

Quantitative seismic interpretation for reservoir characterization: Insights from digital rock physics and seismic attributes analysis

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**QUANTITATIVE SEISMIC INTERPRETATION FOR
RESERVOIR CHARACTERIZATION: INSIGHTS
FROM DIGITAL ROCK PHYSICS AND SEISMIC
ATTRIBUTES ANALYSIS**

CHANDOEUN ENG

JULY 2018

QUANTITATIVE SEISMIC INTERPRETATION FOR RESERVOIR CHARACTERIZATION: INSIGHTS FROM DIGITAL ROCK PHYSICS AND SEISMIC ATTRIBUTES ANALYSIS

by

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Abstract

After the Industrial evolution, hydrocarbon becomes an important part of society and technology, which is still continuing and increasing demand for energy consumption. Thus, oil and gas industry focus on the exploration of hydrocarbon in continental margin (e.g., forearc basin) and deep-water reservoir, where these reservoirs have attracted great attention for contributing world potential energy resources. Knowledge of the subsurface distribution of free gas (and gas hydrate) is important not only for evaluation of potential hydrocarbon gas resources but also for identification of potential geologic hazards associated with subsurface gas, such as submarine landslides. Furthermore, by injecting CO₂ into reservoirs at the continental margin (CO₂ geological storage), CO₂ emission can be decreased from atmosphere. However, continental margin is often characterized by complex geology, and reservoir descriptions based on conventional seismic data and well-log analysis are often qualitative in these environments. To reveal these reservoir systems in more accuracy, seismic attributes analysis and digital rock physics approach are applied as more quantitative seismic interpretation techniques. These methodologies were applied to characterize hydrocarbon reservoirs in Sanriku-Oki forearc basin, northeast Japan, and evaluated rock evolution process of the accretionary prism in Nankai Trough area, southwest Japan. This dissertation consists of four chapters and the main contents in each chapter are described as follow:

Chapter 1 introduces the background, motivation and objectives of this research. Seismic data and digital rock physics were described to quantify reservoir rock. The outline of the dissertation was described in this chapter.

In Chapter 2, a series seismic attributes analysis was performed on 3D seismic data in the Sanriku-Oki forearc basin in order to better define the influence of geological structures (e.g., faults, chimney, slumping and coal-bearing formation) on hydrocarbon reservoirs and migration pathways. The Sanriku-Oki gas reservoir is one of the biggest potential gas reservoirs around Japanese Island. To identify coal-bearing formation, 3D acoustic impedance distribution was calculated by integrating 3D seismic data and logging data through waveform inversion. Results revealed that Miocene and late

Oligocene major coal-bearing formations characterized as low acoustic impedance formations and gas-bearing sediments characterized as anomalously high reflection strength are widely distributed beneath the bottom simulating reflector (BSR). The gas-charged zone is commonly distributed in Quaternary sediments, but with a greater accumulation of gas in the north-east of the 3D seismic area at $\sim 2.5\text{--}2.9$ s two-way traveltime ($\sim 400\text{--}800$ m below seafloor), where there are successive slump sequences and gas chimneys. These suggest that the presence of a BSR with an underlying gas accumulation in the Sanriku-Oki forearc basin that developed as a consequence of the expulsion of hydrocarbon gases from Cretaceous to Oligocene coal bearing formations and their subsequent upward migration through gas chimneys and faults that cut across the basin. The migration and accumulation of gas were further influenced by a series of porous slump sequences. Because the gas spot was found above the edge of slumping, gas migration process from the edge of the slump sequences could be important. Therefore, the intensive tectonic movement of plate convergent margins is an important control on hydrocarbon gas systems in the Sanriku-Oki forearc basin.

In Chapter 3, the digital rock physics approach was developed to further quantify the physical and hydraulic properties of heterogeneous reservoir rock, and rock evolution process (e.g., mineral precipitation). Intensive geophysical surveys were conducted in Nankai Trough, thus P-wave velocity (V_P) and S-wave velocity (V_S) in this area can be used to evaluate rock evolution process in the plate convergent margin. In this study, the seismic velocity (V_P and V_S) of digital rock models constructed from core samples of an ancient plate boundary fault in Nobeoka, Kyushu Island, Japan was calculated. The 3D digital rock models were constructed from microcomputed tomography images of the core samples and identified their heterogeneous textures such as cracks and veins. The cracks and veins were replaced with air, water, quartz, calcite and other materials with different bulk and shear moduli. Using the Rotated Staggered Grid Finite Difference Method, dynamic wave propagation simulations were performed and quantified the effective V_P and V_S of the 3D digital rock models with different crack-filling minerals. The results demonstrate that the water-saturated cracks considerably decreased the seismic velocity and increased the ratio of V_P to V_S (V_P/V_S). The V_P/V_S of the quartz-filled rock model was lower than that in the water-saturated case and in the calcite-filled rock

model. By comparing the elastic properties derived from the digital rock models with the seismic velocities (e.g. V_P and V_P/V_S) of accretionary prism estimated from field seismic data, the evolution process of the accretionary prism, as well as seismogenic plate boundary fault, can be characterized. The high V_P/V_S and low V_P observed at the transition from aseismic to coseismic regimes in the Nankai Trough can be explained by open cracks (or fractures), while the low V_P/V_S and high V_P observed at the deeper coseismic fault zone suggests quartz-filled cracks. The quartz-rich fault zone characterized as low V_P/V_S and high V_P in this study could partially relate to the coseismic behaviour as suggested by previous studies because quartz exhibits slip-weakening behaviour (i.e. unstable coseismic slip).

Chapter 4 summarized the highlighted results of this research. In this study, seismic attributes and digital rock analysis have been emphasized and showed how these methodologies can be helpful to guide the quantitative seismic interpretation for reservoir or lithology characterization. This dissertation demonstrated that fault and slumping (i.e., tectonic activity at the plate convergent margin) largely influence on hydrocarbon reservoir, and rock evolution process around the plate boundary fault in plate convergent margin can be identified. These approaches could be important both for geologists and geophysicists because they open a new door to link between these two different research fields.

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Chapter 1

Introduction

1.1 Objective

The main objective of this dissertation is to characterize hydrocarbon reservoir and rock evolution process by employing seismic attributes analysis and digital rock physics analysis. This general objective contains two more specific goals: 1) To characterize hydrocarbon reservoir, migration pathway and sources (coal-bearing formation), and to discuss the relationship among hydrocarbon accumulation, slumping and geological structure (e.g., fault); 2) To calculate the influence of rock evolution (e.g., mineral precipitation) on seismic velocity from digital rock physics modelling in order to evaluate rock evolution process in seismogenic fault. The motivations and current issues for each of these specific objectives are described below.

1.2 General background and motivation

Gas hydrate and free gas occur in worldwide regions, including sedimentary sequence at continental margins (e.g., forearc basin) (Collett, 2002; Kvenvolden, 1993). The presence of gas hydrate can trap free gas (Miller et al., 1991; Mackay et al., 1994; Chhun et al., 2017), led oil and gas industry to invest in efforts of exploring these hydrocarbon resources. Gas hydrates are naturally occurring ice-like crystalline compounds in which methane are trapped with a lattice of water molecules (Figure 1.1). The crystal unit structures of gas hydrate can be classified into three types as shown in Figure 1.1. The presence of gas hydrates is controlled by temperature, pressure and

availability of appropriate gases and water. They occur in the permafrost region and deep water sediments (Kvenvolden, 1993).

