In the Kingdom of Saudi Arabia, Lower Paleozoic rocks crop out extensively in many areas and are well known from the subsurface. In the southern part of the country, the Paleozoic deposits are known as the Wajid Group, which is composed of five formations. Two of them, the Sanamah Formation and the Juwayl Formation record the two major Paleozoic glaciations that affected large parts of Gondwana.

The Sanamah Formation is of presumed Late Ordovician or Early Silurian age. It was mainly deposited in a succession of channels that are deeply cut into the underlying rocks; the maximum depth of the channels hitherto observed is on the order of 80 m. We have distinguished several lithologic units within the Sanamah Formation. The basal succession consists of red conglomerates and coarse-grained sandstones. Most of the clasts are rounded to well-rounded quartz pebbles, cobbles are very rare. Sorting is moderate to poor. Sedimentary structures include large-scale trough cross bedding and lateral accretion complexes. The second unit is composed of massive yellow to beige coarse-grained sandstones. There is hardly any cross bedding visible, and only a few reactivation surfaces have been found. Close to the top of the unit a few horizons have been found that show ripple marks. The third unit is a succession of sandstone that shows repeated horizons of slumping. The sediments are well bedded; grain size is medium to coarse sand. Along the margins of the channels, thin units of conglomerates are preserved that show trough cross bedding, a bad sorting and clasts that are subangular to subrounded. In these sediments, a few striated clasts have been found. Here too, the majority of the clasts are quartz pebbles.

The Juwayl Formation is of Permian age. It is a complex arrangement of different lithofacies. Similar to the Sanamah Formation, the Juwayl Formation was deposited in long and broad channels. In contrast to the Sanamah Formation, however, their geometry is rather well known (Kellogg et al., 1986). They are several km wide and a couple of hundred meters deep. The valley fill consists of massively bedded sandstones or conglomerates, often with no visible internal structure which we have called "sorbet-facies". Where individual sand bodies were identified, their erosional bases indicate permafrost conditions. Vertical and even overhanging forms have been observed in the friable medium- to coarse-grained sandstones which can only have been produced in a frozen state. The sorbet facies of the Juwayl have no known modern analogue. In our interpretation, these sorbet facies represent episodic gravitational sediment transport from the valley slopes or of sander flats during thawing events. We assume high-density sediment creep downslope the existing morphology during seasonal, summer events. Alternatively, these sand bodies might have been created through melt water discharge at the base of large ice masses where the overburden of the ice leads to partial melting with the water being pressed away to the sander.
flats where it remobilizes the sand. This model, however, can hardly be applied to the Juwayl Formation as this facies is confined to broad channels; deposition on some kind of flat seems rather unlikely.

On top of the valley fills and on the bordering highlands, lake sediments are present that show typically developed varves. Varve sediments are also present as reworked clasts at the base of the channels. In some of the lake sediments, soft sediment deformation is present that is typical of ground contact of drifting icebergs. Locally, these lake sediments are strongly brecciated. In addition, dropstones of granitic and basic basement composition are present, but clasts of the underlying Khusayyayn Formation have also been observed. The basement clasts often show well-developed glacial striations. The lake deposits extend far beyond the Juwayl channels which are running a northwest – southeast direction in the northern part of the study area. Lake deposits are found as far south as Bani Kathmah (northeast of Najran). There, the Juwayl sediments show almost an entire dictionary of glacial or proglacial deposits. Features include dropstones, varve sediments, small fluvial channels with a basal lag deposits of conglomerate, glacial diamictite, boulder pavements, and “flame structures” typical of grounding ice bergs. In the absence of any major compressional deformation that would have affected the entire sedimentary succession, brecciation and folding of the Juwayl lake sediments is interpreted as an indicator of a major glacial advance across these sediments.

Both units are interpreted to have been deposited in glacial environments. However, their glacial inventory differs from modern environments and some features lack an actualistic counterpart. Both formations were deposited in large channels whose origin is not clear. They may be of glacial origin, of fluvial origin, or they may represent tunnel valleys developed in front of the glaciers. The dimensions of the valleys in the outcrop area, several km long and some 100m deep, alone cannot be used as an indicator of their origin, because sea-level changes on the order of 100 m are known during glacial intervals. Hence, these valleys may have been carved fluvially during sea-level lowstand, but similarly, they may represent tunnel valleys. From seismic interpretations from the subsurface in northern Saudi Arabia, it is known that in the Ordovician similar valleys attain 600 m of depth (Konert et al., 2001). There, an origin as fluvial valleys can be excluded (Sharland et al., 2001) as river incision is ultimately directly dependant from the rate of sea-level change and a change of 600 m during a single glacial cycle has never been documented. In the Juwayl Formation, the orientation of the channels is NW – SE, away from the main ice shield on Gondwana and directed towards a major lake in the Rub’ Al Khali area. Here it seems that the channels are glacial valleys, because they are filled with the sorbet facies and discharged into a major lake.

