From field analogues to realistic seismic modelling:

A case study of an oil-producing andesitic sill complex in the Neuquén Basin, Argentina

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Abstract: Interpretation of seismic data has played a major role for recent advances in the studies of igneous sill complexes. Seismic modelling studies based on field analogues represent a promising tool to close the scale gap between observations from outcrops and seismic data and support seismic interpretation. Virtual outcrop models are commonly used to include high-resolution geological structures in models of seismic-scale field analogues. However, realistic seismic modelling requires not only detailed structural input, but also well-constrained elastic properties and an adequate seismic modelling technique. Here, we present a seismic modelling study of oil-producing andesitic sills in the Neuquén Basin, Argentina, which implements all modelling elements at high accuracy by combining virtual outcrop models, well data, and a 2(3)D filtering method. Our results indicate that the modelled seismic signatures of intrusive bodies observed in field analogues are characterized by frequency-dependent interference and strong amplitude variations due to highly variable elastic properties of both host rock and sills. We demonstrate that detailed waveform patterns observed in real seismic data can be linked to intrusive bodies below the traditionally assumed limit of resolution via realistic seismic modelling. This illustrates how an integrated modelling approach based on field analogues can aid seismic interpretation.

In recent years, research has provided evidence for the presence of large volumes of igneous intrusions in numerous sedimentary basins around the world. Intrusive complexes comprising volcanic sills and laccoliths can have a strong impact on basin dynamics and the related petroleum systems, as well as on hydrocarbon exploration and production (Cartwright and Hansen 2006; Infante-Paez and Marfurt 2017; Planke et al. 2005; Senger et al. 2017). These effects may include local source rock maturation (e.g., Rodriguez Monreal et al. 2009), trap formation through host-rock and overburden deformation (Hansen and Cartwright 2006; Schmiedel et al. 2017), creation of barriers or pathways for fluid flow (Rateau et al. 2013), or, if the intrusions are fractured, intrusions may themselves form atypical hydrocarbon reservoirs (e.g., Witte et al. 2012).

3D seismic reflection data are often the primary basis for the mapping and characterization of large-scale intrusive complexes (e.g., Jackson et al. 2013; Magee et al. 2013; Planke et al. 2005; Schmiedel et al. 2017; Schofield et al. 2015). A key reason for the advances in seismic mapping of intrusions is that they are commonly represented by prominent high amplitude reflections, which are easy to map in seismic data (Planke et al. 2005; Planke et al. 2015). However, a variety of problems is related to the seismic imaging of igneous intrusions. With respect to a typical seismic wavelength, sills often represent thin geological layers of high seismic velocity (Planke et al. 2015). Importantly, recent studies indicate that many sills are too thin to be recognised in seismic images and locally up to 88% of sills could be missing when interpreting seismic data in volcanic basins (Magee et al., 2015, Schofield et al., 2015). Additionally, intrusives are usually considered to create high risk for hydrocarbon exploration, including overmaturation of source rocks, poor reservoir quality, negative effects on imaging, and challenging drilling conditions (Farooqui et al. 2009; Rohrman 2007; Senger et al. 2017). Therefore, they are still rarely drilled compared to sedimentary rocks, although progress has been made in several basins in the availability of well data (e.g., Bischoff et al. 2017). Nevertheless, the validation of observations from seismic data remains difficult in many cases.

Seismic modelling of field analogues is therefore important for the seismic interpretation of intrusive complexes, because it creates a vital link between geological field observations at the outcrop scale and their expression in seismic data (Lecomte et al. 2016). Few such seismic modelling studies of intrusions in sedimentary basins are available, and in many cases sketched, simplified intrusion shapes are used, and additionally, elastic properties of sedimentary units and intrusions are poorly constrained (Magee et al. 2015; Planke et al. 2015). Commonly, 1D convolutional seismic modelling is used to synthesize seismic sections due to its simplicity and low computational cost (Magee et al. 2015; Rohrman 2007; Schofield et al. 2015). 1D convolution assumes a horizontally layered geological model devoid of lateral velocity variations, which proves to be inaccurate for geologically complex areas, often typical of regions where igneous bodies are found, as well as for geometrically complex intrusive bodies themselves (Eide et al. 2017; Lecomte et al. 2016). To our knowledge, only one detailed seismic modelling case study exists that focuses on igneous intrusions and uses real intrusion shapes from outcrops to explore imaging effects beyond 1D convolution (Eide et al. 2017).

Although simple seismic modelling studies provide important insights into the expression of igneous intrusion in seismic images, interpreters need more locally calibrated and realistic seismic modelling studies of field analogues. This can provide more in-depth analysis of the expected seismic expression of intrusions in each case study, especially regarding interference patterns caused by small geological features and potential amplitude variations. Such realistic seismic modelling requires (1) high-resolution geological interpretations to provide structural input for the model geometry, (2) strong constraints on the distribution of elastic properties of both intrusions and their host rocks, and (3) use of an adequate modelling technique that correctly implements the 2(3)D resolution and illumination conditions in the subsurface.

Here, we present a case study of hydrocarbon producing andesitic sills in the Río Grande Valley in the northern Neuquén Basin, Argentina, to illustrate an integrated approach to seismic modelling of field analogues of intrusive complexes. Our study is designed to satisfy all three criteria for realistic seismic modelling through a combination of (1) high-resolution, seismic-scale virtual outcrop models of a sill complex, (2) well data to obtain relevant elastic properties of both sills and their host rock, and (3) the usage of a 2(3)D prestack-depth migration (PSDM) simulator superior to 1D convolution in complex geological settings (Lecomte et al. 2015; Lecomte et al. 2016). The aim is to investigate the seismic response for a variety of model scenarios: (1) comparison of a simple, binary geological model to a realistic model including host rock variations and sill geometries far below the classical ¼-wavelength “seismic resolution limit”, but potentially within the “limit of detectability” of down to 1/30-wavelength (Simm et al. 2014) and (2) examination of the influence of elastic property variations between the intrusions and the host rock within a well constrained range. The results are integrated with geological observations and 3D seismic data to allow direct comparison to real subsurface data in order to evaluate how realistic, locally calibrated seismic modelling based on field analogues may facilitate more confident, detailed seismic interpretation.

