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SEISMIC IMAGING AND PETROLEUM IMPLICATIONS OF IGNEOUS INTRUSIONS IN SEDIMENTARY BASINS CONSTRAINED BY OUTCROP ANALOGUES AND SEISMIC DATA FROM THE NEUQUÉN BASIN AND THE NE ATLANTIC

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ABSTRACT

Igneous sheet intrusions are commonly present in prospective sedimentary basins worldwide and may have a wide impact on all aspects of a working petroleum system including maturation, migration, and trapping of hydrocarbons. We have interpreted a major sill complex of 80,000 km2 in the Vøring and Møre basins offshore mid-Norway based on seismic characteristics such as high amplitude reflections and saucer-shaped geometries. The sills are commonly associated with pipe-like hydrothermal vent complexes. However, only a few intrusions and vents have been drilled in this region. Recently we have conducted field work in the Neuquén Basin, Argentina, on kilometer-scale outcrop sections where sill complexes are intruded into Cretaceous host rocks, in order to better constrain the seismic wave propagation and imaging implications of sill-sediment complexes. Seismic modeling studies based on field analogues represent an important tool to close the scale gap between observations from outcrops and seismic data and to support seismic interpretation. Virtual outcrop models are generated based on photogrammetric imaging, and seismic properties are constrained from borehole data. Our results indicate that the seismic signatures of outcrop-scale geological features observed in field analogues are characterized by frequency-dependent interference and strong variations depending on the elastic properties of both host rock and sills. The high velocity of intrusions leads to strong attenuation, offset-dependent tuning, post-critical reflections, and converted waves. The results from the integrated modeling approach have led to more reliable interpretations of the presence, thickness, and distribution of sills in seismic data in volcanic basins, and an understanding of the implications of sills on the hydrocarbon system in extensional and compressional basins.

RESUMEN

Las intrusiones ígneas laminares o filones-capa o sills están comúnmente presentes en varias cuencas sedimentarias prospectadas a través del mundo, y pueden tener un gran impacto sobre el sistema petrolero en funcionamiento, incluida la maduración, la migración y la entrampamiento de hidrocarburos. Hemos interpretado un complejo de intrusiones ígneas tipo sill, de 80,000 km2, en las cuencas de Vøring y Møre, costa afuera de Noruega, basándonos en características sísmicas tales como reflexiones de gran amplitud y geometrías en forma de palangana. Los sills se asocian comúnmente con complejos de chimeneas hidrotermales, similares a tuberías. Sin embargo, solo se han perforado algunas intrusiones y chimeneas en esta región. Recientemente, hemos llevado a cabo trabajos de campo en la Cuenca Neuquina, Argentina, en secciones de afloramiento a escala kilométrica, donde se intruyen complejos de sills en rocas del Cretácico, con el objetivo de comprender mejor la propagación de ondas sísmicas y las implicaciones de los complejos de sills-sedimentos. Los estudios de modelado sísmico basados en análogos de campo representan una herramienta importante para cerrar la brecha de escala entre las observaciones de los afloramientos y los datos sísmicos, y para apoyar la interpretación sísmica. Los modelos de afloramiento virtual se generan en base a imágenes fotogramétricas, y las propiedades sísmicas han sido determinadas a partir de datos de pozos. Nuestros resultados indican que las señales sísmicas de los rasgos geológicos a escala de afloramiento, observados en los análogos de campo, se caracterizan por una interferencia dependiente de la frecuencia y fuertes variaciones que dependen de las propiedades elásticas, tanto de la roca de caja como de los sills. Las altas velocidades de las intrusiones producen una fuerte atenuación, unaentonación/tuning dependiente deloffset/distancia fuente-receptor, reflexiones poscríticas y ondas convertidas. Los resultados del modelo integrado han permitido lograr interpretaciones más confiables de la presencia, grosor y distribución de sills en datos sísmicos en cuencas volcánicas, y una comprensión de las implicaciones de sills en el sistema de hidrocarburos en régimen extensional y compresional.

INTRODUCTION

Extrusive and intrusive igneous rocks are present in many sedimentary basins. Volcanic basins are here defined as sedimentary basins containing a significant volume of primary deposited igneous rocks (Figure 1). The shallow plumbing system of volcanic basins typically consist of a network of interconnected sills and dykes. Sill intrusions are dominantly layer-parallel in the deepest part of the basin (>5 km), but commonly develop characteristic saucer-shaped geometries at intermediate depths. Sub-horizontal sheets and peperites are more abundant in the uppermost kilometer, whereas dikes are less common. In some basins, pipe-like hydrothermal vent complexes (HTVCs) connect the tip of sill intrusions with the paleosurface. These vent complexes are formed as a consequence of gas generation and pressure build-up in metamorphic aureoles around cooling intrusions, and consist mainly of fractured and remobilized sediments. Lava fields are formed by emplacement of lava erupted from volcanic vents or fissures. Explosive eruptions lead to deposition of tuff units, whereas hyaloclastites are formed by rapid lava cooling and fragmentation in coastal and lacustrine environments.

Major volcanic basins are present along the margins of the Atlantic Ocean and in intra-continental basins of the surrounding continents (Figure 2). Large Igneous Provinces (LIPs) are characterized by voluminous basaltic extrusive deposits emplaced in a short time interval of less than one to a few million years. LIPs include volcanic rifted margins (e.g. the NAIP and the S Atlantic margins), continental flood basalt provinces (e.g. the CAMP age Parana province in Brazil and the Karoo province in South Africa), and heavily intruded intra-continental basins (e.g. the HALIP aged East Barents Basin and the CAMP aged Amazon Basin). Volcanic basins are also present along compressional margins (e.g. the Neuquén Basin in Argentina).

Intrusive igneous complexes influence the basin temperature history, fluid flow, and structure, both during the time of magma emplacement and during the subsequent basin infill and subsidence (e.g. Senger *et al.* 2017). In some volcanic basins intensely fractured intrusions comprise atypical hydrocarbon reservoirs (Monreal *et al.* 2009; Witte *et al.* 2012), whereas elsewhere the intrusions may form seals. Accurate identification and mapping of intrusive complexes on seismic data can be challenging, where the sill complexes are typically thin high-velocity bodies causing transmission losses, interference, and scattering. The limited seismic resolution of conventional seismic reflection data (typically resolution limit of 30-60 m and detection limit of 5-10 m for igneous units) makes it important to study analogue outcrops to obtain reliable and detailed interpretations of volcanic basins.

We have conducted field work in the Neuqúen Basin during the past two decades, with a particular focus on the interaction of sedimentary and igneous sequences (e.g.Galland *et al.* 2007; Mazzini *et al.* 2010; Leanza *et al.* 2013). Recently, we have investigated spectacular outcrops of igneous sills emplaced in the organic-rich formations of the Mendoza Group. The most extensive

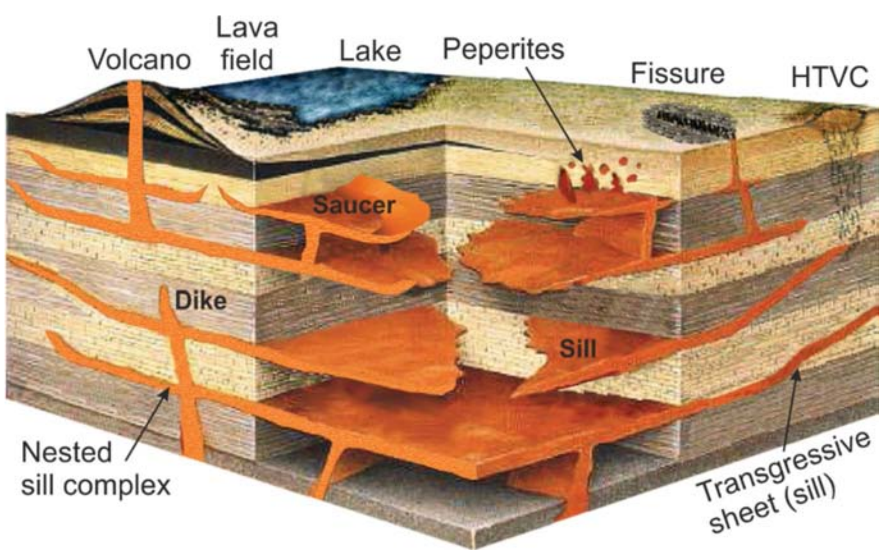

Figure 1. Cartoon showing the main igneous elements in a volcanic basin. Modified from http://thebritishgeographer.weebly.com/vulcanicity-and-seismicity.html.

