Application of spectral decomposition and seismic attributes to understand the structure and distribution of sand reservoirs within Tertiary rift basins of the Gulf of Thailand

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The Tertiary rift basins in the Gulf of Thailand are the major hydrocarbon producing areas of Thailand. The reservoirs in these basins are predominantly Lower to Middle Miocene fluvial channels and overbank sands and these reservoirs are segmented due to post-depositional faulting (Racey, 2011). There are small closely spaced sealing faults, which compartmentalize the sand reservoirs and are not easy to map on conventional full spectrum seismic data. This fault system is oblique to the regional north-south extensional fault system and is related to graben shifts/transfer zones associated with changes in dip of graben provinces and zig-zag map pattern of the regional north-south faults (Kornsawan and Morley, 2002). Most wells until now have been drilled on structures along the faults and it is common to encounter different sand facies with different fluid contents in closely spaced wells at the same depth intervals. Because of these structural and stratigraphic complexities, it is required to develop geophysical workflows to better image faults related with graben shifts and map the reservoir sands in the area. In this study, we analyzed a 3D seismic data set over a gas field in the Pattani Basin (Figure 1) where we applied a spectral decomposition technique to resolve these exploration issues. Moreover, semblance and sweetness attributes were also calculated to assist in the fault and sand detection, respectively.

Geological background
The Gulf of Thailand is composed of a number of Tertiary north-south-trending extensional basins (Figure 1). These basins appear to be evolved largely because of east-west extension, which produced north-south-striking normal faults in the area (Morley et al., 2004). The study area in the Pattani Basin consists of elongated horsts, grabens, and tilted fault blocks bounded by closely spaced north-south-trending normal faults. Some faults trending oblique (i.e., northeast-southwest and northwest-southeast) to the regional north-south trending faults also are observed. These faults have been interpreted as transfer zones/graben shifts influenced by oblique pre-existing fabrics (Morley et al., 2004). The Pattani Basin contains more than 7600 m thickness of predominantly nonmarine fluvial-deltaic sediments and stratigraphically it has been subdivided into five sequences (Morley and Racey, 2011). These depositional sequences evolve from lacustrine and alluvial dominant syn-rift sediments in the Eocene-Oligocene to postrift fluvial-dominant sediments in the Early to Middle Miocene, to marginal marine-dominant sedimentation in the Late Miocene to the Recent. Pay sands are mostly encountered in postrift section within mainly thin fluvial sand layers. The depth of these pay zones is about 1500–2600 m in the study area. The source rock intervals are lacustrine shales and coals of syn-rift Oligocene sequence and Lower Miocene to Middle Miocene coals and mudstones (Racey, 2011). The basin-bounding faults of the Pattani Basin were active throughout most of the basin’s history and could act as conduits for vertical hydrocarbon migration.

Techniques adopted to resolve issues
The zone of interest is defined from 1400–2100 ms (1500–2600 m depth) which includes fluvial sand reservoirs of the Early to Middle Miocene. Three key seismic horizons (H1, H2 and H3), previously interpreted over the 3D seismic volume, were refined and interpolated to get continuous horizon surfaces for extracting attributes (Figure 2). To resolve subtle faults and to delineate channel sands, a spectral decomposition technique was applied to the original 3D data set. Spectral decomposition is a tool for better imaging and mapping temporal bed thickness and geological discontinuities within 3D seismic surveys (Partyka et al., 1999) and it aids in seismic interpretation by analyzing the variation of amplitude spectra and phase spectra. Amplitude spectra delineate thin-bed variability via spectral notching patterns that can be used to map the subtle stratigraphic changes such as due to channel systems, whereas phase spectra respond to lateral discontinuities, which can be used for delineation of subtle faults. Seismic data over the zone of interest (1500–
2100 ms) were transferred into the frequency domain via a discrete fourier transform (DFT) in zones of short window-length intervals of 50 ms. The outputs of this process are frequency slices generated over a time-windowed zone of interest which is termed the tuning cube. The vertical axis of this cube is frequency instead of time. Through animation of the tuning cube, the frequency range was selected which showed the most meaningful geological structures on phase and amplitude slices. Based on the selected frequency range, iso-frequency volumes of amplitude and phase spectra were generated through the DFT process by setting a 24-ms window. Time and horizon slices of amplitude and phase spectra of iso-frequency volumes were analyzed for the detection of channels and minor faults, respectively. In order to interpret vertical segments of faults in the 3D seismic volume, a band-pass filter was designed for the appropriate range of frequencies. The frequency range of bandpass was selected based on the phase spectra of discrete frequencies that highlighted minor faults. In addition to spectral decomposition, we also calculated sweetness and semblance attributes of the 3D seismic volume to map sand bodies and discontinuities in the study area, respectively. Mathematically, the sweetness attribute is derived by dividing the reflection strength (or instantaneous amplitude envelop) by the square root of instantaneous frequency (Radovich and Oliveros, 1998) and semblance is a measure of similarity (i.e., similar regions will have high values while dissimilar regions will have low values). The sweetness attribute was compared with GR logs at well locations to check the validity of any relationship between this attribute and sandy zones. In order to understand the geological nature of anomalies of sweetness and amplitudes at discrete frequencies, shallow tectonically undisturbed sections were analyzed to obtain analogs for deeper sections at reservoir levels.

