Available online at www.sciencedirect.com

ScienceDirect

Earth and Planetary Science Letters 266 (2008) 195 – 204

EPSL

www.elsevier.com/locate/epsl

Saucer-shaped intrusions: Occurrences, emplacement and implications

Stéphane Polteau [a,*], Adriano Mazzini [a], Olivier Galland [a],
Sverre Planke [a,b], Anders Malthe-Sørenssen [a]

[a] *Physics of Geological Processes, University of Oslo, P.O. Box 1048, Blindern, Oslo, Norway*
[b] *Volcanic Basin Petroleum Research, Oslo Innovation Center, Gaustadalléen 21, 0349, Oslo, Norway*

Received 31 May 2007; received in revised form 18 October 2007; accepted 11 November 2007
Available online 21 November 2007
Editor: C.P. Jaupart

Abstract

Magmatic intrusions and fluidized injected sands represent the two main types of sheet intrusions in the Earth's crust. In this paper we show that both intrusion types often display a saucer-like geometry, as revealed by 3D seismic imaging and field observations. Saucer-shaped intrusions are fairly common in sedimentary basins, as for example offshore in the Norwegian and North Sea basins and onshore in the Karoo Basin of South Africa. The formation of the saucer geometry is controlled by the low-viscosity of the injected fluid and by the interaction between a growing shallow hydraulic fracture and overburden deformations. Statistics gathered from observations and modelling show a linear relationship between the depth of emplacement and the size of the saucer-shaped intrusions. We anticipate future cross-disciplinary studies aiming to discover other occurrences of saucer-shaped intrusions and to identify the physical processes controlling the development of this fundamental geometry.

Keywords: saucer-shaped sill; magmatic intrusion; injected sand; Karoo, North Sea

---

1. Introduction

Sheet-like intrusions represent the principal pathways to transport magma and fluidized sediments through the upper crust. The intrusions have traditionally been studied through geological field investigations. Nowadays, high-resolution seismic imaging allows geoscientists to visualize the detailed three-dimensional (3D) geometries of deeply buried intrusions. These large-scale sheet-like intrusions, sometimes described as lopoliths (Blatt et al., 2005), can develop spectacular saucer-like morphologies (Fig. 1). A saucer-shaped intrusion is divided into three distinct portions (Chevallier and Woodford, 1999):

- a sub-horizontal *inner sill* forming the base,
- a steeply dipping *inclined sheet* cross-cutting the stratification, and
- a sub-horizontal *outer sill.*

Magmatic intrusions and injected sands represent the best natural examples of saucer-shaped intrusions. Saucer-shaped magmatic intrusions are intimately related to voluminous magmatism in undeformed sedimentary basins. These intrusions may act as water reservoirs and barriers

---

* Corresponding author.
E-mail address: polteau@fys.uio.no (S. Polteau).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2007.11.015

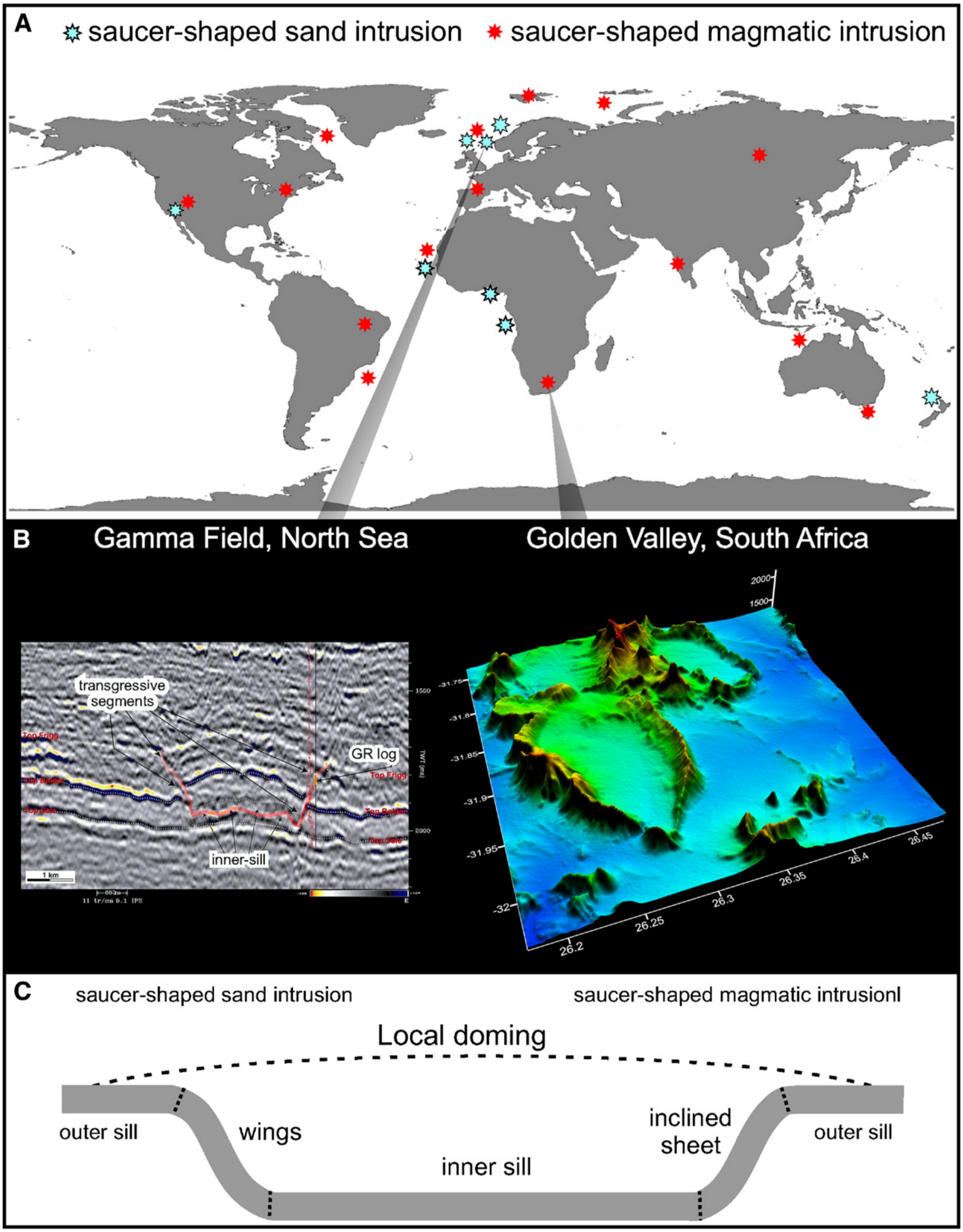

Fig. 1. (A) World-wide distribution of known and interpreted saucer-shaped sills and sand intrusions. (B) 3D representation of saucer-shaped Gamma field sand injectite (Huuse et al., 2004) and Golden Valley sill (Karoo) with (C) corresponding terminology.