outcrop is located approximately 10 km west of the Los Cavaos oil field, where the Sierra Azul basement thrust has brought to outcrop the organic-rich Vaca Muerta and Agrio formations intruded by numerous andesitic sills (Figure 3). This El Manzano outcrop expose a 4-km long section where both the sills and the host rock are accessible, and the outcrop is a direct analogue for the nearby oil fields (Spacapan *et al.* 2018). Another extensive outcrop is located a few kilometers east of the Las Loicas village, where intrusion fingers are emplaced within the Agrio Formation. Well-exposed sills and dikes are also exposed in recent roadcuts along the National Road 40 at Cuesta del Chihuido, 50 km south of Malargüe (Spacapan *et al.* 2016).

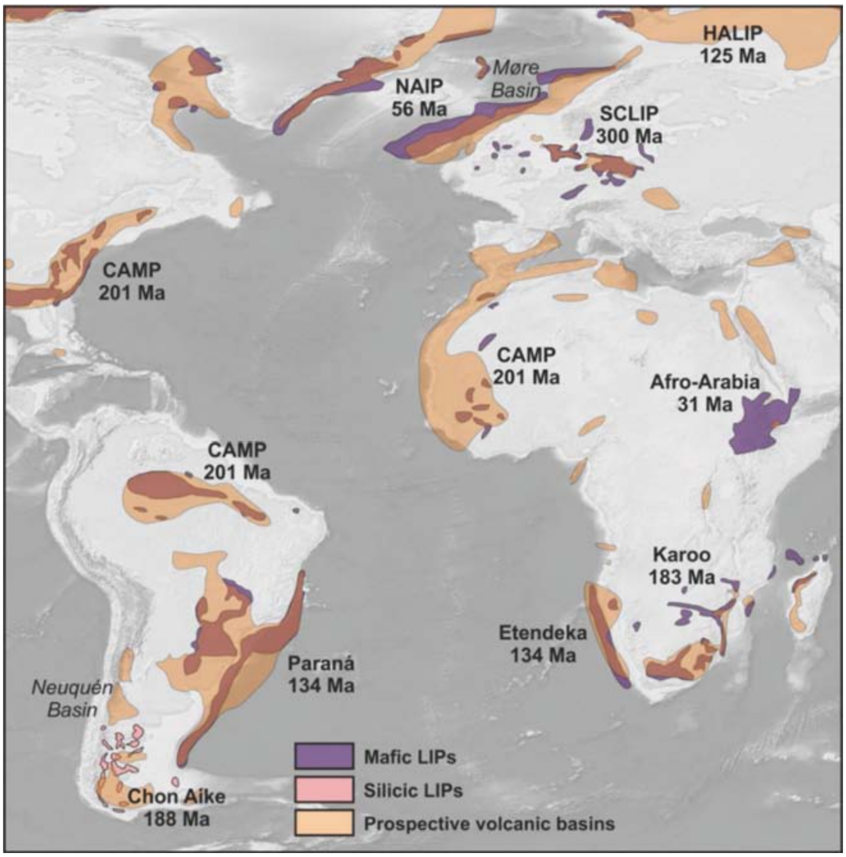

Figure 2. Distribution of large igneous provinces (LIPs) and prospective volcanic basins system in the Atlantic region where both syn- and post-magmatic influences comprise important elements of the petroleum system are highlighted. LIPs modified after Bryan and Ferrari (2013).

The aim of this study is to link outcrop exposures in the Neuquén Basin with seismic images from the NE Atlantic and Argentina to better constrain the seismic interpretation of the buried igneous complexes, including the interpretation of the thickness and extent of the sills, the estimation of the presence of sub-seismic scale intrusions, and the assessment of the lateral continuity of the intrusions. By generating and analyzing 3D outcrop models from the spectacular exposures in the Neuquén Basin, synthetic seismic modelling has been performed which enables sensitivity testing of key features of these settings in order to better assess real seismic examples. We furthermore provide a general synthesis of the positive and negative implications of igneous processes and deposits on the hydrocarbon system, with a particular focus on basins located in compressional settings.

DATA AND METHODS

The offshore dataset used here is from the mid-Norwegian continental margin which is covered by a dense grid of 2D and 3D seismic reflection data acquired by the petroleum industry, and about 25 exploration wells that have been drilled in the outer parts of the Vøring and Møre basins (e.g. http://www.tgs.com/data-library; http://www.npd.no). Over the past few decades, we have developed methods for seismic interpretation of igneous deposits in volcanic basins, including the concepts of seismic volcanostratigraphy (Planke *et al.* 2000; Abdelmalak *et al.* 2016a), sill complex interpretation (Planke *et al.* 2005; Planke *et al.* 2015), and igneous seismic geomorphology (Planke *et al.* 2017). The distribution and facies of the igneous complexes on the mid-Norwegian margin have been interpreted using a combination of KingdomSuite, DUG, and Petrel software.

In this project we have generated high-resolution 3D virtual outcrop models of several exposed andesitic sill complexes, including the El Manzano sill complex west of the Rio Grande Valley in the Neuqúen Basin (Figure 3). A 3D meshed surface model was computed using structure-from-motion photogrammetry (e.g. Westoby *et al.* 2012) from 254 partially overlapping photographs collected from a drone survey in 2015 (using a 12 megapixels built-in camera). The model texture built from the photographs was draped over the topographic surface model to give a fully scaled photorealistic 3D representation of the outcrop. The interpretation of the sill intrusions were performed directly on the virtual model resulting in a network of partly interconnected sills and sill fingers of <1 m to 30 m thickness, and sub-meter scale geological details such as intrusive steps, junctions, and sill-host rock lenses (for details, see Rabbel *et al.* 2018). The interpreted geometries were subsequently projected onto a vertical, outcrop-parallel plane.

The applied seismic modelling workflow was designed to compare different geological settings in which sills occur: (1) homogenous host rocks with average properties of clastic sediments, (2) layered host rock calibrated to the Norwegian margin clastic rocks, and (3) layered host rock calibrated to the organic-rich host rocks of the Neuquén Basin (Mendoza Group). We followed the seismic modelling procedure described by Rabbel *et al.* (2018). The homogenous model has a binary lithology (host versus intrusion) based on average values for clastic and igneous rocks (Magee *et al.* 2015). The layered Neuquén Basin model use Vp and density logs from a well in the nearby Los Cavaos oil field to derive an acoustic impedance (AI) log. Vs values were derived using fixed vp/vs rations or 1.8 for sediments and 1.9 for sills, respectively. The layered Norwegian margin model is populated using the same log values but scaled to a typical range for intruded