Study area and geological setting

The study area is located in the northern Neuquén Basin, approximately 70 km south of the town of Malargüe on the eastern flank of the Andes (Fig. 1). The Neuquén Basin is one of the foreland basins of the Andes and comprises a nearly continuous, up to 6000 m thick succession of late Triassic to Cenozoic sedimentary rocks (Howell et al. 2005). It hosts significant amounts of hydrocarbon 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 Triassic-Jurassic period and subsequently evolved into a back-arc-basin phase 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, calcareous shales of the Vaca Muerta and Agrio formations within the Mendoza group, which represent the main regional source rocks. In addition, the massive Chachao limestone, as well as the evaporites of the Huitrín formation, were deposited during this period. 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, combined with a rotation of the regional tectonic stresses, 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 study area is located in the Malargüe fold-and-thrust belt (Giambiagi et al. 2009).

The compressional tectonics were coeval with successive periods of extensive volcanism and widespread intrusion of magma into the sedimentary rocks (Kay et al. 2006). In many cases, these intrusions are intensely fractured and comprise a number of atypical hydrocarbon reservoirs in the basin (Rodriguez Monreal et al. 2009; Sruoga and Rubinstein 2007; Witte et al. 2012). Our study area is located in the Río

Grande Valley (Fig. 1), where oil is produced from andesitic sills in several fields (e.g., Los Cavaos, Los Volcanes), which intruded in 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) close to the study area between 10.5 Ma and 7 Ma (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). Approximately 10 km west of the Los Cavaos oil field, the Sierra Azul basement thrust brought to outcrop, among others, the Vaca Muerta and Agrio formations intruded by numerous andesitic sills (Fig.1). In this study, we focused on a 4km long continuous section, where both the sills and the host rock are accessible in a very high quality outcrop. This exceptional outcrop is a direct field analogue of the nearby Los Cavaos field.

Data and methods

The aim of our study is to perform geologically realistic seismic modelling of sill complexes. To achieve this, we implemented the workflow described in Figure 2. This workflow integrates (1) the geological interpretation of a seismic-scale virtual outcrop model, which yields high-resolution, geologically relevant structural input, (2) well data, such as P-wave, S-wave and density logs which are used to constrain the elastic properties of the geological units and permit the representation of sub-seismic scale property variations, and (3) seismic survey parameters such as signal frequency, survey geometry, and the velocity model in the overburden of the modelling target, which are required to include information about the local conditions for resolution and illumination (Lecomte et al. 2015). Finally, we use a 2(3)D convolution modelling algorithm that allows accurate, rapid, and low-cost modelling of PSDM seismic sections.

Virtual Outcrop Model of the El Manzano Sill Complex

Advanced seismic modelling requires high-quality structural input. Here, we used a high-resolution 3D virtual outcrop model of an exposed sill complex (Fig. 3a), which is considered a direct outcrop analogue to the oil-producing sills in the Los Cavaos oil field (Fig. 1). The 3D meshed surface model was obtained by Structure-from-Motion photogrammetry (e.g., Westoby et al. 2012) and computed from 254 partially overlapping photographs collected from a drone survey (built-in camera, 12 megapixels) along the roughly 4 km long and up to 250 m high outcrop face. The mesh contains more than 11 million triangles, corresponding to a spatial resolution of around 25 cm. Subsequently, the model texture built from the photographs was draped over the surface model to give a photorealistic representation of the outcrop. To ensure correct global orientation and positioning of the resulting models, differential Global Navigation Satellite System (GNSS) measurements of 39 ground control points were taken along the entire outcrop. The interpretation of the sill geometries within the intrusive complex was performed directly on the virtual model and includes a network of interconnected sills and sill fingers of <1 m to 30 m thickness, and other sub-metre scale geological details, such as intrusive steps, junctions, or host rock lenses (Fig. 3b). The small-scale interpretations were constrained by ground-truthing through direct observations collected along the entire outcrop to ensure robust geological interpretation (Fig 3c). Due to limited control on the geological geometries in the third dimension, and in order to facilitate the model building and simulation process, the lines were projected onto a vertical plane aligned with the average outcrop orientation. This yields a seismic scale, sub-seismic resolution 2D model of the El Manzano sill complex (Fig. 3d).

Rock properties from well analysis

Meaningful seismic forward modelling requires the allocation of realistic seismic properties to the geological units represented in the model. In the case of the El Manzano sill complex, the geological units represented in the model obtained from virtual outcrop mapping comprise the sills and their sedimentary host rock. In order to compare a simplistic approach to a more realistic scenario, we set up two modelling scenarios, Model 1 and Model 2.

Model 1 consists of a simple binary lithological model (figure 3d), where the sills and the host rock are each given a distinct but homogeneous set of seismic properties including P-wave velocity, S-wave velocity, and density (Table 1). We interpreted the lithology in the well logs from three wells in the Los Cavaos oil field based on log signature, as well as cuttings and core descriptions from internal well-reports, and defined the average P-wave velocity and density of the host rock and intrusions. S-wave velocities for the sills were based on literature values for the V_p/V_s-ratio of igneous rocks and carbonates ($V_p/V_s = 1.9$) and similar shale intervals ($V_p/V_s = 1.7\text{-}1.8$) in other parts of the Neuquén Basin, respectively (Fernandez-Concheso 2015; Klarner and Klarner 2012).