Figure 1.2 shows that the occurrences of bottom simulating reflectors (BSRs) or gas hydrates are widely distributed around Japan islands (MH21, 2009). Their presence has been proved by either direct or indirect evidence. The former is directly drilling with irrefutable core samples. The latter is inferred from indications of geophysical anomalies of well logging data and BSRs from seismic profiles. Studies of these hydrocarbon resources are interested because it is thought that large amounts of natural gases could be used as future energy resources (Miller et al., 1991; Mackay et al., 1994; Chatti et al., 200). However, most of the undiscovered hydrocarbons hide within smaller, more complex and deeper reservoirs requiring new and sophisticated methods for successful exploration and reservoir characterization. Currently, exploring this hydrocarbon is harder, riskier, and more expensive, but demand continues and increases, forcing geologists and geophysicists to challenge with complex geology or deep reservoirs. A key to take over this complexity is quantitative reservoir characterization including quantitative seismic interpretation. Quantitative seismic interpretation techniques have become common for oil, gas industry, exploration seismology (Avseth, 2000), and other geo-engineering fields as these can validate hydrocarbon anomalies and give essential information during prospect evaluation and reservoir or subsurface characterization.

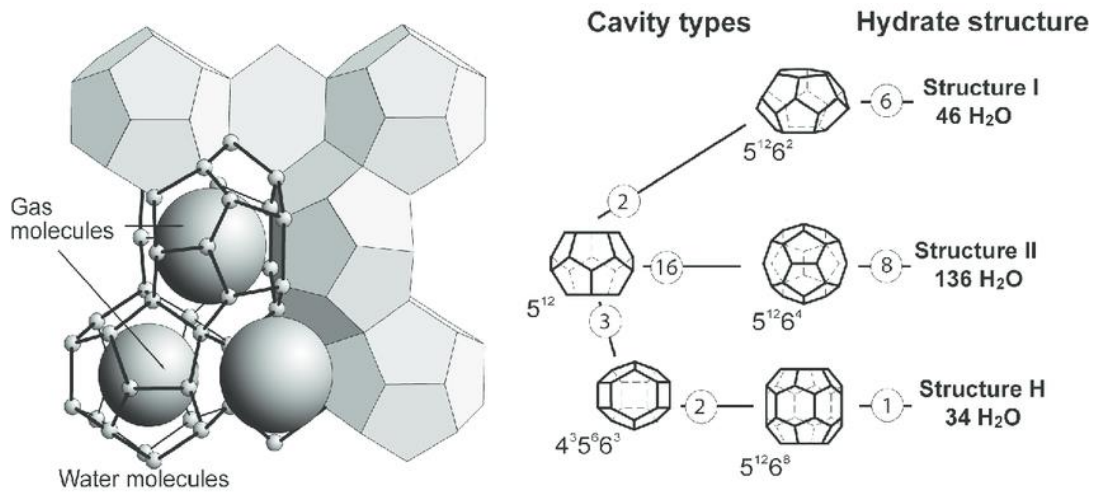


Figure 1.1 Gas hydrate crystal unit structures. Left: Gas hydrate of type structure I; small spheres are water molecules forming cages; large spheres are gas molecules. Right: Cage types and the number of individual cages forming the three common hydrate crystal structures. The circled numbers denote the numbers of the cages used to form the hydrate structure (Bohrmann and Torres, 2006).

Quantitative seismic interpretation involves many components: rock physics, seismic attributes analysis, and synthetic seismogram from well log (Avseth et al., 2010, Avseth, 2000). These components seek to extract additional information of the reservoir. The objective of quantitative seismic interpretation is to apply seismic attributes and digital rock physics analysis in order to predict quantitative reservoir parameters, such as lithologies and porosity (Adekanle and Enikanselu, 2013; Walls et al., 2002), earthquake fault (i.e., evolution process of seismogenic fault), hydrologic properties of rock (Jiang and Tsuji, 2016), and elastic properties of heterogeneous rock (Saenger et al., 2011). Using seismic attribute and digital rock physics analysis, we can extrapolate to geologically plausible conditions that might exist away from the well, and explore how the seismic signatures might change, which could open up new doors for seismic reservoir interpreter.

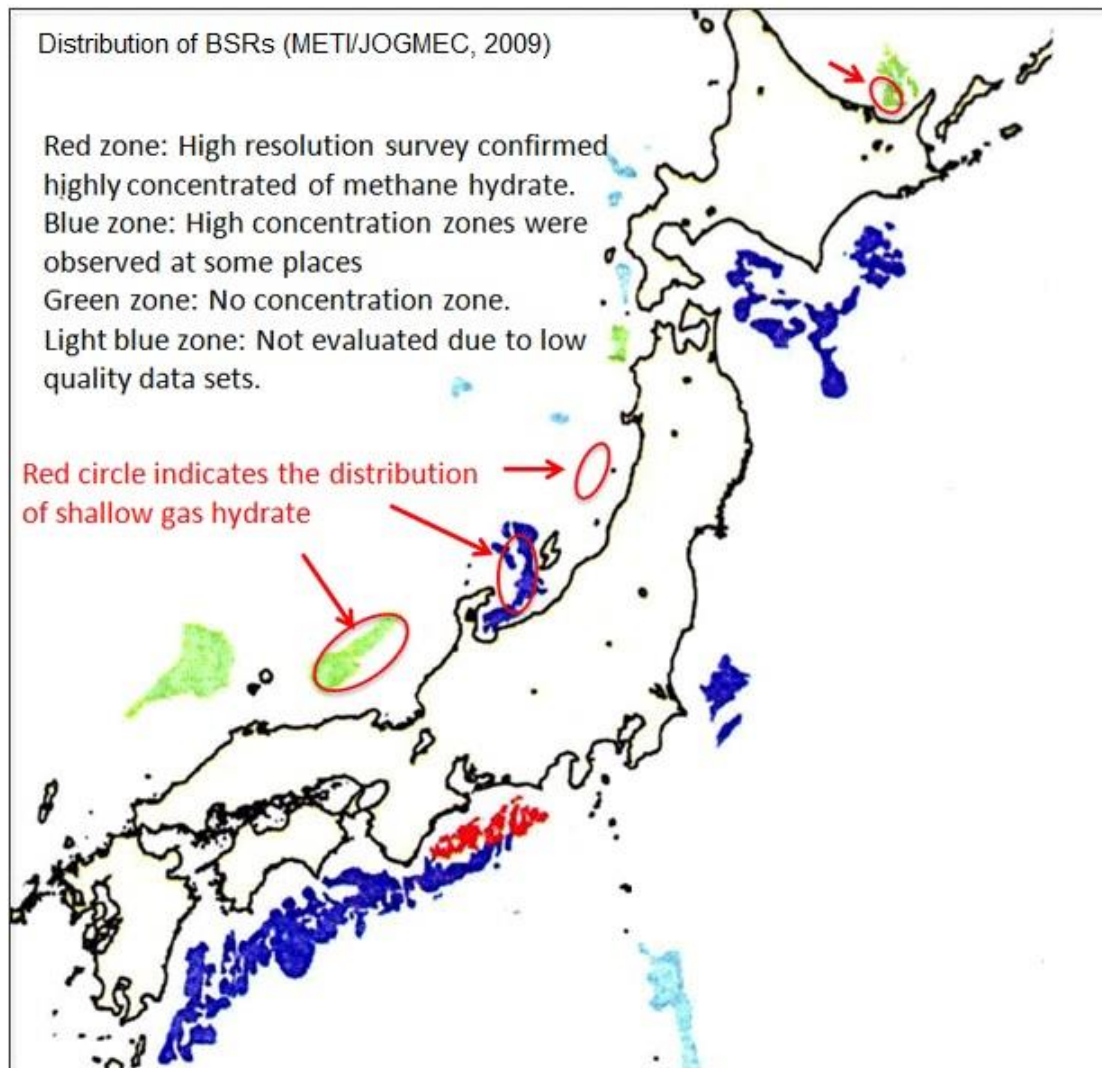


Figure 1.2 Distribution of bottom simulating reflectors and shallow gas hydrate around Japan islands (Research Consortium for Methane Hydrate Resources in Japan, 2009)