[e.g. in the arid Karoo Basin, South Africa, Chevallier and Woodford, 1999], affect hydrocarbon maturation and migration pathways, and represent promising targets for oil exploration (e.g. Paraná Basin of Brazil (Schutter, 2003) and Neuquén Basin in Argentina (Rossello et al., 2002)). Similarly, injected sands are present in clastic sedimentary basins and may form hydrocarbon reservoirs or high-porosity fluid migration pathways (Dixon et al., 1995; Lonergan et al., 2000a; Aiello, 2005).

Despite their world-wide distribution, the emplacement mechanisms and geological implications of saucer-shaped intrusions are not fully understood. The aims of this paper are (1) to show that emplacement mechanisms of saucer-shaped intrusions are controlled by the same physical parameters, and (2) encourage the mapping of saucer geometries in nature.

Our aims are valid both for the direct industrial applications and space exploration programs. This paper describes classical examples of saucer-shaped intrusions, reviews analogue and numerical models and gives insights on common mechanisms that control the final saucer morphology.

2. Occurrences and characterization of saucer-shaped magmatic intrusions

The best examples of saucer-shaped magmatic intrusions, commonly described as “saucer-shaped sills”, occur in sedimentary basins intruded by large amounts of magma (Fig. 1). Detailed seismic analysis (Fig. 2) allowed the identification of saucer-shaped sills offshore Mid-Norway in the Vøring and Møre basins (Malthe-Sørenssen et al., 2004; Planke et al., 2005; Hansen and Cartwright, 2006), offshore Scotland in the Rockall Trough (Thomson and Hutton, 2004), in the Faroe-Shetland Basin (Smallwood and Maresh, 2002; Hansen et al., 2004), offshore Senegal (Rocchi et al., 2007; Hansen et al., in press), and on the NW Australian shelf (Symond et al., 1998). 3D seismic data in the North and Norwegian Seas shows the presence of magma channels suggesting a radial upward and outward magma flow (Thomson and Hutton, 2004; Hansen and Cartwright, 2006). Seismic interpretations also show that the sediments overlying individual saucers form a characteristic dome structure (Hansen and Cartwright, 2006).

The largest and best known exposed saucers occur in the Karoo Basin of South Africa, and spectacular outcrops are also observed in Nevada (Keating et al., 2002) and on Svalbard. In South Africa, voluminous amounts of magma were injected into undeformed Permo-Carboniferous sediments about 183 Ma ago (Svensen et al. 2007). Differential erosion under arid conditions has created outstanding exposures of doleritic intrusions. Hence the Karoo Basin represents our reference site to study large-scale saucer-shaped intrusions. Extensive planar sills with local transgressive segments occur at the deepest level in the Karoo stratigraphy. Closer to the paleosurface the sills develop striking saucer morphologies, with diameters up to 60 km. Individual saucers are interconnected to form sill complexes. The dip of the inclined sheets ranges from 20° to 45° (Chevallier and Woodford, 1999), climbing 100–400 m above the sub-horizontal inner sill. Geological mapping clearly shows that the inclined sheets systematically cross-cut the horizontally layered strata demonstrating that the saucer morphology is a primary feature rather than related to late-stage sinking/sagging. The sub-horizontal outer sill corresponds to a series of tongue-like offshoots connected to the inclined sheets.

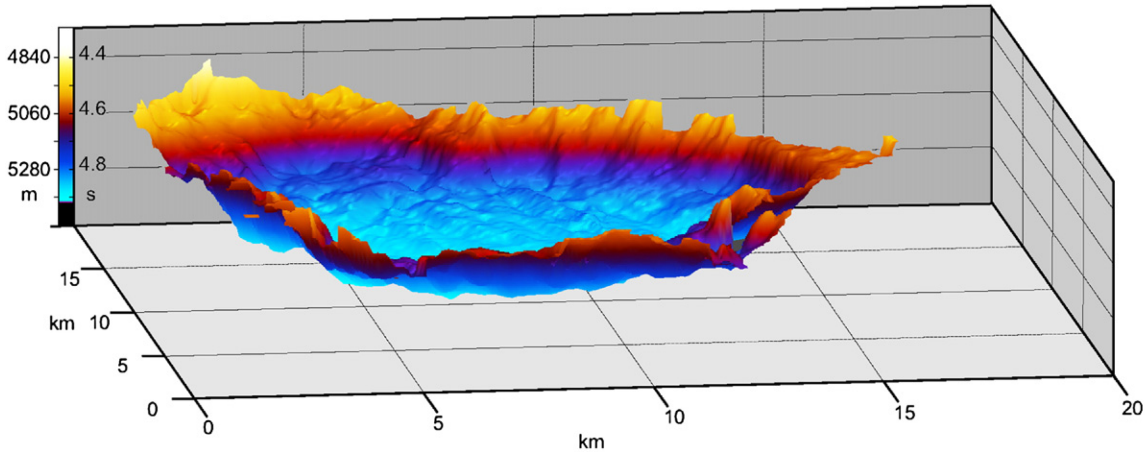

Fig. 2. Visualizations of a saucer-shaped sill interpreted from 3D seismic data in the Møre Basin offshore Mid-Norway. Depths are measured in meters and seconds (two-way travel time).

