

Introduction: subsurface sand remobilization and injection

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Abstract: Observation of basin-scale networks of sandstone intrusions are described from subsurface studies and outcrop locations. Regional scale studies are prevalent in the volume and two new regionally significant subsurface sand injection complexes are described. Higher resolution studies, both outcrop and subsurface, show the small-scale complexity but high level of connectedness of sandstone intrusions. Discordance with bedding at all scales is diagnostic of sandstone intrusions. The propensity of hydraulic fractures to develop and fill with fluidized sand in a broad range of host rocks is demonstrated by examples from metamorphic and magmatic basement, and lignite. Terminology used to describe sandstone intrusions and other elements of sand injection complexes is diverse.

This volume originated as a call for papers that addressed ‘subsurface sand remobilization and injection: implications for oil and gas exploration and development’: 32 oral presentations were offered and accepted, 15 from industry authors and 17 from academia, with several papers combining industry and academic authorship. Of these, 15 papers – less than half the oral presentations – form the body of this volume. Of those, nine are largely based on the interpretation of 3D seismic surveys both with and without borehole calibration (subsurface interpretation), and six papers are based on outcrop studies, one of which presents data from a regionally extensive outcrop similar in scale to the subsurface sand injection complexes known from petroleum systems.

Evidence of large-scale sand fluidization and injection is a significant shallow crustal process that is increasingly recognized in outcrop and subsurface studies (Fig. 1). Giant sand injection complexes develop regionally in areas of 100s to 1000s km² and reservoir commercial volumes of hydrocarbons. These are extensively documented from the Norwegian and UK continental shelves (Hurst *et al.* 2005) but are developed globally. Networks of sandstone intrusions are known to act as conduits for hydrocarbon migration (Jenkins 1930) and may

compromise hydrocarbon seals (Cartwright *et al.* 2007). Understanding, describing and predicting sand injection complexes is also important in other subsurface-related energy systems from site evaluations, resource storage including carbon capture and storage (CCUS) and subsurface radioactive waste disposal.

Appraisal and development of hydrocarbon reservoirs in sand injection complexes is complicated by the challenge of resolving thin (<10 m) sandstone that may be laterally discontinuous and bedding discordant sandstone often too steep to be detected using seismic data (Huuse *et al.* 2007). In combination these add significant uncertainty to locating and quantifying pay and reservoir connectivity, which impacts recoverable resource estimates (Grippa *et al.* 2019). Although the most numerous identifications and descriptions of sandstone intrusion reservoirs are from offshore northwestern Europe (Denmark, Norway and UK), and despite an ‘oil industry myth’ that sand injectites only occur in the North Sea, they have global occurrence (Braccini *et al.* 2008; Huuse *et al.* 2010); two new global occurrences are documented in this volume (Chenrai & Huuse 2020; Serié & Pemberton 2020). Examples of giga to microscale

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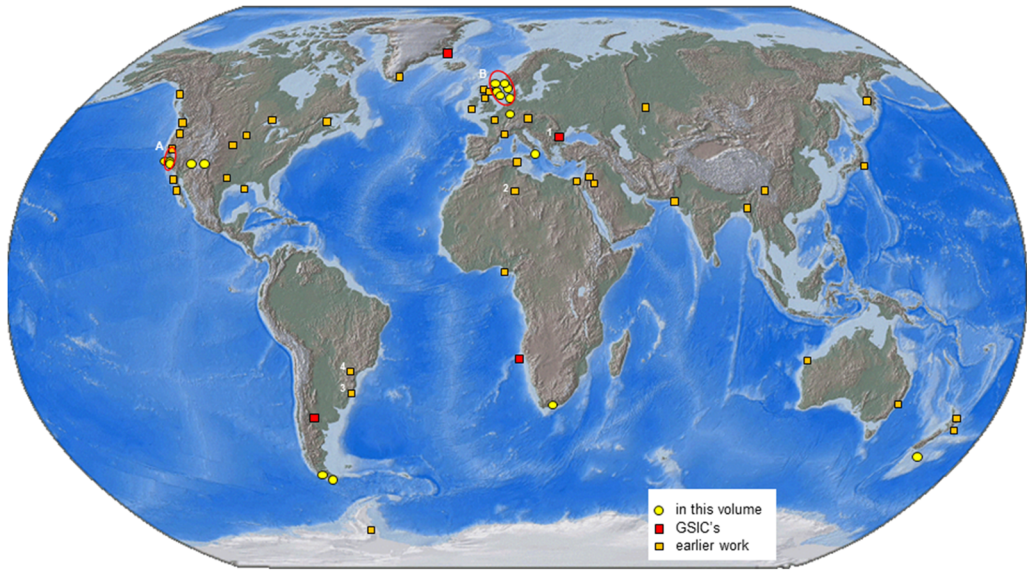


