Spit-systems – an overlooked target in hydrocarbon exploration: the Holocene to Recent Skagen Odde, Denmark

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Well-constrained depositional models are essential for successful exploration and field development. The Skagen spit-system offers a unique possibility for the establishment of a depositional model constrained by excellent outcrops, well-defined palaeogeography, good age control and detailed observations on hydrodynamics and morphology of the prograding part of the spit-system. The model offers a supplementary interpretation of shallow marine sandstones to the existing delta and linear shoreface models. The sand-dominated Skagen spit-system is *c.* 22 km long, 4 km wide and up to 35 m thick, with a sand volume of *c.* 2.2 km^3. If filled with oil, this system would contain 0.6 km^3 corresponding to 3.8 $\times$ 10^9 barrels assuming a porosity of 30% and an oil saturation of 90%. This is comparable in size with the largest Danish oil field (the Dan field), in the North Sea.

Reservoir models for isolated linear 'offshore' sandstone bodies have been controversial for many years. Their size and internal indications of palaeocurrent directions are similar to those of the spit-system model, and this model may therefore be applicable for some of these bodies.

Depositional model for the Skagen spit-system

The Skagen spit-system is part of the large triangular coastal complex termed Skagen Odde that forms the northern tip of Jylland (Fig. 1). The complex began to form at 7150 years BP, and the actual spit-system has developed within the past 5500 years (Fig. 1); (Nielsen & Johannessen 2001, 2004). The older parts of the spit-system have been raised *c.* 13 m above present-day sea-level as a result of the rate of glacial rebound has exceeded the rate of eustatic sea-level rise during the Holocene and can therefore be studied in cliff sections (Fig. 2). The distal youngest part of the spit-system is still prograding by several metres per year, and the depositional processes can be studied at the point of the spit (Fig. 3). Age relationships are well constrained by C^{14} dates of peat and shells along the 22 km long spit-system (Hauerbach 1992; Clemmensen *et al.* 2001). The possibility of direct comparison between geological sections in the older raised part of the spit and the Recent depositional processes at the point of the spit is unique, and provides a very high degree of certainty to the interpretation of the sedimentary units. The Skagen spit-