1.2.1 Reservoir characterization using seismic data

Reservoir characterization plays an essential role in the exploration and development of a given field. It involves a set of processes that define the quantitative distribution and reveal the uncertainties according to their spatial variability. Obtaining qualitative and quantitative information about reservoir properties is an essential objective in seismic exploration, especially in new field that lack well control. Indeed, seismic data provides the images of the subsurface (i.e., reflection seismic profile) and yields valuable information that could lead to discovery of hydrocarbon accumulation. Moreover, seismic data give not only a structural and stratigraphic framework, but also contain information about the spatial variability of certain important physical properties (lithology and fluid content) (Angeleri and Carpi, 1982).

The recent development of 3D and 4D seismic imaging, has given us a unique opportunity to conduct seismic reservoir characterization with improved certainty and in a more efficient way. Seismic attributes analysis has been extensively used to enhance the values of seismic interpretation (Rijks and Jauffred, 1991; Chopra and Marfurt, 2005) for predicting the lithological and petro-physical properties of reservoir in which help in hydrocarbon exploration. In addition, it can also help to understand whether direct hydrocarbon indicators, such as flat spots, bright spots, dim spots or polarity reversals are expected (Wilkins and Pambayuning, 2016). Figure 1.3 shows bright spot of hydrocarbon on seismic reflection profile and high anomaly or high envelope value of hydrocarbon charged-sediment (Bitrus et al., 2016).

Seismic attributes analysis has been common used within petroleum industry to define reservoir architecture and heterogeneity. Various successful case studies used seismic attributes for reservoir characterization (Hardage et al., 1996; Almoqbel, 2012; Chambers et al., 2002), mapping geological structure (e.g., fault; Randen et al., 2001; Cohen et al., 2006; Neves et al., 2004), and identifying gas chimney (Meldahl et al., 2001). Furthermore, to obtain more detailed reservoir parameters and geological structure (e.g., fault), here I further apply digital rock physics approach.

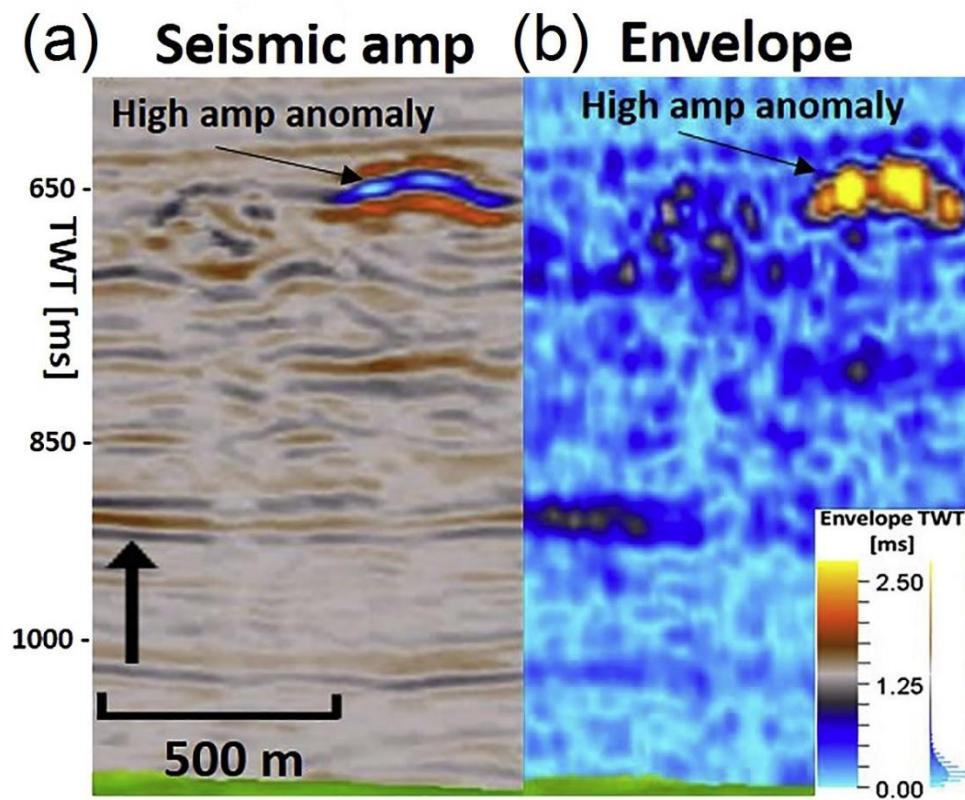


Figure 1.3 Hydrocarbon characterization using seismic attributes analysis (Bitrus et al., 2016). (a) Original seismic reflection profile. (b) Envelope profile emphasizing hydrocarbon distribution.

1.2.2 Quantitative seismic interpretation using digital rock physics

Digital rock physics are useful tool for quantitative seismic reservoir interpretation that allows interpreters to understand rock properties variations for given a set of geophysical attributes. Most commonly, digital rock physics modeling are carried out on 3D digital microstructure obtained using microcomputed tomography (micro-CT) (Saxena et al., 2017; Arns et al., 2001; Saenger et al., 2011). Digital rock physics can be used in combination with seismic derived attributes to estimate reservoir parameters and elastic moduli of rocks on the seismic response (Knachstedt et al., 2009). Moreover, this rock physics approach is capable of acquiring image of pore structure or fracture of fault core samples with resolutions down to the micron scale.

The recent development of digital rock physics in combining elastic properties (e.g., seismic velocity, density and impedance) has become an integral part of efficient interpretation and stands out as a key technology to reduce interpretation risk and improve reservoir forecasting in the petroleum industry and seismology. Several authors have studied seismic properties of rocks in order to quantitative investigate the properties of reservoir and seismogenic fault. These successful examples included the pore fluids (e.g., Jiang and Tsuji, 2016; Wang and Nur, 1990), porosity and saturation (e.g., Bachrach, 2006; Dai et al., 2004), as well as lithology (e.g., Avseth et al., 2001; Blangy, 1992; Chi and Han, 2009), and elastic properties of seismogenic fault. These examples indicate that the existing rock physics theories and models can be applied to predict reservoir parameters from seismic data with greater success than just pure statistical conversion or interpretations of seismic amplitudes. Figure 1.4 shows pore structure characterization of complex carbonate reservoir using digital rock physics approach (Kalam et al., 2011).