Fig. 1. Global distribution of some noteworthy sand injection complexes or notable sandstone intrusions including those described in this volume along with a compilation of similar data from [Hurst & Cartwright \(2007b\)](#), [Braccini *et al.* 2008](#) and [Huuse *et al.* \(2010\)](#). Known Giant Sand Injection Complexes (GSICs), including an offshore example (Angola), are shown (red squares). A new probable GSIC from the Eastern Carpathians, Romania ([Tamas *et al.* 2020](#)) is the red square annotated 1 (white). Areas A (central California) and B (North Sea) in red outlines contain multiple GSICs. Locations from onshore Brazil and Libya are from [Hartmann *et al.* \(2012\)](#) and [Moreau *et al.* \(2012\)](#), respectively.

characteristics of sandstone intrusions include: a newly discovered sand injection complex ([Fig. 2a](#)); a section through a composite wing from a producing field ([Fig. 2b](#)); outcrop of a similar geometry composite wing and parent unit ([Fig. 2c](#)); slabbed core (from the reservoir in [Fig. 2b](#)) with some characteristic internal structures ([Fig. 2d](#)); and micro-fractured sand grains in a sandstone intrusion ([Fig. 2e](#)).

Sand injection, and resultant sandstone intrusions, occur on many scales both within giant complexes and as smaller discrete features ([Hurst *et al.* 2003](#); [Hurst *et al.* 2011](#)). The vast majority of sandstone intrusions form within actively propagating hydraulic fractures that are frequently modified by erosion during emplacement. Exceptions to this, although volumetrically insignificant relative to the total volume of intrusion complexes, are when pre-existing faults are reactivated and sand is injected along them, or when faulting is synchronous with sand injection ([Monnier *et al.* 2015](#); [Palladino *et al.* 2020](#)). Although goals of the conference call included ‘the characterization and interpretation of sandstone intrusions and associated facies, from granulometric- to regional-scale’ only sub-regional-scale studies have significant representation and form a central theme herein. Concurrent industry practice in the North Sea uses outcrop analogue data from sand injection complexes to constrain resource estimates and recovery efficiency by optimizing drilling locations and

well trajectories; themes that are at least partly documented elsewhere ([Briedis *et al.* 2007](#); [Schwab *et al.* 2014](#); [Gibson *et al.* 2020](#); [Pelletier & Gunn 2020](#)). This is particularly important as industry aims to increase efficiency, and better balance cost and value while reducing the energy footprint as we strive for net zero emissions.

Terminology

Sand injectite terminology is not the goal of this compilation nor was it the aim of the conference that preceded it. Sand injectite is the most common and earliest informally adopted collective term for sandstone intrusions, for which it is implicit that sand was injected into host strata to form an intrusion. This contrasts with neptunian sandstone dykes that form by passive fill of pre-existing fractures from above. In this volume, there is little evidence of rationalizing and clarifying ‘sand injectite’ terminology, the 15 papers using at least ten different terms to define the sandstone component of their ‘sand injectite’ ([Table 1](#)). It may be that in practice there is little value in differentiating a sandstone intrusion from a giant sand injection complex but in some cases, for example, distinction between clastic and sandstone intrusions may have significant implications when evaluating seal integrity ([Cartwright *et al.* 2007](#)),