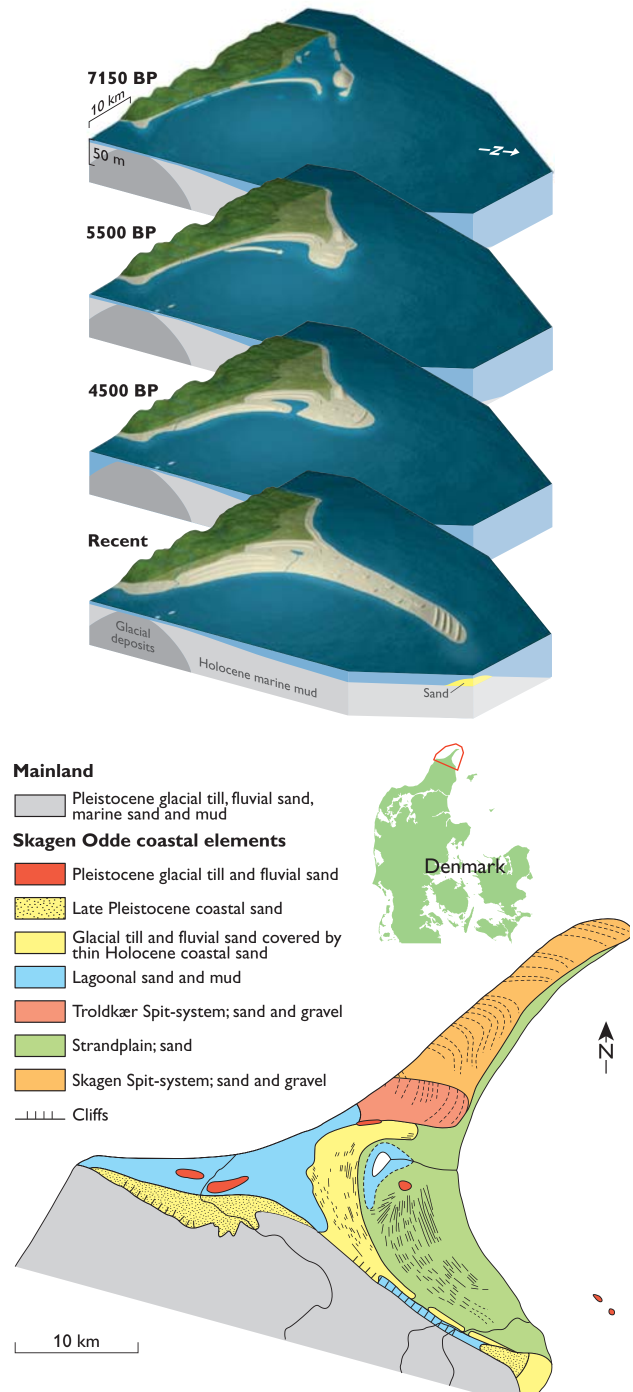


Fig. 1. Geological development and palaeogeographic reconstruction of the Skagen Odde coastal complex. The Skagen spit-system discussed here is shown in **orange** on the lowermost geomorphological map. The Skagen spit-system began to form *c.* 5500 years BP.

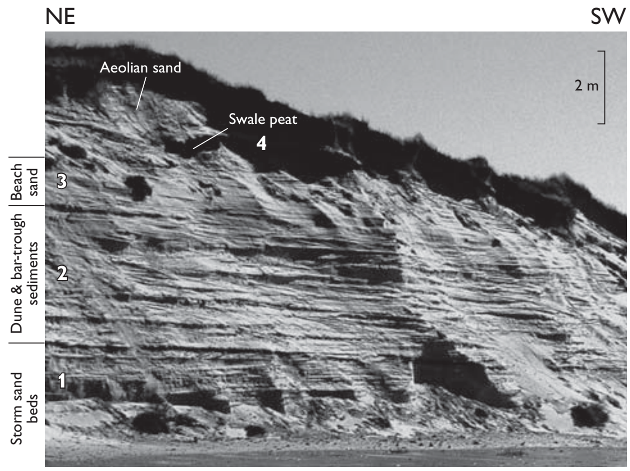
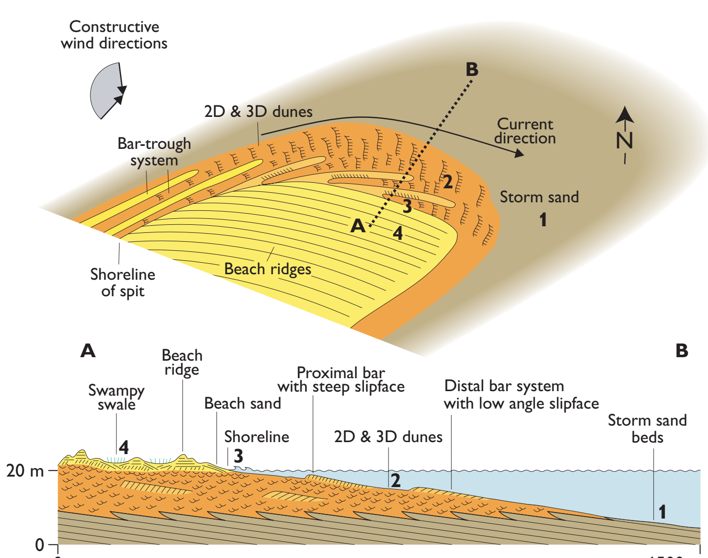


Fig. 2. Coastal cliff-section exposing the raised four depositional units of the Skagen spit-system shown in Fig. 3.

system may thus be regarded as a natural full-scale sedimentological laboratory.

