PALEOCENE SAND REMOBILIZATION IN THE AUSTRAL-MAGALLANES BASIN; IMPLICATIONS FROM BASIN STUDY TO HYDROCARBON EXPLORATION

Christophe Serié[1], Erin Pemberton[1]

1: ConocoPhillips, christophe.serie@conocophillips.com, erin.a.pemberton@conocophillips.com

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RESUMEN

Remobilización de arenas paleocenas en la Cuenca Austral-Magallanes; implicancias del estudio de cuenca a la exploración de hidrocarburos

La actividad de exploratoria reciente en la cuenca Austral-Magallanes ha revelado la presencia de inyectitas de arena de edad Paleoceno. Las inyectitas de arena a gran escala son el producto de la removilización e inyección de arena subsuperficial comúnmente asociadas consistemas de depositacionales de aguas profundas. Las inyectitas han sido bien documentadas a nivel mundial a partir de los estudios de afloramiento, así como de extensos estudios subsuelo en la Cuenca del Mar del Norte, donde constituyen un importante objetivo de exploración.

Este trabajo tiene como objetivo presentar una visión general de la inyección de arena a gran escala en la cuenca Austral-Magallanes basada en la integración de la evolución de la cuenca, datos de reflexión sísmica 3D, datos de corona y perfiles de pozo. La interpretación y visualización sísmica 3D ha resaltado la presencia de características distintivas comparables a las inyectitas de escala sísmica comúnmente observadas en la Cuenca del Mar del Norte. Además, los datos de pozo y de corona han confirmado la presencia de facies de areniscas masivas y sin estructura, comúnmente asociadas con arena removilizada, como lo demuestra la integración de los estudios de corona y afloramiento. El descubrimiento de inyectitas de arena en el subsuelo de la cuenca Austral-Magallanes permite construir una nueva configuración depositacional del Paleoceno y generando un nuevo potencial exploratorio.

INTRODUCTION

Recent exploration activities in the Austral-Magallanes Basin have focused on the unconventional resource potential (Schenk *et al.*, 2016; Zurita *et al.*, 2013). Three-dimensional seismic reflection data has greatly enhanced the detailed observations and stratigraphic interpretationin the western part of the basin. Detailed mapping in the Paleocene interval has revealed the presence of seismic-scale features comparable to sand injectites. Sand injectitesare well documented in the North Sea due to their significant impact on petroleum exploration; however,these features are generally sparsely documentedand relatively poorly understood.

This paper presents the first occurrence of subsurface sand remobilization in the Austral-Magallanes Basin based on the integration of high-quality three-dimensional (3D) seismic reflection, well, and core data, in addition to representing the first onshore exploration program targeting tight sand injectites. Detailed seismic interpretation shows the presence of discordant seismic amplitude anomalies and direct calibration with well and core data has helped to confirm the presence of remobilized sand. Finally, the importance of detailed seismic interpretation is discussed with regard to both subsurface and outcrop analogs, as

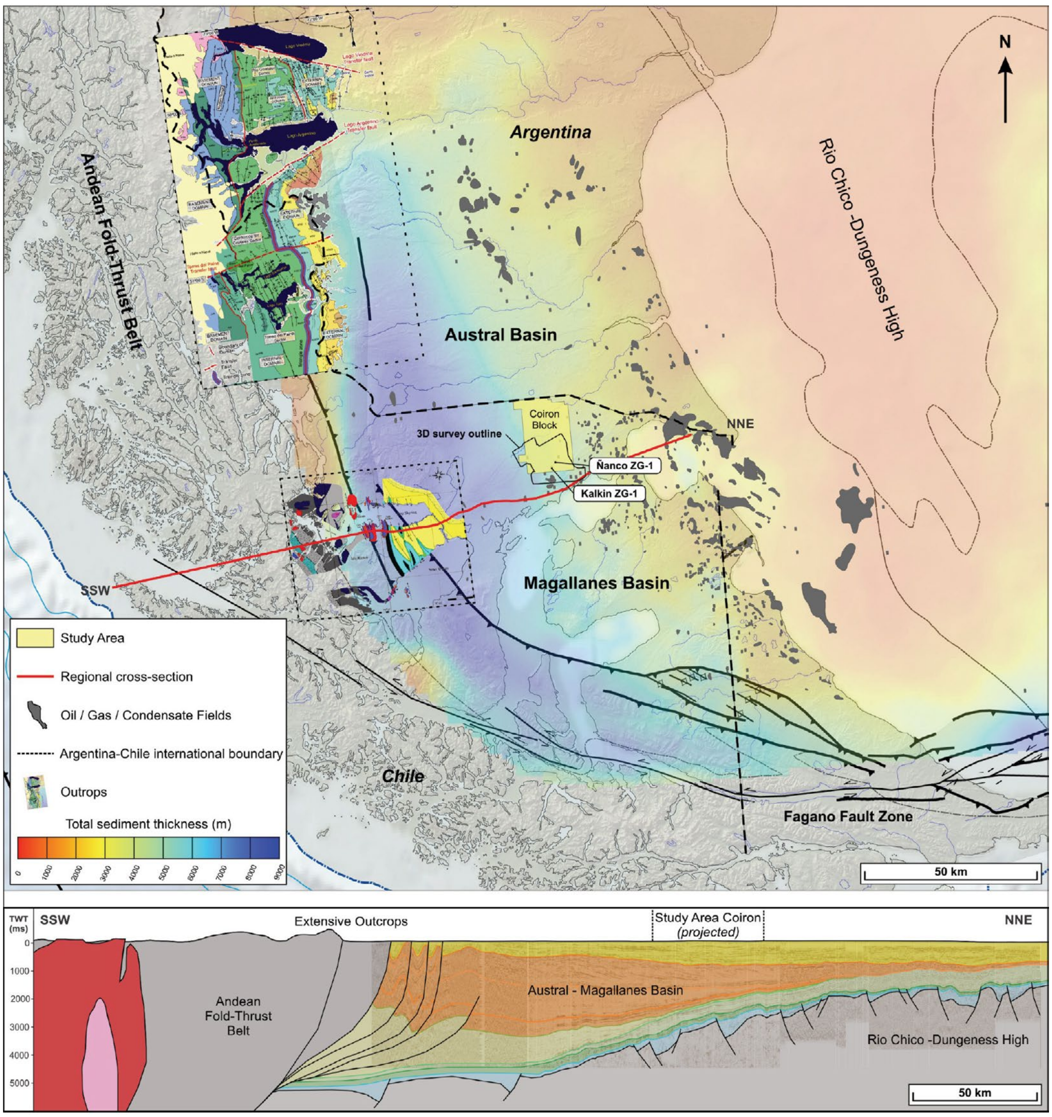

Figure 1. Location map of the study area (a) simplified tectonic map of the Austral-Magallanes Basin including total ispopach and production, (b) geological cross-section illustrating the regional tectonostratigraphic framework through the Austral-Magallanes Basin.

well as their implication for basin evolution and hydrocarbon exploration in the Austral-Magallanes Basin.