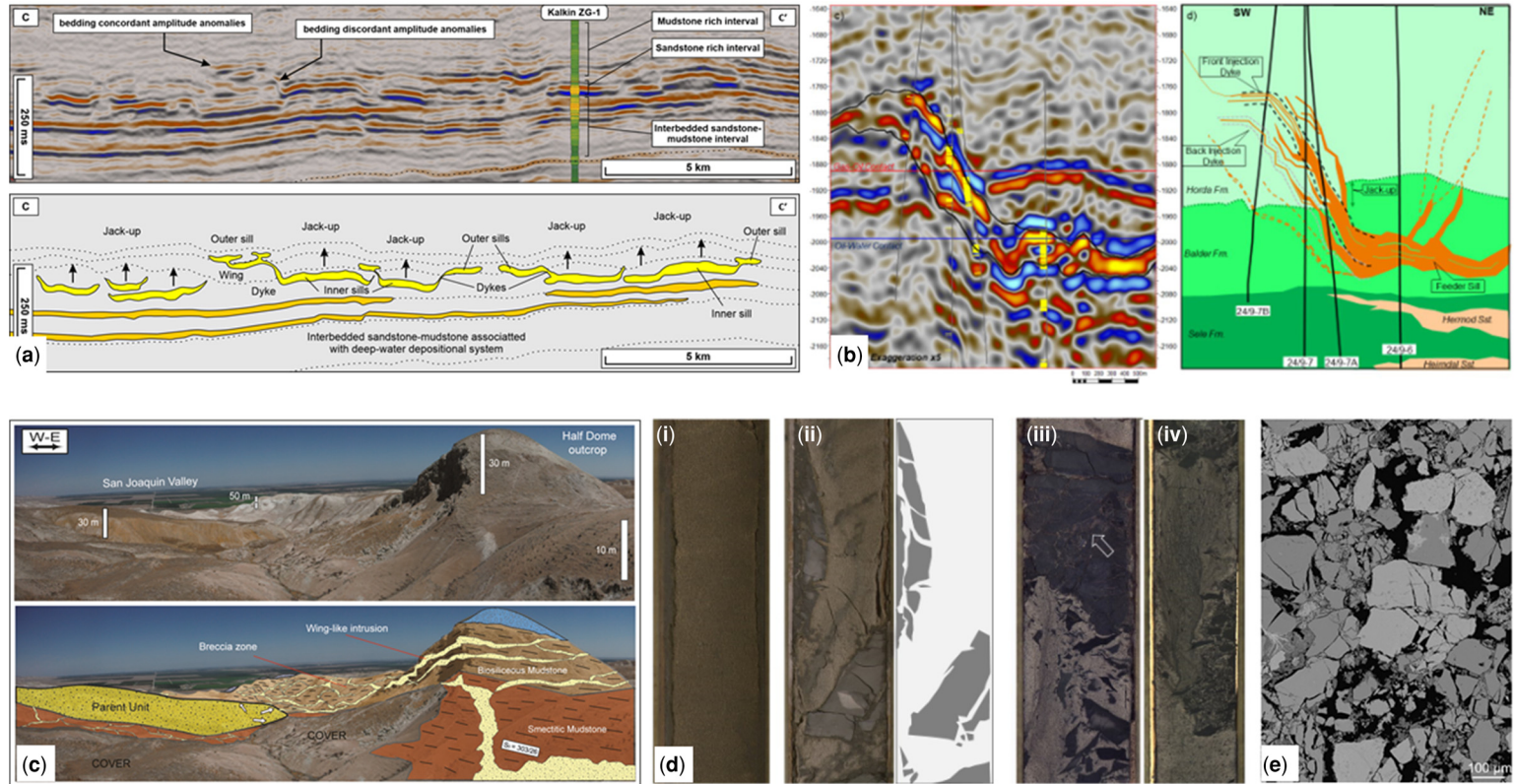


Fig. 2. Some typical characteristics of sandstone intrusions presented in this volume. (a) A 2D seismic reflection profile from the Austral–Magallenes Basin, Chile tied to the Kalkin ZG-1 borehole accompanied by a geological interpretation of an extensive sand injection complex (Serié & Pemberton 2020). (b) Seismic and geo-seismic sections of the southern wing (Volund Field, Norway) showing the composite character of the wing with increased bifurcation of intrusions up-dip and jack-up of host strata (Satur *et al.* 2020). (c) Outcrop of a wing intrusion in the Tumey Giant Injection Complex with a parent depositional unit and sand injection breccia (Zvirtes *et al.* 2019). (d)(i) Slabbed conventional core with structureless sandstone; (ii) jigsaw texture mudstone clasts formed by hydraulic fracturing of host strata during injection, in a sandstone matrix; (iii) an irregular erosion surface at top of a sandstone – the mudstone is micro-fractured with mm-thick sandstone fills; (iv) sandstone and mudstone breccia showing multiple phases of flow (Satur *et al.* 2020). (e) Micro-fractured quartz and feldspar sand grains from a sandstone intrusion (Hurst *et al.* 2020).