The spit-system overlies offshore mud. It shows a weak coarsening-upward trend and consists of three sand-dominated units locally topped by peat. The lowest consists of up to 25 m of storm sand beds (unit 1), and is overlain by *c.* 5 m of dune and bar-trough sediments (unit 2), followed by *c.* 2 m of beach sand and 0–2 m aeolian sand (unit 3), topped by peat lenses up to 1.5 m thick (unit 4; Figs 2, 3). This spit-system succession is overlain by up to 10 m of Recent aeolian sand. In the constructive phases of the development of the spit-system, sand is transported from eroding glacial deposits more than 40 km south-west of the present tip of the spit,



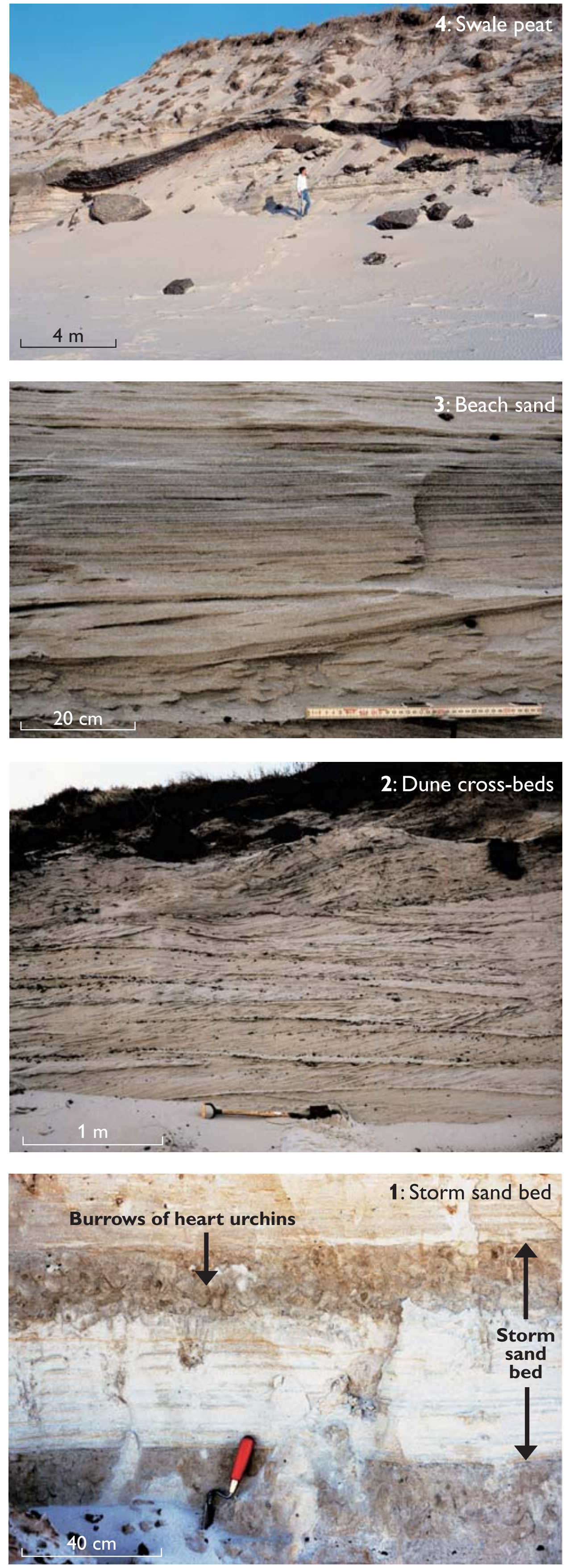


Fig. 3. Photographs of the four depositional units and the sites of their formation (1–4) on the active subaerial spit and the submarine spit-platform at the point of the spit-system (section **A–B**).