GEOLOGICAL SETTING

The Austral-Magallanes Basin is a major sedimentary basin with significant hydrocarbon resources shared between Chile and Argentina (Figure 1). This basin formed as the result of Middle Jurassic to Lower Cretaceous opening of the Rocas Verdes Basin and subsequent closing linked to the Late Cretaceous to Neogene uplift in the southern Andes andassociated foreland basin development (Biddle *et al.*, 1986; Natland, 1974) (Figure 2). The Rocas Verdes tectonostratigraphic sequence is defined by a series of graben dominated by continental and volcanic deposits, followed by a transgressive unit characterized by a proximal succession of fluvial to shallow marine sandstones and equivalent offshore marine shales. The Late Cretaceous to Neogene foreland tectonostratigraphic sequenceconsists of numerous deep-marine to shallow marine sequence successively prograding from the north, west, and south west (Schwartz *et al.*, 2015).

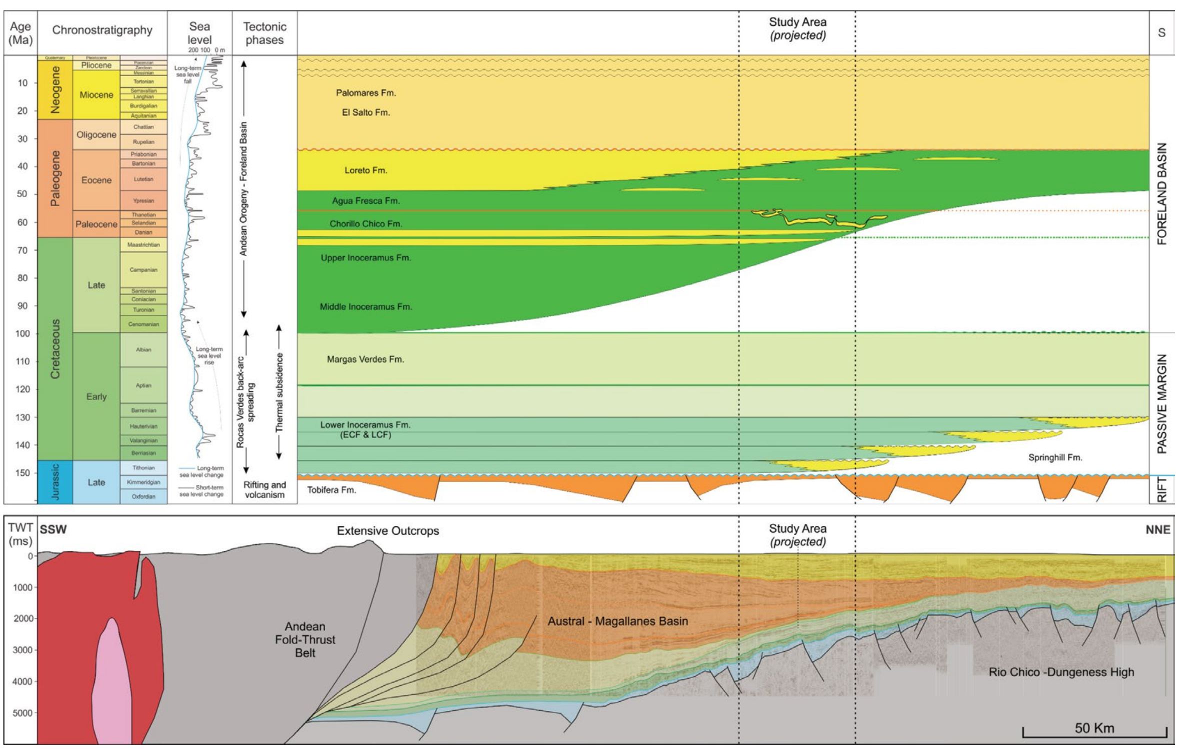

Figure 2. Austral-Magallanes Basin chronostratigraphic chart summarizing tectonostratigraphic framework and petroleum system events.

DATASET

This study is primarily based onhigh-quality 3D seismic reflection data, in addition to regional two-dimensional (2D) seismic lines and two exploration wells with cores data (Figure 1 and 3). The pre-stack time-migrated 3D volume covers an area of ~1000 km^2 with an inline and crossline spacing of 30 m. The average frequency varies between 25 to 30 Hz while corresponding to vertical resolution between 27 to 30 m assuming seismic velocity of 3200 m/s. The seismic data are zero phase with positive amplitudes represented by a downward increase in acoustic impedance depicted by a red, orange, or yellow peak. Negative amplitudes represent upward increase in acoustic impedance and are depicted by a light blue trough. 3D seismic interpretation was integrated in a broader regional framework using regional 2D seismic reflection profiles and exploration wells including two recent wells within the study area. The recent wells include a full suite of wire-line-log data with excellent core coverage through the interval of interest allowing the observed seismic anomalies to be calibrated to lithology and depositional facies.