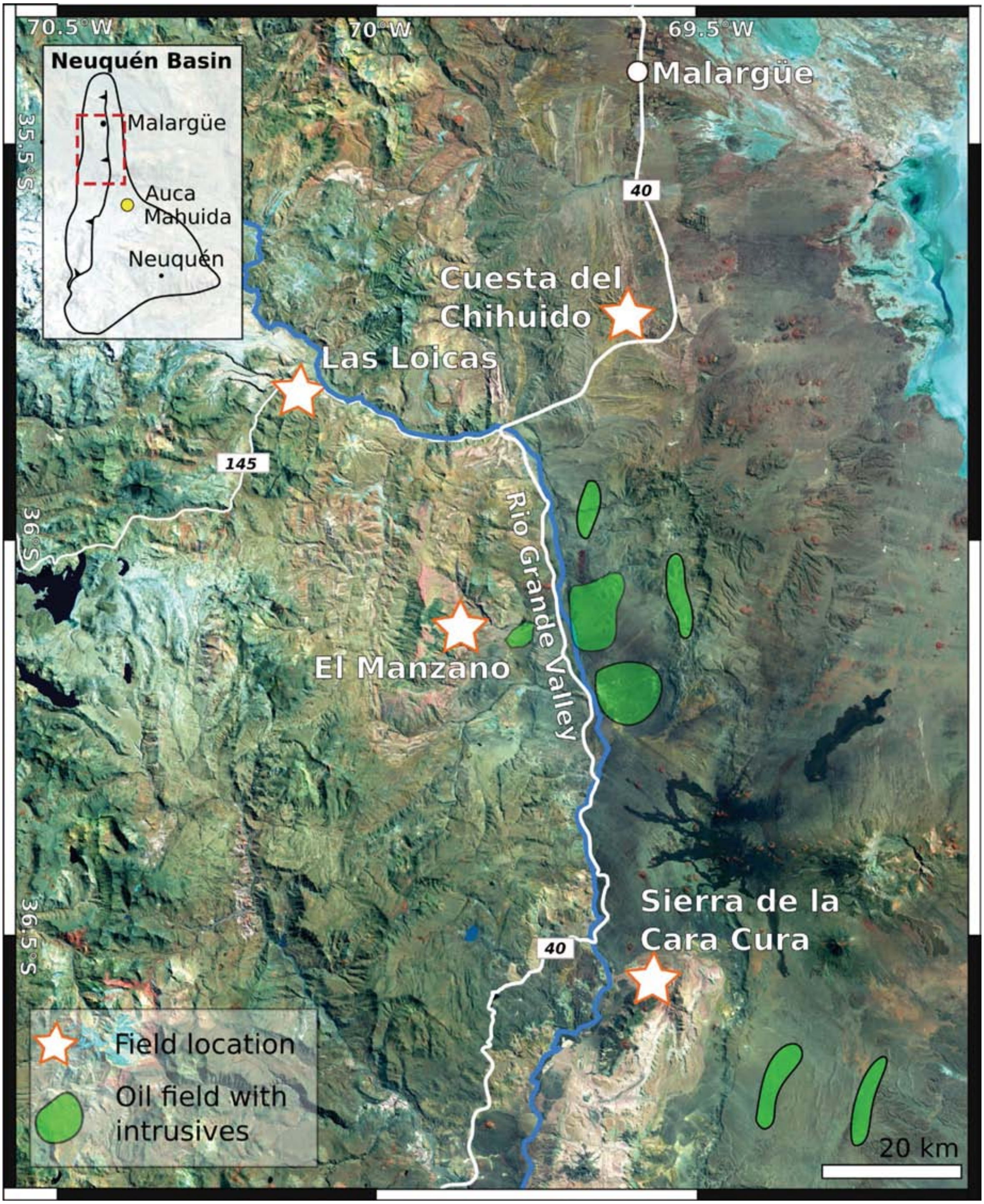

Figure 3. Map showing the Neuquén Basin study area south of Malargüe, Argentina. The stars indicate main outcrop localities of igneous sills, which we used as analogues to subsurface sill complexes. Note in particular the close proximity of the El Manzano outcrop to several oil fields in the Rio Grande valley, where the direct subsurface analogues are producing from igneous reservoirs. Landsat satellite image.

sediments in the NE Atlantic (e.g. Magee *et al.* 2015; Schmiedel *et al.* 2017). The sills have identical seismic properties in all the models. To create the synthetic seismic images, we employed a 2D convolution method which simulates pre-stack depth migrated (PSDM) seismic images (Lecomte 2008; Lecomte *et al.* 2015). Angle-dependent reflection coefficients were derived from vp, vs and density values in each formation. In lack of explicit survey geometries and accurate overburden models, we synthesized the 2D convolution operator based on Ricker wavelets that corresponds to a survey with maximum illuminated dip of 45 degrees. The seismograms obtained from this PSDM simulator do not offer as complete results as full-wavefield approaches, but the method has the major advantage of producing synthetic seismic sections very rapidly and at low cost (Lecomte 2008).

NE ATLANTIC

The northeast Atlantic region experienced a long period of extension and sedimentary basin formation after the collapse of the Caledonian mountain chain in the Devonian, culminating with the continental breakup of northwest Europe and Greenland in the earliest Eocene, about 55 million years ago (e.g. Doré *et al.* 1999). Deep Cretaceous basins are located on the mid-Norwegian margin and on the conjugate northeast Greenland shelf, and are dominantly filled with up to 5-10 km thick sequences of shales and minor sandstones. Massive breakup-related magmatism occurred during the late Paleocene and earliest Eocene (60-54 Ma), with the most voluminous activity near the Paleocene-Eocene boundary (55.8 Ma; Svensen *et al.* 2010). Volcanic rocks are present as 5-6 km thick subaerially emplaced seaward-dipping reflection (SDR) sequences along the continent-ocean boundary, subaerially emplaced landward flows on the Møre and Vøring marginal highs, and sub-aqueously emplaced inner flows in the Møre and Vøring basins (Figure 4). The landward flows and inner flows domains are separated by kilometer-high buried escarpments, the Faroe-Shetland and Vøring escarpments (Abdelmalak *et al.* 2016b; Planke *et al.* 2017).

Extensive sheet intrusions are present in the Cretaceous and Paleocene sediments in the Vøring and Møre basins (Figure 4), covering an area of approximately 80,000 km2 (Svensen *et al.* 2004; Planke *et al.* 2005). The intrusions are identified as high-amplitude reflections, commonly displaying saucer-shaped geometries when present in layered Cretaceous basin segments. More than 700 pipe-like hydrothermal vent complexes have been mapped in the intruded basin provinces (Planke *et al.* 2005). A majority of the vent complexes originate from the upper terminations of sill intrusions, and may display crater, eye, or mound geometries on the paleosurface.

Only a few wells have sampled the igneous rocks (Figure 4). ODP Hole 642E drilled through morethan 100 subaerially emplaced basalt lava flows and a few basaltic andesites and dacites of earliest Eocene age (Abdelmalak *et al.* 2016a). Two thick sills (90 m and >50 m thick) were drilled by exploration borehole 6607/5-2. The sills caused extensive thermal maturation and methane generation in 100 m thick metamorphic aureoles around the intrusions, but also enhanced maturation in the 700 m interval between the two sills (Aarnes *et al.* 2015). The hydrothermal vent complexes have been penetrated by one well, 6607/12-1 (Svensen *et al.* 2003). The vent complexes consist of fractured sediments and were formed by the release of high-pressure fluids generated by degassing of intruded sedimentary rocks (Jamtveit *et al.* 2004; Aarnes *et al.* 2012).