and from the older uplifted part of the spit-system. The preferential wind directions are from the south-west and west creating a strong shore-parallel northward flowing current capable of transporting large amounts of sand (up to *c.* 1.5 million m^3/year) along the coast. By far the greater part of the sediments are deposited in front of the spit point where storm sand beds are deposited from heavily loaded suspension currents in water depths of *c.* 7–30 m causing progradation (Fig. 3). Sandy 2D and 3D dunes migrate northwards along the spit coast, and pebbles are transported in the swash-backwash zone. Deposition occurs mainly where the spit coast bends and refraction of the waves results in reduction of the transport capacity. At the same time, the longshore currents expand over the area at the tip of the spit, as the controlling effect of the subaerial spit ceases and water depth increases. This combination causes high sedimentation rates on the platform at the tip of the spit. The majority of the dunes migrate obliquely basinwards on the gentle seaward dipping platform surface in front of the spit, leaving behind thick units of cross-bedded sand that is deposited in water depths of *c.* 0.3–9.5 m (Fig. 3). Occasionally, a shore-attached bar-trough system is formed in the surf zone along the front of the spit. Such bars migrate towards the coast, emerge and become swash bars with swash-backwash lamination forming on the seaward side. During severe storms from the north, pebbly beach ridges are formed on the backshore up to *c.* 1 m above average sea-level. Peat formation takes place in swales between beach ridges up to a few hundreds metres from the active spit coast. Aeolian dunes subsequently develop and migrate across the spit.

Spit-systems may be differentiated from other shallow marine sandstones by the presence of platform foresets (e.g. Nielsen *et al.* 1988), curved beach ridges showing pronounced lateral fining of grain-size, curved peat deposits, and palaeocurrent directions that differ from deltaic and linear shoreface sandstones (Fig. 3). For instance, the foresets of the 2D and 3D dune sands in unit 2 show nearly unimodal palaeocurrent directions obliquely to the accretionary spit coast and therefore show palaeocurrent directions at high angles to the long, exposed side of the spit-system (Figs 1, 3).

Preservation potential

The subaerial part and the upper marine part of the spit-system may be subject to erosion during transgression, and parts of the aeolian sand, peat lenses and beach sand may be eroded away and replaced by a thin transgressive sand. However, the remaining part of the spit-system has a high preservation potential and may be enveloped and sealed by offshore mudstones.

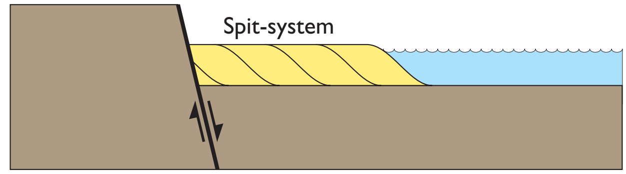


Fig. 4. Spit-system formation and preservation on a hanging-wall fault block.

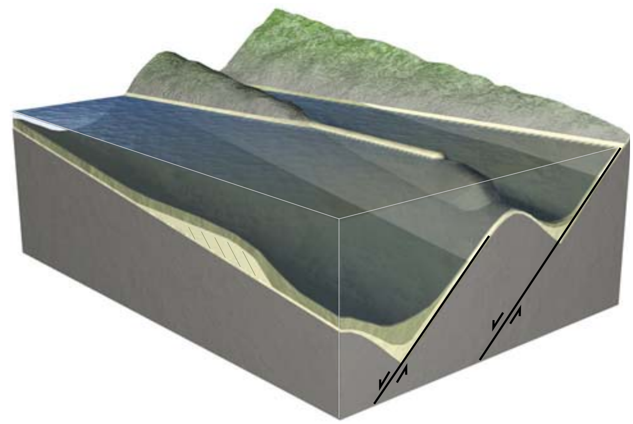


Fig. 5. Conceptual model of spit-systems attached to plunging fault block crests and prograding on the submarine part of the fault block crest.

Exploration and reservoir model for spit-systems

Headland-attached spit-systems

Linear coast and delta progradation systems depend on sediment input from rivers and distributary channels. Spit-systems, on the other hand, rely on wave erosion and longshore drift and may be found downdrift from a headland (as the Skagen spit-system) or a fault block partly submerged and exposed to waves. In the latter case spit-systems may form on a hanging-wall fault block down-drift from a footwall block (Fig. 4). The thickness of the spit-system succession depends on the water depth in which it progrades; the platform will be thick above topographic lows and thin over highs. Spit-systems have a tendency to prograde on top of elevated areas such as submarine ridges, because the progradation rate is greater at shallow water levels over the ridge than at deeper water depths on both sides of the ridge. Consequently, spit-systems preferentially prograde on the plunging crest of fault blocks. A potential reservoir is therefore situated on the elevated crests rather than lying in the deep parts of the hanging-wall blocks (Fig. 5).