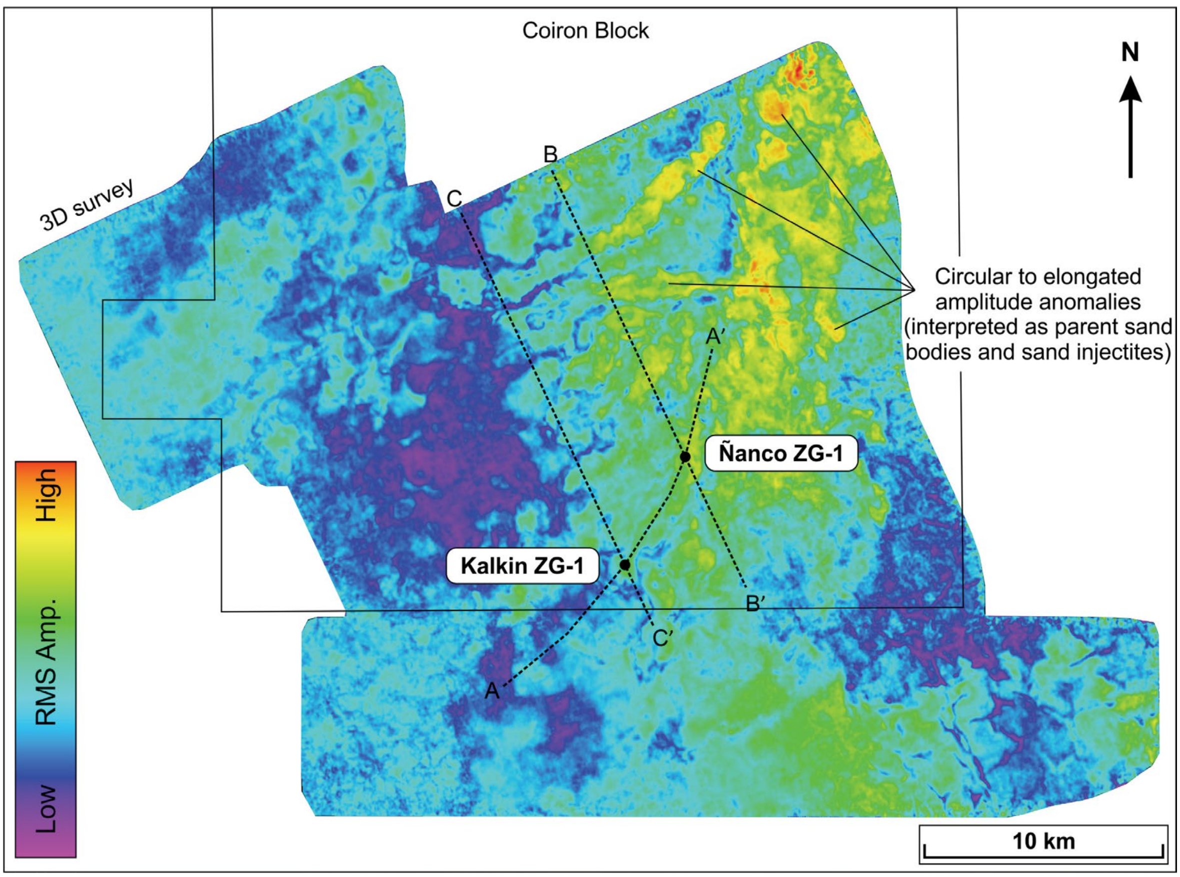

Figure 3. RMS Amplitude map showing amplitude anomalies interpreted as parent sand bodies and sand injectites with locations of two-dimensional seismic reflection profiles and wells through the Paleocene stratigraphic interval (see Figure 4).

RESULTS

3D SEISMIC

Three-dimensional seismic interpretation based on the regional tectonostratigraphic framework shows the presence of amplitudes anomalies in the up-dip part of the Paleocene interval thinning out onto the Rio Chico High. Detailed 3D seismic interpretation reveals numerous amplitudes anomalies with circular to elongated shape in plan view (Figure 3) with discordant reflection cross-cutting sub-parallel reflections in as much as 100 ms with dips between 10-20° (Figure 4).

WELL / CORE

Two recent exploration wells targeting the amplitude anomalies within the Paleocene interval have helped to calibrate the seismic response to lithology and depositional facies. In both wells the top and base of this interval corresponds to a sharp inflection in the gamma-ray log, indicating a radioactive contrast with the shale-rich background. These intervals correspond to thickness between 30-40 m and yield a blocky gamma-ray log motif (Figure 5).

Detailed core description has helped to identify four sedimentary facies within the interval of interest including 1) structureless sandstone, 2) bioturbated siltstone and mudstone, 3) mudclast breccia, and 4) thin-bedded normally-graded sandstone and siltstone (Figure 5).

1) Structureless sandstone- The structureless sandstone facies consists of very fine to fine grained massive sandstone with no discernable primary sedimentary or biogenic structures. Contacts with underlying and overlying facies (typically bioturbated siltstone and mudstone) are always sharp, at high angles to the known bedding character and show discontinuous and angular relationships with all other facies. This facies can appear as thick unit or it can occur in thin units that appear to cross-cut host facies (typically bioturbated siltstone and mudstone) at high angles and non-uniform orientations. This facies is interpreted to be remobilized sands and represents the body of a clastic injection feature as evidenced by the near structureless character of the sandstone and evidence of smaller scale clastic dykes and sills encased entirely in "host" (bioturbated siltstone and mudstone) facies (Duranti *et al.*, 2002; Eggenhuisen *et al.*, 2010).
2) Bioturbated siltstone and mudstone- This facies consists of biogenically churned siltstones and mudstones (Bioturbation index 4-5) but when interpretable the bedding character appears to be mainly parallel however when near the Structureless sandstone facies the bedding/bedding plane horizontal trace fossils can appear contorted and/or fractured and occasionally associated with calcite and/or pyrite mineralization. Abundant Chondrites,Zoophycos, Cosmorhaphe and Phycosiphon with rare Thalassinoides and

