**ABSTRACT**

The Cenozoic Phitsanulok rift basin (Thailand) is extensively affected by igneous intrusions and lava flows. In the Ruang Thong–Sai Ngam area, the E-A01 well drilled the early Miocene synrift Lan Krabu Formation, and unexpectedly encountered a 300-m-thick olivine dolerite sill (sill 3). The top and base of the sill are characterized by medium- to low-amplitude contrasts, atypical for most (high amplitude) responses from intrusions. Seismic interpretation, artificial neural networks, and model-based inversion were used to understand the seismic response of the intrusions. Two key factors combined to mask sill 3: (1) stacking of common depth point gathers resulted in lower amplitudes at the top and base of the sill, and (2) multiple intruded sills separated by thin shales caused internal reflectivity. Using the sill geometries, sill stratigraphic position, and inferred magma flow directions from broken bridges, an estimate of the relative timing of the sills, and the local stress orientations at the time of displacement was made. Three sills are inferred to have been emplaced during the Miocene when the maximum horizontal stress direction (Shmax) was north-south and two were emplaced during the Miocene when the stress direction was approximately east-west. Such orientations are compatible with known phases of Miocene inversion (east-west Shmax) and extension (north-south Shmax), although local stress changes associated with igneous bodies could also explain rotation to an east-west Shmax.

**INTRODUCTION**

There is considerable interest in the interaction between extensional magmatic processes in rifts, including the relationships between magmatism and deformation style (e.g., Morley, 1999; Corti et al., 2003) and how magmatic processes may progressively take over from faulting during continental extension (e.g., Mohr, 1989; Morley, 1994; Kier et al., 2013). Our understanding of igneous intrusion geometries has been greatly improved over recent years by a combination of interpretations based on outcrop and seismic reflection data, supported by numerical and analogue models (e.g., Pollard and Johnson, 1973; Symonds et al., 1998; Smallwood and Maresh, 2002; Thomson and Hutton, 2004; Planke et al., 2005; Mathieu et al., 2008; Polteau et al., 2008; Galerne et al., 2011; Schofield et al., 2012a, 2012b; Galland and Scheibert, 2013; Magee et al., 2013; Sun et al., 2014; Barnett and Gudmundsson, 2014; Rivalta et al., 2015). A review by Magee et al. (2015) discussed considerable successes made in understanding igneous intrusions, particularly using seismic reflection data, but noted the scarcity of borehole calibration for seismic studies (however, see Schofield et al., 2017). In this study we describe intrusions from an onshore rift in central Thailand, where hydrocarbon exploration wells have penetrated igneous intrusions in a region of the Phitsanulok Basin (Fig. 1) where three-dimensional (3D) seismic reflection data have been acquired.

Igneous intrusions have the potential to affect hydrocarbon exploration in a number of different ways, depending upon their location, extent, and relative timing in basin development (e.g., Reeckmann and Mebberson, 1984; Schutter, 2003; Rohrman, 2007; Rodriguez Monreal et al., 2009; Holford et al., 2012, 2013). In the Phetchabun Basin, which is southeast of the Phitsanulok Basin, igneous intrusions act as a fractured reservoir and have probably influenced maturation of the source rock in what is a relatively shallow basin (Barr and Cooper, 2013). Intrusions may also influence hydrocarbon migration pathways (Holford et al., 2012, 2013; Rateau et al., 2013), and if late in a basin history may breach seals of hydrocarbon traps. It is conceivable that domal uplifts (forced folds) associated with some intrusions could form economic hydrocarbon traps (e.g., Kumar et al., 2013). Igneous bodies can also cause drilling problems, or at least slow drilling; therefore, identification of their location for well planning is important (Millett et al., 2016). Consequently, understanding the timing and locations of sills is significant economically.

The Phitsanulok Basin is filled by late Oligocene–Miocene sedimentary rocks deposited in a continental environment (see Fig. 2 for the basin stratigraphy). The basin is strongly affected by extensional faults, and tilted fault blocks characterize the 3D seismic data of the study area (Fig. 3). In the Ruang Thon–Sai Ngam area of the Phitsanulok Basin (Fig. 1C), exploration Well E-A01 (see Fig. 4 for location) penetrated the updip position of...
reservoir sands of the early Miocene synrift Lan Krabu Formation. The aims of this well were to evaluate the petroleum system and potential hydrocarbon accumulations in this area. The well encountered multiple reservoir sands within the Lan Krabu Formation (sands LKU D, LKU K, LKU L, and LKU M), and also encountered intrusive igneous sills. A 300-m-thick sill complex penetrated by the well did not exhibit the typical high-amplitude seismic reflection characteristics of igneous intrusions (Fig. 5C2), such as those described and modeled by Magee et al. (2015). This study uses 3D seismic data in the Ruang Thong–Sai Ngam (RTG-SNM) area to provide insights regarding the characteristics, distribution, and facies of igneous intrusives by means of seismic interpretations, and analysis of the post-stack seismic data using artificial neural networks, and model-based inversion. We address why sills may not always be well imaged in the subsurface. One possible contributing factor is the unusually large thickness (~100 m) of some contact metamorphic aureoles to sills, which may be related to growth of thicker sills or sill complexes by accretion (e.g., Menand, 2008).
addition, we discuss the implications for timing of igneous emplacements on the hydrocarbon system.

GEOLICAL BACKGROUND

Most Cenozoic volcanic rock outcrops in Thailand are scattered flows that were extruded during the Pliocene–recent (Barr and Cooper, 2013). In the subsurface lava flows and intrusions are known from the Phitsanulok, Suphan Buri, and Phetchabun Basins. The Phetchabun Basin actually has hydrocarbon production from fractured igneous intrusions (Barr and Cooper, 2013). Around the southern part of the Phetchabun Basin a cluster of older volcanic rocks is present that show igneous activity between 24 and 9 Ma, as well as Pliocene–recent activity (Barr and Cooper, 2013). Within the Wichian Buri subbasin (of the Phetchabun Basin) basalts, gabbros, and diorites (24–11.6 Ma) are intruded in the synrift sediments as sills and laccoliths, and are penetrated by exploration wells (Barr and Cooper, 2013).