Detached spit-systems – a model for offshore sand bars?

During progradation of a spit-system the headland and the proximal part of the spit may be eroded by wave activity and

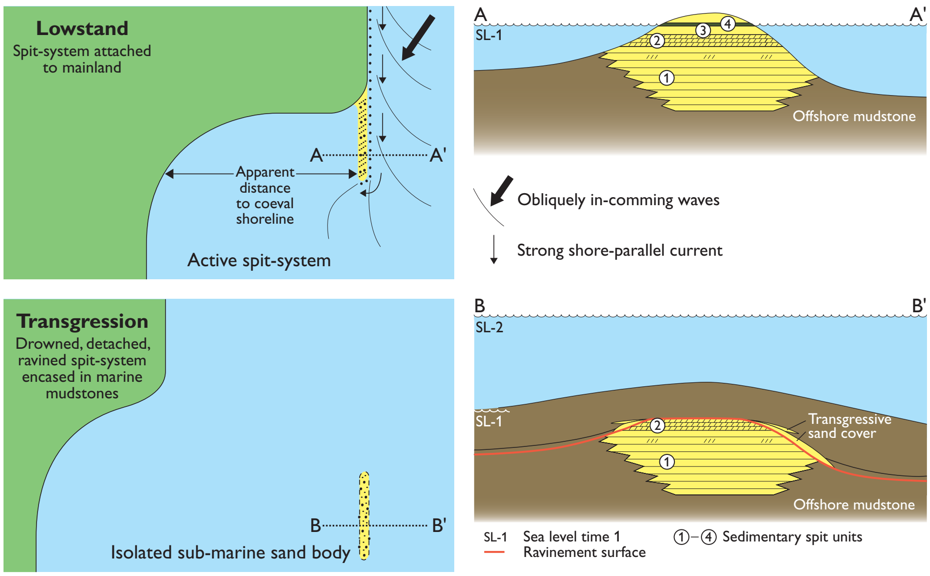


Fig. 6. Conceptual model of detached spit-systems. Isolated, elongated sandstone bars in the Western Interior Seaway (USA) may originally have been spit-systems prograding from a headland (**A–A'**). Later they became detached from the headland due to erosion of the headland and the proximal part of the spit-system. During subsequent transgression the headland became submerged and upper parts of the spit-system was eroded (**B–B'**) and the preserved sandstone bars may appear to have formed at great distance from the mainland.

longshore currents, and the spit-system may eventually be detached and become an isolated sand body (Fig. 6). The upper part of the sand body will be exposed to erosion, and only the lower part of the former spit-system may be preserved. Elongated, isolated sandstone bars (up to 35 km long, 2–4 km wide and 30 m thick) encased in offshore mudstones and apparently deposited some distance from land are common hydrocarbon exploration targets in the Western Interior Seaway of the USA (e.g. Suter & Clifton 1999). However, their genesis has been controversial for decades, and the reservoir models are poorly constrained. Some of these sandstone bodies contain unimodal cross-bedded units which indicate palaeocurrents at an acute angle to the length of the bars. Their size, facies and palaeocurrent directions are similar to those of the spit-system model.

Concluding remarks

The Middle and Upper Jurassic in the North Sea rift basins are characterised by heavily block-faulted areas subjected to transgressions. As extensive spit-systems can develop within a few thousand years under the right conditions, it is likely that spit-systems were locally formed on partly submerged, fault block crests and on hanging-wall fault blocks. Aspects of the Skagen spit-system model have been applied in the mapping of reservoirs in the Troll Field in the Norwegian North Sea (Dreyer *et al.* 2005).

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