Model 2 consists of a layered host rock model derived from well log data from Los Cavaos (Fig. 4). We used sonic and density logs from a 500 m interval within the target formations between 2-2.5 km depth, including the organic rich shales of the Mendoza group, as well as local carbonate layers and the evaporites of the Huitrín Formation (Fig.1). To generate the host model, we removed the intrusions in this interval from the well data and replaced them with host rock values from the closest host rock interval to isolate the host rock response, while maintaining the correct depth of the log measurements (Fig. 4a). The logs are then combined to create an acoustic impedance log used to create a 1D layer model by averaging the acoustic impedance in intervals of a user-defined thickness of 5 m (Fig. 4a). The 1D model was then extended laterally and deformed according to a deformation function that describes tectonic folding along the lateral extent of the outcrop, such that the sill geometries interpreted from the virtual outcrop model are concordant with the host rock layering (Fig. 4b), as observed in the field. This pseudo-2D approach is realistic, since in both the outcrop and in the subsurface, more significant tectonic features are absent at the scale of our model, and the sedimentary host rock sequence represents low-energy marine deposits, which show only small lateral variations. Similar to the binary scenario, the seismic properties of the sills are derived from statistical analysis of sonic and density logs from several wells, and defined as impedance endmembers at one standard deviation around the average. The variation in V_p values between 4.7 km/s and 5.5 km/s is most likely the result of a variable degree of fracturing within the sills (Witte et al. 2012). S-wave velocity values were derived from the same V_p/V_s-ratios as in the binary model. The property values for Model 2 are summarized in Table 1.

Seismic modelling

Seismic forward modelling predicts the seismic response of a geological model and can thereby help to understand real seismic data and validate their interpretation. When the geological model stems from a kilometre-scale outcrop (as is the case here), seismic modelling is particularly powerful, since the geometries correspond to real geological observations rather than sketched concepts or simplified shapes (Lecomte et al. 2016). For our study, we use a 2(3)D convolution method to simulate realistic PSDM seismic images, because this type of migration represents the ideal and expected migration approach as soon as the geology diverges from the simplistic horizontally layered model, i.e., superior to what post-stack and/or time migration methods can perform (Lecomte 2008; Lecomte et al. 2015). From a modelling perspective, this means that the results represent the best possible image of the modelled target structure and thereby yield the limit of what seismic imaging may achieve in a real case. 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 resource cost (Lecomte 2008), allowing efficient testing of relevant parameters. In our case, an individual 2D simulation was usually computed in less than two minutes. Lecomte et al. (2016) also demonstrated the method's superiority to 1D convolution, because it accounts for 2(3)D illumination and resolution effects that are angle-dependent and may vary with parameters such as background velocity model, survey geometry or wavelet. 1D convolution neglects lateral smearing and predicts that steeply-dipping reflectors are also illuminated, which in reality is often incorrect. In addition, it is based on the elastic, rather than only acoustic, properties and includes diffraction energy, which is necessary to model complex structures (e.g., Botter et al. 2014; Lecomte et al. 2016). The efficient calculation allows the implementation of geological details at a very high resolution (in our case tens of centimeters) even on a standard workstation, thus avoiding any upscaling approach, which might oversimplify the geological structures. The PSDM simulator makes use of the image response of a point scatterer (so-called Point Spread Function, PSF), the size and shape of which yield information on spatial resolution as well as the maximum illuminated dip in the considered case (Lecomte 2008; Lecomte et al. 2015). This method therefore provides explorationists with a reliable tool to rapidly assess their seismic interpretations using modelling studies.

We designed the seismic modelling workflow applied to the El Manzano case study to address three main issues: (1) influence of a realistic representation of the host rock impedance structure based on well data compared to a simple binary model, (2) difference in the response of seismic property endmembers of the sills in a given, realistic host rock, and (3) impact of seismic image resolution due to varying signal frequencies in order to assess 2D interference between thin intrusions and host rocks, i.e. beyond a 1D convolution view point. Note that although the PSDM method is available in 3D, we focus on 2D phenomena due to the 2D nature of our geological models. Frequency spectrum analysis of the 3D seismic survey from Los Cavaos revealed a center frequency of 20-30 Hz at the target depth, such that the investigated frequencies were chosen to be 20 Hz, 30 Hz and 40 Hz in order to represent realistic values. The geology beneath the Los Cavaos field comprises minor inversion of normal faults and some shallow-dipping layers, but generally lacks complex structures (Witte et al. 2012). It should be noted that the presence of near-surface basalt layers does probably limit the illumination conditions at Los Cavaos, following Eide et al. (2017) who give a thorough discussion of this imaging problem. In our case, this limited-illumination effect is difficult to quantify due to the lack of an accurate velocity model. Therefore, we chose to only define the PSF analytically, i.e., without considering a specific overburden velocity model and a given survey (Lecomte et al. 2016). We select a maximum illuminated dip of 45 degrees, which corresponds to standard 3D seismic illumination and about half-wavelength lateral resolution (Simm et al. 2014), and consider an average velocity of 4 km/s in the targeted area. We only modelled zero incident-angle cases, for the sake of simplification and because we do not consider an actual survey geometry. However, it should be noted that larger incident angles would result in a poorer resolution, both vertically and laterally.

Results

Model 1 vs. Model 2

We observe significant differences between the modelled seismic response of the simple binary model (Model 1) and the model containing a realistic, layered host rock (Model 2) at the investigated seismic signal frequencies ranging from 20-40 Hz (Figs. 5 and 6). For each frequency, we will describe the seismic image of the binary model (Fig. 5a) first, and then point out the differences that arise from the introduction of host rock layering (Fig. 5b). Figure 6 shows close-up seismic images to highlight detailed observations of waveform patterns. For each seismic image, the corresponding point-spread function is displayed to illustrate the 2D resolution and illumination.