The Phitsanulok Basin is the deepest of a series of north-south–trending extensional Cenozoic basins in the central plain of Thailand (Fig. 1). The basin is surrounded by Paleozoic to Mesozoic age sedimentary, metamorphic, volcanic, and plutonic rocks, which also form the economic basement under the basin. The maximum width of the basin is 100 km. In the Sukhothai depression (a subbasin of the Phitsanulok Basin) the late Oligocene–Neogene half-graben basin fill is as much as 8 km thick (Knox and Wakefield 1983; Flint et al., 1988). This basin overlies the suture between the Sibumasu and Indochina continental blocks and was formed in an intracratonic extensional to transtensional setting (Morley et al., 2007a, 2007b, 2011). The sedimentary fill is continental and ranges from Oligocene alluvial fan and alluvial plain deposits (early rift stage), through early to mid-Miocene lacustrine and alluvial plain sediments (main rift stage) to late Miocene alluvial plain and alluvial fan sequences (late rift stage; Fig. 2). The early Miocene Chum Saeng claystones and the interbedded claystones in the Lan Krabu Formation (LKU) are the major lacustrine source rocks in the study area (Flint et al., 1988) (Fig. 2). Oil generation started ca. 14 Ma at depths exceeding 4000 m and migrated laterally as much as 16 km from the kitchen (Knox and Wakefield, 1983). The lacustrine source rock produces a waxy, low-sulfur, high-pour-point crude that is light (American Petroleum Institute gravity degree, 40° API) in the Sirikit field (Knox and Wakefield, 1983) but heavy (17°–23° API) in shallower accumulations due to bacterial degradation. The main play consists of fault-bound structural traps or structural-stratigraphic traps involving fluviodeltaic sands of the Lan Krabu Formation, which is sealed by lacustrine shales of the Chum Saeng Formation, and is trapped by fault-bound structures (Bal et al., 1992; Morley et al., 2007a, 2007b).
Figure 3. Three-dimensional seismic line across the study area showing the mapped horizons and typical structure of the area. See Figure 4 for location. MMU—Mid-Miocene Unconformity.
Figure 4. Time-structure maps of mapped horizons from the study area (see Fig. 1C for location. (A) Horizon MMU (Mid-Miocene Unconformity). (B) Horizon L. (C) Horizon PTT. See Figure 3 for location of the horizons on seismic lines.
Figure 5 (Continued on next page). Time-structure maps and representative seismic lines of the five largest sills in the area. (A) Sill 5. (B) Sill 4. (C) Sill 3. (D) Sill 2. (E) Sill 1. Small white maps of sills with red arrows indicate magma flow direction based on orientation of steps and bridges, and the assumption that the sills have propagated in the direction of deepest to shallowest. TWTT—two-way traveltime; MMU—Mid-Miocene Unconformity.
Figure 5 (Continued).
IMAGING OF IGNEOUS INTRUSIONS ON SEISMIC DATA

Igneous sills are typically imaged on seismic reflection data as high-amplitude, strata-concordant, and strata-transgressive segments (Planke et al., 2005). The high amplitudes are due to the high acoustic impedance contrast between less dense, slower velocity sedimentary rocks, and the relatively dense, high-velocity intrusions (e.g., Gibb and Kanaris-Sotiriou, 1988; Planke et al., 2005; Hansen and Cartwright, 2006). Within undeformed passive margin basins, sills commonly exhibit saucer-shaped morphologies, such as those documented from the Vøring and Møre Basins, Norway (Malthe-Sørenssen et al., 2004; Planke et al., 2005; Hansen and Cartwright, 2006). More varied intrusion geometries are found in structured basin segments, where the magma was emplaced along weak zones such as fault planes and along stratigraphic layers (Planke et al., 2005).

High-amplitude reflections may commonly correspond with the upper interface between an intrusion and the country rock (Smallwood and Maresh, 2002; Thomson, 2005). Sometimes, the lower, or both upper and lower, contacts are imaged (Jackson et al., 2013). However, in most cases relatively minor intrusions such as sills and small laccoliths are not thick enough to be fully resolved by seismic reflection data, and hence are imaged as tuned reflectors (Smallwood and Maresh, 2002; Magee et al., 2015). While the broad characteristics of the intrusions can be determined from tuned reflection packages, sill thickness can only be estimated.

DATA AND METHODS

The project database consists of a 3D survey with an area of 164 km², and 5 wells (Fig. 4). The information from these wells available for this study included well reports and composite logs, but only two wells in the data set have check shot surveys. In addition, well E-A01 drilled through igneous intrusions, and an unpublished petrographic analysis report of rotary sidewall core samples from the igneous intrusions was available.

Seismic interpretation was carried out in Petrel E&P Software Platform 2014 (http://www.software.slb.com). The interpretation of reflection relationships associated with igneous bodies can be described and mapped using the concept of seismic facies analysis described by Vail et al. (1977) initially used for sedimentary environments (e.g., Planke et al., 2000). Seismic facies types of these sills were identified and categorized in terms of seismic amplitude, frequency continuity, smoothness, location, depth range, and geometry of reflection packages. These intrusives were mapped via normal picking and autotracking on both vertical seismic profiles and time slices over the area.

The Gabor transform (Daubechies and Planchon, 2002) is a special case of the short-time Fourier transform, which permits good time-frequency analysis of a seismic data set (Naghadeh and Morley, 2016c; Naghadeh et al., 2017). Based on such time-frequency analysis, the data set has dominant frequency equal to 45 Hz and the propagation velocity is 5700 m/s. The tuning thickness, which is one-quarter of the dominant wavelength, is almost 32 m, hence reflections from the tops and bases of sills maybe distinguished when sills exceed 32 m thickness.

Four main steps were undertaken in analysis of the data: (1) data preconditioning, (2) seismic interpretation, (3) use of artificial neural networks, and (4) seismic inversion.

Data Preconditioning

Reflectors are best developed between 0 and 1800 ms two-way travel-time (TWT; Fig. 3), where most of the discontinuities are well imaged and the seismic data degrade considerably below 1800 ms. The final migrated seismic volume was used as an input to generate a volume attribute by structural smoothing with dip guiding and edge enhancement methods to improve the continuity of the seismic reflectors before autotracking.

Seismic to well ties were made for A-A01, B-A01, C-A01 and E-A01, and were further substantiated by making synthetic seismograms. Due to the available log types and hole conditions, E-A01 is considered the most reliable well. A synthetic seismogram was generated from well E-A01, which has available sonic and density logs as well as check shot data. Reliable synthetics to seismic matches for horizons LKU K and LKU L were obtained in well E-A01. This well to seismic calibration work was further used for artificial neural network and seismic inversion analysis.

A summary of the characteristics of sills in well and seismic data is given in Table 1. Sills have been identified in three wells: well C-A01 encountered a diorite sill (sill 4) between 800 and 900 m within a claystone dominated succession. A dolerite sill (sill 2) was penetrated in B-A01 between 960 and 1010 m. Well E-A01 penetrated an olivine dolerite sill >200 m thick (~1270 m thick), and a quartz diorite sill at ~2418 m.