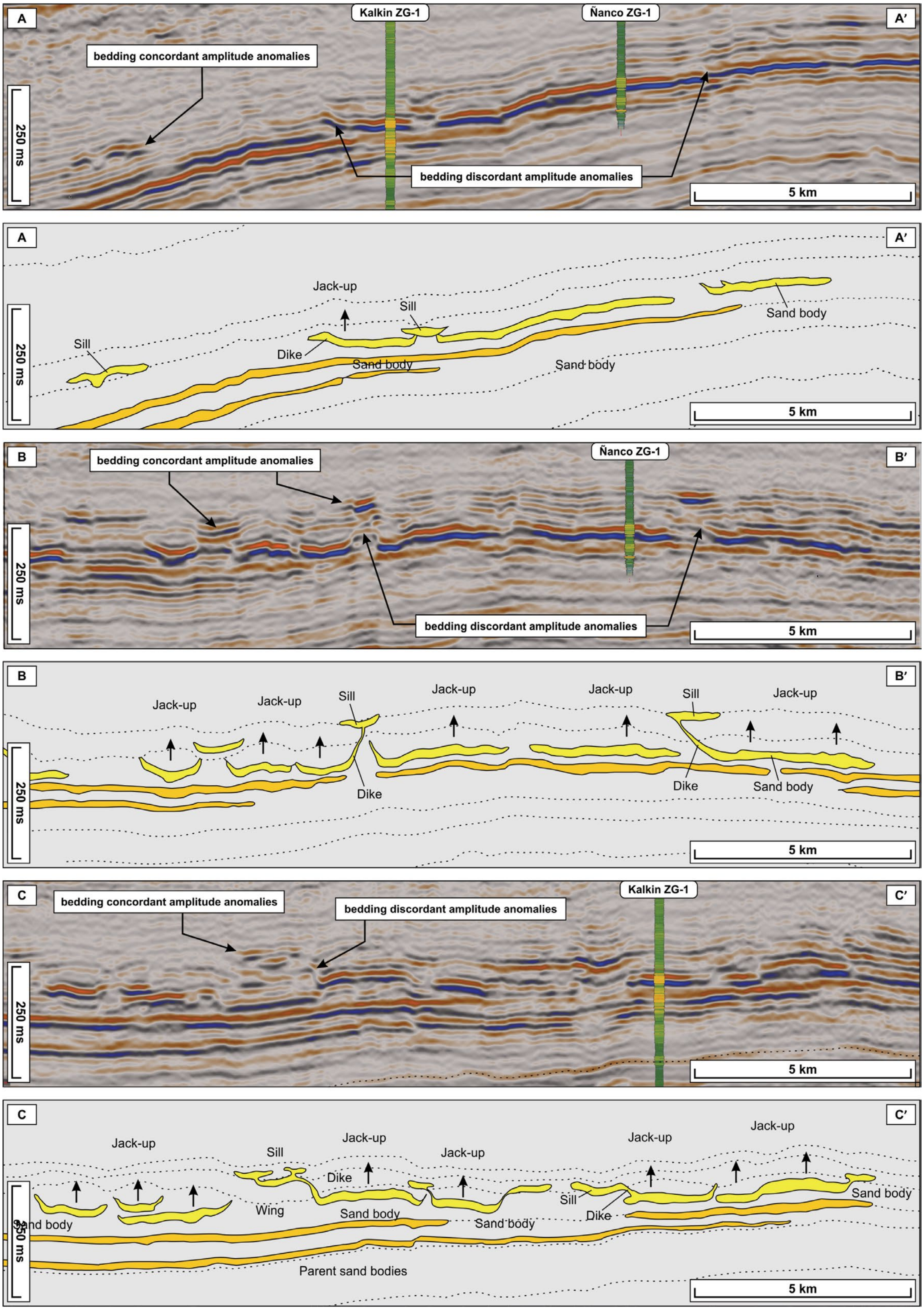

Figure 4. Two-dimensional seismic reflection profiles through exploration wells showing seismic amplitude anomalies within the Paleocene stratigraphic interval and interpreted profile illustrating geometries of sand injectites and relationship to parent body.

Planolitesare preserved. This facies is interpreted to be "background facies" of a deep-water depositional system as evidenced by the regional context, ichnological content (ZoophycosIchnofacies- (Pemberton, 1992; Pemberton and Maceachern, 2005), planar nature of beds and bioturbation index (4-5). This material acts as the "host" that the structureless sandstone facies intrudes or is injected into (Hurst *et al.*, 2011). This results in massive sandstone facies virtually encased in fine-grained "host" material (Hurst *et al.*, 2011).

3) Mudclast breccias- Angular mudclasts are evident within a fine to medium grained sandy matrix. Clasts can be oriented in a random fashion or appear slightly imbricated in an upward fashion. The mudclasts consist of material that is described in the Bioturbated

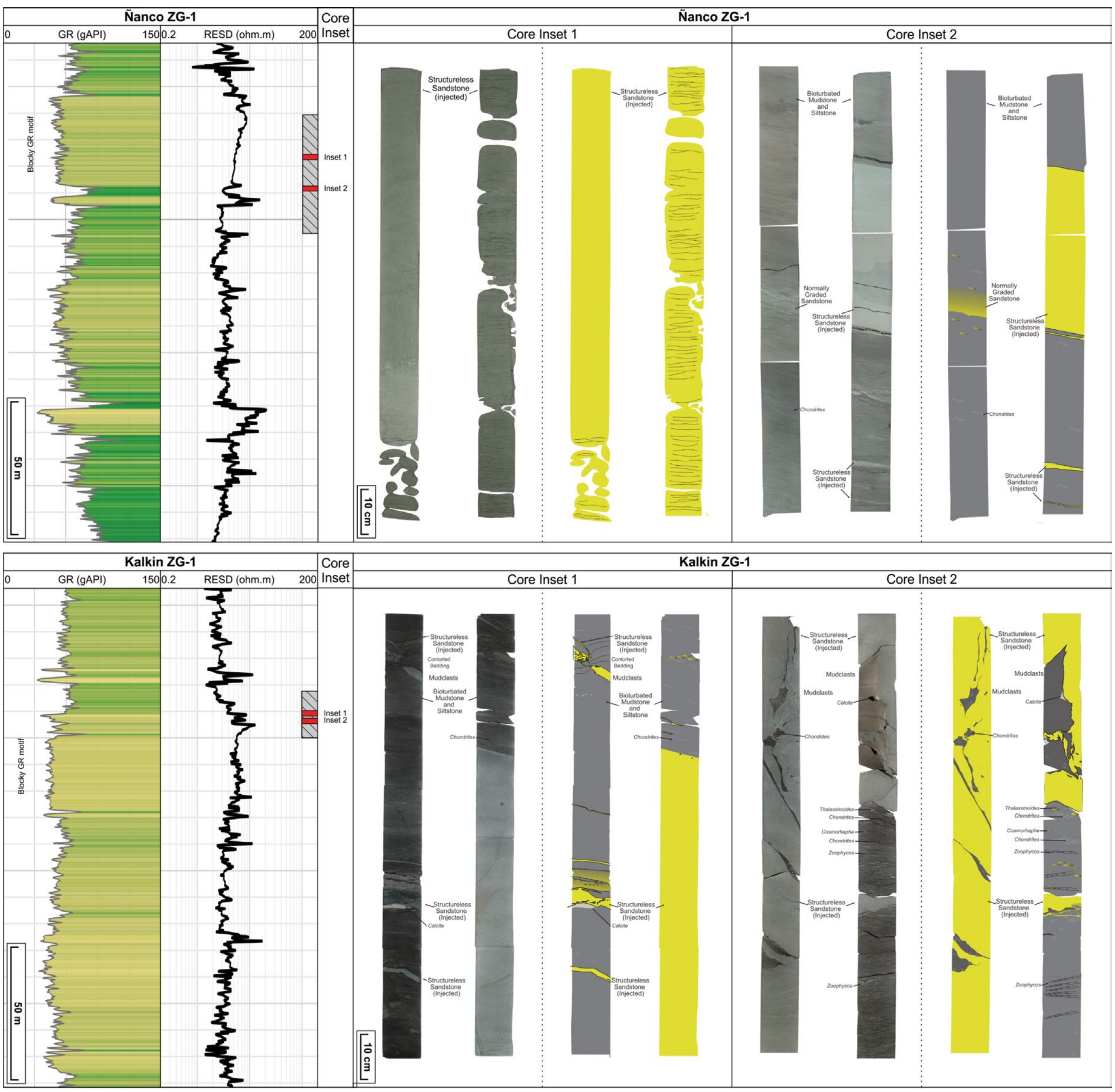

Figure 5. Well profiles illustrating log motifs associated with sand injectites, as well as selected core interval illustrating observed sedimentary facies.

siltstone and mudstone facies and discernable parallel laminae and biogenic features (often Chondrites) are evident. This facies is interpreted as an injection breccia which forms on the edges and bases of clastic injectites and is due to the rapid emplacement and injection of sandstone into host material (Duranti *et al.*, 2002; Szarawarska *et al.*, 2010). Portions of the "host" material are forcefully ripped up and injected with the remobilized sandstone (Szarawarska *et al.*, 2010). Often wispy edges to the mudstone clasts suggest the clasts have not been transported great distances and when they were transported were poorly consolidated/lithified (Duranti *et al.*, 2002).