The intrusion of magma into sedimentary basins cause deformation of the host rocks. Doming of the overburden is frequently observed above saucer-shaped sills, forming so-called 'forced folds'. These domes are potential hydrocarbon reservoirs, and one such structure was drilled by exploration well 6302/6-1 (Tulipan) in 2005 (Figure 5). The well made a small gas discovery in lower Paleocene sandstones above a saucer-shaped sill. This sill has a diameter of approximately 12 km, and is well-imaged in 3D seismic data (Figures 4 and 5). The dome above the Tulipan sill was formed due different mechanisms, including elastic bending, shear failure, and differential compaction (Schmiedel *et al.* 2017). Eight hydrothermal vent complexes are located in a semi-circular pattern above the upper termination of the Tulipan saucer. The vent complexes were likely formed by aureole degassing during the Paleocene-Eocene thermal maximum (Kjoberg *et al.* 2017). The hydrothermal venting in the NE Atlantic likely triggered the Paleocene-Eocene Thermal Maximum (PETM), a global warming event caused by the release of large volumes of greenhouse gases (Svensen *et al.* 2004; Frieling *et al.* 2016).

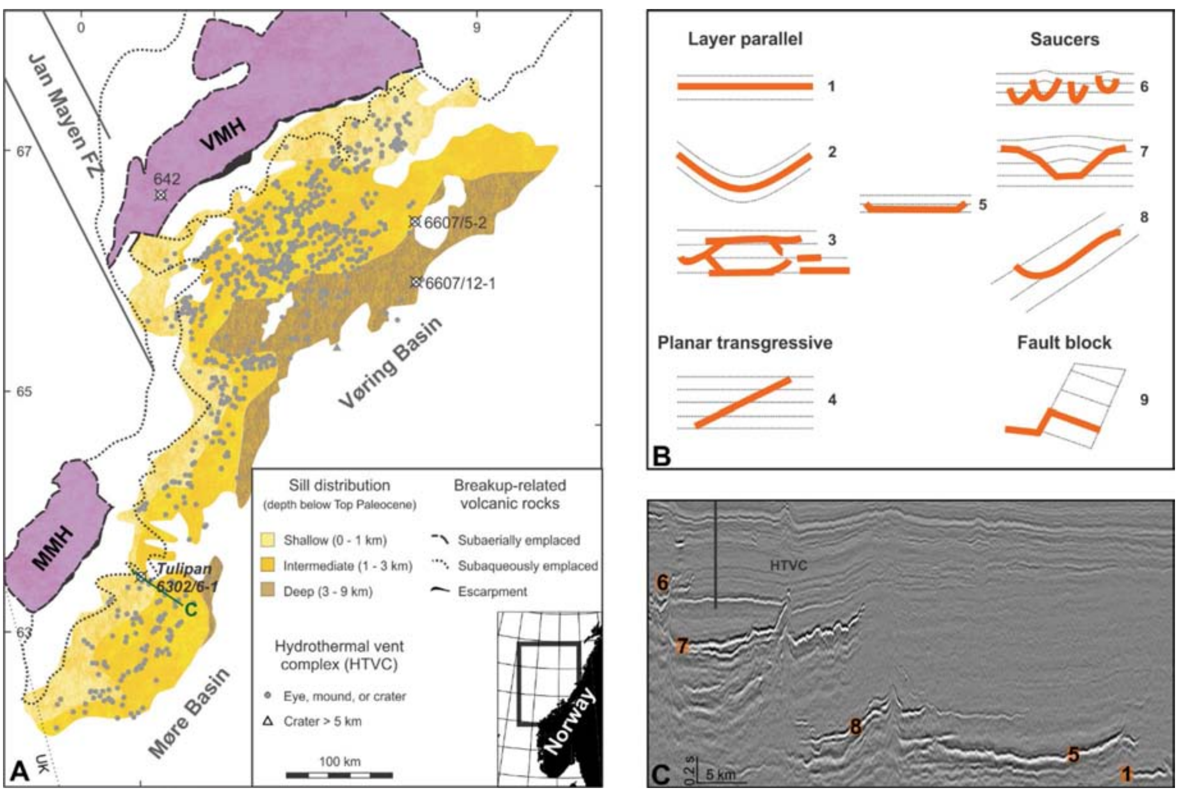

Figure 4. Distribution and seismic characteristics of intrusive complexes on the mid-Norwegian continental margin. a) Distribution of lava, sills, and hydrothermal vent complexes in the Vøring and Møre basins. Key igneous wells are also located. b) Characteristic geometries of sill reflections. c) Seismic profile showing high-amplitude sill reflections in the Møre Basin. Numbers represent geometries shown in Figure 4b. A and b modified from Planke *et al.* (2005).

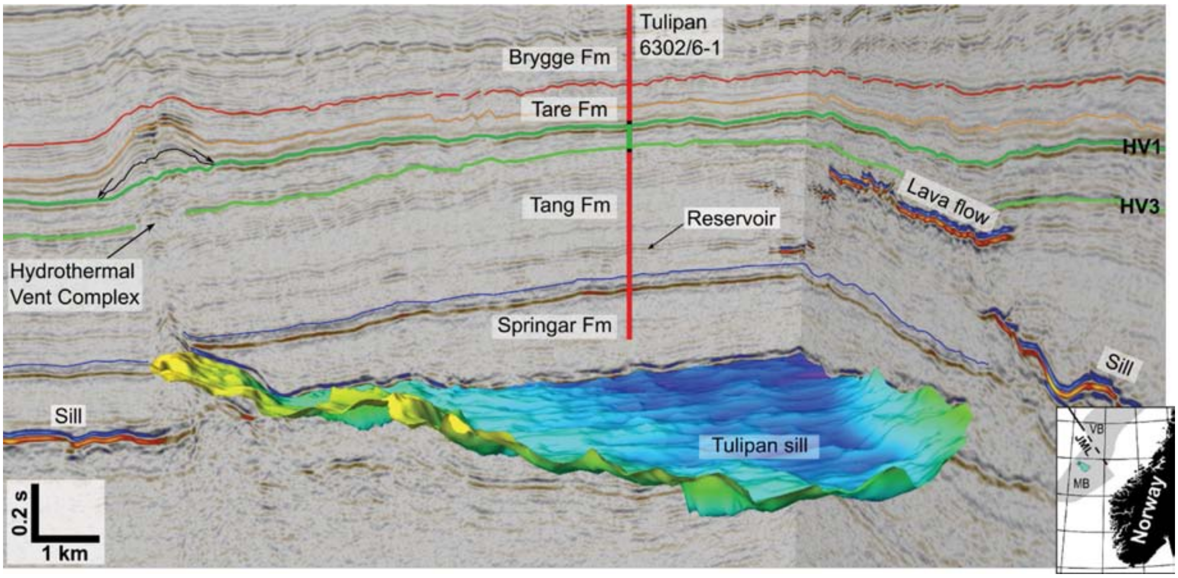

Figure 5. Three-dimensional image of the Tulipan saucer-shaped sill and overlying forced fold in the Møre Basin (Figure 3). A small gas discovery in Paleocene sandstones of the Tang Fm. was proven by well 6302/6-1. The paleosurface is located near the HV3 horizon. Modified from Kjoberg *et al.* (2017).

NEUQUÉN BASIN

4.1 Geological setting

The field study area is located in the northern Neuquén Basin, approximately 70 km south of the town Malargüe on the eastern flank of the Andes in a fold-and-thrust belt (Figure 3; Giambiagi *et al.* 2009). The Neuquén Basin is one of the foreland basins of the Andes and comprises a nearly continuous succession of late Triassic to Cenozoic sedimentary rocks which reaches up to 6000 m thick (Howell *et al.* 2005). It hosts significant amounts of hydrocarbons and is regarded as one of the most important hydrocarbon province in Argentina (Sruoga and Rubinstein 2007).