Seismic Structural Interpretation

Six key horizons were interpreted (Fig. 3) based on well tops from seismic well ties. The horizons were mapped on a 5 x 5 line grid, infilled by autotracking, cross-checked, and edited. Surfaces were made using the convergent interpolation method for all interpreted horizons. Fault interpretation involved detailed manual picking every 10 lines. Horizontal correlations on time slices were also used to constrain the fault interpretation. Three of the horizon maps representative of deep, middle, and shallow levels in the basin are shown in Figure 4.

Due to the clear high amplitude and locally highly continuous seismic reflection, seismic attributes, artificial neural network, and seismic inversion were applied to characterize and identify the boundaries of the sill complexes on seismic profiles and time slices throughout the RTG-SNM seismic volume. The seismic attributes applied include variance (without dip guidance).
and root mean square (RMS) amplitudes. The combination of these two attributes applied over the entire seismic volume helped in the display of the anomalies and highlighting the body of interest. Examples of how the sills can be identified using RMS amplitude and variance attributes show in Figures 6 and 7.

**Artificial Neural Network**

Neural networks are trained to identify particular characteristics in a data set (Haykin, 1994). In the standard training strategy, two data sets must be created from the available data, a training set and a test set. The training set is the one used for training the neural network; and the test set is used for applying a stopping criterion. Each element of these sets is composed of a well log sample and related seismic attribute samples. Genetic inversion based on the artificial neural networks is conducted in order to generate a single nonlinear multitrace for inversion. Nonlinear inversion using well logs is much better than a linear inversion, but an exact fit can never be achieved because of limitations in the computation procedure. In this study the genetic seismic inversion technique was used as a nonlinear, multitrace modeling approach (see Veeken et al., 2009).

Normally, sills can be identified as very high amplitude reflections over lower amplitude reflections, whereas for sill 3 the RTG-SNM seismic data set shows medium- to low-amplitude contrast, and low-frequency appearance (Fig. 5C). As a consequence, some igneous intrusions appear to be difficult to identify on conventional seismic images. Genetic inversion by artificial neural network was applied on a 3D seismic cube across the RTG-SNM area. Neural network training was performed on well E-A01 by training log of the P-wave resistivity and log of the LWD resistivity (see Veeken et al., 2009). Genetic and artificial neural networks are applied on a 3D seismic cube across the RTG-SNM area.

### TABLE 1. SUMMARY OF WELL AND SEISMIC CHARACTERISTICS OF SILLS 1–5

| Sill unit | Location and stratigraphy | Area and thickness | Mineral composition from mud log | Petrophysical properties |
|-----------|---------------------------|--------------------|---------------------------------|--------------------------|
| 5         | Deepest sill complex overlying the basement; located in the northeastern part of the three-dimensional survey, is offset by a fault. Probably intruded into the P-Sands Formation deposited in alluvial plain environment. | Resistivity log shows thickness from 2460 to 2565 (55 mTMD). Logging while drilling (LWD) log from D-A01. Within the time interval of 950–2100 ms two-way traveltime, covers an area of ~28 km². | Identified as quartz diorite from petrographic analysis of sidewall core (well E-A01; Clews, 2014). From mud log: 30%–40% quartz, 15%–20% plagioclase feldspar, 15%–20% K-feldspar, and other mafic minerals. | This unit is characterized by low gamma ray (20–30 GAPI, American Petroleum Institute gravity degree) and high resistivity (200–300 Ohmm) in LWD logs (D-A01). |
| 4         | Sill complex located in the southern part of the survey, intruded into a downdropped fault block. Probably intruded between L and K reservoir sands of Lan Krabu Formation. | More than 100 m (850–950 mTMD) (well C-A01), covers an area of ~26 km², time interval ranging from 800 to 1350 ms. | Mottled black and white diorite composed of quartz, feldspar, and biotite. | Low gamma ray (30–40 GAPI), high resistivity (100–150 Ohmm), low slowness (50 US/f), low porosity (0.2 v/v), and high density (2.75 g/cm³) from well log. |
| 3         | Located in the southern part of the survey area; intruded between the early Miocene reservoir sands, e.g., K and L (horizons) of Lan Krabu Formation, interbedded with claystone (seal); deposited as interbedded lacustrine and alluvial plain deposit. | Approximately 230 m (1220–1450 mTMD) from (well E-A01); from seismic data is within the time interval 750 to 1025 ms, a thickness of >300 m, and covers an area of ~9 km². | Olivine dolerite; mud log description missing for the intrusion. | Low gamma ray (20–30 GAPI), high resistivity (200–300 Ohmm), low slowness (45 US/f), and high density (2.95 g/cm³). |
| 2         | Intruded into an upthrown fault block beneath horizon LKU K (LKU is Lan Krabu Formation). Some parts reach the top of the LKU K horizon (sandstone) interbedded reservoir sand and clay seal of Lan Krabu Formation. | Approximately 90 m (1000–1090 mTMD) (well B-A01). | Identified as dolerite (well B-A01). | Low gamma ray (30–40 GAPI), high resistivity (80 Ohmm), low slowness (55 US/f), low porosity (0.20–0.25 v/v) and high density (2.60–2.80 g/cm³) from well log (well B-A01). |
| 1         | Shallowest sill located in the east of the survey, overlying the Mid-Miocene Unconformity, no erosional truncations evident. Intruded or extruded(?) within the Ping Formation (alluvial fan). | Approximately 20 m (540–560 mTMD) (well log B-A01); between time depths of 320 and 480 ms and covers an area of ~63 km². | Identified as basalt or dolerite (well B-A01). | Low gamma ray (35 GAPI), high resistivity (It not very clear, 25 Ohmm), low slowness (40 US/f), low porosity (0.20 v/v), and high density (2.60–2.80 g/cm³) from well log (well B-A01). |

Note: mTMD—total measured depth in meters; US/f—microseconds per foot.
velocity, and then an inversion operator was computed that transformed the 3D seismic cube into an inverted P-wave velocity equivalent. The inverted P-wave velocity cube provides an estimate of the extent of the velocity anomaly, and hence provides an indication of the sill distribution.