4) Thin-bedded normally-graded sandstone and siltstone- This facies consists of thinly bedded sandstone that primarily grades upward into siltstone and occasionally mudstone. The fine-grained tops of the beds rare often bioturbated and any evidence of discernable sedimentary structures is nearly obliterated. These thinly bedded units are interpreted to be small low-density turbidites (Bouma, 1965). The distinct grading and coherence with regional bedding orientations suggest this facies is "in place" and has not been subject to remobilization or injection.

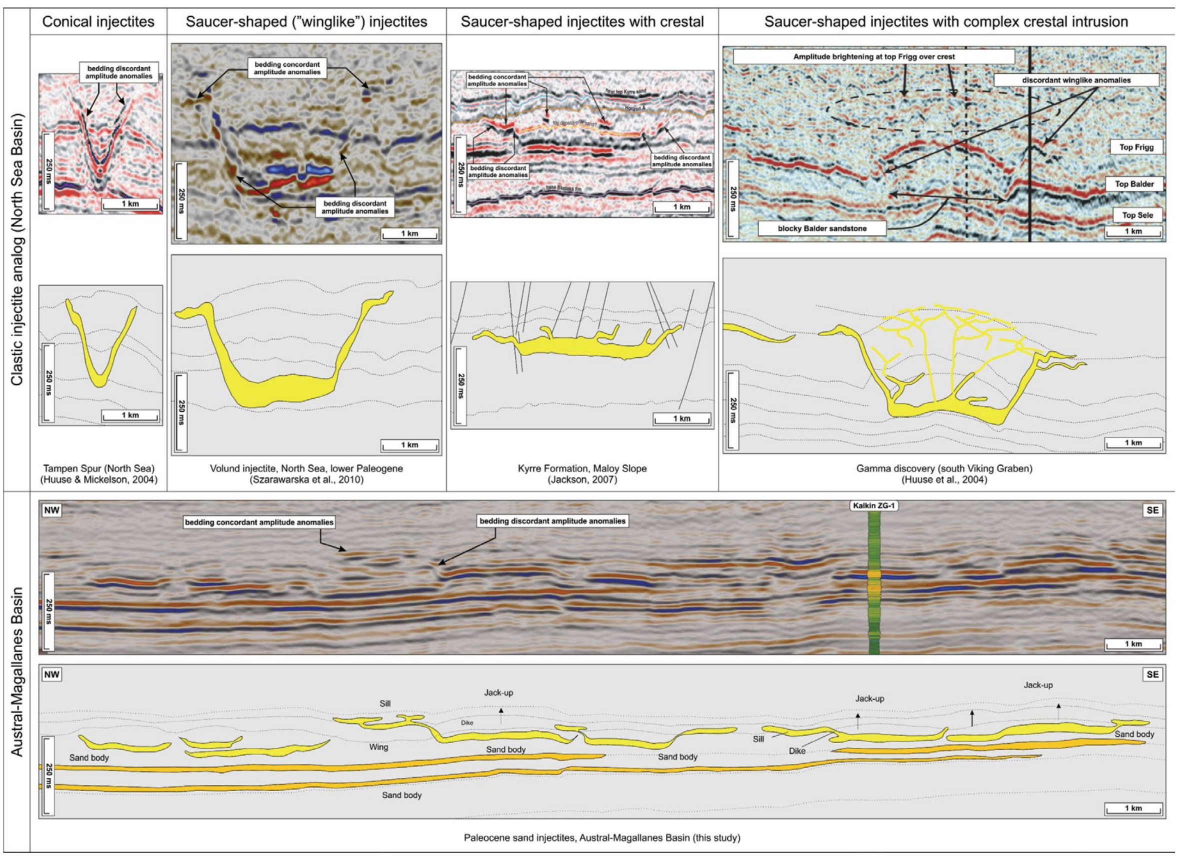

Figure 6. Seismic-scale sand injectite analogs illustrating representative geometries from conical injectites to saucer-shaped injectites with a varied degree of crestal intrusion compared to observed sand injectites in the Austral-Magallanes Basin. (Note: all examples are to scale allowing proper comparison)

DISCUSSION

SAND REMOBILIZATION

The recent discovery of subsurface injectites in the Austral-Magallanes Basin based on the integration of 3D seismic, well, and core data are comparable to subsurface and outcrop analogs (Figure 6). Sand injectites remain globally underexplored and poorly understood; however, subsurface analogs from the North Sea Basin are seismically well understood as well as extensively calibrated by boreholes. Recent advances in seismic imaging have greatly enhanced the detailed observationsand mapping,allowing the visualization of complex geometries, which are critical to the interpretation of sand injectites (Huuse *et al.*, 2007). Seismic-scale injectitesare usually characterized by discordant amplitude anomalies with geometries varying from conical to saucer-like features with wingsand more complex geometries with small-scale crestal intrusions, all of which might occasionally be associated withextrusive features (Andresen and Clausen, 2014; Huuse *et al.*, 2007; Jackson *et al.*, 2011) (Figure 6).

The subsurface characterization of clastic injectites is mainly controlled by seismic qualitywith limited borehole calibration; therefore, a more rigorous understanding of the mechanisms and controls of clastic intrusions are critical in understanding and predicting the degree of modification of the primary/parent depositional sand body and the resulting complex injectite geometries. For instance, significant effort has been invested in interrogating outcrops analogs in order to better understand fine-scale details associated with sand remobilization (Scott *et al.*, 2013), as well as experimental and numerical modeling to better understand formation mechanisms (Rodrigues *et al.*, 2009). Numerous outcrops have provided detailed observations, which can be leveraged in seismic interpretation and prediction including the outcropping clastic injectites observed from the Austral-Magallanes Basin (Hubbard *et al.*, 2007, Tudisca *et al.*, 2012) (Figure 7).