The geodynamic evolution of the Neuquén Basin comprises three main phases. It initially formed as an elongated rift system in the Permian-Triassic period and subsequently evolved into a back-arc-basin with regional thermal subsidence after the onset of Andean subduction in the early Jurassic (Howell *et al.* 2005). During this stage, and until the Early Cretaceous, an up to 1300-1500 m thick succession of marine sediments was deposited (Bettini and Vasquez 1979; Manceda and Figueroa 1995). This succession includes the organic rich shales of the Vaca Muerta and Agrio formations within the Mendoza group, which represent the main regional source rocks. From the Early Cretaceous and onwards, the tectonic regime shifted to compression, initiating the third, foreland basin phase during which up to 3000 m of syn-tectonic continental deposits of the Neuquén and Malargüe groups were deposited (Howell *et al.* 2005; Kozlowski *et al.* 1989).

The compression triggered the rise of the Andes, and caused inversion of the Mesozoic rifts, as well as the formation of several N-S oriented fold-thrust belts (Howell *et al.* 2005; Manceda and Figueroa 1995).

The compressional tectonics were coeval with successive periods of extensive volcanism and the widespread intrusion of magma into the sedimentary rocks (Kay *et al.* 2006). Our study area is located near the Río Grande Valley (Figures 3 and 6), where oil is produced from andesitic sills, which are intruded into the Vaca Muerta and Agrio formations (Witte *et al.* 2012). These sills are likely associated with the Upper Miocene Huincán Eruptive Cycle with reported radiometric ages (Ar/Ar) between 10.5 Ma and 7 Ma from nearby to our study area (Nullo *et al.* 2002; Witte *et al.* 2012). Many of the sills are heavily fractured, but show generally low porosity except for a few strongly altered “cavity zones” (Witte *et al.* 2012).

4.2 Seismic outcrop modeling

We used seismic modelling to test the effect of the host rock layering on the seismic imaging of sill complexes. In order to achieve this synthetic seismic profiles are compared with (1) homogeneous host rock, (2) low acoustic impedance of sedimentary formations of the Norwegian Sea, and (3) highly variable acoustic impedance of the sedimentary formations of the Neuquén Basin (Mendoza group).

The differences between the synthetic seismic sections from the El Manzano obtained from the models with homogenous host rock versus a variable realistic property distribution, demonstrates the strong effect of meter-scale property variations on the seismic response for the case of a variable host rock lithology (Figure 7). The images from the homogenous model and the model with low-impedance layers show some interference, but suggest that, overall, the main elements of the sill complex would be identifiable in a seismic section. At 25 Hz signal frequency, even very thin sills of <10 m thickness cause strong reflections compared to intra-sedimentary reflections when they occur isolated. However, a stack of such thin sills separated by only a few meters of sediments between each intrusion occurs as a single reflection (Figures 7b and 7c). Although this can serve as a justification to use a simplified homogenous host rock model in this case, note that including a layered host has almost no additional cost and is preferred, because fewer assumptions are made in the model. This is especially valid in the light of newly described low-velocity silicic intrusions in the Faroe-Shetland Basin, where seismic interference can occur even with low-impedance sedimentary rocks (Mark *et al.* 2018).

In contrast, the more realistic images that consider a highly variable host rock lithology reveal that only thick sills that are layer-discordant and cause a strong impedance contrast to the surrounding host rock can be mapped with high confidence (Figure 7d). Sills emplaced into high-velocity rocks such as carbonates or evaporites are challenging to detect and are merged in frequency-dependent interference of reflections from host rock layers and intrusions. However, the sills with thicknesses within the 1/30-wavelength limit of detectability may cause characteristic waveform patterns, especially when closely stacked. By comparison to the areas in the model that lack intrusions, we are able to detect intruded intervals that show a strong disturbance of the otherwise parallel layer reflections. Where characteristic interference patterns, such as amplitude anomalies, braided or abnormally wavy reflections, or isolated reflection offsets with a fault-like appearance are present, we interpret this as an indicator for the presence of thin, potentially branching intrusions within an otherwise parallel layered host rock.

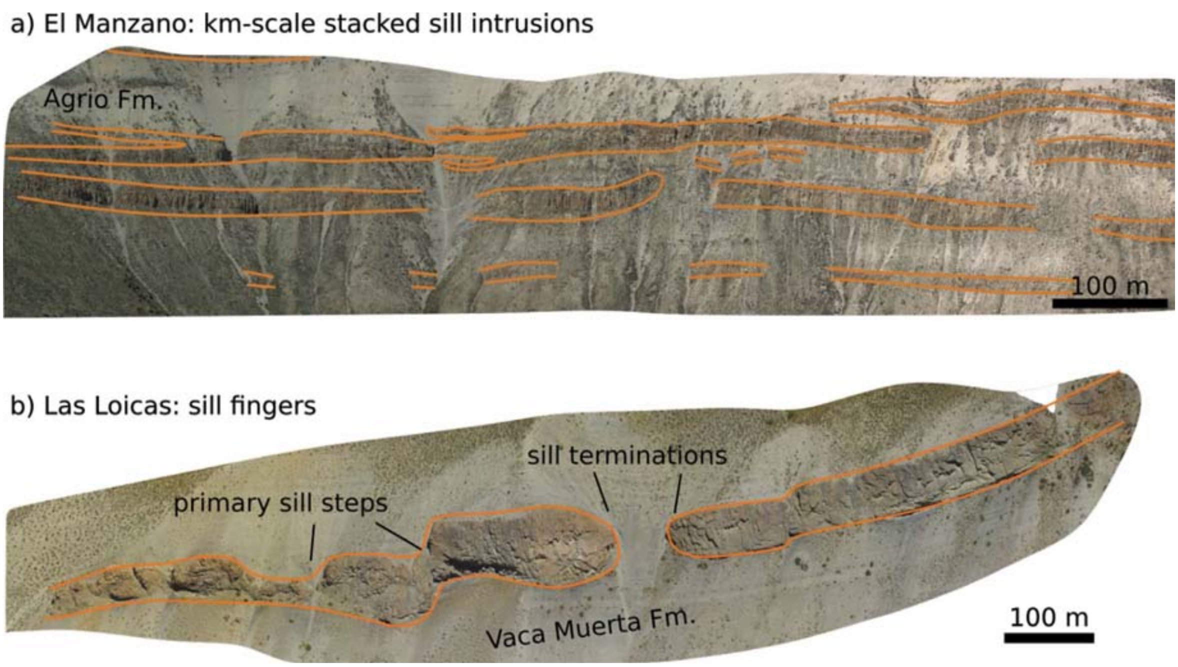

Figure 6. Examples of outcropping intrusions from a) El Manzano and b) Las Loicas, with sills emplaced in the Agrio and Vaca Muerta formations, respectively (sills between orange lines). We captured both outcrops using drone-based photogrammetry surveys. The kilometer-scale sill complex exposed at El Manzano was digitally mapped and used as structural input for the seismic modelling presented in Figure 7.