**Post-Stack Seismic Inversion**

Seismic inversion is a procedure that extracts information related to rock properties from seismic data, particularly acoustic impedance, based on the traveltime, amplitude, and phase information (Sheriff, 2002). Post-stack seismic inversion analyses of the stacked seismic traces help to reconstruct the velocity structure or the acoustic impedance. Model-based inversion (Russell and Hampson, 1991) uses a generalized linear inversion algorithm, which assumes that the seismic trace (S) and the wavelet (W) are known, and attempts to modify the initial model by comparison with the resulting synthetic seismic section until a best fit can be achieved with the observed seismic data. A synthetic seismic section is generated by convolving a reflectivity series extracted from the initial model with an extracted wavelet to correlate with the seismic data. This method is effective when there is considerable information about the geology of the study area. The reliability of the inversion results can be degraded due to factors such as noise or inaccurate calculation. More information about inversion methods can be found in Aki and Richards (1980), and Russell (1988).
Model-based inversion was undertaken in the CGC geophysical interpretation tool HampsonRussell 10.0 (http://www.cgg.com/en/What-We-Do/GeoSoftware/Solutions/HampsonRussell). The major steps used in the acoustic impedance inversion framework start with extraction of a statistical seismic wavelet (Levy and Oldenburg, 1987; White, 1988; van der Baan, 2008; Naghadeh and Morley, 2016a, 2016b) from the stacked section near well E-A01, followed by making a seismic-to-well tie to obtain a good correlation coefficient. Well control and the interpreted horizons were used to build an initial low-frequency model based on geological knowledge. The synthetic data were created by convolving a wavelet with the estimated reflection series from well log data. To conduct seismic inversion it is necessary to minimize the objective function, which is the decreasing difference between the observed and estimated data. The high-frequency acoustic impedance (AI) model extracted from the seismic data is then merged with the low-frequency model to create an absolute AI model (Chopra and Marfurt, 2012).

The initial model calculated from well E-A01 and seven horizons permitted the generation of an initial AI model, which was used during the post-stack analysis and final poststack seismic inversion. Once the initial modeling was completed a poststack inversion analysis was used to generate the final model-based poststack inversion volume, which shows lateral variations of the units that were not present in the initial model.

**INTERPRETATION**

**Horizon Interpretation**

Horizon PTT (Fig. 3) is the deepest horizon interpreted in this area, and is the base of the synrift section, which is the base of the Khom Formation. The pre-rift section in the Phitsanulok Basin than can directly underlie horizon PTT.

Figure 7 Time slice at 400 ms through a Variance attribute cube showing how a sill (blue dashed boundary) is differentiated from the country rocks.
includes Paleozoic–Cretaceous clastic and carbonate units, as well as granites, metasedimentary units, Triassic volcanics and volcanioclastics, and ultrabasic rocks. The horizon is seismically poorly defined and follows a reflection of medium to low amplitude and low frequency. Continuity is good in the eastern area and diminishes toward the central and western areas. The PTT horizon ranges between time depths of 600–2400 ms TWT (Fig. 4C).

Within the Lan Krabu Formation are key sandstone reservoir horizons M, L, and K, which have been mapped as seismic horizons, and are important stratigraphic markers that are correlated between wells. Horizon M (Fig. 3) is at the base of the Lan Krabu Formation and ranges between 700 and 1800 ms TWT. Horizon L is within the Lan Krabu Formation (Fig. 3) and ranges in time depth between 600 and 1500 ms TWT. The faults a 1ecting the Lan Krabu Formation horizons strike northwest-southeast, and the structure dips are primarily toward the northeast. Horizon K (Fig. 3) also is within the Lan Krabu Formation and ranges in time depth between 600 and 1400 ms TWT. The Chum Saeng Formation comprises lacustrine shales that interfinger with and overlie the Lan Krabu Formation. The part of the Chum Saeng Formation that overlies the Lan Krabu Formation forms a packet of high-amplitude relatively continuous reflections and is known as the main seal because it caps key hydrocarbon accumulations (e.g., Morley et al., 2007a, 2007b). Horizon MS is mapped as the top of the main seal, and the seismic character of the horizon correlates well with synthetic seismogram results. The most reliable well to seismic calibrations was from well E-A01. The time-structural map of horizon MS ranges between 500 and 1300 ms TWT.

Horizon MMU is the Mid-Miocene Unconformity (Fig. 3) and follows a reflection of medium amplitude, low to medium frequency; the continuity is good in the eastern part and almost disappears in the central and western parts. The time-structural map of the MMU horizon ranges between the time intervals of 400 and 1100 ms TWT; the horizon dips toward northeast (Fig. 4A). In the eastern and southeastern parts of the area the MMU truncates horizons M, K, and MS. Horizon Intra-Ping (Fig. 3) is at the base of the Lan Krabu Formation and ranges between 700 and 1800 ms TWT, and the structure dips toward northeast. Horizon MMU is the Mid-Miocene Unconformity (Fig. 3) and follows a reflection of medium amplitude, low to medium frequency; the continuity is good in the eastern part and almost disappears in the central and western parts. The time-structural map of the MMU horizon ranges between the time intervals of 400 and 1100 ms TWT; the horizon dips toward northeast (Fig. 4A). In the eastern and southeastern parts of the area the MMU truncates horizons M, K, and MS. Horizon Intra-Ping (Fig. 3) is at the base of the Lan Krabu Formation and ranges between 700 and 1800 ms TWT, and the structure dips toward northeast.

Fault Interpretation

Most of the faults in the RTG-SNM area strike northwest-southeast (Fig. 4) and have the same orientations as the regional major faults, which control this small basin. The majority of these faults dip southwest at ~60°–70°. The distribution of faults in the Cenozoic section is parallel to the preexisting fabric of pre-Cenozoic structures, which is northwest-southeast. The distribution of faults can be compared to the distribution of intrusive igneous sills in order to study any fault control on igneous intrusions. These faults are less continuous upsection toward the MMU surface. Some faults were reactivated later than horizon MS. A number of faults in the area are associated with inversion anticlines below the MMU surface. Several small normal faults occur within the crest of the anticlines, but are less continuous at the level of the MMU surface, and are completely confined below the Intra-Ping horizon (Fig. 3).

Igneous Intrusions

Igneous intrusions are typically characterized by high-amplitude anomalies, hence RMS amplitude extraction from the seismic volume is a simple means of identifying many igneous intrusions. For example, Figure 7 shows an RMS time slice at 400 ms TWT, where a high-amplitude anomaly with a distinct boundary is present in the central part of the study area. These high-amplitude reflectors are locally highly continuous, but dim along the edges (Figs. 6 and 8).

Results of the variance attribute without dip guiding, extracted from the seismic volume, show that textural variations in the time slice help define the lateral extension of sill complexes (Fig. 7). The variance time slice at 400 ms TWT shows high similarity of signal with the sill forming a transparent region with a well-defined boundary (Fig. 7).

Detailed mapping of more than five igneous intrusives in the RTG-SNM area was undertaken. The morphology and geometry of the five largest intrusions are described in the following and are summarized in Table 1.