The few studies focussing on the processes leading to the formation of saucer-shaped intrusions are generally based on analyses of the intrusion geometry, and the spatial relationship between individual intrusions and potential feeder-dykes (Francis, 1982; Chevallier and Woodford, 1999; Malthe-Sørenssen et al., 2004). New research shows that magma flowed radially upward to form the saucer-shaped Golden Valley Sill. The magma flow directions are based on flow indicators such as ropy-flow structures (Liss et al., 2002) and magma channels (Thomson and Hutton, 2004), as well as magnetic fabric measurements. The current emplacement models of saucer-shaped sills are controlled by parameters such as density contrast between injected fluid and country rocks (Anderson, 1951; Lister, 1990), the tectonic stress field (Hubbert and Willis, 1957; Lister, 1990; Sibson, 2003), the overburden thickness (Mudge, 1968), mechanical properties of the country-rocks (Mudge, 1968; Gretener, 1969; Lister, 1990), and ultimately by the presence of mechanical heterogeneities such as bedding and fractures in the country-rocks (Leaman, 1975; Francis, 1982; Liss, 2003; Kavanagh et al., 2006).

3. Occurrences and characterization of injected sands

Injected sands, also referred to in the literature as sand intrusions and injectites, form spectacular outcrops in many sedimentary basins (e.g. California, Southern France, Greenland (Thompson et al., 1999; Surlyk and Noe-Nygaard, 2001; Boehm and Moore, 2002; Jonk et al., 2003; Aiello, 2005;)). Saucer-shaped sand intrusions have also been identified in seismic data from offshore petroleum provinces, e.g. the North Sea, the west African basins, and offshore Mid-Norway (Hurst and Buller, 1984; Lonergan et al., 2000a; Møller et al., 2001; Duranti et al., 2002; Davies, 2003; Hurst et al., 2003b). Analysis of 3D seismic surveys shows the presence of saucer-shaped sand intrusions above Paleocene reservoirs of the northern North Sea (Fig. 1). Seismic profiles show that the saucer-shaped sand intrusions crosscut the horizontal sedimentary strata and create local doming of the overburden sediments (e.g. Lonergan et al., 2000a; Molyneux et al., 2002; Hurst et al., 2003a; Huuse and Mikelson, 2004).

The best known saucer-shaped sand intrusions are located in the North Sea basins. Some authors (e.g. Molyneux et al., 2002; Huuse and Mikelson, 2004; Huuse et al., 2004, 2005) described injected sands as “V-shapes”, implying that the injections were generated from a narrow source point representing the apex of conical features. However the term “V-shape” originated from enhanced vertical exaggeration of seismic profiles, which, once rescaled to 1:1 revealed a saucer-like morphology. The sub-horizontal inner sill forms the base of the saucer. The inclined sheets, referred in the literature as “wings”, usually dip inward with a 20–40° angle (Lonergan et al., 2000b; Duranti et al., 2002, or estimated 45–60° before compaction; MacLeod et al., 1999; Jolly and Lonergan, 2002). These saucer-shaped sand intrusions have diameters ranging from some hundred meters up to a few kilometers and reach heights of up to 300 m (Lonergan et al., 2000a; Huuse and Mikelson, 2004; Huuse et al., 2005). The sub-horizontal outer sills of many injected sands in the North Sea basins terminate along regional unconformities (Hurst et al., 2003b; Duranti and Hurst, 2004; Huuse et al., 2004, 2005; Shoulders et al., 2007).

Our understandings of the sand intrusion morphology and emplacement models are not well-constrained and strongly depend on the resolution of the seismic data. The evolution of the geometry of a sand injection into a saucer has not yet been studied. The possibility that saucer-like morphologies developed following pre-existing fractures has been ruled out based on the observation that V-shaped injectites and polygonal-faults have mostly non-overlapping dip populations (Huuse and Mikelson, 2004; Huuse et al., 2005; Shoulders et al., 2007). New observations from reservoirs (e.g. Hamsun 24/9-7, North Sea) reveal that the whole sand-body was injected to form the saucer-shaped intrusions. Recent seismic data from the Gamma Field in the North Sea (Huuse et al., 2004) show interconnected and superposed saucer-shaped sand intrusions (Figs. 1B, 3D). The main triggering factors for injected sands are considered to be earthquake-induced liquefaction or large pore fluid pressure increase caused by the addition of hydrocarbon-rich fluids (Lonergan et al., 2000a; Jolly and Lonergan, 2002; Mazzini et al., 2003; Huuse et al., 2005; Duranti and Mazzini, 2005).

4. Emplacement processes of saucer-shaped intrusions

The main observations common to saucer-shaped magmatic and sand intrusions are:

- The saucer morphology occurs in undeformed sedimentary basins.
- The inclined sheets cross-cut sub-horizontal sedimentary strata.
- The overlying strata are lifted to form dome-like structures.
- Saucer-shaped intrusions are interconnected and superposed to form sill (or sand) complexes.

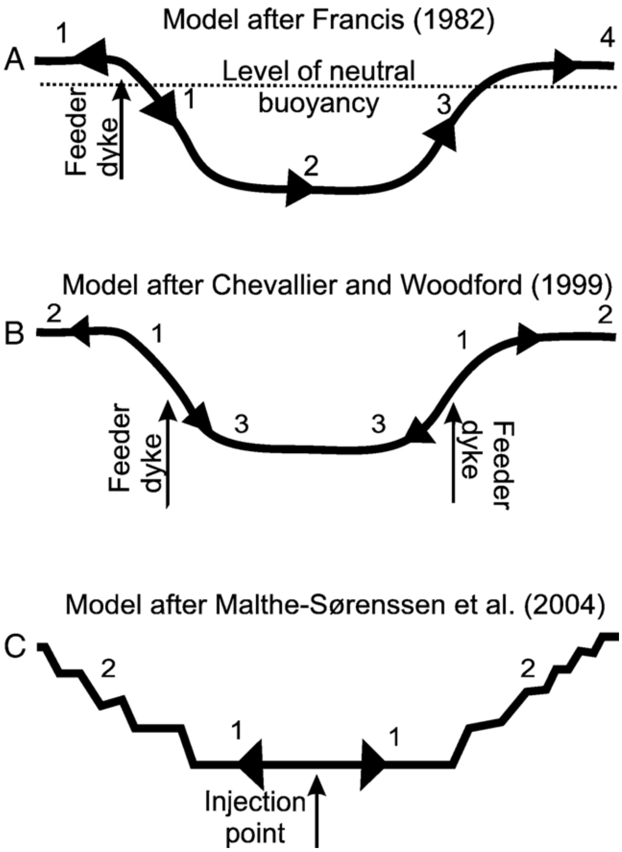

Fig. 3. A) Francis (1982); B) Chevallier and Woodford (1999), and C) Malthe-Sørenssen et al. (2004) models of magma emplacement. The numbers show the progression of the intruding magma. The individual models are characterised by different feeders and magma flow directions.