Results and discussion

Fault detection. The calculated semblance volume based on full-spectrum seismic data highlights discontinuities in two different orientations (Figure 3). These are oriented north-south and northwest-southeast. North-south discontinuities are distributed throughout the area and can be clearly seen on the semblance time/horizon slices, whereas the northwest-southeast set of discontinuities is observable only in some places and not as clear as the north-south discontinuities in the semblance volume. On the other hand, the tuning cube calculated over the zone of interest more clearly shows north-south and northwest-southeast discontinuities on phase spectra of frequency slices ranging from 25~35 Hz. Phase spectra of iso-frequency volumes of selected frequencies (25~35 Hz) also indicated the same two categories of discontinuities as observed on the semblance volume (Figure 4). The northwest-southeast discontinuities observed on discrete frequency phase volumes are better imaged as compared to the discontinuities in the same direction observed on semblance and these can be more precisely mapped on phase horizon/time slices of iso-frequency volumes. The north-south discontinuities match the regional north-south interpreted faults on conventional full-spectrum seismic data. The
northwest-southeast discontinuities are further confirmed by the displacement of sand channels on amplitude spectra of discrete frequency volumes (Figure 5). Vertically these faults can be interpreted by using a bandpass-filtered (20, 25–35, 40) volume. The frequency range for bandpass filter was based on frequencies that highlight discontinuities on the tuning cube. These northwest-southeast discontinuities are at high angles to the regional north-south faults and these are observed at places where opposite dipping north-south faults are juxtaposed with each other or at places where the north-south faults show bends (Figure 4). The northwest-southeast discontinuities most probably represent faults related with localized graben shifts/transfer zones, as they are associated with juxtaposition of opposite dipping north-south faults and bends in the regional north-south faults. Other possible geological features such as channels can also produce discontinuity in phase. However, the discontinuities under discussion most likely represent faults because: (1) the observed discontinuities are almost straight which would be unlikely in the case of channels, (2) the bandpass-filtered sections clearly show the vertical fault segments, and (3) the observed high-amplitude channels on amplitude spectra are cut by the northwest-southeast discontinuities.

Figure 5. Time slice of amplitude spectra of 30-Hz phase at 1624 ms.

Figure 6. Sweetness section along the well and GR curve is displayed for comparison. Circled sand zones are of thickness 13–15 m, showing good correlation as compared to relatively thinner sands.

Sand mapping
Throughout the area, amplitude anomalies are scattered within the zone of interest along the faults and in the unfaulted zones. The synthetic modeling indicates that these anomalies are of negative seismic amplitudes associated with sands and some strong anomalies are because of hydrocarbon presence that has been proved by drilled wells. The sweetness attribute, which is an amplitude-based attribute, shows good correlation with sand zones of 13–15 m thickness up to 1700–1800 m depth when compared with the GR log at well locations (Figure 6). This correlation depicts that sweetness can successfully predict 13–15 m thick sand up to 1700–1800 m depth, whereas below 1700–1800 m sweetness does not show such a good correlation. This may be because of compaction of sands at greater depth, which consequently reduces the acoustic impedance contrast with respect to surrounding shales. However, down to certain depths, sweetness can be used to predict the sand distribution at different levels of reservoirs in the study area. Amplitude and sweetness anomalies are distributed along both the regional...
north-south and secondary northwest-southeast sets of faults (Figure 7). Therefore, it is equally important to map subtle northwest-southeast faults to know the reservoir geometries which could not be properly mapped on full-spectrum seismic data. The time slices of the shallow section reveal that high amplitudes on discrete frequency outputs of spectral decomposition data and high sweetness are associated with two types of features: (1) broad amplitudes associated with high sinuous channels of low sweetness and low amplitudes and, (2) narrow band of high amplitudes and high sweetness associated with channels of low sinuosity (Figure 8 and 9). The high amplitudes associated with the highly sinuosity channels are interpreted as broad sandy point bars, whereas the narrow bands of high amplitudes and high sweetness indicate sands associated with narrow meander belts. This information from the shallow section can be useful as an analog for the deeper sections of exploration interest, because the sediment deposition is predominantly fluvial throughout the depositional history of the basins in the Gulf of Thailand. Similar amplitude anomalies associated with deeper channels are observed on frequency slices ranging from 25–30 Hz on the tuning cube volume in the zone of interest (1400–2100 ms). Based on this observation, time-domain iso-frequency volumes were calculated for the frequency range of 25–30 Hz. These volumes were analyzed for high-amplitude anomalies over the zone of interest. Similar to the shallow section, two types of anomalies were observed (Figure 10). Some intervals clearly show broad anomalies associated with highly sinuous channel geometries although other high amplitudes are limited to narrow zones. Sweetness time/horizon slices also show similar broad and narrow patterns of anomalies. These are point bar sands along the highly sinuous channels and sands associated with narrow meander belts, respectively. Consequently, the intervals of broad amplitude and sweetness are more promising for hydrocarbon exploitation as compared to the narrow anomalies. The amplitude mapping on the discrete frequency volumes and on the sweetness volume may help to map the reservoirs more effectively as compared to conventional seismic data.
Conclusions

The main conclusions of the present study are summarized as:

- Spectral decomposition can be used to detect subtle faults, especially related with graben shifts or transfer zones, in the Gulf of Thailand.
- NW-SE faults may help to compartmentalize the reservoir.
- Amplitude spectra of 25–30 Hz can be used to detect the nature of channels and predict the sand distribution associated with fluvial systems in the zone of interest.
- Sweetness volumes may help to predict the sand distribution down to certain depths.
- Two types of channels are detected: (1) highly sinuous with broad point bars and (2) narrow meander belts.
- Broad point bars and sands associated with narrow meander belts can be identified on amplitude spectra of selected frequencies and sweetness volumes within the zone of interest.

References


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