Sill 1 was identified as a dolerite from cuttings and composite logs in well B-A01 (Fig. 5E). In additional, a K/Ar radiometric age indicates the age of intrusion as 10.3 Ma (Royal Dutch Shell plc unpublished reports, and Knox and Wakefield, 1983). This sill is located in the east of the survey, is between time depths of 320 and 480 ms, and covers an area of ~63 km² (Fig. 5E). Sill 1 is the shallowest sill and overlies the MMU; no erosional truncations are evident. Figure 5E shows that the sill is a reflection of high amplitude, medium frequency, and high continuity, with steps and layer-parallel morphology.

Sill 2 was identified by lithology from the mud log and composite logs in well B-A01 (Fig. 5D), and is a dolerite. In addition, a K/Ar radiometric age indicates the age of intrusion as 10.3 Ma (Knox and Wakefield, 1983). This sill is located in the north of the survey, is between time intervals 600 and 1100 ms, has a thickness >60 m, and covers an area of ~17 km² (Fig. 5D). Sill 2 was intruded into an upthrown fault block beneath horizon LKU K. Some parts of this sill reach the top of the LKU K horizon. This sill is characterized by a reflection of high amplitude, medium frequency, and medium continuity. The morphology of the sill includes steps, transgressive segments, concave-upward geometries, and locally saucer morphologies (Fig. 5D).

Sill 3 (Fig. 5C) was identified by the lithology of cuttings in a mud log and by composite logs from well E-A01. Petrographic analysis of sidewall core indicates an olivine dolerite lithology for the sill in well E-A01. This sill is located in the southern part of the survey area and is within the time interval 750–1025 ms, has a thickness >200 m, and covers an area of ~9 km². Sill 3 was intruded between horizons K and L, and shows low-amplitude folding attributed to the inversion of the synrift section. This sill exhibits reflections of low to medium amplitude, low frequency, and high to medium continuity.
Sill 4 (Fig. 5B) is known to be an igneous intrusion from mud log and composite log data from well C-A01 and is compositionally a quartz diorite. This sill is located in the southern part of the survey area and is at time depths between 800 and 1350 ms TWT, is >100 m thick, and covers an area of ~26 km². This complex sill is intruded into the downthrown side of a major fault block, and appears to have been involved with inversion after emplacement. The sill is characterized by reflections of high amplitude, medium frequency, and medium continuity. Sill 4 exhibits variable geometries with different segments exhibiting saucer, layer-parallel, and planar transgressive morphologies. In greater detail the morphology of the sill exhibits a number of steps (Fig. 5B2).

Sill 5 (Fig. 5A) is known to be an igneous body from cuttings in a mud log and LWD (logging while drilling) logs from well D-A01. Petrographic analysis of sidewall cores in D-A01 indicates that the sill is a quartz diorite (Clews, 2014). This sill is the deepest of all the intrusions in this area; it is located in the northeastern part of the 3D survey area, is within the time interval of 950–2100 ms TWT, and covers an area of ~28 km². Unit 5 is offset by a fault, and exhibits a layer-parallel sill morphology. The sill is characterized by reflections of high amplitude, low frequency, and high continuity (Fig. 5A).

**TIMING OF SILL EMBLACEMENT**

Neogene igneous activity is scattered throughout central and northern Thailand (Barr and Cooper, 2013); surface volcanism is dated as between ca. 9 and 0.5 Ma, and subsurface igneous activity in the Phetchabun and Phitsanulok Basins is primarily of Miocene age (Fig. 9). Well penetrations in the Phetchabun Basin indicate that, as expected, there is not necessarily a strong stratigraphic ordering to the intrusions that occur in the deeper parts of the section of the basin. For example, the Bo Rang-1 well encountered 6 intrusion with K-Ar dates from top to bottom as 16 Ma (basalt),...
11.6 Ma (diorite), 11.6 Ma (diorite), 16 Ma (gabbro), 16 Ma (gabbro), and 11.6 Ma (diorite) (Barr and Cooper, 2013). However, clearly with ages of intrusions in the Phitsanulok Basin spanning 24–2 Ma within a late Oligocene–Holocene age sedimentary section there is an overall younging of igneous intrusives upward within the sequence.

During their initial exploration for hydrocarbons in the Phitsanulok Basin in the 1980s, Royal Dutch Shell plc identified a number of igneous bodies (mostly interpreted to be lava flows, with a few sills) in their exploration wells. Unpublished K/Ar ages of basalts encountered in the exploration wells yielded data for the igneous units as follows: 17–15 Ma, 14–13 Ma, 13.5–11 Ma, 11.3–9.6 Ma, and 10.3–9.2 Ma (Fig. 9; unpublished data in PTTEP archival reports). The areal extent of the individual flows or sills ranged between 44 and 223 km².

The relationships between structures and sills can help with relative timing; for example, if the intrusions follow faults and are not offset by them, then they are younger than the faults. If sills are folded by inversion structures, then they are younger than the inversion. Therefore, the timing of sill emplacement is based on: (1) the geometric relationship between structures and sills, (2) radiometric ages, and (3) the stratigraphic age of section into which the sill is intruded.

Sill 5 is characterized as a quartz diorite. Sill 5 was affected by faulting and by inversion, and is within the early Miocene Nong Bua Formation (Knox and Wakefield, 1983). Therefore, the emplacement is inferred to be of early to middle Miocene age.

Potassium/argon dating of an igneous rock sample from well A-A01 indicates an age of emplacement of ca. 10.3 Ma (Knox and Wakefield, 1983) (upper Miocene). These data can be correlated with sills 1 and 2. Sill 2 is within the early to middle Miocene section. Sill 1 intrudes into the section overlying the MMU (middle-late Miocene Ping Formation) and is a very shallow level sill intruded probably within ~100 m of the surface. Sills 3 and 4 (olivine dolerite) are affected by low-amplitude folding, and are offset by faults. These intrusives are below the MMU, their maximum depths of intrusion (assuming the dikes are no younger than 10.3 Ma) were probably ~2000–1500 m, while the shallowest parts of the sills were probably at 1000–800 m depth.

### DISCUSSION

The dynamics of sill intrusions are characterized by the magma propagation direction, which is thought to parallel intrusive steps or magma fingers in sills (Pollard et al., 1975; Rickwood, 1990; Schofield et al., 2012a). These intrusive jogs form by propagation of magmatic segments along nearby but different planes. Where the sill segments that start to separate or combine do not laterally overlap they form steps; where the segments overlap they are called bridge structures if they are continuous features; and broken bridges where discontinuities are present (Magee et al., 2016; Schofield et al., 2012b; Planke et al., 2005).
Shallow intrusion of sills (<500 m below the surface) into marine sediments is thought to change the characteristics of the intrusions because magma is interacting with soft, waterlogged sediments (Einsele et al., 1980; Schofield et al., 2012a). Consequences of the magma-sediment interaction include the development of compressional ridges as the more rigid upper layer of the magma buckle in response to flow of underlying magma, and the formation of lobate sill segments and magma fingers (Trude, 2004; Miles and Cartwright, 2010; Schofield et al., 2010, 2012a). Sill 1 is a shallow intrusion that might be expected to show these features, but none are apparent. However, the shallow section intruded in the Phitsanulok Basin comprises continental fluvial sandstones and overbank deposits that would be more consolidated and have lower porosity and water saturation characteristics than marine sediments. Therefore, in the Phitsanulok Basin the characteristics of shallow sill intrusion may not differ very much from deeper sills.