Table 1. Summary of terms used in this volume to describe sand injectites and/or their constituent parts

	Terminology
INTRUSIONS the body of sandstone preserved	sand injectites, sandstone intrusions, sand injection complexes, sand injections, clastic intrusions, injected sands, remobilized sands, giant sand injection complex, intruded sandstones, injected sand
PROCESS (of sand injection)	remobilization, fluidization, liquefaction, sand fluidization, sand fluidization and injection
ORIGIN OF INJECTED SAND source derivation of sand	parent sand, parent unit(s), parent bed, parent sandstone
EXTERNAL GEOMETRY	conical to saucer, wings and saucers, bowls, saucer-shaped, sills, dykes, wings

where clastic may include shale or mudstone dykes (approximately zero pay), whereas sandstone dykes often form reservoir facies (Grippa *et al.* 2019).

The process by which sand is injected is described variously as (sand) remobilization, fluidization, liquefaction, sand fluidization and sand fluidization and injection (Table 1). Although pervasive liquefaction in discrete depositional sandstone units may be associated with small-scale sand injection (Lowe 1975), sand injection complexes of relevance in subsurface interpretation are several orders of magnitude larger (Huuse *et al.* 2005; Hurst & Vigorito 2017). Fluidization (sand or other grain size fractions) is an important term and may occur in the absence of sand injection, thus differentiation between sand fluidization and injection and sand fluidization is important. Although remobilization is widely used, it often lacks a common definition, or is synonymous with sand fluidization or sand injection.

The interval from which sand is fluidized and injected is a fundamental element of sand injection on any scale. In Table 1 it is termed parent sand, parent unit or units, parent bed and parent sandstone. In small injection systems the parent may be a single bed, but the favoured and least ambiguous term is parent unit (Vigorito & Hurst 2010; Hurst *et al.* 2011).

Discordance to bedding is diagnostic of sandstone intrusions and even when close to bedding parallel (sills) discordance is present (Hurst *et al.* 2011). Most of the terms to describe external geometry referred to in this volume (Table 1) are in common use. Wings and saucer-shaped intrusions are the typical targets for hydrocarbon exploration and production wells (Huuse *et al.* 2004; Huuse *et al.* 2005; De Boer *et al.* 2007) and known and described from several outcrops (Table 2; Hubbard *et al.* 2007; Huuse *et al.* 2007; Surlyk *et al.* 2007; Scott *et al.* 2009; Vigorito & Hurst 2010). Reservoir-scale saucers and wings are invariably a composite of sills, low- and high-angle to bedding dykes (Hurst & Vigorito 2017; Grippa *et al.* 2019). Conical intrusions are identified on seismic but without vertical exaggeration usually resemble saucer-shaped intrusions. Outcrop

examples of conical intrusions are to date elusive. Bowl geometry is referred to but how and why this differs from saucers is unclear (Cobain *et al.* 2019; Chenrai & Huuse 2020). Dykes are by far the most abundant sandstone intrusions documented but comprise relatively small reservoir volume (Grippa *et al.* 2019) and generally have poorer reservoir quality than sills, wings and saucer-shaped intrusions (Scott *et al.* 2013). When steep to bedding, dykes are usually undetectable as planar features using seismic data (Huuse *et al.* 2007; Grippa *et al.* 2019).

Timing of sand injection

Only when fossil material is extracted from rock samples where sand extrusion onto a palaeoseafloor (or that of a non-marine water body) is preserved (Schwartz *et al.* 2003), and is spatially and temporally associated with an underlying sand injection complex, can the timing of sand injection be reliably constrained (Vigorito & Hurst 2010). Not all sand injection complexes extruded sand onto palaeoseafloors, nor are all sand extrusions preserved. Not all sand extrusions yield suitable fossil material. Thus, even high-quality outcrop or continuous core may not yield reliable estimates of the timing.