The recurrence of saucer-shaped intrusions in sedimentary basins suggests that the formation of these features is controlled by similar physical processes.

One set of models is based on field observations and theoretical considerations. The models assume that saucer-shaped intrusions are dyke-fed and that the downward and upward magma flow is largely controlled by the level of neutral buoyancy. Bradley (1965) first proposed the concept of “compensation level” that corresponds to depths where the magma pressure equals the lithostatic pressure. Bradley’s model implies that the sill geometry represents a mirror image of the topography, which in turn controls the lithostatic pressure. Francis (1982) and Goultry (2005) developed this concept further, suggesting that the magma can exceed the compensation level (Fig. 3A). Once the compensation level exceeded, the magma can subsequently flow a) gravitationally downward to the inner sill via the inclined sheets due to magma/host-rock density differences; and b) upward to the opposite outer sill via the inclined sheets due to hydrostatic equilibrium requirements. Chevallier and Woodford (1999) explain the formation of the inner sill by a descending magma flow controlled by the country-rocks downward fracturation due to the overburden uplift (Fig. 3B) (Chevallier and Woodford, 1999).

Another set of models are based on field observations, numerical and analogue modelling. These models consider a point source feeding the saucer-shaped intrusions with upward magma flow. In these models, the interaction with the free surface is more important than the level of neutral buoyancy.

Pollard and Johnson (1973) carried out experiments on the emplacement of flat-lying laccoliths by injecting low-viscosity grease into gelatine. Besides laccoliths, Pollard and Johnson obtained a saucer-shaped intrusion during their experiments. Pollard and Holzhausen (1979) and Fialko (2001) explained this result theoretically as due to interactions between an initially horizontal fluid-filled crack that propagates into an elastic media near a deformable free surface. These authors consider a low-viscosity fluid that propagates by hydraulic fracturing parallel to the maximum principal stress (σ_1). Doming of the overburden develops with increased growth and inflation of the sill and generates an asymmetric stress field at the sill tips causing σ_1 to rotate. Consequently the propagation direction of the fracture is deflected to form inclined sheets.

Recent experimental and numerical simulations consist of injecting a low-viscosity fluid at the level of neutral buoyancy into an elastic medium (Malthe-Sørenssen et al., 2004; Bunger et al., 2005). Initially, the intrusion develops into a sub-horizontal inner sill that will inflate and deform the overburden. The orientation of the inner sill is controlled by a symmetrical stress field at the sill tip (Malthe-Sørenssen et al., 2004). When the inner sill diameter exceeds the overburden thickness, the deformation and uplift of the overburden increase and cause the stress field at the sill tips to become asymmetrical (Malthe-Sørenssen et al., 2004; Bunger et al., 2005). Consequently the inner sill branches steeply upwards to form inclined sheets due to the asymmetry of the stress field. Once the level of neutral buoyancy is exceeded, the ascent of the inclined sheets decreases due to internal pressure reduction which, in turn, causes the stress field at the sill tips to be symmetrical (Malthe-Sørenssen et al., 2004). The inclined sheets can then develop into sub-horizontal outer sills as the intrusion propagates further (Fig. 3C).

Additional experimental modelling simulates the sedimentary rock behaviours by using a Mohr–Coulomb material, which fails in shear mode. Galland (2005), Galland et al. (2006), successfully reproduced saucer-like morphologies and associated doming of the free surface. In their experiments, peripheral shear-bands develop and control the formation of steeply dipping inclined sheets (40°–60°).