**Stress Evolution in the Phitsanulok Basin**

The Phitsanulok Basin, along with other basins in northern Thailand, exhibits a complex Neogene structural history (Morley et al., 2001, 2007a, 2007b). While the basin shows predominantly extensional characteristics in the Sukhothai depression (of the Phitsanulok Basin), there are two phases of inversion in the Miocene farther to the south in the Phitsanulok Basin. These phases are marked by folding that is truncated by an unconformity and by mixed extensional and reverse offsets along a few faults (Morley, 2016). Outside of the strongly inverted areas this change in stress is marked by a reorientation of normal faults in the middle Miocene, from a predominantly north-south trend to a predominantly northeast-southwest trend (Morley et al., 2007a, 2007b). There are also inversion anticlines formed around the late Miocene–Pliocene boundary (Morley et al., 2007a, 2007b, 2011). The complex changes between extension and inversion probably reflect the interaction between the various boundary forces in the Southeast Asia region (Andaman Sea, northern Himalayas, South China Sea; Pubellier and Morley, 2016).

Given the complex history of extension and inversion in the Phitsanulok Basin, and the extended period during the Miocene–Pliocene when igneous intrusions and extrusions occurred, it is possible that some intrusions were emplaced during periods of extension, while others were emplaced during periods of inversion. We explore whether the morphology of the igneous intrusions can suggest the stress regime at the time of emplacement. For example, observation by Walker et al. (2017) from the San Rafael subvolcanic field in Utah suggest that particular sill network geometries specifically formed during mild horizontal shortening. There are various ways of trying to date intrusions in the absence of radiometric dating: (1) height in the stratigraphy (intrusions must be older than the youngest country rocks they are within), (2) sills jog along preexisting faults (i.e., faults are older than sills), or sills are offset by faults (sills are older than the increment of fault displacement that affects them), and (3) intrusion morphology (i.e., feeder dike morphology, sill bridges and intrusive steps) that indicates a response that favors a particular stress field. Hence intrusion geometries might vary in a basin where the stress field has changed over time.

**Sill Morphology as Indications of Stress Changes in the Phitsanulok Basin**

Natural and artificial tensile fractures under the simplest conditions are oriented perpendicular to the minimum principal stress ($s_3$), and are in the plane of the intermediate and minimum principal stresses ($s_2$ and $s_3$, e.g., Nelson, 2001). Artificial hydraulic fractures generated from wells tend to propagate furthest in the $s_1$ direction and a shorter distance in the $s_3$ direction (e.g., Fisher and Warpinski, 2012; Nolen-Hoeksema, 2013). However, factors such as mechanical stratigraphy, local stress rotations, rock strength anisotropy, preexisting fabrics (including fractures), and pore fluid pressure distribution can also influence fracture propagation characteristics (e.g., Amadei and Stephansson, 1997; Nelson, 2001; Kim and Moridis, 2015). Assuming east-west extension in the Phitsanulok Basin, $s_3$ would be oriented north-south. If stresses were locally rotated in order to permit sill intrusions (so that the vertical principal stress is $s_2$; Barnett and Gudmundsson, 2014), then the effects of the far-field extensional stress regime would still favor a north-south–trending maximum principal stress orientation, and an east-west intermediate stress. Consequently, steps, bridges, and broken bridges would be expected to trend predominantly east-west in sills that developed during a phase of extension in the Phitsanulok Basin. In the Phitsanulok Basin study area we have mapped five sills. Sills 1, 2, and 4 exhibit steps and bridges that indicate the direction of magma flow (Fig. 5). Sill 3 has no steps bridges. Sills 1 and 2 show a trend in increasing depth of the sill either from north to south or south to north. Sills 2, 3, and 5 are elongated in a north-south direction, and faults may play a role in limiting the lateral extent of the sills. Sills 1 and 4 are more equidimensional, but in sill 1 the deepest area is in the north, while for sill 4 the deepest area is in the west.

There are two possible ways to interpret the elongate geometries of the sills: (1) the sill is a north-south trend off an approximately east-west–trending dike (Fig. 10A); (2) the elongate geometry is due to the feeder dike trending north-south (Fig. 10B). The north-south–trending dike seems an appealing solution to explain why the sill is elongated north-south, and the stress orientation would be appropriate for an east-west extensional setting. There are, however, two main problems with this interpretation. (1) An underlying feeder dike would be expected to cause saucer-shaped intrusion geometry, deepest along the axis of the fault with the sill becoming transgressive toward the east and the west (Fig. 10B; e.g., see the experiments by Galerne et al., 2011). This morphology is not observed (Fig. 5). (2) The mapped orientation of steps and bridges in the sills indicates an approximately north-south to north-northwest–south-southeast magma flow direction (Fig. 5).

Naviset et al. | Sill emplacement, Phitsanulok Basin, Thailand

Downloaded from https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/13/6/2017/3990753/2017.pdf by guest
The morphology of sills 1, 2, and 5, cutting higher in north to south or south to north directions suggests that the source for the sill was not a long, underlying north-south–trending dike, but that they propagated from sources at the northern or southern parts of the area. The bridge orientations are approximately north-south (Figs. 5D, 5E), indicating a similar magma flow direction. These sills are best explained by the presence of an east-west–trending feeder dike (Fig. 10A). The east-west maximum horizontal stress direction (Shmax) direction is inappropriate for formation of the dikes during extension. The change in Shmax direction could be explained by local rotation of stresses, for example associated with magma chambers or pipes (e.g., Halls, 1982; Ernst et al., 2001; see review in Gudmundsson, 2006). Alternatively, rotation of tectonic stresses during inversion can be invoked to explain inferred east-west dike orientations. Rotation of tectonic stresses is possible in the basin because at least two middle Miocene phases of inversion separated by a phase of extension have been identified for the (Morley, 2015), as discussed above, with another phase of inversion during the late Miocene–Pliocene (Morley et al., 2001).