Estimation is even more challenging using seismic data. Seismic data are unlikely to detect the steep sandstone dykes that dominate the shallow parts of injection complexes (Huuse *et al.* 2007; Grippa *et al.* 2019) meaning that the shallowest detectable intrusions may be 10s to 100s m below the palaeoseafloor. When drill cuttings are available knowing where to sample is problematic, and further complicated by the coarse sampling interval of cuttings and the low preservation potential of sand grade material. When inferring the timing of sand injection from seismic data it is wise to assume that the shallowest (youngest) level at which intrusions are detected gives timing of injection as ‘an age no older than’. Occasionally geomorphic features such as large sand volcanos (on palaeoseafloors) are

Table 2. Summary characteristics of some significant outcrop of sand injection complexes

Injection complex (IC)	Country	Outcrop area (km ²)	Geological setting	Depositional setting		Injectite elements							Outcrop quality (q) and size (s)	
				environment	element	parent unit	dyke	sill	wing	jack-up	breccia	extrudite		
Panoche Giant IC*	USA	c. 400	forearc basin	middle/lower slope	channel complex	yes	yes	yes	yes	yes	yes	yes	yes	excellent (q) extensive (s)
Vocontian Basin	France	c. 1.5	passive margin	mid slope	channel complex	yes	yes	yes	no	no	no	no	no	moderate (q) moderate (s)
Numidian Flysch	Tunisia	c. 0.5	foredeep basin	lowerslope/basin floor	channel complex	yes	yes	yes	no	no	no	no	no	excellent (q) small (s)
Santa Cruz IC	USA	c. 8	transpressive transform margin	upperslope/outer shelf	slope/tidal complex	yes	yes	yes	yes	no	yes	yes	yes	moderate (q) moderate (s)
Hareelv Formation*	Greenland	c. 2000	rift basin	slope	channel complex	yes	yes	yes	yes	no	yes	no	no	very good (q) extensive (s)
Tierra del Fuego	Argentina/Chile	c. 2	foreland basin	lower slope to basin floor	lobe complex (probably)	yes	yes	yes	?	?	?	no	no	moderate (q) moderate (s)
Tumey Giant IC*	USA	>100	forearc basin	upper/middle slope	channel complex	yes	yes	yes	yes	yes	yes	yes	yes	excellent (q) extensive (s)
Austral/Magallanes Basin	Argentina/Chile	>2	foreland basin	slope	channel/lobe complex	yes	yes	yes	yes	no	no	no	no	excellent (q) moderate (s)
Karoo Basin	South Africa	c. 5	foreland basin	basin floor	channel/lobe complex	yes	yes	yes	no	no	no	no	no	moderate (q) small (s)
East Carpathian Fold Zone*	Romania	c. 250	foreland basin	slope	channel complex	yes	yes	yes	7	yes	yes	no	no	good (q) extensive (s)
Nanaimo Basin	Canada	several c. 0.5	forearc/foreland basin	submarine canyon	channel complex	yes	yes	yes	no	no	no	no	no	good (q) small (s)

Locations from onshore Brazil and Libya are from [Hartmann *et al.* \(2012\)](#) and [Moreau *et al.* \(2012\)](#), respectively.

*Four examples (bold type) of regionally developed Giant Sand Injection Complexes (GSICs) in which subsurface-scale sandstone intrusions and other key injectite elements are preserved.

imaged (Andresen *et al.* 2009), unfortunately these are not commonly identified.

Papers in this volume

Subsurface and outcrop case studies form the two sections in this volume. All but two papers study sand injection complexes from the Paleogene and Neogene (Table 3) the exceptions being the Mesozoic example of giant pipes (Davison 2019) and the mid Proterozoic (*c.* 676 Ma) sandstone intrusions in basement (Siddoway *et al.* 2019). Paleogene and Neogene examples dominate in the subsurface examples because they are hydrocarbon prospective that in some cases were drilled *en route* to accessing deeper and older prospective intervals.