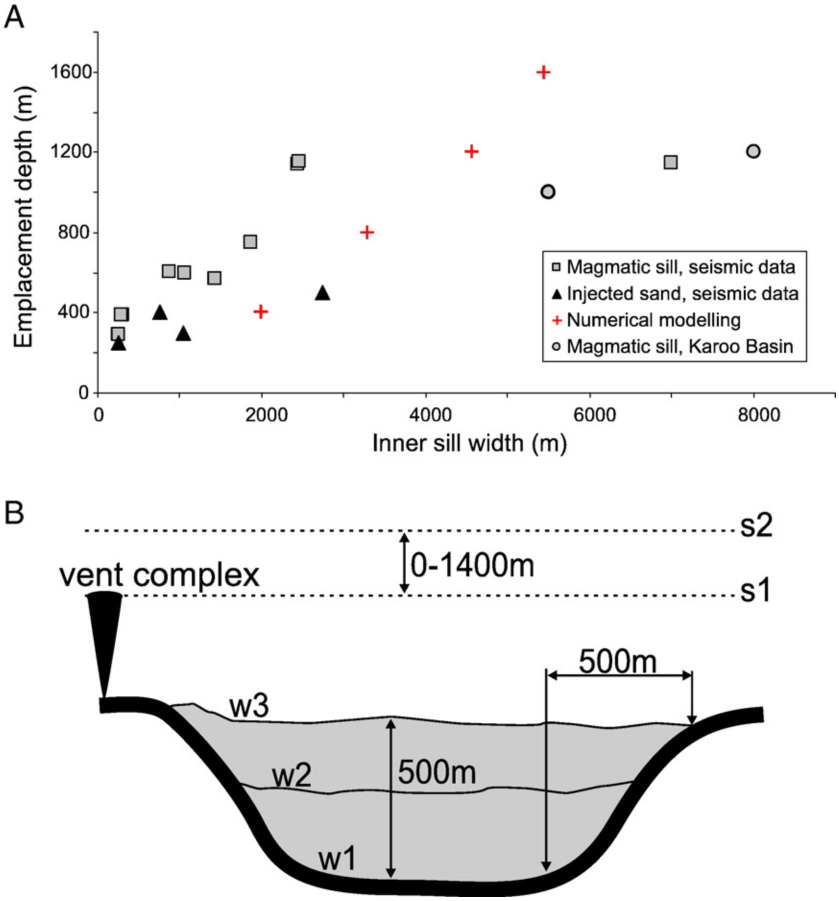

Fig. 4. A) Bivariate plot showing the relationship between the sill basal widths (i.e. inner sill diameter) vs. their corresponding emplacement depths. Data is from Table 1. The dimensionless values from the numerical model of Malthe-Sørenssen et al. (2004) were divided by 5. B) Schematic representation of maximum uncertainties in measuring the diameter of the inner sill and the depth of emplacement.w1, w2 and w3: erosional levels 1, 2 and 3. s1 is the top Clarens paleosurface, s2: is the top of the Lesotho lava. Additional paleosurface(s) may be present between s1 and s2.

5. Discussion

5.1. Depth/size relationship

The relationship between the size (inner sill diameter) and the emplacement depth of the intrusions can be measured using seismic, outcrop and numerical data (Fig. 4, Table 1). The reliability of the inner sill and emplacement depth measurements are very good on seismic data. The uncertainty of the emplacement depth is generally within a few hundred meters, depending on the accuracy of the time-depth curve and the seismic picking of the paleosurface (Planke et al., 2005). The emplacement depth of the sand intrusions corresponds to the elevation difference between the inner sill and outer sill because the outer sill is interpreted as material erupted on the paleosurface (Hurst et al., 2003b; Duranti and Hurst, 2004; Huuse et al., 2004, 2005; Shoulders et al., 2007). Core studies and petrographic/geochemical analyses imply that most of the injections occurred at shallow burial depth of few hundred meters (Mazzini et al., 2003; Hurst et al., 2003b; Huuse et al., 2004; Duranti and Mazzini, 2005).

The size and emplacement depth measurements of exposed sand intrusions and saucer-shaped sills are more uncertain. The poor reliability of sand intrusions measurements reflects the general low outcrop quality that inhibited the recognition of the saucer morphology. In the Karoo Basin, the magmatic inner sill diameter may be over-estimated by up to ~1000 m and the emplacement depth may be under-estimated by up to ~500 m depending on the erosional levels (Fig. 4B). Additional uncertainties for the emplacement depth correspond to unknown number of intrusive events and hence positions within the 1400 m thick Lesotho basalts of corresponding paleosurfaces (Jourdan et al., 2007). Outcrops of hundreds of craters of hydrothermal vent complexes in the Clarens Formation are the only evidence for the presence of a major syn-intrusive paleosurface and suggest that the majority of the sills were emplaced immediately before the Lesotho basalt eruption (Svensen et al., 2006, 2007). Thus the reliability for the emplacement depth of the Karoo saucer-shaped sills is a) within a few hundred meters when a given sill can be directly associated with a hydrothermal vent complex, b) within ~1500 m when the inner sill elevation is know and c) up to ~2000 m when the inner sill is not exposed.

Table 1
Inner sill diameter versus depth of emplacement for selected saucer-shaped intrusions

67-A (Norwegian Sea)	1870	749	Hansen, 2004	S
67-B (Norwegian Sea)	1434	572	Hansen, 2004	S
38-41 (Norwegian Sea)	867	602	Hansen, 2004	S
38-40 (Norwegian Sea)	1057	601	Hansen, 2004	S
38-45 (Norwegian Sea)	310	387	Hansen, 2004	S
38-38 (Norwegian Sea)	280	386	Hansen, 2004	S
38-46 (Norwegian Sea)	254	294	Hansen, 2004	S
Tulipan (Norwegian Sea)	7000	1150	This study	S
Qoqodala ring (South Africa)	8000	1200	This study	O
Golden Valley Sill (South Africa)	5500	1000	This study	O
Gamma (North Sea)	2750	500	Huuse, pers. comm.	S
Hamsun (North Sea)	750	400	Hurst et al., 2003a,b	S
Faroe-Shetland basin	250	250	Shoulders et al., 2007	S
Alba (North Sea)	1050	300	Duranti et al., 2002	S
numerical model	1982.5	400	Malthe-Sørenssen et al., 2004	N
numerical model	3275	800	Malthe-Sørenssen et al., 2004	N
numerical model	4555	1200	Malthe-Sørenssen et al., 2004	N
numerical model	5430	1600	Malthe-Sørenssen et al., 2004	N

S = seismic reflection data, O = outcrop, N = numerical modeling.

Fig. 4A suggests a linear relationship between the emplacement depth and the inner sill diameter. This relationship is supported by numerical and analogue modelling showing that the spacing between the inclined sheets, and thus the saucer dimensions, are depth dependant. In particular, Malthe-Sørenssen et al. (2004) show that the diameter of the sub-horizontal inner sill is 4–5 times the thickness of the overburden. A near-linear correlation is also confirmed by experiments using Mohr–Coulomb materials (Galland et al., 2007).

5.2. Saucer as a fundamental geometry

The emplacement models for the saucer-shaped magmatic intrusions reflect:

- The low-viscosity nature of the injected fluid.
- The tensile strength of the country rock allowing hydraulic fracturing.
- The elastic interactions of the inflating sill intrusion with the deforming free surface.
- The development of an asymmetrical stress field at the sill tips.

None of these models accounts for magma temperature and the models are therefore also suitable for modelling the emplacement of saucer-shaped sand intrusions. The physical processes forming saucer-shaped sand and magma intrusions must therefore be similar because the controlling parameters and resulting structures are identical.