Even though several rock physics theories (conventional experiment and simulation) have been previously proposed to estimate reservoir rock properties, using digital rock physics approach we can change any crack-filling materials, characterize mineral precipitation, and apply dynamic wave propagation simulation compared to conventional experiment. Furthermore, the effect of elastic moduli of rock on seismic velocity is crucial key for quantitative seismic reservoir characterization. Figure 1.5 shows characterization of mineral precipitation in sandstone reservoir using digital rock.

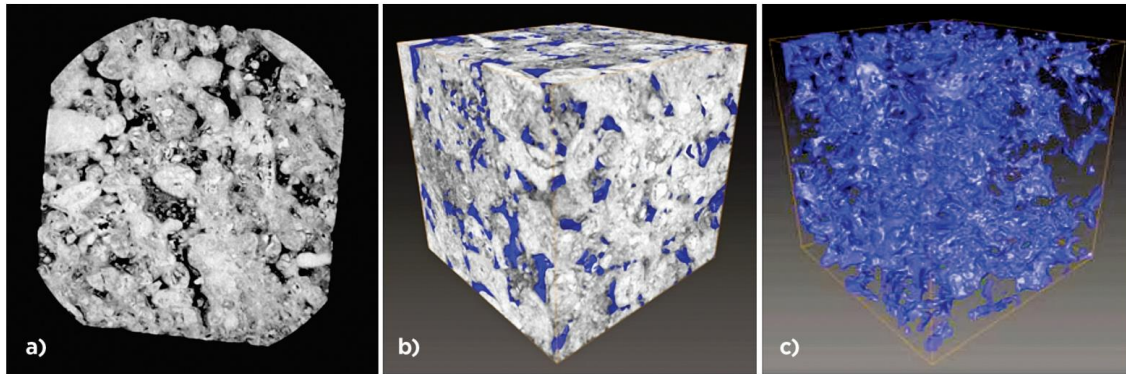


Figure 1.4 A single 4mm CT slice showing pores and calcite, with total porosity of 22.6 %. (b) A 1mm 3D cube showing porosity in blue. (c) The full pore structure of the cube. (Kalam et al., 2011).

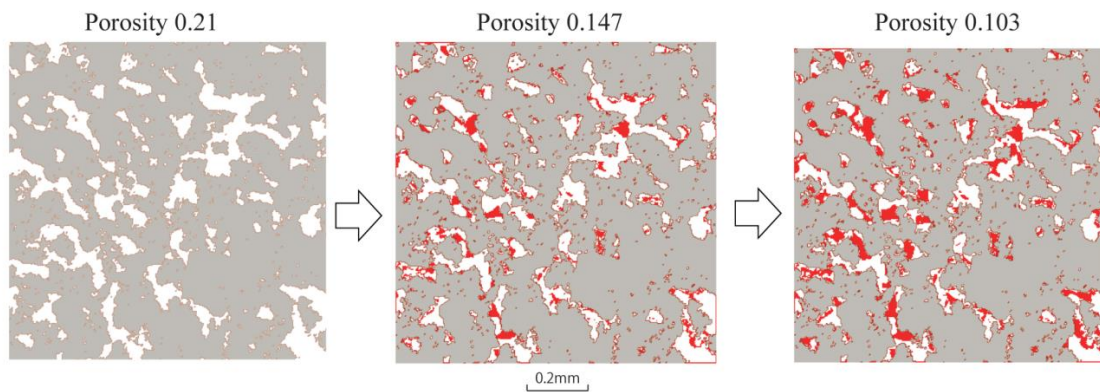


Figure 1.5 Evolution of pore structure resulting from precipitation at intersections perpendicular to the flow direction (light gray, original; dark red, precipitated regions (Jiang and Tsuji, 2014).

1.3 Research route map

This dissertation focuses on the link between seismic attributes and digital rock physics analysis for reservoir characterization. This dissertation consists of four chapters, including this introduction. The chapters are linked together and represent different stages in the presented methodology. The main methods employed are overviewed in Chapter 2 including a series of seismic attributes analysis for hydrocarbon characterization and dynamic wave propagation modelling of digital rock model is described in detail in Chapter 3. The summary of each chapter is described below.

Chapter 2 describes about hydrate and free gas reservoirs characterization in the Sanriku-Oki basin, Japan. By employing seismic attributes analysis to 3D seismic data, I could discuss the hydrocarbon gas reservoir, migration pathway, and coal-bearing formation (potential source of hydrocarbon). Based on the results, I further discuss that tectonic activities in the plate subduction zone (e.g., slumping and fault) largely influence upon the gas hydrate and free gas distribution. Geologic interpretation using one of seismic attributes, acoustic impedance, was presented at International Symposium on Earth Science and Technology 2016 (Eng et al., 2017). This chapter has been submitted to Marine and Petroleum Geology (under review).

Chapter 3 introduces digital rock physics approach for rock evolution process in order to characterize reservoir in quantitative way. The dynamic wave propagation modelling is applied to the digital rock model by changing crack-filling materials and measuring effective seismic velocity (e.g., V_P and V_S). Subsequently, the results of effective V_P and V_S are compared with those estimated from field seismic data. Then, based on these results, the rock evolution processes of Nankai seismogenic fault are characterized. This work was presented at Japan Geoscience Union Meeting 2016, Formation Evaluation Symposium of Japan 2016, International Symposium on Earth Science and Technology 2016, and Joint Scientific Assembly of International Association of Geodesy and International Association of Seismology and Physics of Earth's Interior 2017. This chapter was published from Exploration geophysics (Eng et al., 2017).

Chapter 4 summaries the thesis and makes suggestions for the future work on quantitative seismic interpretation in order to characterize the reservoir rock.

In the Appendixes, I described the research papers of Chapter 2 and 3, which was published in *Exploration Geophysics* (Eng et al., 2017) and submitted in *Marine and Petroleum Geology* (Eng and Tsuji, 2008).

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Chapter 2

Hydrocarbon Reservoir Characterization Using Seismic Attributes Analysis

2.1 Introduction

Gas hydrate and free gas in marine sediments account for a large proportion of known natural hydrocarbon gas accumulations (Judd, 2003; Kvenvolden, 1993). Gas hydrate forms as a solid compound binding water and gas molecules that is stable at the high pressures and low temperatures found in permafrost regions and in deep water sediments (Judd and Hovland, 2002; Kinoshita et al., 2011; Berndt et al., 2002; Holbrook et al., 1996; Kvenvolden, 1993, Sloan and Koh, 2007; Claypool and Kaplan, 1974). In seismic reflection data, the phase boundary between methane hydrate and underlying free gas produces a prominent negative-polarity reflection known as a bottom simulating reflector (BSR) (Bale et al., 2014; Kinoshita et al., 2011; Holbrook et al., 1996). BSRs are widely distributed in the forearc basins of convergent plate margins worldwide, such as offshore Oregon (Milkov et al., 2003), South Setland margin (Lodolo et al., 2002), Nankai Trough (Bale et al., 2014; Jia et al., 2016) and off southwest Taiwan (Lin et al., 2009), and are clearly evident on seismic profiles in the Sanriku-Oki forearc basin in north-east Japan (Figure 2.1). The existence of BSR could indicate gas migration from deeper formation. Knowledge of the subsurface distribution of gas hydrate and free gas is important not only for evaluation of potential hydrocarbon gas resources but also for identification of potential geologic hazards associated with subsurface gas, such as submarine landslides (Kvenvolden, 1993; Sloan and Koh, 2007; Sun et al., 2017), and

understanding the role of gas hydrates in global climate change (Judd, 2003; Holbrook et al., 1996; Kennett et al., 2003; Paull et al., 1991).