Sand injectites have been observed globally in all sedimentary environments with varying degree of scale and abundance; however, large-scale sand remobilization is commonly observed within deepwater depositional systems (Jolly and Lonergan 2002; Hurst and Cartwright, 2007). Injectites are commonly associated with clastic turbidite slope channel systems (Jackson *et al.*, 2007) as well as basin floor fan systems (Cobain *et al.*, 2017).

Even though sand injectionsare recognizable in seismic, well, and outcrops;the mechanism involved in their formation is poorly constrained. Violent and rapid injection processes can be linked to the combination of overpressure *build-up* and triggering events (Hurst *et al.*, 2011). Overpressure is considered as the main driving force associated with the formation of sand injectites; however, a particular mechanism cannot be constrained with certainty and may include, disequilibrium compaction, lateral pressure transfer, and fluid migration(Jolly and Lonergan, 2002; Yardley and Swarbrick, 2000). In combination with overpressure, sand injectites require triggering

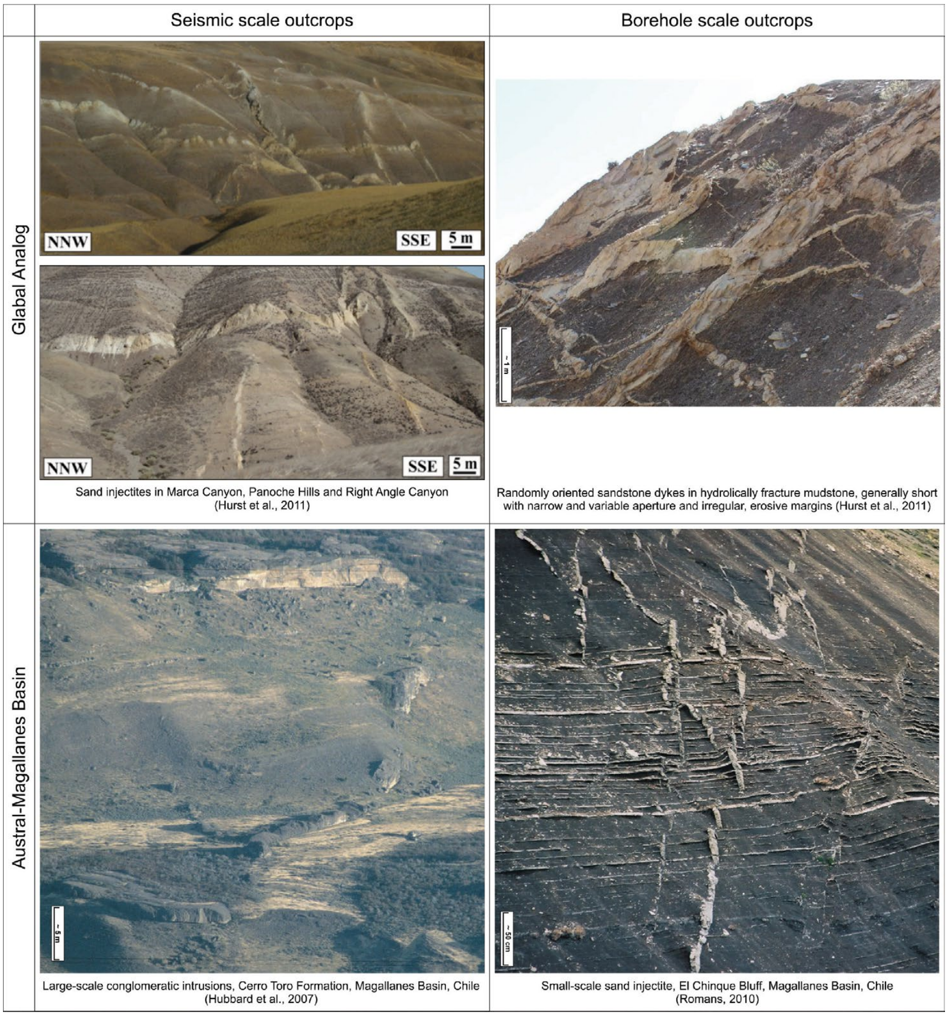

Figure 7. Outcrop analog of sand injectites from global examples compared to examples from the Austral Magallanes Basin illustrating large scale sand geometries, as well as small scale complexity which is comparable to features observed in well and core data.

events including large magnitude earthquakes, meteorite impacts, or a widespread faulting episode (Hurst *et al.*, 2011).

The recent discovery of sand injectites in the Austral-Magallanes Basin have brought new insight in understanding the depositional setting of thePaleocene interval equivalent to the Chorillo Chico Formation (Biddle *et al.*, 1986) (Figure 8). Comparison with seismic analogs, well, and core has helpto better understand the primary/parent depositional bodies, injectitegeometries,and their potential formation mechanisms. Based on regional study, the Paleocene stratigraphy is associated with deep-water depositional processes and a sand-rich turbidite system onlapping onto the Rio Chico High to the east which is associated with the progradation of western and northerndeltaics systems. This sand rich interval was overlain by the deposition of deep-water mudstones acting as a regional seal and later followed by the rapid eastward shelf progradation resulting in the filling of the deep foreland basin and onlapping onto the Rio Chico High (Gallardo, 2011). The combination of a large Paleocene sand rich aquifer, regional seal, and rapid loading provide the key elements commonly controlling the formationof sand injectites. For instance, the combination of rapid loading in the western part of the basin and the presence of a regional seal can simply explain the lateral pressure transfer along the Paleocene aquifer pinching out onto the eastern edge of the basin and subsequentoverpressure buildup. In addition, possible tectonic events associated with the Andean orogen may have acted as a triggering event and could potentially explain the timing of emplacement of sand injectites.