At 20 Hz center frequency, none of the individual sill segments is resolved in Model 1 (Fig. 5c). Instead, stacks of thin sills are merged into a single, continuous top reflection, and a slightly irregular bottom reflection with some discontinuities. Some of the thicker sills diverge and converge with respect to their vertical spacing and cause the associated reflections to split into two, or merge into a single reflector, respectively. Locally, sill terminations cause an apparent offset of a reflection and create a fault-like appearance (Fig. 6a). In contrast, when the realistic host rock is included, it becomes much more difficult to interpret intrusions (Model 2; Fig. 5d). Particularly when the intrusions are mostly layer-parallel, the majority of intrusions only cause very subtle modifications of the existing host rock reflections and are effectively invisible. Where the sills have slightly undulating geometries and split into small fingers, interference between the sill and host rock reflections cause a wavy and braided waveform pattern (Fig. 6b). As a consequence, the only sills identifiable are located in areas where they either cause a strong impedance contrast, exhibit laterally confined amplitude variations, are not layer-parallel, or a combination of these features (Fig. 5d, left side, Fig. 6b). Apparent (fault-like) offsets related to sill reflections are observed at some locations, but are less pronounced. Also, note that we find some of the strongest reflection amplitudes to be related to high impedance contrasts within the host rock, while some intrusions create relatively weak amplitudes (Figs. 5d, 6b).

The 30 Hz signal frequency does not resolve individual sills in Model 1, however, Figure 5e shows that closely stacked intrusions are now represented by several reflections in some places of the binary model. Depending on sill thickness and spacing, the top and bottom reflections of individual sills interfere, often destructively, and the sills still cause reflection offsets with an appearance similar to small-scale faults Figs. 5e, 6c). In Model 2, the reflection pattern of the host rock changes as a result of the increased frequency, and the distortion of the layered host rock response caused by intrusions is more pronounced compared to the 20 Hz image (Figs. 5f, 6d). Therefore, we observe not only a generally increased resolution, but also a change in the interference patterns between host rock layers and intrusions compared to the previous image at 20Hz. The stacked sills in the right side of the model remain difficult to see since they cause a layer-parallel, partly irregular, reflections that show medium, but slightly varying amplitude as a result of interference. The thicker, layer-discordant sills can now be identified in their lateral extent, although some sill terminations still cause fault-like reflection offsets (Figs, 5f, 6d). A sill underlying the high-impedance layer caused by evaporites now causes a broadening of the host-rock reflection rather than a clear strong amplitude anomaly (Fig. 6d). In the center of the image, a sill splitting into several small fingers causes a complicated pattern of undulating, braided reflections of weak amplitude which strongly alters the host rock reflection pattern (Fig. 5f, 6d.)

In the 40 Hz image based on the binary model (Model 1; Figs. 5g, 6e), a larger number of the thinner sills are imaged, sill terminations and connectivity can be assessed in most cases, and the point-spread function indicates that the thickest sills are within the resolution limit. Using this seismic section (Fig. 5g), careful interpretation could probably recover most intrusions of the sill complex observed in the outcrop. In principle, the interference patterns observed in the previous images now apply to the intrusions of approximately less than 10 m thickness. At 40 Hz signal frequency, it is possible to discern that most of the visible apparent offsets between reflections are related to different intrusions rather than an actual offset, for instance due to a fault (Fig. 6e). The result of Model 2 at 40 Hz frequency reveals a greater degree of detail in many areas of the image, such as the representation of sills of medium thicknesses (10-15 m) with distinct top and bottom reflections, and more pronounced amplitude drops caused by sill terminations (Figs. 5h, 6f). In particular, intrusions that could be identified already at lower frequencies are now imaged in high detail. However, interference with host rock layers still causes interference patterns such as braided reflections that do not allow the interpretation of distinct sill geometries (Fig. 6f). Additionally, some layer-parallel intrusions in areas of relatively high host rock impedance remain essentially hidden in reflections caused by the sedimentary rocks (Fig. 5h, right side).

Effect of elastic property variations in sills

Based on statistical well data analysis from the Los Cavaos oil field, we now investigate the influence of seismic property variations of intrusions on the resulting seismic images from Model 2 (Fig. 7). The zero-angle reflection coefficient R_0 ("reflectivity") is derived from the two endmembers for acoustic impedance of the sill intrusions embedded in the identical layered host rock and presented within a detailed section (Figs. 7a, b). The two endmembers differ by only 0.7 km s^{-1} in their P-wave velocity, corresponding to a relative acoustic impedance change of 13%. However, the zero-angle (i.e., normal incidence) reflectivity in each model differs significantly due to the high variability in the host rock impedances, as illustrated by the three areas highlighted in Figs. 7a and b. In the high-impedance case, nearly all sills constitute positive top reflectors, i.e. increasing acoustic impedance, with a relatively high, but variable zero-angle reflection coefficient R_0. Reflectivity is significantly reduced wherever sills occur in high-impedance host rock layers (upper sills in area 3 in Fig. 7a). In contrast, the reflectivity pattern arising from the low-impedance sill reveals that the changes in impedance contrasts cause a significant drop in the reflection coefficient in some areas. R_0 is generally reduced (e.g., area 1 in Figs. 7a,b), in some cases by up to two orders of magnitude, and even turns negative where high-impedance host rocks are present (upper sills in area 3 in Fig. 7b). Consequently, those intrusions (e.g., area 1 in Fig. 7b) become essentially transparent with respect to their reflection coefficient or produce a seismic reflection with negative amplitude from this surface. The transgressive sill limb (area 2 in Fig. 7b) acts as a positive reflector with relatively high impedance, with the exception of its upper part. Here, higher host rock impedance causes smaller contrasts and, accordingly, reflection coefficients drop in magnitude.