Subsurface studies

Characteristics of subsurface sand injection complexes is investigated in eight papers that range from basin, sub-regional to oilfield scale. These capture the different stages of understanding of petroleum systems in which regionally developed (giant) sand injection complexes occur. Together they offer insight into the range of geometry and architecture present in injection complexes and how through detailed observation insight is made into possible controls on both geometry and distribution of the sandstone intrusions.

A 'seismic-scale' (regionally developed) sand injection complex is described from the Upper Paleocene in Great South Basin, New Zealand (Chenrai & Huuse 2020) with spatial and geometric features to similar scale injection complexes in the North Sea. The Great South Basin remains a frontier basin for hydrocarbon exploration. Discordant

intrusions are associated with a submarine channel complex, interpreted as the parent units for the intrusions. In mudstone overlying the injection complex polygonal faults are pervasive and are observed to have downward termination close to the top of the injection complex. No evidence of a palaeoseafloor is presented.

Upper Cretaceous to Paleocene strata in the Chilean part of the Austral–Magallanes Basin host regionally developed sandstone intrusions that are identified by discordant margins between sandstone intrusions and the host mudstone (Serié & Pember-ton 2020). Borehole core interpretation confirms the presence of sandstone intrusions and leads to changes in interpretation of the sedimentary evolution of the basin, from shallow-marine to a deep-water depositional system. The deep-water system pinches out onto contemporaneous submarine relief; sand injection occurs above the pinch out. Consequently, in addition to improving understanding of the petroleum system, new onshore petroleum potential is identified in a sand injectite play.

A synthesis of the geometric characteristics of sandstone intrusions in the Norwegian–Danish Basin (NDB) enables a qualitative evaluation of the relationships between parent units, intrusion geometry and generation of overpressure, and the significance of halokinetic faulting as a trigger for sand injection (Andresen 2020). The NDB is a mature offshore hydrocarbon province in which sand injection complexes are well known and contain significant resource volumes. It is suggested that the location of parent units and their burial depth partly control intrusion geometry and size. In geometrically confined parent units effected by halokinesis, faults were potential local triggers for sand injection, and sandstone intrusions occur close to the top of parent units. Larger scale, less spatially constrained parent

Table 3. Stratigraphic position of Paleogene or younger sand injection complexes described in this volume; examples from the subsurface and outcrop are black and open diamonds, respectively

Epoch*	Occurrence of sand injectites	Location
Pliocene	◆	Utsira High, North Sea
Miocene	◆◆◆◆◆	Norwegian–Danish Basin and Utsira High (North Sea), Lower Rhine Embayment, Calabria–Peloritani terrane (southern Italy), Santa Cruz Mudstone (California)
	◆	Utsira High, North Sea
Oligocene	◆	Norwegian–Danish Basin (North Sea)
	◆◆	Norwegian–Danish Basin and Utsira High (North Sea)
Eocene	◆◆◆◆	North Sea and Tumey Giant Injection Complex (California)
	◆◆◆◆◆	North Sea and Norwegian–Danish Basin
Paleocene	◆◆	Great South Basin (New Zealand), Austral/Magallanes Basin (Chile)
	◇	Panoche Giant Injection Complex (California)

*Timing of injection is the youngest age provided by the authors. The only known example where timing is constrained biostratigraphically is the early Paleocene (Danian) Panoche Giant Injection complex (PGIC, Vigorito & Hurst 2010).

units cause sand injection to occur higher in the overburden. Overpressure is inferred to result from differential loading and lateral pressure transfer.

Using 3D seismic data [Hermanrud et al. \(2019\)](#) investigate trigger mechanisms for sand injection in Oligocene to Miocene strata (to top Hordaland Group) above the Utsira High by examining the regional distribution of mounds. Observations indicate that the height of jack-up folds is usually greater than sandstone thickness within mounds, sandstone deposits onlap mounds whereas mudstone deposits do not. Rim synclines are absent adjacent to Oligocene and Eocene mounds, and mounds on the top Hordaland Group surface are restricted to basin flanks and flank-basin transitions, but are absent in basin centres. Sand injection is inferred to be triggered by incipient slab sliding.