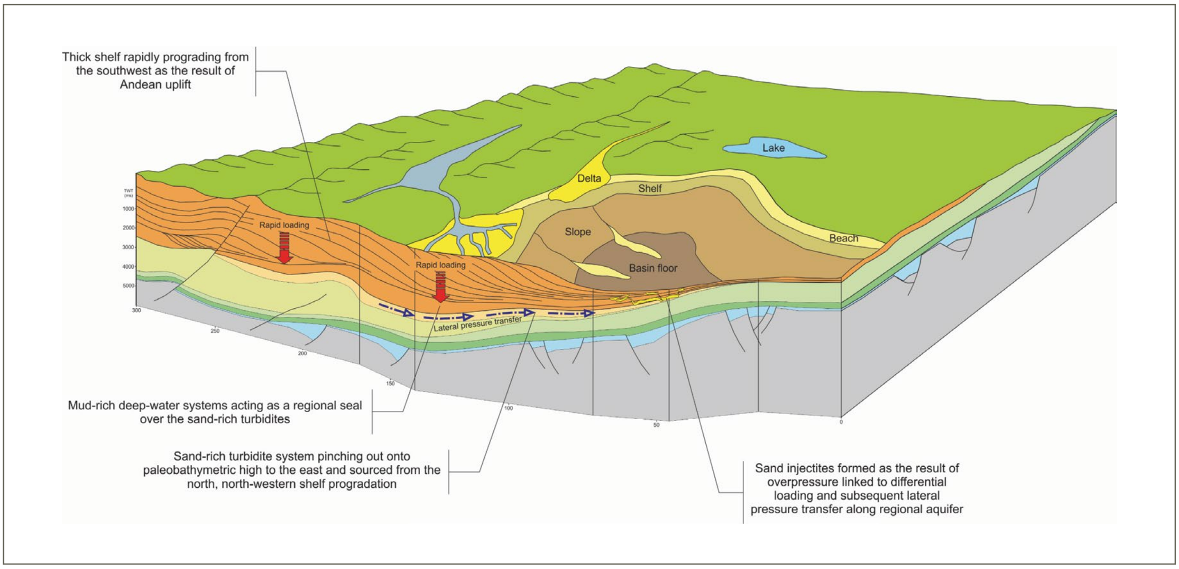

Figure 8. Block diagrams illustrating the depositional setting of the Paleocene interval and overburden stratigraphy leading to the formation of sand injectites in the Austral-Magallanes Basin.

PETROLEUM SYSTEMS

Recent research on sand injectites has revealed their importance in sedimentary systems as well as their significant implication for petroleum system elements including trap, reservoir, seal, and migration (Hurst *et al.*, 2005) (Figure 9). Sand injectites have been defined as intrusive traps in comparison to the more common structural and stratigraphic traps (Hurst and Cartwright, 2007). Intrusive traps are combinations of dikes, sills, and more irregular features that have intruded into sealing interval composed of low-permeability mudstones or shales. Sand injectites contain substantial volumes of homogeneous fine- to medium-grained sand with reservoir porosity averaging 30% and permeability in the Darcy range for producing oil fields in the North Sea (Hurst *et al.*, 2005), apart from units rich in mudstone clasts and carbonates cement. In addition, the complexity of small clastic sills and dykes below seismic resolution provide additional volume in the order of 15 to 30%, as well as enhancing connectivity (Hurst and Huuse, 2017).

Sand injectites have also been recognized to play a major role in fluid migration and hydrocarbon migration(Hurst *et al.*, 2003; Murphy and Wood, 2011). Clastic injection throughthick, low-permeability mudstones can compromise the seal integrity of primary/parentdepositional systems and result in a breached trap, or on the contrary can provide pathways for hydrocarbon migration into shallower reservoir sections.

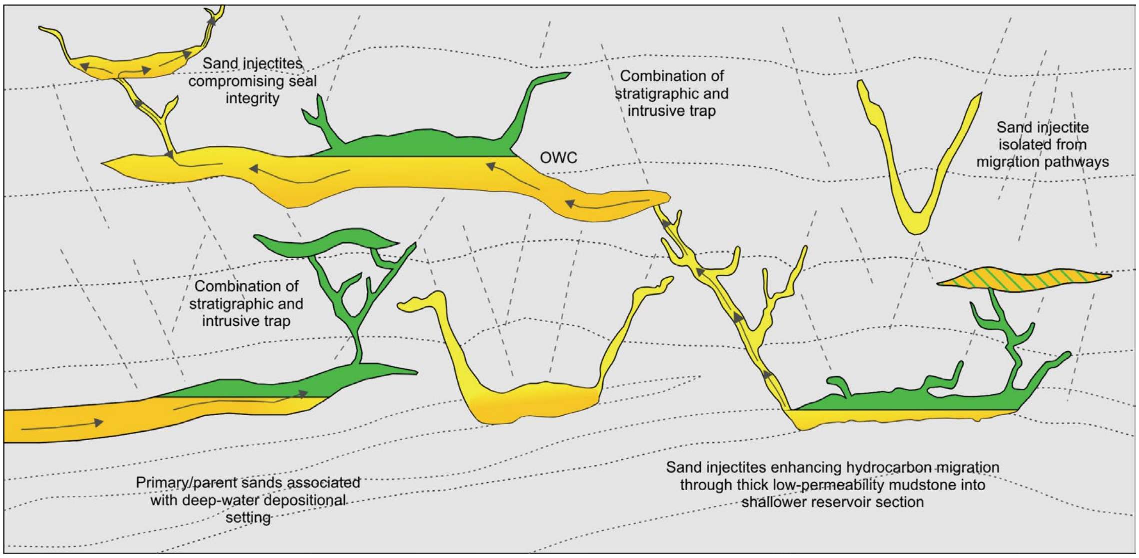

Figure 9. Schematic diagram illustrating implications of sand injectites with respect to petroleum system elements including trap, reservoir, seal, and migration (Modified from Murphy and Wood., 2011).

EXPLORATION POTENTIAL

In the last two decades, sand injectites have been recognized as a new exploration play in the North Sea Basin following a strong research effort in understanding sand remobilization and subsequent impact on petroleum systems(Hurst *et al.*, 2005). Sand injectites now account forsignificant hydrocarbon accumulations based on their intrusive trap geometries and remarkable reservoir properties(Hurst and Cartwright, 2007). Advances in three-dimensional (3D) seismic data quality, improved coring techniques, and extensive outcrops studies have enhanced theunderstanding of sand injectites from seismic down to the reservoir scale(Hurst and Cartwright, 2007; Scott *et al.*, 2013). Sand injectites constitute volumetrically significant reservoirs, impact reservoir quality and distribution, provide vertical and lateral connectivity across long distances, and potentially constitute drilling hazards (Huuse 2007).

The recent discovery of sand injectites in the Austral-Magallanes Basin have proved a new exploration play. Based on the current results, sand injectites in the Paleocenehave confirmed the presence of a tight-sand reservoir between 37 to 45 m thick with total porosity between 21 and 23 %, and low permeability between 0.2 and 0.3 mD.Based on these tight reservoir properties, reservoir interconnectivity between the primary/parent depositional bodies, the large intrusive, and the small sill and dykes below seismic resolution might play a significant impact on reservoir geometry, volumetric, and development strategy as compared to producing North Sea analogs. In addition, low reservoir permeability might also affect the charge story for sand injectites incased in mudstone with low connectivity to preferred migration routes.