The seismic images demonstrate the consequence of the different reflectivity patterns arising from the different elastic impedances at a signal frequency of 20 Hz, 30 Hz and 40 Hz, respectively (Figs. 7c-g). At 20 Hz, high-impedance intrusions (Fig. 7c) can be identified due to amplitude increase (areas 1, 2), transgressive reflections (area 2), and terminating reflections (area 3), although the low resolution does not reveal further details. At the same frequency, the only identifiable feature in the low-impedance endmember is caused by the transgressive sill limb (Fig. 7d, area 2), while strong amplitude variations and terminating reflections are not observed in the other parts of the image.

The increase in resolution seen in the 30 Hz images reveals more details in the corresponding seismic images (Figs. 7e, f). However, when the sills cause stronger impedance contrasts, the improvements appear to be more pronounced, since some thinner sills can be detected as interference features, and the shape of the transgressive sill and the sill terminations are more accurately imaged (Fig. 7e). In the low-impedance case, the higher resolution reveals the transgressive sill, but does not resolve further intrusions (Fig. 7f). As a result of interference of reflections from the host rock with relatively weak reflections from intrusions, the sill-related reflections are of low to medium amplitude and include reflection broadening (area 1, Fig. 7f) as well as discontinuous reflections in areas with complex intrusion shapes (area 3, Fig. 7f).

At 40 Hz, the increased resolution contributes to a higher degree of detectable detail of the sills – if they have high acoustic impedance relative to the host rock (Fig. 7g). The low-impedance endmember gains detail, but the small contrasts, as well as the blending of peaks and troughs caused by the intrusions in some cases (area 3) create a complicated pattern that is difficult to relate to the real intrusion geometries (Fig. 7h).

Interpretation of the case study

In the interpretation of the case study from the El Manzano outcrop, we focus on three issues: (1) the influence of the host rock implementation (binary vs realistic) on the predicted seismic expression of the sill complex, (2) the effect of reduced seismic impedance of fractured intrusions within the realistic host rock, and (3) a comparison between a 2D seismic section and 3D seismic data of the Los Cavaos oil field.

Influence of including host rock layering and seismic properties on the modelled seismic response

The differences between the synthetic seismic sections from El Manzano obtained from the models with binary properties (Model 1) versus a variable realistic property distribution (Model 2) demonstrate the strong effect of metre-scale property variations on the seismic response for the case of a variable host rock. The images from the binary model (Figs.5c, e, g) show some interference, but suggest that, overall, the main elements of the sill complex would be identifiable in a seismic section. On the contrary, the more realistic images that consider a layered host rock 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 (Figs.5d, f, h). Apart from the highest resolution image at 40 Hz, the other sills are challenging to detect and are merged in frequency-dependent interference of reflections from host rock layers and intrusions. However, the detailed observations in Fig. 6 indicate that features at the scale within the 1/30-wavelength limit of detectability may cause characteristic interference 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. Note that the exact position and thickness of such intrusions will still be difficult to determine, and significant tectonic faults are absent in the models.

Effect of reduced impedance of fractured intrusions

The absolute values for the acoustic impedance of the sills are reduced by less than 13% between the two endmembers, but depending on the host rock properties, the impedance contrasts on the top of intrusions drop from strong positive values to values close to, or even below, zero in some parts of the section. As a result, these particular sills show a different response with commonly much weaker amplitudes which are nearly impossible to recover by seismic interpretation. Although there are still some low amplitude disturbances visible at 30 Hz and 40 Hz, we are less confident that intruded areas can be identified based on disturbance of sedimentary layers, especially in areas of relatively high-impedance host rock layers where the amplitude reduction is most significant (areas 1, 3 in Fig. 7b,d,f,g). In the areas where the host rock is characterized by lower acoustic impedance (area 2, Fig. 7), the layer-discordant sill can still be identified with high confidence. Overall, we expect that fewer low-impedance sills can be directly interpreted, and intruded intervals containing such intrusions can be identified.

Comparison to seismic field data

A comparison of the modelling results with a seismic line from a 3D seismic cube from the Los Cavaos oil field shows remarkable similarities of specific waveform patterns that can be attributed to intrusions (Fig. 8a). A schematic interpretation, based on the seismic line and our evaluation the synthetic models, is shown in Fig. 8b. Following our observations from the synthetic seismic sections, we first use strong disturbance of the otherwise parallel sedimentary reflections to subdivide the target interval (Mendoza Group, coloured in the interpretation) into an intruded and non- or less intruded area, respectively. The interpreted non-intruded part of the section appears as a set of undisturbed, flat, parallel, continuous reflections on the right side of the seismic line in Fig. 8a. We suggest that this may be due to the lack of intrusions, since the expected waveform patterns are not observed. In the intruded part, we then focus on layer-discordant reflections to interpret intrusions directly, and interpret thin intrusions where splitting of reflections, braided reflections, lateral amplitude variations occur. Numerous reflections show small offsets in the real seismic data, but whether this is related to intrusions, as suggested by seismic modelling, or small-scale tectonic inversion features of normal faults is not immediately apparent.

Three wells confirm the presence of numerous sill intrusions of 2-40 m thickness where intrusions are interpreted from seismic (Fig. 8), which are identified through a combination of geophysical log signatures, cutting analysis and core descriptions. Examples of well log signatures from Los Cavaos can be found in the literature (Rabbel 2017; Witte et al. 2012). However, it is also clear that only a fraction of the existing intrusions can be recovered in the interpretation, and that neither the exact location nor architecture of intrusions are particularly well defined. Nevertheless, equipped with the results of our modelling study based on the direct field analogue, it is possible to identify the intruded interval and infer the existence of numerous, potentially interconnected intrusions.