DISCUSSION

Improved interpretation of seismic reflection data

The modelling results indicate that the comparison between field-based seismic modelling and real seismic data has strong potential to aid seismic interpretation of intrusive complexes (Figure 7; Eide *et al.* 2018; Rabbel *et al.* 2018). However, our results also demonstrate that this type

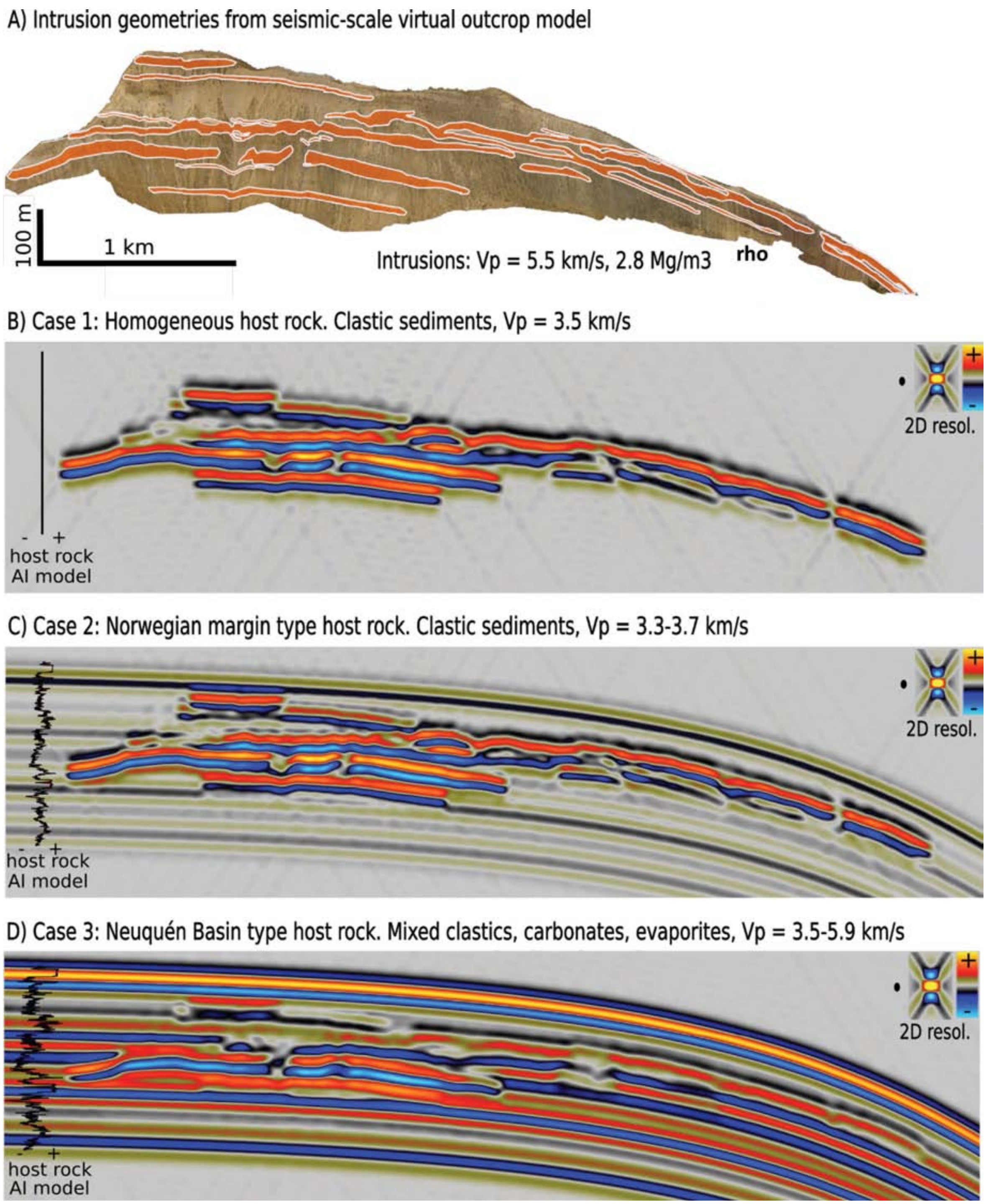

Figure 7. Seismic modelling results based on virtual outcrop models from El Manzano. a) We digitally interpreted the kilometer-scale virtual model to extract detailed geometries of the intrusive bodies. We then superimposed the outcrop-based sill intrusions on a host rock model and generated synthetic seismic sections atc. 25 Hz resolution for three modelling cases: b) homogenous siliciclastic host, c) Norwegian margin type layered siliciclastic host with low acoustic impedance, and d) Neuquén Basin type host including shales, carbonates, and gypsum of the Mendoza Group.

of seismic modelling needs to be performed on carefully calibrated case studies, since the expected seismic signature can vary significantly.

The seismic modeling results presented in this study are directly relevant to compare with pre-stack depth migrated noise free data consisting of primary reflections only. However, seismic wave propagation is highly complex in a volcanic basin, complicating the seismic imaging. Figure 8a shows a very simplified 1D Earth model, including a homogenous high-velocity sill. The presence of a thin high velocity body cause major transmission losses at both the upper and lower sill-sediment contacts, generation of converted waves, ray bending, and interference of reflections originating from the upper and lower sill-sediment boundaries, the so-called tuning effect (Planke *et al.* 2015). Full wave-equation 1D finite element modeling using a realistic marine acquisition geometry documents further imaging and processing complexities, in particular offset-dependent tuning and post-critical reflections at source-receiver offsets of more than c. 5 km (Figures 8c and 8d). The amplitude-versus-offset (AVO) response is also strongly affected by the presence of a velocity aureole (MA) above and below the sill (Figure 8b), with relatively higher near-offset amplitudes in the sill model when compared with the sill + aureole model (Figures 8d and 8e).

In the Norwegian margin, where high-impedance doleritic intrusions commonly intrude low-impedance shale layers, we can use the modeling results to relate interference patterns to stacked sill intrusions, while interference with the sedimentary sequence is negligible. In the Neuquén Basin, a comparison of the modelling results with a composite seismic line from a 3D seismic cube from the Los Cavaos oil field, which shows remarkable similarities of specific waveform patterns that can be attributed to intrusions (Rabbel *et al.* 2018). A schematic interpretation, based on the seismic line and our evaluation of the synthetic models, is shown by Rabbel *et al.* (2018). The interpreted non-intruded part of the section appears as a set of undisturbed, flat, parallel, continuous reflections. Conversely, in the intruded part, layer-discordant reflections can be interpreted as intrusions directly, and splitting of reflections, braided reflections, and lateral amplitude variations can be interpreted as thin intrusions. It is clear that only a fraction of the existing intrusions can be recovered in the interpretation, and that neither the exact location nor the architecture of intrusions are particularly well defined. Nevertheless, equipped with the results of our modelling study based on direct field analogues, it is possible to identify intruded intervals and infer the existence of numerous, potentially interconnected intrusions.

The difference between visible compared to non-visible intrusive elements from seismic data has been shown to be highly variable based on an extensive borehole calibration study in the offshore Faroe-Shetland Basin, UK, where as much as 80% of intrusions encountered in boreholes were not delimited on the associated seismic data (e.g. Schofield *et al.* 2017). The petroleum implications of sills are significant (discussed in detail in the next section), and therefore, tuning interpretation uncertainties in different settings and a move towards quantifying these uncertainties is critical for both basin and petroleum systems analyses. Moving forward, being able to delimit sill intrusions from seismic data, but then also being able to assess the probability of sub-seismic features and their extent for different intrusion geometries and basin settings may be key for improving exploration strategies.

The ability of the modelling to identify some sill junctions and steps is also of key importance when evaluating the petroleum implications of sills in sedimentary basins such as the Neuquén Basin and mid-Norway basins,as well as in other prospective volcanic basins (e.g. South Atlantic).