The migration and accumulation of gas hydrate and free gas is often associated with tectonically activities (e.g., fault and slumping) in the forearc basin in the plate convergent margin. Several studies have characterized hydrocarbon gases migrated through the faults from biogenic and deep thermogenic sources to accumulate in shallow reservoirs (Chhun et al., 2017; Jia et al., 2016; Crutchley et al., 2015; Sun et al., 2012). Furthermore, other studies showed evidence of fluid migration controlled by slump thrusting (Guan et al., 2016; Gamboa and Alves., 2015; Gamboa et al., 2011; Sun et al., 2017). However, the influence of tectonic activities (e.g., fault) upon gas migration and accumulation mechanisms in the Sanriku-Oki forearc basin of the Japan Trench has not been well characterized by applying seismic attributes analyses to 3D seismic volume.

In the Sanriku-Oki forearc basin, intensive slumping is clearly observed on the seismic profiles (Morita et al., 2012). Furthermore, strong reflections immediately below BSR (Figures 2.2 and 2.3) suggests the presence of methane gas where a strong upward flux of free hydrocarbon gases occurs from deep hydrocarbon sources (Bale et al., 2014; Taira et al., 2005; Inagaki et al., 2012). Such accumulations of gas give rise to acoustic impedance contrasts that produce strong reflections (Berndt et al., 2002; Judd and Hovland, 1992; Andreassen et al., 2007). Analyses of logging data and core samples from Integrated Ocean Drilling Program (IODP) Site C0020 identified coal beds 0.3 to 7.3 m thick in formations at depths of ~1.5 to 2.5 km below the seafloor (Inagaki et al., 2012). These coal beds are the likely source of hydrocarbon gases in the Sanriku-Oki forearc basin (Oda, 2003; Osawa et al., 2002; Inagaki et al., 2016).

Numerous previous studies of the Sanriku-Oki forearc basin have included investigations of its hydrocarbon potential (Osawa et al., 2002), stratigraphy and seismic facies (Takano and Tsuji, 2017), tectonic evolution (von Huene, 1990, Itoh and Tsuru, 2006; Regalla et al., 2013; Takano et al., 2013), and its potential for coal exploration (Inagaki et al., 2016; Gross et al., 2015). However, the relationship between hydrocarbon system and tectonic activities in the Sanriku-Oki forearc basin has not been well understood.

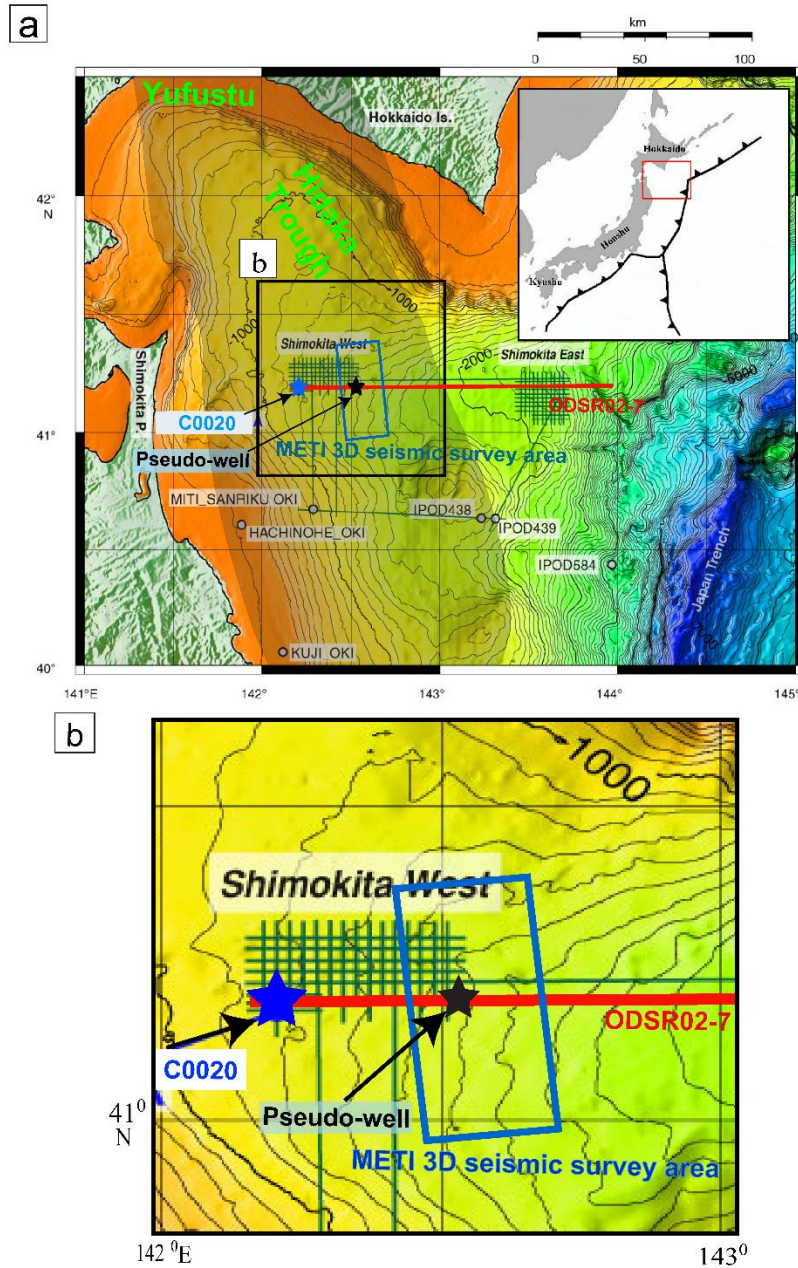


Figure 2.1 (a) Location map of study area, northeast Japan with bathymetry (Inagaki et al., 2012). Inset map exhibits plate configuration around Japanese Island and the location of the study area (red square). Grey shadow indicates forearc basin (b) Enlarged bathymetry map around the METI 3D seismic survey area. Blue and black stars represent IODP Site C0020 and pseudo-well. Blue rectangular indicate the METI 3D seismic volume. Thick red line indicates 2D seismic line ODSR02-7.

In this study, seismic attribute analyses of 3D seismic data were used to estimate the spatial distribution of coal-bearing formations (i.e., potential source rocks) and gas-bearing sediments (i.e., reservoir rocks) to improve our understanding of the geological structures and tectonic events that have controlled migration pathways for hydrocarbon gases in the Sanriku-Oki forearc basin. The results reveal that tectonic activities in the plate subduction zone (e.g., slumping and faults) largely influence upon the gas hydrate and free gas distribution.

2.2 Geological setting and basin evolution

The Sanriku-Oki forearc basin lies between the north-eastern Japan Arc and the Japan Trench within a narrow N–S-trending zone extending from the southern coast of central Hokkaido to the area offshore from the north-east coast of Honshu Island (Figure 2.1). The Sanriku-Oki forearc basin was formed as a consequence of subduction of the Pacific tectonic plate beneath north-eastern Honshu Island (Maruyama et al., 1997; Gross et al., 2015) and is one of a series of long and narrow connected sedimentary basins in Japan Trench area. The Sanriku-Oki basin is expected to contain similar hydrocarbon reserves to those of the Yufutsu oil and gas field on the southern coast of Hokkaido (Osawa et al., 2002; Oda, 2003; see grey shaded area in Figure 2.1a), because these oil and gas fields have the productive amount of hydrocarbon from Cretaceous and Oligocene coals and coaly shales .