Variations of seismic property contrasts

Similarly to the result obtained from Model 2, the strongest reflection amplitudes are associated with local evaporite and carbonate layers, and may therefore be misinterpreted as sills (Fig. 7, 8a). Each of the three wells confirm 2-6 closely stacked intrusions of 2-22 m individual thickness in the interval below the Chachao limestone, which are extremely difficult to identify in the seismic line. Small impedance contrasts between the host rock and the intrusions may be a possible explanation why these relatively thick packages are not visible. Since one of the intrusions in this interval represents a fractured reservoir, it is likely that the associated velocity reduction has an additional negative effect. In strong contrast to the imaging problems in the target interval, it is worth to notice the high amplitude, layer-discordant, laterally discontinuous reflection in the Neuquén Group at around 1.5 s two-way travel time (TWT) (Fig. 8a). Although we lack well logs from this interval, this feature has been confirmed as a saucer-shaped intrusion (J.B. Spacapan, pers. comm., 2017). The interlayered continental clastic sediments of the Neuquén group are likely to have significantly lower seismic impedance values and therefore the sill creates a strong contrast, leading to the seismic response that is similar to the characteristic response reported from sills emplaced in clastic sediments (e.g., Eide et al. 2017; Planke et al. 2005).

Discussion

The ability to interpret complex geological structures, such as igneous sill complexes, on seismic images relies to a large degree on the understanding of seismic wave propagation in the subsurface and geological concepts based on field analogues (e.g., Lecomte et al. 2016; Magee et al. 2015). Here we will discuss our results in the light of the usage of realistic seismic modelling based on field analogues and well data to aid seismic interpretation of igneous intrusions by bridging the scale gap between outcrop observations and seismic data. First, we will examine the range of applications and advantages of our approach to realistic seismic modelling of field analogues. Thereafter, we outline potential implications of our study from the Neuquén Basin for seismic studies of intrusive complexes, and discuss its relevance in comparison to case studies from other geological settings.

Applicability and advantages of the modelling workflow

The three-fold workflow to seismic modelling of field analogues described in this study represents a realistic approach, because it reduces simplifications in the model: (1) the structural input for geological features represent real geology derived from virtual outcrop models (Fig. 3), (2) direct implementation of well data creates real property variations down to the scale of well log sampling, and is somewhat similar to a well tie in seismic interpretation (Fig. 4), (3) the 2(3)D filtering technique accounts for spatial resolution and illumination effects, while being computationally efficient. This allows the extensive testing of different scenarios, such as the acoustic impedance endmember cases presented in Fig. 7, even at the high level of detail represented in the model. We have customized our workflow to the specific case of modelling a sill complex emplaced in a host rock with highly variable lithologies, including shale, carbonate and evaporite layers. However, as long as virtual outcrop models of a field analogue and suitable well data are available, our approach can be applied in a range of settings, including other types of intrusions, such as laccoliths. In fact, Bakke et al. (2008) applied a comparable approach to turbidite systems, but without the use of virtual outcrop models.

Seismic modelling based on field analogues is becoming an increasingly popular method to assess the validity of seismic interpretations of igneous intrusions (Eide et al. 2017; Lecomte et al. 2016; Magee et al. 2015). It is advantageous to use real geometries of sill complexes in seismic modelling studies of a specific geological setting, because the intrusion architecture will reflect the details that can be expected in the subsurface. Importantly, Eide et al. (2017) demonstrate that intrusions down to 1/50 of the dominant wavelength may be imaged in seismic data. This implies that architectural details of intrusions on the metre-scale need to be taken into account in seismic modelling. In contrast, idealized shapes may be very useful to isolate and analyse certain imaging effects, for instance to raise awareness for the general importance of interfering reflections from igneous intrusions (Magee et al. 2015; Planke et al. 2015). However, the applicability of the results for specific interpretations on real seismic data remains limited. Interpreters should be aware that the expression of igneous intrusions in a geologically more realistic and potentially more complex setting may look very different.

The direct implementation of well data to allocate host rock properties has strong benefits, and also represents the main difference to other available seismic modelling studies of sill complexes. This approach ensures that the host rock response correctly scales with the chosen seismic signal frequency in each modelling case (Figs. 5-7). In previous studies, sedimentary layers are taken into account at the scale of several tens of metres (Eide et al. 2017; Magee et al. 2015). This creates an unrealistic representation of the seismic response of the host rock, and may lead to “white space” between layer reflections at higher frequencies (Magee et al. 2015). Note that in settings where the host rock impedance is very low relative to intrusions, these effects might play a minor role (e.g., Eide et al. 2017). However, this issue can be ruled out by generating a high-resolution host rock model directly from well data, ensuring that interference effects at different scales are not neglected.

Implications for seismic studies of intrusive complexes in variable host rocks

The complex geometrical architecture of interconnected sills emplaced in host rocks of variable acoustic impedance leads to complex interference patterns in the seismic response. This makes the detection of single intrusions very difficult, but modelling results nonetheless indicate that intruded intervals can be detected (Figs. 5,6). Highly variable seismic properties in the sedimentary rocks, e.g. interlayered shale, carbonates and evaporites, lead to intra-sedimentary reflections of comparable amplitude to sill-related reflections, as well as sill reflections of relatively low amplitudes. As a consequence, the interference of these reflections plays a much larger role compared to intrusions in settings with less variable host rock properties (Eide et al. 2017; Magee et al. 2015). In settings that are comparable to the northern Neuquén Basin, interpreters need to be aware that amplitudes characteristics can be everything between very strong positive to essentially zero, especially when the intrusions' acoustic impedance is reduced because of fractures or other alterations (Fig. 7).