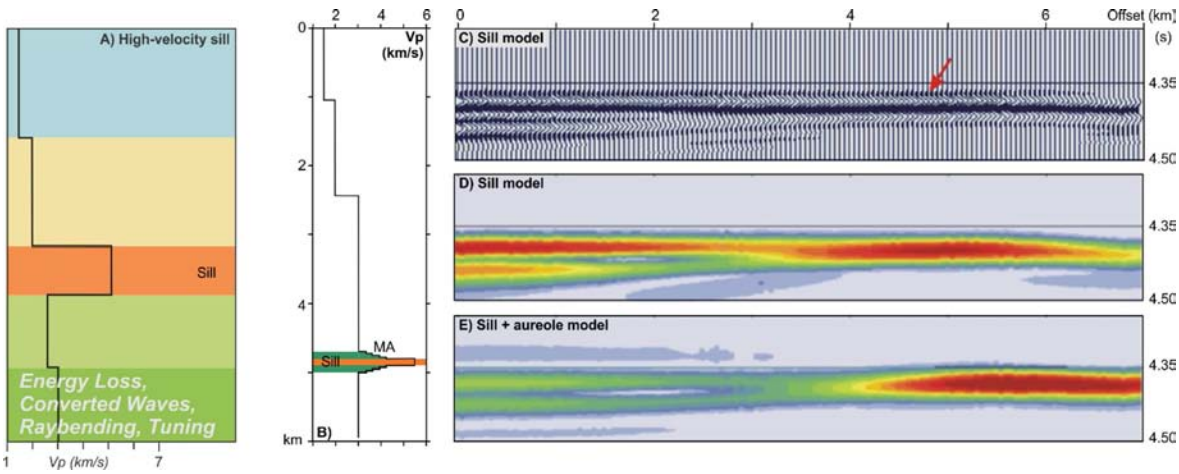

Figure 8. Aspects related to seismic imaging of sill intrusions. a) Schematic Earth model of a high-velocity sill intrusion in the sedimentary basin. b) Velocity model of an intruded basin simplified from observations in the Vøring Basin used for synthetic seismic modeling in c to e. c) Flattened seismic gather for model without a MA. d) Flattened instantaneous amplitude in model without MA; red shows high amplitudes. e) Flattened instantaneous amplitude in model with a MA; red shows high amplitudes. MA: Metamorphic velocity aureole. See Planke *et al.* (2015) for modeling details.

This relates to the impact of intrusions on fluid flow within sedimentary basins as outlined below, in the context that a continuous sheet intrusion covering large areas of a basin will have a potentially very different impact than a series of stacked or overlapping lobes that do not form a continuous barrier in 3D. Our modelling results clearly identify these features and therefore give improved confidence and constraints as to the interpretation of similar features from seismic data and their associated potential impacts on petroleum systems.

Synthesis of igneous influenced hydrocarbon systems

Hydrocarbons are produced from igneous intrusions in several regions in the Neuquén Basin, e.g. in the Auca Mahuida area (Figures 5 and 9), and indeed from around the world (Schutter 2003; Senger *et al.* 2017). However, igneous rocks and processes may influence all aspects of a working hydrocarbon system in a volcanic basin. A synthesis of igneous-related hydrocarbon reservoirs and magmatic influences on petroleum systems in compressional basin settings is shown in Figure 10, and discussed in more detail below.

In order for a successful working petroleum system to exist, five critical elements must be present including: 1) source rock and maturation, 2) migration, 3) reservoir, 4) seal, and 5) trap. These five elements are of equal importance for any petroleum accumulation, however, the risk associated with the presence/effectiveness of each will vary markedly depending on the basin or play that is being explored. In volcanic basins, the influence of magmatism and igneous rocks on each of these petroleum system elements has been extensively explored over recent decades with the clear conclusion: magmatism can have a major influence (both positive and negative) on all aspects of a working petroleum system (e.g. Schutter 2003; Delpino and Bermúdez 2009; Jerram 2015; Senger *et al.* 2017). At the same time, it is also true that in many cases, magmatism has only a very minor influence, the difference depending critically on the nature of magmatism and timing in relation to a petroleum systems evolution. It is therefore critical to appraise the nature, distribution, timing, and associated implications of different magmatic features within a sedimentary basin in order to robustly appraise prospectivity within volcanic basins.

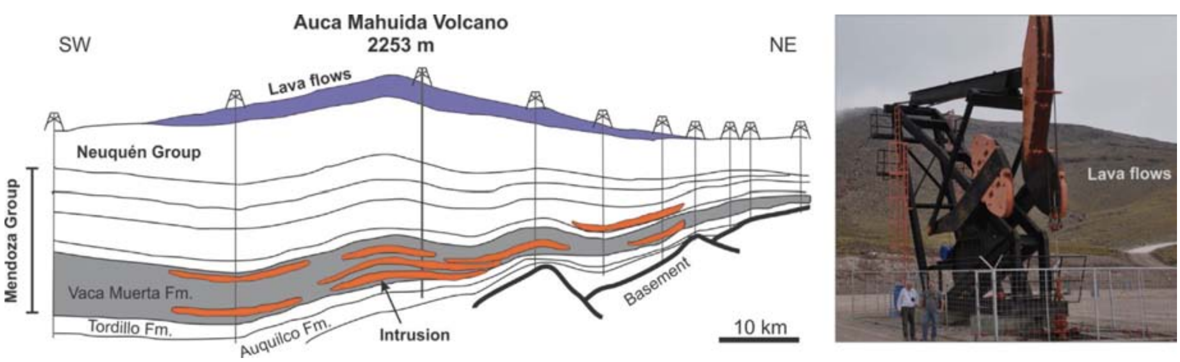

Figure 9. Schematic drawing of the Auca Mahuida oil field. Picture shows an oil pump near the summit of the volcano. Héctor A. Leanza and Sverre Planke for scale. Drawing modified after Rossello *et al.* (2002).

In general, the influence of volcanism on petroleum systems can be divided into syn-magmatic and post-magmatic. Syn-magmatic or dynamic influences can be defined as those associated with the transit and emplacement of hot magma through and into basins as intrusions, along with any eruption of deposits at the surface. Examples of syn-magmatic influences include host rock maturation, hydrothermal venting and rapid surface loading by the extrusion of dense lava flows. Post-magmatic influences include all features that remain within the basin system after the end of magmatism. Examples include all potential reservoirs hosted in the solidified remains of volcanic facies, fracture networks associated with intrusions, hydrothermal vent complexes, and structural elements associated with erosion or differential compaction of magmatic features. In practice,

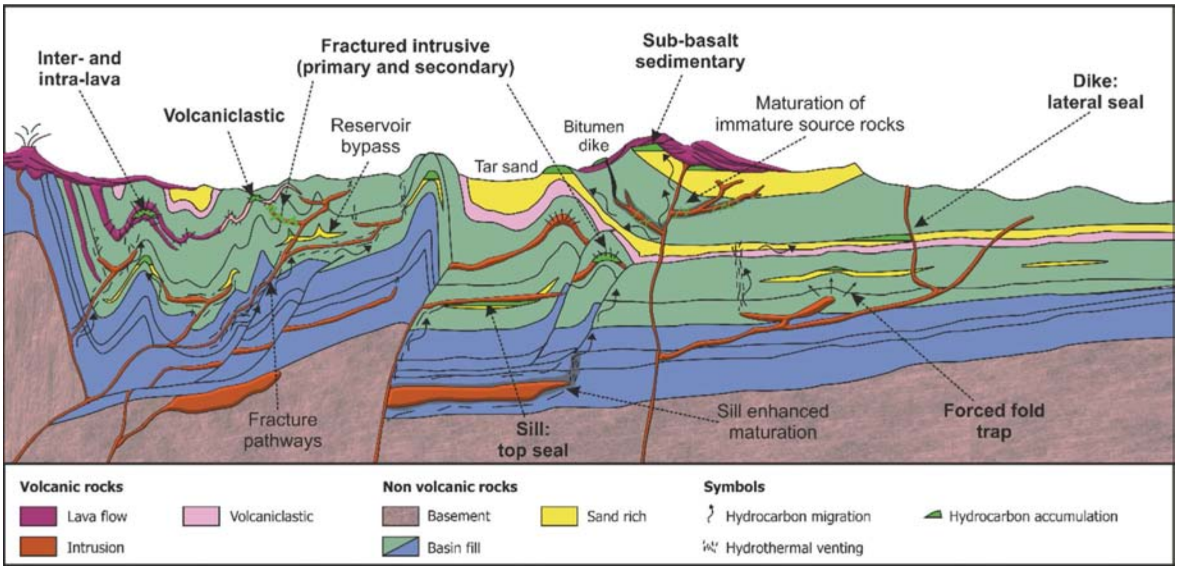

Figure 10. Conceptual model of a compressional margin setting with volcanic associated petroleum system influences annotated. The tectonic structure is broadly based on an E-W cross section through the Neuquén Basin, after Uliana and Legarreta (1993), but the annotated features bear no geographical relation to the section and are generic to compressional margins.

many features have both syn- and post-magmatic influences, however, we find differentiating between dynamic magmatic influences, and those associated with the return of a basin to more ambient conditions with the magmatic remnants still in place useful.