Based on subsurface data from Balder Field on the eastern flank of the Viking Graben, Lower Jurassic sandstone is suggested as the parent unit for part of a widespread sand injection complex in the shallower Paleogene section ([Wild 2021](#)). Analogous processes documented elsewhere are used to corroborate the interpretation. Fluids associated with sand injection are thought to be derived by migration from deeper areas of the Viking Graben and associated with early Eocene inversion. Large sills formed above multiple seal breaches, and within the sills internal structures are speculated to record lateral accretion in turbulent, transitional, or laminar flow of a granular suspension.

[Laake \(2019\)](#) presents examples of variations in sandstone intrusion geometry above a Tertiary shelf-edge fan delta where geometric and thickness relationships that are related to spatial variations in the parent unit. Intrusions with irregular geometry occur in shallower areas of the fan delta. In proximal areas, large diameter, approximately circular (in cross section) intrusions are developed. Extensive thin sheet-like sandstone occurs along faults, some of which are spatially associated with the margins of pre-existing pockmarks.

Interpretation of broadband 3D seismic of the Upper Paleocene Maureen and Lista formations ([Cobain et al. 2019](#)) enables mapping of bowl-shaped sandstone intrusions, 200–900 m wide and 60–85 m high. These are the major reservoir facies in the Lista Formation. No depositional sandstone is identified below the ‘bowls’ and injected sand is assumed to have formed sand welds with the underlying Maureen Formation. Examples of core and outcrop data are provided to confirm the sand injectite origin.

Reservoirs in the Volund Field (Norwegian Continental Shelf) are entirely composed of sandstone intrusions that form laterally interconnected sandstone-prone wings creating high reservoir connectivity and increased recovery potential ([Satur et al. 2020](#)). Appraisal and development of Volund’s

southern wing reveals a composite character with three smaller wings coalescing to form the reservoir. Sandstone, mudstone and mudstone-prone facies are present, the latter including mudstone clast (injection) breccia. Breccia has sand-supported mudstone clasts with excellent porosity and permeability and constitutes significant missed (sub-seismic) pay. Volund’s wings are known to become more mudstone- and breccia-rich upward and c. 100 m above the base of wings. Average porosity has a broader spread of values that is attributable to the presence of greater volumes of breccia. Porosity determination from borehole logs fails to differentiate mudstone clast breccia (pay) from siltstone (non-pay) making it a challenge to assess total reservoir potential from log-based petrophysics alone.

The presence of the Eocene Brimmond deep-water channelized sand fairway was recognized during drilling of the Paleocene Forties Field. Sandstone intrusions, including conical geometry, sills and some dykes are clearly recognizable on 3D seismic data ([van Oorschot et al. 2019](#)). High resolution seismic imaging combined with inversion and direct hydrocarbon indicator volumes constrain the identification of reservoir quality pay targets thereby enabling optimized development of the Brimmond, Tonto and Maule fields. 4D seismic imaging is used to identify unswept intervals during production.

Outcrop studies

Outcrop data have played key roles in exploration, appraisal and development of sand injectite fields and prospects (papers in [Hurst & Cartwright 2007a, b](#); [Schwab et al. 2014](#); [Hurst & Vigorito 2017](#); [Satur et al. 2020](#)). Significant impacts of outcrop studies are (1) to validate the interpretation of the external geometry of sandstone intrusions mapped in subsurface studies and to associate these with sub-seismic pay, and (2) to identify and characterize the internal structures in sandstone intrusions that are challenging to discern from borehole core and logs, and seismic data ([Duranti & Hurst 2004](#); [Scott et al. 2009](#); [Hurst et al. 2011](#); [Cobain et al. 2015](#)) and support their differentiation from depositional sandstone. Examples in which the value of core calibration of subsurface models is demonstrated or implicit are exemplified in this volume by [Cobain et al. 2019](#), [Satur et al. 2020](#), [Serié & Pemberton 2020](#) and [van Oorschot et al. 2019](#).

Excellent oilfield-scale exposure of part of the Tumey Giant Injection Complex (TGIC) is presented for the first time ([Zvirtes et al. 2019](#)). Intrusions are emplaced in deep-water mudstone in which turbiditic channels, now intensely modified by sand fluidization, are the sole parent units for intrusions. Clay mineral rich mudstone is present in the lower interval

where sills with stepped and multi-layered geometry dominate. In the upper interval bio-siliceous mudstone hosts characteristic wing-like intrusions and extensive injection breccia. Intrusions and fractures are dominantly sub-parallel to the basin axis and structurally driven hydraulic fracturing is inferred. Laterally derived fluid pressure through turbiditic sandstone is probable given the absence of evidence for an underlying aquifer drive from parent units.