This makes interpretation of intrusions from seismic data extremely challenging, and in some cases impossible, because intrusions might be hidden in the background seismic response (Figs. 5,7). In the seismic interpretation, a significant part of the intrusions identified in wells is missing, including sills that are well within the detection limit (Fig. 8a). Detailed seismic modelling of suitable field analogues represents one way of helping interpreters to look for specific seismic signatures. At Los Cavaos, this approach enabled us to interpret a few single intrusions, and outline the main intruded interval (Fig. 8b). In the model, variations of seismic rock properties must be implemented at high resolution to allow the prediction of detailed waveform patterns arising from interference. The comparison between binary and realistic layered host rock (Fig 5,6) shows that oversimplification, especially of the host rock, will not give a sufficiently accurate image of expected imaging conditions.

Our case study, despite lithological complexity, does not include tectonic faults, subvertical dykes or features such as potentially high-impedance contact metamorphic aureoles or host rock deformation due to intrusion emplacement. The extent and expression of these features vary strongly (e.g., Eide et al. 2016;

Spacapan et al. 2017), but they are often observed around igneous sills. It is clear that such features, if they are observed in the study area, should be included in the model, since they will likely influence the details of the seismic image. Recently, Eide et al. (2017) demonstrated that high-impedance layers in the overburden have strong negative effects on signal frequency and lateral resolution. Therefore, the overburden should be taken into account to apply realistic imaging conditions. This may complicate seismic interpretation even more, but based on our results we suggest that the details must be evaluated through case studies before further conclusions are drawn.

Comparison to seismic expression of igneous intrusions worldwide

The results of our case study stand in strong contrast to the findings of most previous seismic interpretation studies of igneous intrusions, where consistently high amplitudes are reported for sills (e.g., Planke et al. 2005; Schofield et al. 2012; Schofield et al. 2015). These studies were conducted in settings where high-impedance mafic intrusions are emplaced in low-impedance siliciclastic host rocks, leading to strong impedance contrasts and high seismic amplitudes (Eide et al. 2017; Planke et al. 2005). Interestingly, despite these seemingly favourable imaging conditions, well data show that significant amounts of intrusions are missing in the seismic interpretation (Omosanya et al. 2016; Schofield et al. 2015). This is most likely a result of decreased resolution below thick sill intrusions, rather than small impedance contrasts between igneous and sedimentary rocks (Eide et al. 2017). In the study of Schofield et al. (2015), high host rock velocities of more than 4.5 km/s may contribute to lower seismic amplitudes of sill-related reflections, since the seismic property contrasts between host-rock and intrusions are reduced.

However, also the more general seismic modelling studies of seismic signature of sill intrusions have implicitly focused on settings where clastic sediments host very-high impedance intrusions (e.g., North Atlantic), and promoted high seismic amplitudes as one of the main characteristics of igneous intrusions in seismic data (Magee et al. 2015; Planke et al. 2015). Based on our results, we find it important to point out that the seismic expression of igneous intrusions needs to be explicitly viewed in their respective geological setting. General statements based on a specific setting should be avoided, because it might represent a pitfall for interpreters. We are able to show that very different seismic expressions can co-exist in a single seismic data set. The seismic line from Los Cavaos (Fig. 8a) shows the faint expression of the sill complex emplaced in the complex lithology of the Mendoza group, as well as a high-amplitude reflection of a transgressive andesitic sill within the low-impedance clastic rocks of the Neuquén group. There is a significant risk that a seismic interpreter who is unaware of the potential for low-amplitude sill reflections will only identify the most prominent sill.

In addition to the Neuquén Basin, there are other examples of sedimentary basins that host both high-impedance host rocks and host intrusive complexes, including the Santos Basin, Brazil (Klarner et al. 2006; Klarner and Klarner 2012), several New Zealand basins (Bischoff et al. 2017), and the Permian section of the Barents Sea (Polteau et al. 2016). Fracturing and alterations of igneous rocks have been reported from very different geological settings (e.g., Bischoff et al. 2017; Rateau et al. 2013; Witte et al. 2012). As a consequence, seismic properties and impedance contrasts may vary significantly, regardless of the chemical composition of the intrusion (Magee et al. 2015). In those settings, this may lead to challenges with the detection of igneous bodies, or distinction from other lithologies with similar seismic properties.

Conclusions

Our seismic modelling case study of a field analogue of an oil-producing igneous sill complex in the Neuquén Basin, Argentina, demonstrates how virtual outcrop models and well data can be integrated to build high-resolution, well-constrained geological models and conduct realistic seismic modelling of igneous sill complexes. We compare the modelling results to seismic field data from the Neuquén Basin in order to evaluate the benefit of this approach to seismic modelling, especially in geological settings with highly variable lithology. Additionally, we assess the level of geological detail that may be revealed from interpretation aided by a properly calibrated seismic modelling study. From the results presented, we draw the following conclusions:

(1) Realistic seismic modelling based on field analogues can be accomplished by a combination of (1) high-resolution, seismic-scale virtual outcrop models, (2) borehole data to allocate well constrained seismic properties including metre-scale property variations, and (3) a suitable modelling technique that accounts for both complex, high-resolution geological models and 2(3)D resolution and illumination effects.

(2) Including sub-seismic scale geometries allows the investigation of complex interference patterns and their link to the interplay of intrusion geometry and host rock layering that cause them. Such waveform patterns include splitting and transgressive reflections, braided reflections and reflection offsets that could be mistaken for small-scale faults.

(3) Comparison to real seismic data shows that the waveforms described in (2) may be used as indicators for the presence of multiple, potentially stacked and interconnected sills, or intruded intervals that may otherwise not be identified. The individual sills causing such patterns may be less than 10 metres thick in some cases.

(4) Direct implementation of well data to represent sedimentary layers at the metre-scale is particularly important in cases of highly variable host rock lithology with strong seismic property contrasts (e.g., interlayered limestone, calcareous shale, evaporites). This ensures that the host

rock response and associated interference of reflections scales correctly with the seismic signal frequency chosen in each simulation.