The Sanriku-Oki forearc basin is bordered to the west by the Japan volcanic arc and to the east by an area uplifted along the trench slope break (Gross et al., 2015). Basin-fill sedimentation in the group of forearc basins began in the Late Jurassic and has continued until the present to produce a thick sequence (~6000 m) comprising several stratigraphic packages separated by four major unconformities (Cretaceous, Oligocene, Miocene, and Quaternary) (Figures 2.2 and 2.3; Takano and Tsuji, 2017). The depositional environment during the Cretaceous and Palaeogene was fluvial with deposition mainly of coals and coaly shales. The vitrinite reflectance of these coals indicated between 0.5 to 0.7% (Osawa et al., 2002), showing relatively immature to mature coals are buried in the

ocean. *In situ* temperature derived from thermal gradient (~ 22.5 °C/km) is well within the range of habitable zone of microbes. The organic type (II/III) and the high total organic carbon indicated that coals succeeded in producing natural gases (Osawa et al., 2002; Oda, 2003). During Late Palaeogene, the main source of sedimentation was the materials from volcanic arc in the west side of the forearc basin (von Huene et al., 1982). During the Late Oligocene and Miocene, the depositional environment of the basin began to change to a slope environment in response to broad-scale subsidence along a hinge line (Takano, 2017). As a consequence, the Oligocene unconformity surface was overlain by a transgressive succession, which was further followed by a deep marine muddy facies over the Neogene and Quaternary succession (Takano, 2017).

2.3 Data

Well-logs and seismic data were used to characterize coal-bearing formation, gas reservoir and fault system.

2.3.1 Seismic data

In 2002 and 2003, 2D seismic survey off Shimokita Peninsula was carried out by the Japan Agency for Marine Earth Science and Technology (JAMSTEC) in a 15 km (north–south) $\times$ 30 km (east–west) area using the *R/V* Polar Duke and *R/V* Polar Princess with line spacing around 2 km (Inagaki et al., 2012; Figure 2.1). Acquisition was implemented using a source array of 3500 in³ at 6 m depth and a single streamer with 408 primary and 12 auxiliary 6 channels (Taira et al., 2005). Well C0020 (red star in Figure 2.1) is located close to one 2D seismic line of ODSR02 7 (thick red line in Figure 2.1). The 2D seismic data was processed by using bandpass filtering, migration, multiple removal with parabolic radon transform and deconvolution (Taira et al., 2005).

In 2008, 3D seismic survey Sanriku-Oki conducted by Ministry of Economy, Trade and Industry Japan (METI) was performed by the 3D seismic vessel, *R/V* Shigen

(Figures 2.1, 2.2, and 2.3). The METI 3D seismic data was acquired by National Program for Oil and Gas Prospecting, 2010 FY Geophysical Survey and Basin Evaluation Project “Sanriku-Oki 3D”. The rectangular survey area is oriented slightly toward the west and covers an area of 806.3 km². The dimensions of the survey area are 40 km for in-line (N-S) direction and 20 km for crossline (W-E) direction. The bin size is 12.5 m for In-line direction x 25.0 m for cross-line direction. Acquisition was implemented using a source array of 3090 in³ at 6 m depth, and the source characteristics are similar to 2D seismic data. The data processing included bandpass filter (6Hz- 206Hz), surface related multiple elimination (SRME), radon demultiple, and pre-stack time migration (PSTM).

2.3.2 Logging data

The Integrated Ocean Drilling Program (IODP) drilled at Site C0020 (red star in Figure 2.1) within the 2D seismic survey area off Shimokita in 2012 (Inagaki et al., 2012). Site C0020 is the extension of JAMSTEC hole C9001 drilled during Chikyu shakedown cruise in 2006 (Aoike, 2007). In this hole C9001, the drilling pilot by both riserless and riser drilling systems was terminated at 647 m below seafloor (mbsf). IODP Expedition 337 cruise drilled from 647 mbsf to the final depth of 2466 mbsf of thick sedimentary sequence with 1180 m water depth. The logging data used here is from 1252 to 2466 mbsf, including gamma ray, resistivity, sonic velocity, density, and combination nuclear magnetic resonance porosity (Figure 2.4). Sonic velocity and density are used for acoustic impedance (AI) inversion. Coal seams in area had been identified based on cross-examination between logs and described lithology from core samples. Fourteen coal layers were found at depth between 1825 and 2450 mbsf (Figure 2.4; Inagaki et al., 2016). Coal-bearing formations consist of coal, coaly shale, sandstone, siltstone, beach sand, carbonates and conglomerate, and they can be correlated with the available seismic data. The coal-bearing sequences were dominantly in Unit III (Figure 2.4) at IODP Site C0020; the values of P-wave velocities, densities, and gamma ray decrease sharply, and resistivity increases at the depth corresponding to coal-bearing formations (Inagaki et al., 2012).