In terms of syn-magmatic influences on prospective basins, by far the most obvious influence is associated with the emplacement of bodies of hot magma (c. 1000-1200°C) into source rocks where oil is generated above c. 60°C and is progressively replaced by gas from c. 90-150°C. The volume, thickness and geometry of magmatic intrusions along with a whole host of other parameters relating to the intrusion will dictate the thermal budget which must then be equilibrated with the host rock thermal regime over time (Aarnes *et al.* 2012; Aarnes *et al.* 2011; Iyer *et al.* 2017). A comprehensive range of parameters are now being incorporated into robust sill maturation modelling workflows in order to replicate natural observations from outcrop, seismic and borehole data (e.g. Aarnes *et al.* 2015; Iyer *et al.* 2017). The petroleum implications are best demonstrated in a number of studies relating to producing fields hosted within intrusions in otherwise often immature source rocks (e.g. in the Vaca Muerta, Neuquén Basin) (Figure 9; Monreal *et al.* 2009; Spacapan *et al.* 2018).

Post-magmatic effects of intrusive networks can also be extensive, with fractured intrusions known to form both conduits and barriers to migrating fluids in different settings along with reservoirs in some cases as mentioned above (e.g. Rateau *et al.* 2013; Senger *et al.* 2017; Mark *et al.* 2018). In cases where intrusions form complex impermeable networks, compartmentalization of both source rocks and reservoirs is possible, with potentially significant implications for charge volumes and reservoir connectivity (e.g. Holford *et al.* 2012).

Also associated with intrusions is the development of syn-magmatic hydrothermal fluid circulation systems and hydrothermal vent complexes, which are formed when overpressure, generated by host rock devolatilization processes, exceeds the lithostatic pressure promoting catastrophic overburden failure (Svensen *et al.* 2004; Aarnes *et al.* 2012; Reynolds *et al.* 2017). Hydrothermal fluids and venting may have syn-magmatic effects whereby hot fluids can cause heating of host rocks far beyond the limit of conductive cooling, along with potential degradation of pre-existing reservoirs. Also there is evidence that venting can occur into early volcanic layers within the system as it develops, affecting the nature and integrity of the base basalt/sediment interface (Angkasa *et al.*, 2017). More significantly, they may also have post-magmatic influences whereby hydrothermal vent complexes and associated fracture networks can be used as long-term migration pathways within a sedimentary basin, long after the initial hydrothermal fluid flux (Iyer *et al.* 2017) and associated temperatures have been equilibrated.

Sill intrusions are also known to form traps due to overburden deformation and the development of so-called 'forced-folds' as mentioned above. The Tulipan discovery offshore mid-Norway reveals a type-example of a hydrocarbon accumulation hosted within a forced fold structure above a saucer-shaped intrusion (Kjoberg *et al.* 2017). Additional to syn-magmatic host-rock deformation, the dense and largely incompressible nature of sill intrusions after cooling, can create scenarios where differential compaction exaggerates or compounds the net closure of forced fold structures during post-emplacement burial (Schmiedel *et al.* 2017).

Although not relevant to the presented modelling study, extrusive volcanism may also exert a major influence on petroleum systems in volcanic basins and a short summary is therefore included for completeness. The huge diversity of extrusive volcanic facies can lead to highly variable influences on petroleum systems in volcanic basins (e.g. Jerram 2015). Some examples include the eruption of regionally extensive tuffs which can form excellent seals when deeply altered, as for example in the case of the Balder Tuff in the North Atlantic (Underhill 2001; Watson *et al.* 2017). The highly reactive nature of many volcanic products such as volcanic glass or weathered basalt leads to both positive and negative implications for reservoir sands depending on the percentages of volcaniclastic sediment. Minor amounts of volcaniclastic material for instance can be positive in cases where it promotes early chlorite cement, which can inhibit quartz overgrowths from occluding pore space up to significant depths (Ólavsdóttir and Ziska 2009). However, with increasing volumes of volcaniclastic material, the potential for pore clogging and significant permeability reduction becomes large. A wide range of primary and secondary porosity in volcaniclastic reservoirs is also known and requires detailed appraisal on an individual basis as both good and bad volcaniclastic reservoirs are well documented (e.g. Willumsen and Schiller 1994; Sruoga and Rubinstein 2007).

Increasingly, the potential for reservoirs being hosted in more coherent volcanic facies such as lava flows is being investigated with notable occurrences being known from offshore Brazil (e.g. the Badejo field; Bruhn *et al.* 2003) and onshore India (e.g. Raageshwari deep gas field; Chowdhury *et al.* 2014). In each case the complex interplay between primary volcanic facies and extensive secondary alteration makes reservoir characterization and prediction challenging. In almost all cases, however, it can be shown thatthe primary volcanic facies exert a principle influence on the subsequent reservoir development. Significant accumulations of hydrocarbons are also now being found within entirely non-volcanic sedimentary layers inter-digitated with lava flows, as in the case of the Rosebank field, Faroe-Shetland Basin, offshore UK (Hardman *et al.* 2017), and the Kudu Gas field, Namibia (Jerram *et al.* 1999).

CONCLUSIONS

Within this study we have presented new seismic outcrop analogue modelling results from the Neuquén Basin and linked these to seismic observations and examples from both the Neuquén Basin and the mid-Norwegian NE Atlantic margin. The results of our study can summarized as follows:

- Outcrop analogue modelling has the ability to bridge the gap between seismic to sub-seismic geological features and improve confidence in seismic interpretation of sill intrusions from sub-surface data. Careful calibration of the chosen seismic properties is critical.
- Seismic property contrasts between intrusions and host rocks can vary significantly, leading to reflection amplitudes variations between very strong and close to zero, even within a single data set. Low sill-related amplitudes may occur when carbonates and evaporites are present.
- Analogue modelling reveals important constraints on the imaging potential of different scales of known sill intrusion features such as magma fingers, steps, broken bridges and thin layers enabling future improvements on interpretation uncertainties in different settings.
- The ability of the seismic technique to image discontinuities and complex geometries within sill bodies has important implications for assessing fluid flow and petroleum systems within volcanic basins, and our modelling gives key constraints for screening for the presence of these features.
- Sill intrusions can have a fundamental influence, both positive and negative, on all aspects of the total petroleum system from source to seal, and therefore the robust imaging and assessment of intrusions within prospective volcanic basins is a critical element of robust petroleum systems analyses.

Our results demonstrate the important variations that both host rock and sill properties can have on seismic imaging of sill complexes in different settings. These results coupled with extensive seismic examples from around the world enable increased confidence in the interpretation of igneous intrusions in the sub-surface and a parallel ability to better appraise their influence on associated petroleum systems. Important factors include the connectivity of sills, their geometry, and the nature of fractures associated with their emplacement. How the sills interact with the host rock can also produce additional important structures such as hydrothermal vet complexes. If formed these with alter the basins permeability structure, and may have longer term influences on fluid flow. As confidence grows in the ability to correctly identify igneous related features in offshore datasets, then improved basin models and a better risk analysis of volcanic basins can be achieved. This study highlights the relative strengths of linking both onshore and offshore observations at different scales, towards the common goal of the best available interpretation of geological models in the subsurface.

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