In the Sanamah Formation, the basal conglomeratic channel fill facies is not a typical glacial facies, instead the lateral accretion complexes with their large foresets resembles fluviodeltaic deposits. In the absence of any indicator of a marine or lacustrine setting, the deltas may be interpreted as fan deltas in a lacustrine setting or as braid deltas in a marine environment. The presence of angular clasts of friable sandstone within these sediments suggests that the channel fill was derived from a glacial source in which permafrost conditions prevailed. These clasts apparently were transported in a frozen state and thus were preserved despite their transport in a fluvial, proglacial environment. Together with the other lithologic characteristics of the red facies, the most likely scenario for formation of these sediments is a fluvial system in a periglacial environment. The majority of the clasts are of multi-cyclic origin as shown by the dominance of rounded to well-rounded quartz pebbles. These clasts were eroded from their original deposit in a late stage of glaciation when sufficient running water was present to erode and to transport the coarse-grained material through pre-existing channels. These channels were then filled with a finer-grained sandy but still fluvial facies. We would argue that these events and sediments record a first glacial
event. A second event is inferred from the following observations. Close to the top of the Sanamah Formation and close to the edges of the valleys, badly sorted sediments with striated clasts are present that record deposition in a proglacial environment. In addition, several of the underlying sediments show striations which closely resemble “true glacial” striations carved on basement or similar rocks. We have observed up to 5 horizons with striations in a 40 m section of coarse friable sandstone. Their orientation is roughly similar in all horizons and indicates a common transport direction. If these striations are indeed “glacial” striations, then they must have a common, one-time origin. We suggest that these striations were produced during a second glacial episode during which glaciers advanced to the area of the Wajid Sandstone. Our model for the multi-level striations assumes shearing within the sediments through the motion of the glacier. As field observations have shown, shear planes within the sand that was water-saturated and frozen were not necessarily bedding planes.

A major difference between the proglacial deposits of the Sanamah Formation and the Juwayl Formation is the presence of basement boulders as dropstones in the lake sediments of the latter. Hence, the depositional setting differed in the presence of a hinterland that was able to provide basement components. In the Sanamah Formation, the absence of the boulders, together with the well-rounded conglomerates in the basal channels indicates the reworking of older sediments, probably a conglomeratic unit (Late Precambrian or basal Cambrian Unit?) that once had covered the peneplain of the Arabian Shield. The Juwayl glacial deposits, in contrast, were fed by basement d a likely scenario is the presence of nunataks in the hinterland. If this is correct, a mechanism is needed that dissected the peneplain and uplifted parts of it. We interpret these events as a direct evidence for the compressional tectonic events that usually are called “Hercynian” on the Arabian Plate. In the Wajid area and beyond the only consequences of these movements are probably the evolution of some reverse faults with local uplift; no folding or thrusting is observed.

The Sanamah sediments record deposition in a proglacial area beyond the actual reach of the Ordovician ice shield. Only in a late phase they might have been affected by glacier advance as indicated by the striations in different horizons. In contrast, the Juwayl Formation records repeated advance and retreat of glaciers during the Permian (?) and shows a far greater inventory of glacial features.

The Juwayl glaciers seem to have originated in the area of the present day Arabian Shield as indicated by the orientation of the channels. Hence the Arabian Shield seems to have been a positive feature during the Carboniferous and Permian. Although not yet mapped in sufficient detail, our preliminary data indicate that the Sanamah channels might also extend away from the Arabian Shield. This is supported by the orientation of the subsurface channels in the coeval Zarqa – Sarah Formations in northern Saudi Arabia. They indicate a southerly provenance whereas the Sanamah channels indicate a westerly or northwesterly source area. In conclusion, both formations show evidence of deposition in a proglacial to periglacial setting. In both formations, phenomena have been observed that have no known modern equivalents. Both glacial series were fed from the Arabian Shield, however, during deposition of the Snaamah Formation older sediments were reworked, whereas during Juwayl time, a basement source was available. Both units were deposited in channels, for which a fluvial or a glacial origin is invoked. Both sedimentary basins were intracratonic basins, although the Juwayl basin may have been dissected by uplift structures.

References
Plate 1: Glacial phenomena of the Sanamah and Juwayl Formations, Wajid Group, Saudi Arabia. A) Flame structure in the Juwayl Formation interpreted to have been formed through impact of an ice berg onto soft sediment. B) Sorbet facies of the Juwayl Formation; massive structureless sandstone overflowing well bedded sediment. C) Boulder Pavement of basement cobbles and pebbles within the Juwayl Formation. D) Large channel-fill foresets of conglomeratic sandstone of the Sanamah Formation.