The morphology of sill 4 is quite similar to the idealized geometry of Figure 10B. East-west– to northwest-southeast-trending bridges are present, the deep trend is elongate north-south, and the sill is transgressive toward the east. It is therefore inferred that sill 4 was probably intruded during an extensional phase. Sill 3 has a more ambiguous morphology; it is deepest in the southwest, and shallows both to the northeast and east. There are no bridges present to indicate magma flow direction. On balance the morphology of sill 3 is more like that in Figure 10B than in Figure 10A.

Combining the discussion here of relative timing of sill emplacement with the inferred stress orientations, and the timing of inversion discussed in Morley (2015), suggests the following chronology: (1) middle Miocene emplacement of sill 5 during a period of approximately east-west Shmax, (2) middle Miocene emplacement of sills 3 and 4 during extension (approximately north-south Shmax), and (3) late Miocene (ca. 10 Ma) emplacement of sills 1 and 2 during a period of approximately east-west Shmax.

**Sill 3 Seismic Characteristics**

Igneous intrusions are readily identified and mapped using 2D and 3D seismic reflection data because of the large impedance contrast between sedimentary country rocks and the intrusions that results in high-amplitude reflections.
(Smallwood and Maresh, 2002; Magee et al., 2015), and the common crosstraining and truncational geometries exhibited by these intrusion-related high-amplitude events (e.g., Symonds et al., 1998; Morley, 1999; Thomson and Hutton, 2004; Hansen and Cartwright, 2006; Planke et al., 2005, Poiteau et al., 2008; Magee et al., 2013, 2014, 2015). As discussed herein the Phitsanulok Basin 3D seismic data display sills with similar characteristics. However, sill 3 is different and without a well penetrating 300 m of igneous rock this sill would not have been identified. Sill 3 is bound by continuous reflections, but they are not anomalously high amplitude, and the sill is characterized by internal parallel reflections as well. Consequently the body looks more like a continuation of the sedimentary package than a sill. In the following we discuss the seismic characteristics of the sill, how it can be identified, and the possible reasons for its seismic characteristics.

Sill 3 is >200 m thick, sonic velocities from well E-A01 are ~7000 m/s and its average density is ~2.95 g/cm³. The X-ray diffraction data of a sample from its seismic characteristics. Consequently the body looks more like a continuation of the sedimentary package than a sill. In the following we discuss the seismic characteristics of the sill, how it can be identified, and the possible reasons for its seismic characteristics.

Sill 3 is >200 m thick, sonic velocities from well E-A01 are ~7000 m/s and its average density is ~2.95 g/cm³. The X-ray diffraction data of a sample from the sill at ~1270 m show that it is composed of 60% plagioclase, 30% pyroxene, and 10% olivine. The high velocity, which is more typical of ultrabasic rocks (e.g., Berndt et al., 2000), seems anomalous for the composition, but it is what the data indicate. An acoustic impedance model for crossline 8499 based on data from well E-A01 shows an AI increase as expected given the high P-wave velocities in E-A01 associated with sill 3. This sill represents a geological unit with a specific range of P-impedance of ~14,000–19,000 (m/s)(g/cm³), as observed on crossline 8499 (Fig. 11A).

Inverted P-impedance data (Fig. 11B) show that sill 3 is internally layered. Layering can be seen on the well log data set (Fig. 12). Sills are expected to exhibit low gamma ray, high velocity, and high density characteristics. The interval from ~1275 to 1280 shows a spike in gamma ray and decrease in velocity, and marks the top of an interval of relatively low velocity (Vp = 5500–7000 m/s) and moderately higher gamma ray (10°–40° API). Possibly the narrow interval of the most extreme values ~1275–1280 m represents a shale (or hornfels) within a composite sill complex. Alternatively, it marks compositional variation within the sill over the interval between 1275 and 1320 m, and is just the extreme upper end of this variation. The interpretation of shale or hornfels suggests that the sill is composed of several separate sills. Inversion results (Fig. 11B) show internal reflectivity within the intrusive body that is possibly related to different sill bodies (Fig. 11B). We therefore favor viewing sill 3 as a composite intrusion, not a single thick sill. Such stacked sills have been generated in numerical models investigating the mechanics of shallow intrusions that demonstrate that the presence of a dike-fed sill can focus further sill intrusions in the same region, and can lead to the development of shallow magma chambers (Barnett and Gudmundsson, 2014).

Barr and Cooper (2013) described a 200-m-thick sill from the Phetchabun Basin (in well L44G) that produced a metamorphic aureole ~100 m thick. The aureole is indicated by the presence of hornfels cuttings from the well. The presence of a metamorphic aureole is significant because it represents a zone where the sedimentary rock would gradually change its properties, becoming less dense and slowing interval velocities over a broad interval passing away from the sill. Therefore, rather than having a sharp boundary between igneous and sedimentary rocks, the boundary would be more gradational over tens of meters, possibly to >100 m. For sill 3 in well A01, the sonic log shows a gradual increase in velocity within the sedimentary section passing toward the sill over an interval of 100 msTWT (~115 m thickness) above the sill, and 80 msTWT (~92 m thickness) below the sill. This zone is therefore similar in thickness to that expected for a contact metamorphic zone. Such a gradational boundary may partially explain why the thick sill in A01 does not exhibit a characteristic high-amplitude reflection at its upper surface; however, it does not seem broad enough and does not cover enough range of velocities to provide a complete explanation.

Seismic inversion can highlight the location of a sill. However, sill 3 demonstrates that the low reflection amplitude at the top of intrusions makes it difficult to identify all sills using seismic data, particularly when they are composite sills with internal layering. AVO (amplitude versus offset) modeling was undertaken to clarify the reason for the low-amplitude reflections at the top and base of sill 3. AVO-created synthetic gathers, with European polarity, show decreasing amplitude versus offset or angle (Fig. 13). In Figure 14 reflections from the top (red line) and base (blue line) of the sill are shown. Because the post-stack data set is a result of stacking of common depth point (CDP) gatherers from different offsets that also belong to different angles, then stacking of gatherers produces low-amplitude reflections at the top and the base of sill. To detect these kind of intrusions just based on the seismic section, it is essential to take a look at the near offset stack section because the top and base of sill will appear as high reflection amplitudes.

In order to address the issue of identification of intrusive bodies from seismic inversion, when well log data are unavailable we extracted a seismic wavelet using statistical methods (Naghadeh and Morley, 2016a, 2016b) from seismic data, then used deconvolution to remove the source signature effects and convert the seismic section to a reflection series. Using Equation 1 the reflection series (RC) was converted to AI:

\[
AI_{i+1} = AI_i \frac{1 + RC}{1 - RC}
\]

where RC is the reflectivity at the i-th interface and \(AI_i\) is acoustic impedance of the i-th layer.