Saucer-shaped intrusions form at shallow depths (1–5 km) because the Earth's surface represents the easiest boundary to deform. Based on theoretical considerations, deep intrusions may develop an upside-down saucer-like morphology: the intrusion will preferentially deform underlying poorly competent rocks (e.g. salt deposits and shales) rather than lifting the overburden. However upside-down saucer-shaped intrusions have not been described yet in the literature.

The governing physical processes responsible for the development of saucer-like morphologies have a wide-range of industrial applications. Economic implications might become significant as the intrusions represent pathways for the early or late stage migration of water and/or hydrocarbon-rich fluids. In the mining industry the danger of catastrophic roof-collapse in underground excavations can be avoided by controlled roof-caving that isolate blocks along a saucer-shaped fracture (Jeffrey and Mills, 2000). The environmental remediation industry also uses artificially-generated sand-filled saucer-shaped fractures in soils to increase recovery of contaminants at spill-sites (Bunger, 2005; Bradner and Murdoch, 2005).

Many of the large-scale saucer-shaped intrusions can be identified as ring structures with satellite imagery. A similar strategy can be applied for the search of saucer-shaped intrusions in space-exploration programs by using the Earth as analogue. Both Mars and Venus represent the primary target because both planets have experienced intense volcanism.

6. Conclusions

Saucer-shaped sills and injected sands are common in sedimentary basins. Saucer-shaped intrusions are generated by the interaction of a low-viscosity fluid-filled shallow hydraulic fracture and the overburden deformations, both of which control the symmetry of the stress field at the sill tip. A correlation factor of 4–5 between the inner sill diameter and the depth of emplacement exists for both types of intrusions. Saucer-shaped intrusions can develop in materials with totally different physical properties (i.e. elastic and Mohr–Coulomb materials) and therefore represent a fundamental geometry in natural systems. Hydraulic fracturing forming saucer-shaped structures is a multi-scale process, varying from 10's of kilometres for magmatic sills, kilometres for sand intrusions, meters for mining roof-caving, and centimetres in laboratory specimens.

This article envisages the beginning of new cross-disciplinary collaborations for further research on the identification and understanding of other occurrences of saucer geometries developed by magmatic and sand intrusions.

Acknowledgements

H. Svensen, D. Duranti, A. Bunger and M. Huuse are thanked for their fruitful discussion and suggestions. We are grateful to STATOIL for authorizing the publication of Fig. 2, D. Liss for providing Fig. 3, and D.M. Hansen for providing part of Table 1. C. Jaupart and the reviewers are thanked for their constructive comments. We gratefully acknowledge support from the Norwegian Research Council (grant 159824/V30, "Emplacement mechanisms and magma flow in sheet intrusions in sedimentary basins").

References

Aiello, I.W., 2005. Fossil seep structures of the Monterey Bay region and tectonic/structural controls on fluid flow in an active transform margin. Palaeogeogr. Palaeoclimatol. Palaeoecol. 227, 124–142.

Anderson, E.M., 1951. The dynamics of faulting and dyke formation with applications to Britain. Oliver and Boyd. 206 pp.

Blatt, H., Tracy, R.J., Owens, B., 2005. Petrology: igneous, sedimentary and metamorphic. W.H. Freeman. 530 pp.

Boehm, A., Moore, J.C., 2002. Fluidized sandstone intrusions as an indicator of Palaeostress orientation, Santa Cruz, California. Gefluids 2, 147–161.

Bradley, J., 1965. Intrusion of major dolerite sills. Trans. R. Soc. N. Z. 3, 27–55.

Bradner, G.C., Murdoch, L.C., 2005. Effects of skin and hydraulic fractures on SVE wells. J. Contam. Hydrol. 77, 271–297.

Bunger, A.P., 2005. Near-surface hydraulic fracture, PhD, University of Minnesota.

Bunger, A.P., Detournay, E., Jeffrey, R.G., 2005. Crack tip behavior in near-surface fluid-driven fracture experiments. C. R., Mec. 333, 299–304.

Chevallier, L., Woodford, A., 1999. Morpho-tectonics and mechanism of emplacement of the dolerite rings and sills of the western Karoo, South Africa. S. Afr. J. Geol. 102, 43–54.

Davies, R.J., 2003. Kilometer-scale fluidization structures formed during early burial of a deepwater slope channel on the Niger Delta. Geology 31, 949–952.

Dixon, R.J., Schofield, K., Anderton, R., Reynolds, A.D., 1995. Sandstone diapirism and clastic intrusion in the Tertiary submarine fans of the Bruce–Beryl Embayment, Quadrant 9, UKCS. In: Hartley, A.J., Prosser, D.J. (Eds.), Characterization of Deep Marine Clastic Systems, vol. 94. Geological Society of London, pp. 77–94. Special Publication.

Duranti, D., Hurst, A., 2004. Fluidization and injection in the deep-water sandstones of the Eocene Alba Formation (UK North Sea). Sedimentology 51, 503–529.

Duranti, D., Mazzini, A., 2005. Large-scale hydrocarbon-driven sand injection in the Paleogene of the North Sea. Earth Planet. Sci. Lett. 239, 327–335.

Duranti, D., Hurst, A., Bell, C., Groves, S., Hanson, R., 2002. Injected and remobilized Eocene sandstones form the Alba Field, UKCS: care and wireline log characteristics. Pet. Geosci. 8, 99–107.

Fialko, Y., 2001. On origin of near-axis volcanism and faulting at fast spreading mid-ocean ridges. Earth Planet. Sci. Lett. 190, 31–39.

Francis, E.H., 1982. Magma and sediment — I. Emplacement mechanism of late Carboniferous tholeiite sills in northern Britain. J. Geol. Soc. Lond. 139, 1–20.

Galland, O., 2005. Interactions mécaniques entre la tectonique compressive et le magmatisme: expériences analogiques et un exemple naturel, PhD thesis, Université de Rennes1.

Galland, O., Cobbold, P.R., Hallot, E., de Bremond d'Ars, J., Delavaud, G., 2006. Use of vegetable oil and silica powder for scale modelling of magmatic intrusion in a deforming brittle crust. Earth Planet. Sci. Lett. 243, 786–804.