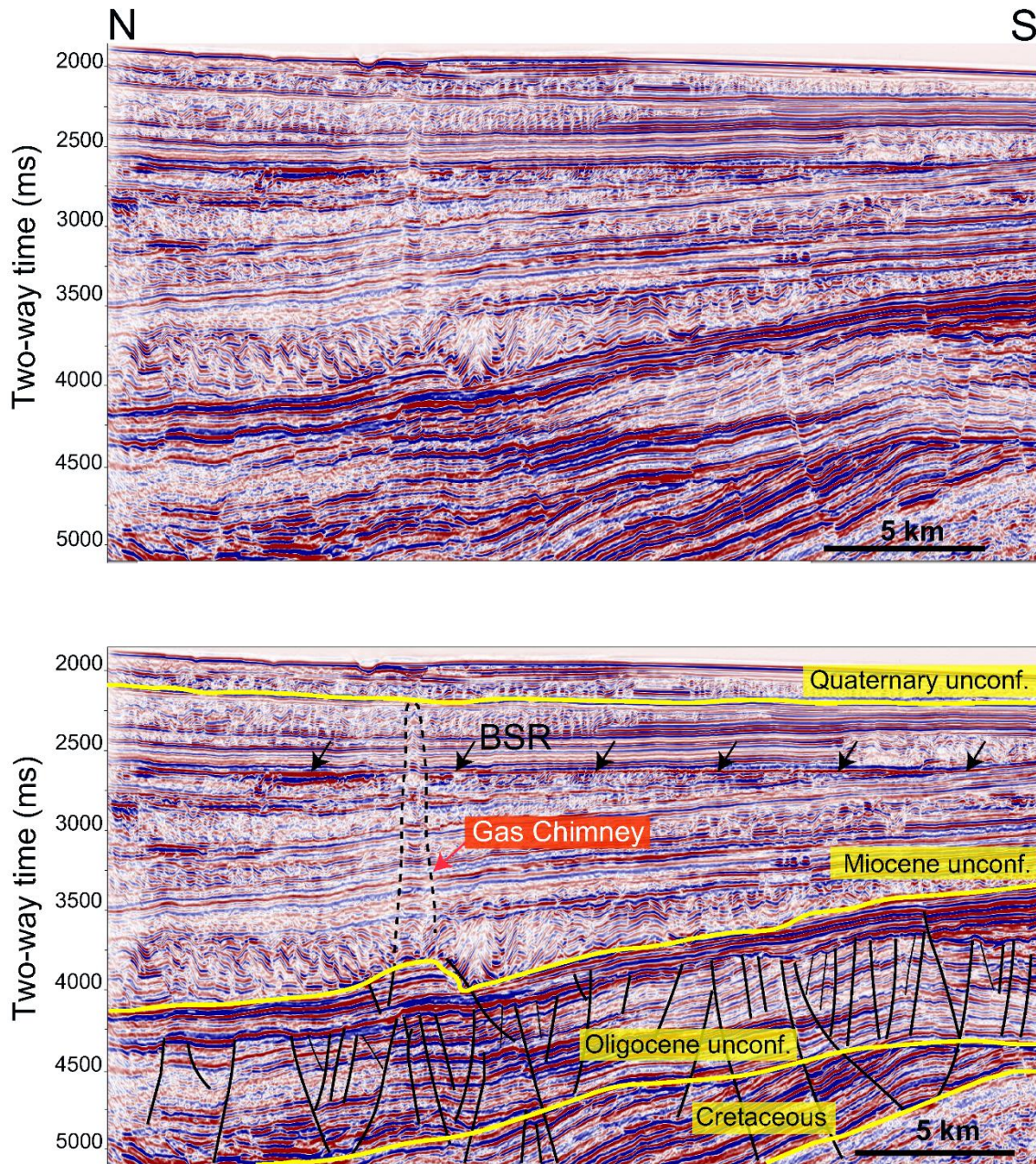


Figure 2.2 Seismic reflection profiles across Sanriku-Oki forearc basin with and without geological interpretation. The profiles for N-S direction, extracted from the METI 3D seismic volume. The strong reflection from 2600 ms to 2500 ms in two-way traveltime indicates the BSR (black arrows). Yellow lines represent the boundary of unconformities (Cretaceous, Oligocene, Miocene and Quaternary). These unconformities are produced by correlation of our seismic data with seismic stratigraphy from Takano, (2017). Black lines indicate intense normal faults. Gas chimney shows in black dashed line.

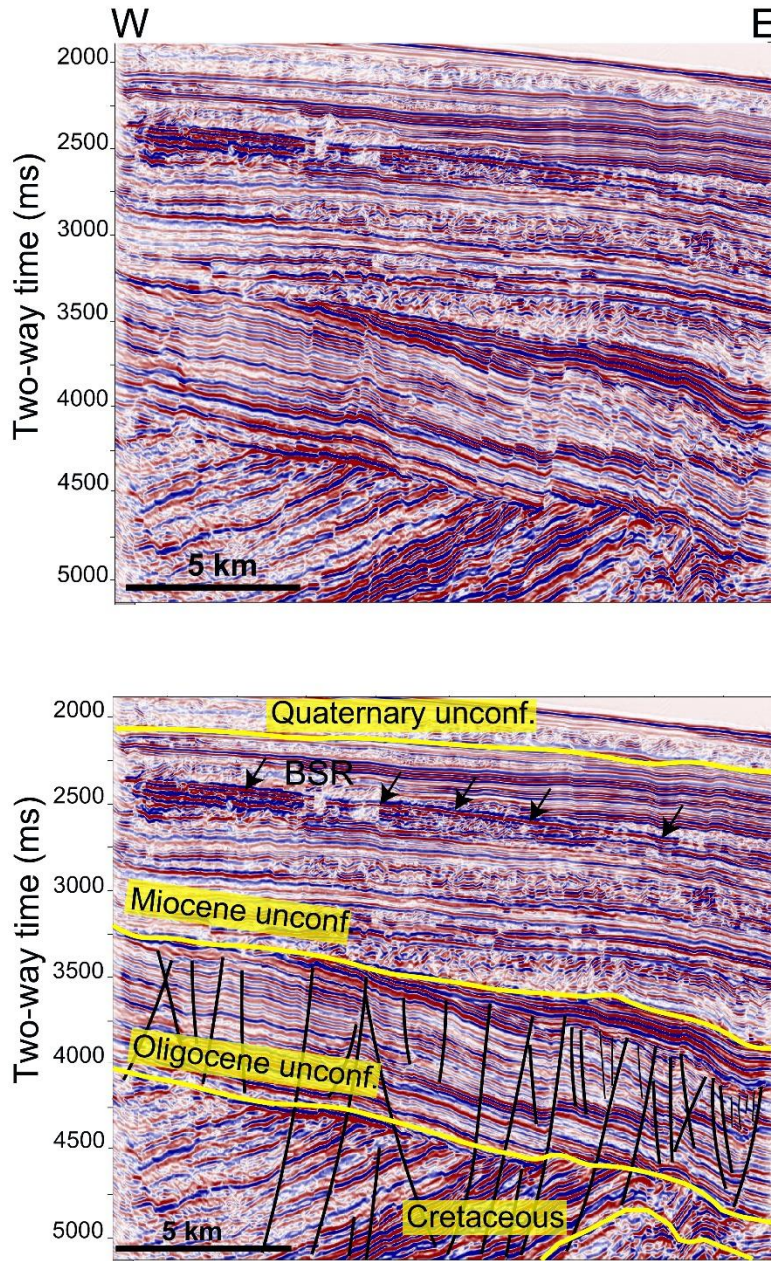


Figure 2.3 Seismic reflection profiles across Sanriku-Oki forearc basin with and without geological interpretation. The profiles for E-W direction, extracted from the METI 3D seismic volume. The strong reflection from 2600 ms to 2400 ms in two-way traveltimes indicates the BSR (black arrows). Yellow lines represent the boundary of unconformities (Cretaceous, Oligocene, Miocene and Quaternary). These unconformities are produced by correlation of our seismic data with seismic stratigraphy from Takano, (2017). Black lines indicate intense normal faults.