CONCLUSIONS

Integration of high-quality 3D seismicreflection data, well data, core observations,and extensive regional characterization in the Austral-Magallanes Basin have brought new insights for the late Cretaceous to Paleocene depositional setting and exploration potential. Detailed seismic mapping has highlighted the presence of unusual amplitude anomalies interpreted as large-scale sand injectitesand later confirmed by well and core data. The discovery of large-scale sand injectites represent the first subsurface example of sand remobilization as an onshore exploration target and confirms a more widespread phenomenon that previously thought.Mainly documented in the North Sea Basin for their economic significance and vast petroleum potential, the presence of sand injectites in the Austral-Magallanes Basin brings new insight with respect to depositional system, basin evolution, and more importantly new exploration opportunities. New play concepts come with their own challenges and rigorous understanding of the mechanisms of clastic intrusion and controls on sandstone remobilizationare key to understanding the nature and degree of primary sand body geometrical modification and the subsequent impacton reservoir distribution, trap geometry, migration pathways, and seal.

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REFERENCES

Andresen, K.J. and Clausen, O.R., 2014. An integrated subsurface analysis of clasticremobilization and injection; a case study from the Oligocene succession of the eastern North Sea. Basin Research, 26(5): 641-674.

Biddle, K., Uliana, M., Mitchum, R., Fitzgerald, M. and Wright, R., 1986. The stratigraphic and structural evolution of the central and eastern Magallanes Basin, southern South America. Foreland basins: 41-61.

Cobain, S.L., Hodgson, D.M., Peakall, J. and Shiers, M.N., 2017. An integrated model of clastic injectites and basin floor lobe complexes: Implications for stratigraphic trap plays. Basin Research, 29(6): 816-835.

Duranti, D., Hurst, A., Bell, C., Groves, S. and Hanson, R., 2002. Injected and remobilized Eocene sandstones from the Alba Field, UKCS: core and wireline log characteristics. Petroleum Geoscience, 8(2): 99-107.

Eggenhuisen, J. *et al.*, 2010. Reconstructing large-scale remobilisation of deep-water deposits and its impact on sand-body architecture from cored wells: The Lower Cretaceous Britannia Sandstone Formation, UK North Sea. Marine and Petroleum Geology, 27(7): 1595-1615.

Gallardo, R.E., 2011. Seismic sequence stratigraphy of a foreland unit inthe Magallanes-Austral Basin, Dorado Riquelme Block, Chile: Implications for deep-marine reservoirs. Latin American journal of sedimentology and basin analysis, 21(1): 49-64.

Hubbard, S.M., Romans, B.W. and Graham, S.A., 2007. An outcrop example of large-scale conglomeratic intrusions sourced from deep-water channel deposits, Cerro Toro Formation, Magallanes basin, southern Chile.

Hurst, A. and Cartwright, J., 2007. Relevance of sand injectites to hydrocarbon exploration and production.

Hurst, A., Cartwright, J., Duranti, D., Huuse, M. and Nelson, M., 2005. Sand injectites: an emerging global play in deep-water clastic environments, Geological Society, London, Petroleum Geology Conference series. Geological Society of London, pp. 133-144.

Hurst, A. *et al.*, 2003. Significance of large-scale sand injectites as long-term fluid conduits: evidence from seismic data. Geofluids, 3(4): 263-274.

Hurst, A., Scott, A. and Vigorito, M., 2011. Physical characteristics of sand injectites. Earth-Science Reviews, 106(3): 215-246.

Huuse, M., Cartwright, J., Hurst, A. and Steinsland, N., 2007. Seismic characterization of large-scale sandstone intrusions.

Jackson, C.A.-L., Huuse, M. and Barber, G.P., 2011. Geometry of winglike clastic intrusions adjacent to a deep-water channel complex: Implications for hydrocarbon exploration and production. AAPG bulletin, 95(4): 559-584.

Jackson, C.A., Hurst, A. and Cartwright, J., 2007. The geometry, distribution and development of clastic injectites in deep-marine depositional systems: Examples from the Late Cretaceous Kyrre Formation, Måløy slope, Norwegian margin. Sand injectites: Implications for hydrocarbon exploration and production: AAPG Memoir, 87: 37-48.

Jolly, R.J. and Lonergan, L., 2002. Mechanisms and controls on the formation of sand intrusions. Journal of the Geological Society, 159(5): 605-617.

Murphy, S. and Wood, P., 2011. Palaeogene remobilized sandstones of the Central North Sea-Implications for hydrocarbon migration. First Break, 29(12): 45-55.

Natland, M.L., 1974. A system of stages for correlation of Magallanes Basin sediments, 139. Geological Society of America.

Pemberton, S.G., 1992. Applications of ichnology to petroleum exploration: a core workshop, 17. Sepm Society for Sedimentary.

Pemberton, S.G. and Maceachern, J.A., 2005. Significance of ichnofossils to applied Stratigraphy, Applied Stratigraphy. Springer, pp. 279-300.

Rodrigues, N., Cobbold, P.R. and Løseth, H., 2009. Physical modelling of sand injectites. Tectonophysics, 474(3): 610-632.

Schenk, C.J. *et al.*, 2016. Assessment of unconventional tight-gas resources of the Magallanes Basin Province, Chile, 2015. 2327-6932, US Geological Survey.

Scott, A., Hurst, A. and Vigorito, M., 2013. Outcrop-based reservoir characterization of a kilometer-scale sand-injectite complex. AAPG bulletin, 97(2): 309-343.

Szarawarska, E. *et al.*, 2010. Three-dimensional seismic characterisation of large-scale sandstone intrusions in the lower Palaeogene of the North Sea: completely injected vs. in situ remobilised sand-bodies. Basin Research, 22(4): 517-532.

Tudisca, E. P., Pazos, P. J., Ghiglione, M. C., and Cianfagna, F. A., 2012. Estudios de "las capas del Cabo Ladrillero Superior" en el Cabo Homonimo, Mioceno Inferior de la Cuenca Austral, Tierra Del Fuego. Revista de la Asociacion Geologica Argentina 69 (1) 43-60.

Yardley, G. and Swarbrick, R., 2000. Lateral transfer: A source of additional overpressure? Marine and Petroleum Geology, 17(4): 523-537.

Zurita, E., Carpinelli, A., Trejo, S. and Saa, A., 2013. Gas resource potential from Maastrichain-Eocene reservoir in Magallanes Basin, Chile. In: A.A.o.P. Geologists (Editor), International Conference and Exhibition, Cartagena, Columbia.

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