Galland, O., Polteau, S., Planke, S., Mazzini, A., Malthe-Sorenssen, A., Svensen, H., Neumann, E.-R., Gundersen, O., 2007. Mechanisms of saucer-shaped sill emplacement and associated doming: insights from experimental modelling. EGU 2007, Vienna.

Goultry, N.R., 2005. Emplacement mechanism of the Great Whin and Midland Valley dolerite sills. J. Geol. Soc. Lond. 162, 1047–1056.

Gretener, P.E., 1969. On the mechanics of the intrusion of sills. Can. J. Earth Sci. 6, 1415–1420.

Hansen, D.M., Cartwright, J.A., 2006. Saucer-shaped sill with lobate morphology revealed by 3D seismic data: implications for resolving a shallow-level sill emplacement mechanism. J. Geol. Soc. Lond. 163, 509–523.

Hansen, D.M., Cartwright, J.A., Thomas, D., 2004. 3D seismic analysis of the geometry of igneous sills and sill junctions relationships. In: Davies, R.J., Cartwright, J.A., Stewart, S.A., Lappin, M., Underhill, J.R. (Eds.), 3D Seismic Technology: Application to the Exploration of Sedimentary Basins 29. Geological Society, London, pp. 199–208. Memoirs.

Hansen, D.M., Redfern, J., Federici, F., di Biase, D., Bertozzi, G., in press. Miocene igneous activity in the Northern Subbasin, offshore Senegal, NW Africa. Marine and Petroleum Geology. doi:10.1016/j.marpetgeo.2007.04.007

Hubbert, M.K., Willis, D.G., 1957. Mechanics of hydraulic fracturing. In: Hubbert, M.K. (Ed.), Structural Geology. Hafner Publishing Company, New York, pp. 175–190.

Hurst, A., Buller, A.T., 1984. Dish structures in some Paleocene deep-sea sandstones (Norwegian sector, North Sea): origin of the dish-forming clays and their effect on reservoir quality. J. Sediment. Petrol. 54, 1206–1211.

Hurst, A., Cartwright, J., Duranti, D., 2003a. Fluidization structures produced by upward injection of sand through a sealing lithology. In: Van Rensbergen, P., Hillis, R.P., Maltman, A.J., Morley, C.K. (Eds.), Subsurface sediment mobilization 216. Special Publication—Geological Society of London, pp. 123–137.

Hurst, A., Cartwright, J., Huuse, M., Jonk, R., Schwab, A., Duranti, D., Cronin, B., 2003b. Significance of large-scale sand injectites as long-term fluid conduits: evidence from seismic data. Geofluids 3, 263–274.

Huuse, M., Mickelson, M., 2004. ocene sandstone intrusions in the Tampen Spur area (Norwegian North Sea Quad 34) imaged by 3D seismic data. Mar. Pet. Geol. 21, 141–155.

Huuse, M., Duranti, D., Steinsland, N., Guargena, C., Prat, P., Holm, K., Cartwright, J.A., Hurst, A., 2004. Seismic characteristics of large-scale sandstone intrusions in the Paleogene of the South Viking Graben, UK and Norwegian North Sea. In: Davies, R., Cartwright, J.A., Stewart, S.A., Underhill, J.R., Lappin, M. (Eds.), 3D Seismic Data: Application to the Exploration of Sedimentary Basins 29. Geological Society, London Memoir, pp. 263–277.

Huuse, M., Cartwright, J., Gras, R., Hurst, A., 2005. Kilometre-scale sandstone intrusions in the Eocene of the Outer Moray Firth (UK North Sea): migration paths, reservoirs and potential drilling hazards. In: Dore, A.G., Vining, B.A. (Eds.), Petroleum Geology: North-West Europe and Global Perspectives — Proceedings of the 6th Petroleum Geology Conference. The Geological Society, London, pp. 1577–1594.

Jeffrey, R.G., Mills, K.W., 2000. Hydraulic fracturing applied to inducing longwall coal mine goaf falls. In: Girard, J., Liebman, M., Breeds, C., Doe, T. (Eds.), Pacific rocks 2000 — Proceedings 4th North American rock mechanics symposium, Seatle, WA, pp. 423–430.

Jolly, R.J.H., Lonergan, L., 2002. Mechanism and control on the formation of sand intrusion. Journal — Geological Society 159, 605–617.

Jonk, R., Duranti, D., Parnell, J., Hurst, A., Fallick, A.E., 2003. The structural and diagenetic evolution of injected sandstones, examples from the Kimmeridgian of NE Scotland. J. Geol. Soc. Lond. 160, 881–894.

Jourdan, F., Feraud, G., Bertrand, H., Watkeys, M.K., Renne, P.R., 2007. Distinct brief major events in the Karoo large igneous province clarified by new 40Ar/39Ar ages on the Lesotho basalts. Lithos 98, 195–209.

Kavanagh, J.L., Menand, T., Sparks, R.S.J., 2006. An experimental investigation of sill formation and propagation in layered elastic media. Earth Planet. Sci. Lett. 245, 799–813.

Keating, G.N., Geissman, J.W., Zyvoloski, G.A., 2002. Multiphase modeling of contact metamorphic systems and application to transitional geomagnetic fields. Earth Planet. Sci. Lett. 198, 429–448.

Leaman, D.E., 1975. Form, mechanism and control of dolerite intrusion near Hobart, Tasmania. J. Geol. Soc. Aust. 22, 177–186.

Liss, D., Hutton, D.H.W., Owens, W.H., 2002. Ropy flow structures: a neglected indicator of magma-flow direction in sills and dikes. Geology 30.

Liss, D., Emplacement processes and magma flow geometries of the Whin Sill complex., PhD, University of Birmingham, 2003.

Lister, J.R., 1990. Buoyancy-driven fluid fracture. Similarity solutions for the horizontal and vertical propagation of fluid-filled cracks. J. Fluid Mech. 217, 213–239.

