were probably very high on the Saharan craton and were favoured by shallow platform morphology. As a consequence, sediment was redistributed offshore by the tidal and wave currents, forming the ramp morphology. Wide tidal plains also extended beyond the ramp in the coastal-plain setting.

Consequences on sequence architecture of the Silurian and Lower Devonian succession
Accommodation variations in the Sahara craton were then controlled by a low subsidence rate, different in each sub-basin, a relatively high sediment flux and high amplitude eustatic variations of glacio-eustatic origin.

Fluvial erosional regional unconformity
In the fluvial domain, the major unconfimities are linked to major base-level fall associated to tectonics (the Caledonian unconformity) or eustatic events, which induced a reorganisation of the entire depositional systems. Generally speaking, an unconformity in the Devonian fluvial systems corresponded to sharp surfaces with a regional extension at the base of the main fluvial units. The unconformity morphology did not show any significant relief, and incised valleys

have never been observed in outcrops. The time gap associated to such unconformity should have been very long, and the lateral migration of the fluvial systems over a substratum, which was easy to erode, smoothed the incision morphology.

Unconformity associated with local uplifts
The uplift of the arches generally induced a condensation of the series. When the uplift accelerated, or when the uplift was contemporaneous of an eustatic sea-level drop, the sedimentary succession was progressively truncated over the highs. Frasnian shells for example directly lies on Upper Silurian shale above the Ahara high. These local unconformities often occurred at the same time in different arches, which suggested that the control of the relative sea-level drop was linked to eustasy. Erosion for example affected the tops of the Ahara and the Tihemboka arches at the same time.

Synchronism or diachronism of the transgressions
The main transgressions related to the high amplitude eustatic variations induced craton-scale transgression. The Silurian transgression, which was initiated by the melting of the Late Ordovician ice shield, inundated huge areas in a relatively short period of time. On the contrary, transgressions in sub-basins were often diachroneous, depending on the location of the sub-basins and their subsidence rate. For example, during the lower Devonian, the transgression which started during the Pragian times in the Berkine basin only reached the Illizi basin during the Emsian times.

Forced regression rather than unconformity in the marine domain
Forced regressions occurred during periods of progressive relative sea-level fall in a platform setting. Forced regression wedges are very frequent in the Silurian offshore and shoreface sequences of the Illizi and Berkine basins, and in the Akakus sandstones of Libya. The progressive lowering of the sea level induced a progressive downward shift of facies, the sediment eroded in the coastal-plain setting being reworked offshore to build a new shoreface wedge. As a result, the Silurian succession shows sharp-based shorefaces truncated on top by distributary channels, and the sequences have a surprising lateral continuity.

Conclusions
One of the main consequences of the low accommodation rate, which prevailed in the Saharan basins during most of the Palaeozoic times, is the surprising continuity of the facies belts within the depositional sequences. In continental environments, the same fluvial sequence can be traced over tens of kilometres without showing any significant facies variations. This continuity is related to the low topographic gradients of the Palaeozoic river systems and the relatively high sediment fluxes, which balanced the accommodation creation. In the marine domain, the tidal ramps show a constant thickness and the transition to the offshore mudstones is very progressive. The continuity is both due to low subsidence rate, the lowstand wedge geometry and the sedimentary dynamic which favoured a reworking of the sands offshore.