In Figure 15, the result of deterministic inversion of crossline 8499 without well log constraint is shown. Because the result of deterministic inversion is relative \(AI_i\), then identification of sill 3 becomes too difficult because high reflection amplitudes are related to high \(AI_i\) contrast and low reflection amplitudes are related to low \(AI_i\) contrast. The main sill body located in the middle part of the seismic section is not detected by deterministic inversion.

Several reasons are discussed below that can explain low amplitudes at the top and base of a sill. One of the pre-processing steps is true amplitude recovery using geometrical spreading correction. Because it is a function of velocity squared, then it is crucial to estimate the correct velocity to apply a correction. Getting offset from source and increasing velocity with depth
Figure 11. (A) Three-dimensional seismic crossline 8499. (B) Inverted P-impedance data set from A. Al—acoustic impedance. See Figure 4 for location.
Figure 12. Well E-A01 log data set across sill 3 shows the sill is actually multiple intrusions (yellow layer) between shales (green layer estimated as shale volume). TVDss—true vertical depth subsea; API—American Petroleum Institute (gravity degree).
Figure 13. AVO (amplitude versus offset) created synthetic gather demonstrates decreasing amplitude versus angle at the top of sill 3. GR (API)—gamma ray, American Petroleum Institute (gravity degree). TVDss—true vertical depth subsea European polarity.
make more spherical divergence, which causes more amplitude attenuation. To compensate for this attenuation the correct velocity is vital. Because the operator does not have any access to well log data set during processing, they will not accept a high velocity (7000 m/s) as the propagation velocity, especially at almost 1000 m depth, so trying to compensate amplitude attenuation because of geometrical spreading will not be successful. It is essential to apply advanced time variant spectral whitening during processing (Naghadeh and Morley, 2017) to compensate the amplitude because of frequency absorption.

Migration as a final step during processing tries to place reflectors at their correct location. Because some migration methods have weakness about dip layer imaging (Naghadeh and Riahi, 2013a, 2013b) it is possible to lose the amplitude of reflected energy. Suddenly increasing velocity can cause turning or diving waves because of considerable bending during propagation; applying a general one-way wave equation migration cannot image those turning energies. The high-amplitude energy during reflected back during migration will be removed from the original shot gathers (Naghadeh and Riahi, 2013a, 2013b).

CONCLUSIONS

Sills have been identified in the RuangThong 3-D seismic data from both seismic characteristics and by well penetrations. The age of the youngest sills have been dated as ca. 10 Ma and while older sills are inferred to be of Middle Miocene age. Sill morphology includes bridge and broken bridge orientation. There are no strong saucer-shaped morphologies commonly described for sills. This is probably due to the constraints on sill propagation imposed by the synrift, tilted fault block morphology.

Of the five sills investigated in detail, three sills are inferred to have been emplaced when the maximum horizontal stress direction was north-south and two were emplaced when this stress direction was approximately east-west. This reflects the known complex history of the basin, which has varied between extension and inversion during the Miocene. The east-west maximum horizontal stress direction is associated with inversion, while the north-south maximum horizontal stress orientation is associated with extension. Using igneous intrusions as paleostress indictors is fraught with problems since features like magma chambers can locally cause near isotropic stress conditions (as indicated by radial dike swarms). Nevertheless sill morphology coupled with implied dike orientations has the potential to help determine stress orientation from seismic data.

Most of the sills in the 3D seismic data set exhibit high amplitudes and locally crosscutting relationships typical of sills observed in basins worldwide. However, the 300-m-thick sill 3 was not easily identified from seismic data alone, and only a well penetration confirmed the presence of the sill. Two key factors combined to mask the sill: (1) the stacking of CDP gathers can result in lower amplitudes at the top and base of the sill than expected, and (2) multiple intruded sills separated by thin shales can produce internal layering of the body that produces reflections that resemble the adjacent sedimentary units. These effects mean that some sills, like sill 3, in a data set can be missed during seismic interpretation, and may produce surprises when they are encountered by wells, and underestimates in the volume of sills affecting a basin.

ACKNOWLEDGMENTS

We gratefully acknowledge PTT Exploration and Production Public Company Limited (Bangkok, Thailand) for providing the seismic data set and generously supporting, by means of student scholarship, this research work. We also thank Schlumberger Limited (Houston, Texas) for making the Petrel E&P software available, and CGG for providing the HampsonRussell software to the Department of Geological Sciences, Chiang Mai University, Thailand. We thank Chris Jackson and Craig Magee for helpful and constructive reviews of this manuscript.
Figure 15. Deterministic inversion of crossline 8499 without the well log constraint. AI—acoustic impedance.

REFERENCES CITED
Aki, K., and Richards, P., 1980, Quantitative Seismology: San Francisco, California, W.H. Freeman and Co., 557 p.
Amadei, B., and Stephansson, Ö., 1997, Rock Stress and its Measurement: London, Chapman & Hall, 501 p., doi:10.1007/978-94-011-5346-1.
Bal, A., Burgisser, H., Harris, D., Herber, M., Rigby, S., Thumprasertwong, S., and Winkler, F., 1992, The Tertiary Phitsanulok Lacustrine Basin, Thailand, in Proceedings, National Conference on Geologic Resources of Thailand: Potential for Future Development: Bangkok, Thailand, Department of Mineral Resources, p. 247–258.
Barnett, Z. A., and Gudmundsson, A., 2014, Numerical modelling of dykes deflected into sills to form a magma chamber: Journal of Volcanology and Geothermal Research, v. 281, p. 1–11, doi:10.1016/j.jvolgeores.2014.05.018.
Barr, S. M., and Cooper, M.A., 2013, Late Cenozoic basalt and gabbro in the subsurface of the Phetchabun Basin, Thailand: Implications for the Southeast Asian Volcanic Province: Journal of Asian Earth Sciences, v. 76, p. 169–184, doi:10.1016/j.jseaes.2013.01.013.
Berndt, C., Skogly, O., Planke, S., Eldholm, O., and Mjelde, R., 2000, High-velocity breakup-related sills in the Voring Basin, off Norway: Journal of Geophysical Research, v. 105, p. 28,443–28,454, doi:10.1029/2000JB900217.
Chopra, S., and Marfurt, K., 2012, Evolution of seismic interpretation during the last three decades: The Leading Edge, v. 31, p. 454–476, doi:10.1190/tle31060454.1.
Clews, P., 2014, Petrography of Sidewall Core Samples Well E-A01: Bangkok, Thailand, GenLabs unpublished report, 50 p.
Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P., and Sokoutis, D., 2003, Analogue modelling of continental extension: A review focused on the relations between the patterns of
geosphere