Lonergan, L., Lee, N., Johnson, H., Cartwright, J.A., Jolly, R., 2000a. Remobilization and injection in deep water depositional systems: implication for reservoir architecture and prediction. In: Wiemer, P., Slatt, R.M., Coleman, J., Others (Eds.), Deep water Reservoirs of the World. GCSSEPM Foundation 20th Annual Bob F. Perkins Research Conference, pp. 515–532.

Lonergan, L., Lee, N., Johnson, H.D., Cartwright, J.A., Jolly, R.J.H., 2000b. Remobilization and injection in deepwater depositional systems: implications for reservoir architecture and prediction. In: Weimer, R.M.S.P., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., Lawrence, D.T. (Eds.), Deep-Water Reservoirs of the World. GCSSEPM Foundation, 20th Annual Conference, Houston, pp. 515–532.

MacLeod, M.K., Hanson, R.A., Bell, C.R., McHugo, S., 1999. Alba Field ocean bottom cable seismic survey: Impact on development. The Leading Edge 18, 1306–1312.

Malthe-Sørenssen, A., Planke, S., Svensen, H., Jamtveit, B., 2004. Formation of saucer-shaped sills. In: Breitkreuz, C., Petford, N. (Eds.), Physical geology of high-level magmatic systems 234. Geological Society, London, pp. 215–227.

Mazzini, A., Duranti, D., Jonk, R., Parnell, J., Cronin, B.T., Hurst, A., Quine, M., 2003. Palaeo-carbonate seep structures above an oil reservoir, Gryphon Field, Tertiary, North Sea. Geo Mar. Lett. 23, 323–339.

Møller, N.K., Kjaernes, P.A., Martinsen, O.J., Charnock, M.A., 2001. Remobilised sands at the Cretaceous/Tertiary boundary in the Ormen Lange Field, offshore mid Norway, Subsurface Sediment Mobilisation Conference, September 2001 Abstract Volume, Gent, Belgium, p. 13.

Molyneux, S., Cartwright, J., Lonergan, L., 2002. Technical article: Conical sandstone injection structures imaged by 3D seismic in the central North Sea, UK. First Break 20, 383–394.

Mudge, M.R., 1968. Depth control of some concordant intrusions. Geol. Soc. Am. Bull. 79, 315–332.

Planke, S., Rasmussen, T., Rey, S.S., Myklebust, R., 2005. Seismic characteristics and distribution of volcanic intrusions and hydrothermal vent complexes in the Vøring and Møre basins. In: Doré, A.G., Vining, B.A. (Eds.), Petroleum geology: Northwest Europe and global perspectives. Geological Society, London, pp. 833–844.

Pollard, D.D., Holzhausen, G., 1979. On the mechanical interaction between a fluid-filled fracture and the Earth's surface. Tectonophysics 53, 27–57.

Pollard, D.D., Johnson, A.M., 1973. Mechanics of growth of some laccolithic intrusions in the Henry Mountains, Utah, II. Bending and failure of overburden layers and sill formation. Tectonophysics 18, 311–354.

Rocchi, S., Mazzotti, A., Marroni, M., Pandolfi, L., Costantini, P., Giuseppe, B., Biase, D.d., Federici, F., Lo, P.G., 2007. Detection of Miocene saucer-shaped sills (offshore Senegal) via integrated interpretation of seismic, magnetic and gravity data. Terra Nova 19, 232–239.

Rossello, E.A., Cobbold, P.R., Diraison, M., Arnaud, N., 2002. Auca Mahuida (Neuquén basin, Argentina): A Quaternary shield volcano on a hydrocarbon-producing substrate. 5th International Symposium on Andean Geodynamics (ISAG 2002), Extended Abstracts, Toulouse, pp. 549–552.

Schutter, S.R., 2003. Hydrocarbon occurrence and exploration in and around igneous rocks. Geological Society of London Special Publications. 7–33 pp.

Shoulders, S.J., Cartwright, J., Huuse, M., 2007. Large-scale conical sandstone intrusions and polygonal fault systems in Tranche 6, Faroe-Shetland Basin. Mar. Pet. Geol. 24, 173–188.

Sibson, R.H., 2003. Brittle-failure controls on maximum sustainable overpressure in different tectonic regimes. Am. Assoc. Pet. Geol. Bull. 87, 901–908.

Smallwood, J.R., Maresh, J., 2002. The properties, morphology and distribution of igneous sills: modelling, borehole data and 3D seismic from the Faroe-Shetland area. In: Jolley, W.D., Bell, R.B. (Eds.), Special Publications, vol. 197. Geological Society, London, pp. 1–35.

Surlyk, F., Noe-Nygaard, N., 2001. Sand remobilisation and intrusion in the Upper Jurassic Hareelv Formation of East Greenland. Bull. Geol. Soc. Den. 48, 169–188.

Svensen, H., Jamtveit, B., Planke, S., Chevallier, L., 2006. Structure and evolution of hydrothermal vent complexes in the Karoo Basin, South Africa. J. Geol. Soc. Lond. 163, 1–12.

Svensen, H., Planke, S., Chevallier, L., Malthe-Sorenssen, A., Corfu, F., Jamtveit, B., 2007. Hydrothermal venting of greenhouse gases triggering Early Jurassic global warming. Earth Planet. Sci. Lett. 256, 554–566.

Symond, P.A., Planke, S., Frey, Ø., Skogseid, J., 1998. Volcanic development of the Western Australian continental margin and its implications for basin development. Petroleum exploration society of Australia, Perth, Australia.

Thompson, B.J., Garrison, R.E., Casey Moore, J., 1999. A late Cenozoic sandstone intrusion west of Santa Cruz, California: fluidized flow of water- and hydrocarbon saturated sediments. In: Garrison, R.E., Aiello, I.W., Casey Moore, J. (Eds.), Late Cenozoic fluid seeps and tectonics along the San Gregorio fault zone in the Monterey Bay region, California GB-76, Annual Meeting of the Pacific Section AAPG, Monterey, California, pp. 53–74.

Thomson, K., Hutton, D., 2004. Geometry and growth of sill complexes: insights using 3D seismic from the North Rockall Trough. Bull. Volcanol. 66, 364–375.