(5) Layer-parallel intrusions with similar seismic properties as the surrounding host rock will most likely not be imaged and therefore missing in the interpretation.

(6) In the presence of high-impedance sedimentary rocks, e.g. carbonates or evaporates, small absolute variations in vp, vs, or density of intrusions can cause substantial changes in reflectivity of more than one order of magnitude. Consequently, the response of the affected igneous features may change from a high-amplitude reflector to essentially transparent or even show phase reversal.

(7) The partially low amplitudes of intrusions in the presented case study stand in strong contrast to previous work, where very high amplitudes are described as one of the main characteristics of igneous sills in seismic images. We conclude that statements on the seismic amplitudes of sills need to be made under explicit consideration of the factors that may influence the seismic property contrasts (e.g., host rock lithology and type, fracturing or alteration of intrusions).

(8) Endmembers of seismic expressions of sills (prominent.high-amplitude reflections vs low-amplitude interference patterns) may co-exist in the same dataset. Locally calibrated seismic modelling can reduce the risk of focusing only on high-amplitude reflections.

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Figure captions

Fig. 1. Geological setting of the study area located in the northern Neuquén Basin, Argentina. (**a**) Satellite image of the Rio Grande Valley with the Los Cavaos oil field, where 3D seismic data and log data from wells (bright spots) are available. Just 10 km to the west, at the El Manzano field site, the corresponding igneous reservoir rocks are well-exposed due to a basement-cored east-verging thrust. Outcropping intrusions are highlighted in red colour. (**b**) Geological section through the study area, indicating main structures and the spatial relation between exposed and subsurface strata.

Fig. 2. Flowchart implemented in this study, including the elements of the proposed workflow for realistic modelling based on field analogues. A virtual outcrop model yields high-resolution, seismic-scale model geometries, well data provide realistic elastic properties, and the seismic survey parameters lead to the pre-stack depth migration (PSDM) filter used for rapid, low-cost modelling that takes the given illumination and resolution into account. Combining the three elements provides the opportunity to perform realistic modelling, which may aid seismic interpretation through parameter sensitivity studies of the expected seismic signature.

Fig. 3. Overview of geological inputs from field analogue in the study area. (**a**) High-resolution, seismic-scale virtual outcrop model of the exposed sills at the El Manzano outcrop. (**b**) Close-up view of contacts between host rock and intrusions (white lines) along the outcrop are interpreted at a resolution of less than 1m. (**c**) Field observations supporting the interpretation of small-scale geological features in the virtual model. (**d**) Resulting high-resolution structural interpretation of the sill geometry from the virtual outcrop model.

Fig. 4. Illustration of the model building from combined well data and geometries from the virtual outcrop model. (**a**) Well logs of density and sonic velocity in the target interval are used to derive an acoustic impedance log (left). The sill intervals (red) are removed and replaced with average host rock values close to the interval (centre). The resulting acoustic impedance log is subsequently used to define a 1D layered model by averaging over intervals of user-defined length (in our case, 5m) (right). (**b**) The 1D model is laterally extended and folded according to the local dip at the field site, and the sill geometries are added to complete the geological model. In our model, P-wave velocity and density of the sills are derived from statistical analysis of well log data (Rabbel, 2017).

Fig. 5. Comparison of the synthetic seismic sections based on Model 1 (homogeneous host rock) and Model 2 (layered host rock) of the outcropping sill complex at El Manzano. (a) Binary model including sills in a homogenous host-rock. (b) Geologically realistic model comprising the sills embedded in a layered and deformed host rock based on well data. Boxes indicate areas that are displayed in more detail in Figs. 6 and 7. (c-f) Resulting seismic sections for the two models at 20 Hz, 30 Hz, and 40 Hz center frequency, respectively. Note that 2D resolution is indicated by the size of the point-spread function (PSF) shown in each seismic section.

Fig. 6. Detailed view for comparison of the synthetic seismic sections at 20, 30 and 40Hz main frequency based on Model 1(left column; a,c,d) and Model 2 (right column; b,d,e), with respect to the real sill contacts (grey lines). The outline of this detail is indicated in Fig. 5b. Note the variety of sill-related, frequency dependent interference patterns in the areas indicated by numbers 1-3 in images a) and b) (see text for detailed descriptions).

Fig. 7. Effect of sill property variations on the seismic modelling results. (a,b) Close-up view (indicated in Fig. 5) showing the zero-angle reflection coefficient R0 for the high- and low elastic impedance end members, respectively, defined from well data. The numbers indicate areas that show distinct differences (areas 1, 3) and similarities (area 2) between the models. (c-g) Resulting detailed seismic sections for both end members at 20 Hz, 30 Hz and 40 Hz, respectively.

Fig. 8. (a) Characteristic seismic section from 3D seismic block from the Los Cavaos oil field, Argentina, including three wells intersecting sills in the intruded target interval. Patterns similar to sill-related reflection patterns obtained from seismic modelling of the field analogue (Figs. 5-7) are highlighted. Note that the right side of the seismic line appears to be nearly undistorted, while the left side is proven to be heavily intruded and exhibits a rougher appearance with distinct interference patterns. (b) Schematic interpretation of the seismic line incorporating seismic modelling results.

Table 1. *P-wave and density values from statistical well log analysis, as well as derived S-wave velocity values for all lithologies present in the geological models.*

	Model 1			**Model 2**		
Lithology	v_p (m s^{-1})	v_s (m s^{-1})	Density (kg m^{-3})	v_p (m s^{-1})	v_s (m s^{-1})	Density (kg m^{-3})
Host	4200	2470	2600	3350-5950	1970-3380	2480-2950
Sill	5500	2890	2800	4700, 5500	2470, 2890	2800