Sandstone intrusion into basement is an increasingly common sand injectite setting and is known to reservoir oil in fractured crystalline basement. [Siddoway *et al.* \(2019\)](#) describe regionally developed sandstone intrusions from the Serre Massif of Calabria, Italy and the Front Range, Colorado, USA that are believed to be analogous in character and scale to similar subsurface injectite systems. In oil industry parlance, basement is assumed to have no or very low potential to deliver commercial hydrocarbons, but these outcrops show how crystalline basement can develop fluid storage and transmissivity when sandstone intrusions are present. A key to success in all basement plays is constraining hydrocarbon volume and whether connected volumes are accessible by wells.

Sandstone intrusions in Miocene lignites form a reduction in resource quality along with depositional sandstone ([Prinz & McCann 2019](#)). 3D models were developed during active open-cast mining that progressively revealed new cross sections of the study interval. Lignite forms the host to highly variable networks of sandstone intrusions with sills, dykes and reticulate intrusions that occur at smaller scale (thickness, length, aperture) but with similar geometry to those in giant injection complexes. Intrusions are differentiated from depositional sandstone by their bedding discordance and a paucity of internal structures. Some depositional sandstone units are identified as parent units for sandstone intrusions.

Large (>4 m diameter) enigmatic sandstone pipes in the Kodachrome State Park are the subject of many research papers that associate their formation with sand fluidization and injection into a sand (stone) host. Using field observations, [Davison \(2019\)](#) reasons that formation of most pipes occurred by *in situ* disintegration of host strata during upward fluid streaming. A strong line of evidence for this process is the presence of large (up to c. 4 m long) sub-horizontally layered sandstone blocks, and preservation of internal sedimentary structures that extend from the host into and across pipes. It is estimated that the proportion of fluidized sand present in the large-diameter pipes is <20% of the total volume fluidized.

Sandstone-filled faults are common small-volume components of sand injection complexes ([Palladino *et al.* 2020](#)). Using outcrop data from the Panoche and Tumey hills in Central California,

numerous sandstone-filled extensional, contractional and strike-slip faults are recorded. Commonly, sandstone-filled faults have small offsets and apertures (centimetres to a few decimetres) and evidence for tectonic deformation is sparse. Over-pressured pore fluid is inferred to have held open the fault walls concurrent with sand emplacement. A predictive model for the distribution of sandstone-filled faults is developed and related to regional stress orientation at the time of emplacement.

Petrographic data from sandstone intrusions are sparse ([Hurst *et al.* 2020](#)) but offer potential to differentiate them from depositional sandstone using grain characteristics. Micro-fractured sand grains and mud clasts with embedded sand grains are pervasive in sandstone intrusions and are evidence of high velocity inter-granular impacts. Quartz grains have randomly oriented fractures that terminate at grain boundaries and are texturally distinct from other impact or tectonically derived micro-fractures. Sand grains embedded in mud clasts formed by corrosion and are texturally and genetically distinct from encrusted mud clasts. Relative hardness and density variations in heavy minerals record abrasive reduction in the abundance of apatite and fractionation of zircon and tourmaline during sand fluidization. All these features characterize sandstone intrusions and some may be diagnostic of sand fluidization.

Together these papers offer valuable insight into recent research and applications on sand injectites. They record analogues to benchmark other studies. In addition to their importance in petroleum systems, where they constitute major reservoir volumes and offer secondary or missing pay targets, they have wider relevance in geo-energy systems that rely at least in part on subsurface studies for their success. Furthering understanding of sand injectites in sedimentary basin evolution will surely contribute significantly to enhancing the understanding the relationships between burial history and overpressure development in the shallow crust. By doing so their relevance to practical applications will broaden, such as other energy-related systems ranging from site evaluations for wind farms to resource storage including CCS and subsurface waste disposal. There remains much to be understood about sand injectites, their formation, characterization and significance.

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