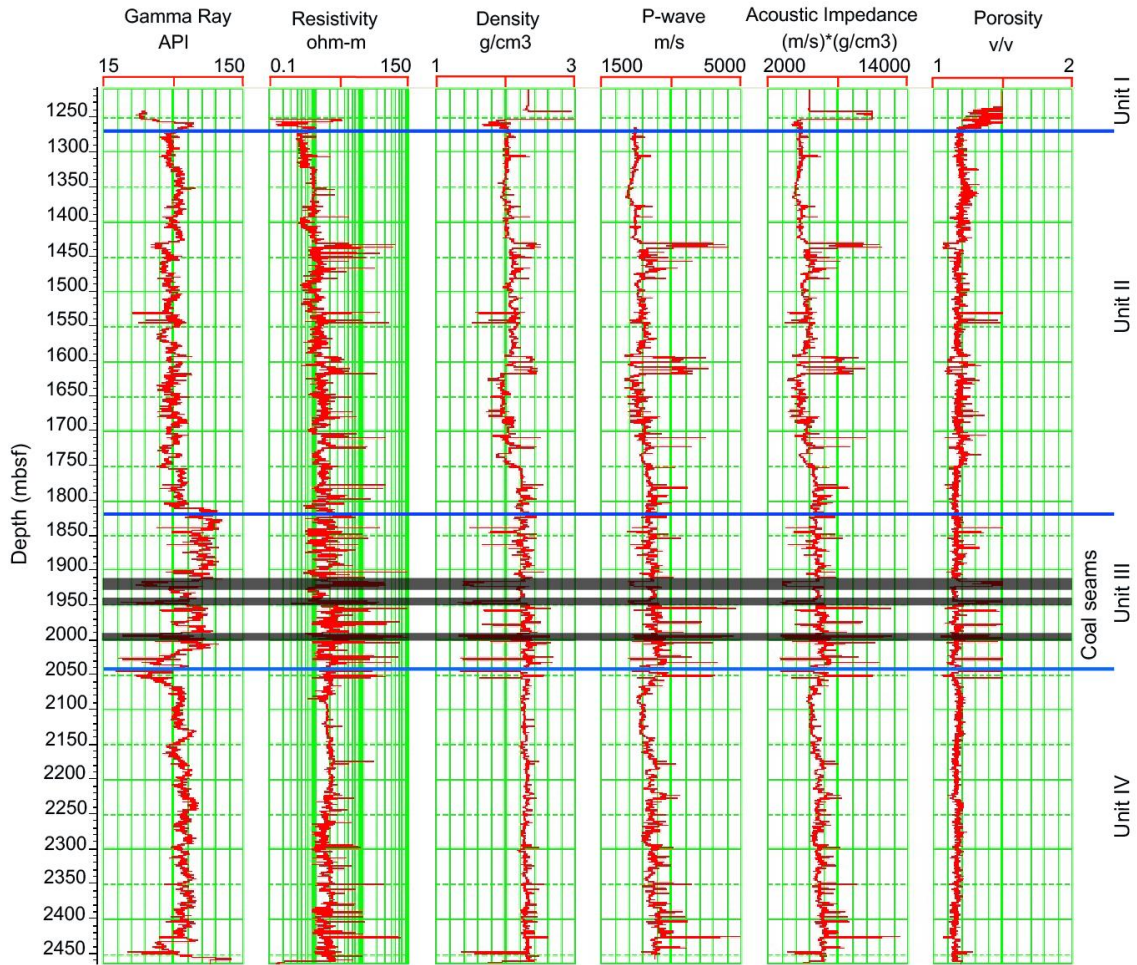


Figure 2.4 Logging data from 1200 to 2466 meter below seafloor (mbsf) at IODP Site C0020, showing natural gamma ray, resistivity, density, porosity, P-wave velocity, and acoustic impedance (Inagaki et al., 2012). Coal-bearing formations including several coal seams are marked by black color. Blue lines are the boundaries of four lithologies units.

2.4 Methods

2.4.1 Seismic attributes

Seismic attributes are any properties derived from seismic reflection signal. Attributes may be compared to lithology in an attempt to devise a method of property prediction away from well control. Seismic profiles generated using the volume seismic attributes enhance or quantify certain anomalies or characteristic features, which are unrecognizable on the original profile (Taner et al., 1979). To investigate the hydrocarbon systems in Sanriku-Oki forearc basin, a series of seismic attribute was used, such as acoustic impedance, envelope, chaos and ant-tracking. Acoustic impedance inversion was performed for characterizing coal-bearing formations, because the formations can be characterized low acoustic impedance in logging data. The hydrocarbon migration pathways through faults were identified using chaos and fault ant-tracking map. This study further used envelope to estimate gas-bearing sediments.

2.4.1.1 Acoustic impedance

Acoustic impedance inversion was conducted (Ecker et al., 2000; Lu and McMechan 2002; Jia et al., 2016) to estimate the spatial coal-bearing formation. As well-logs data provide geologic information in high-resolution, the well information was extended using post-stacked seismic data in the acoustic impedance inversion. The seismic inversion is the process of calculating a subsurface acoustic impedance model consistent with corresponding seismic data. Figure 2.5 illustrates the principle of acoustic impedance inversion.

Acoustic impedance AI is the product of rock density (ρ) and compressional (P-wave) velocity.

$$AI = \rho \times V_p \quad (2-1)$$

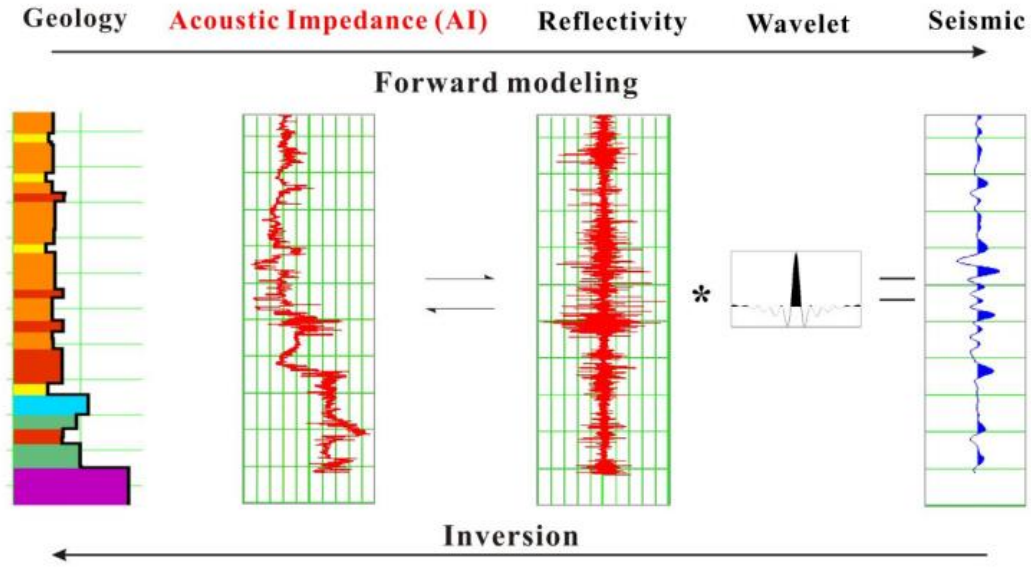


Figure 2.5 Principle of acoustic impedance inversion. In Geology column, different colors represent different lithological information.

The reflection coefficient r_i can be calculated from the acoustic impedance contrast at formation interface, as follow.

$$r_i = \frac{AI_{i+1} - AI_i}{AI_{i+1} + AI_i} \quad (2-2)$$

where AI_i is the acoustic impedance of the overlying formation, and AI_{i+1} is the acoustic impedance of underlying formation. The seismic trace is considered as a convolutional result from the reflectivity r_i and the source wavelet W_i .

Acoustic impedance also represent as the pseudo-acoustic impedance log at every seismic trace (Latimer et al., 2000). Acoustic impedance is converted from the seismic reflection data to layer rock properties data, and it can be used for direct geologic interpretation (lateral lithologic variation) and reservoir characterization. The seismic trace is considered as a convolutional result from the reflectivity of the interface of subsurface layers and the wavelet. To estimate acoustic impedance from the post-stack reflection waveforms, the model-based inversion was used based on the convolution model.

$$T_i = \sum_j r_j W_{i-j+1} + e_i \quad (2-3)$$

where T_i is seismic response, and e_i represents additive measurement noise.

The seismic inversion procedure employed in this study involves horizontal picking, wavelet extraction, log to seismic traces calibration, estimation of low-frequency model and seismic inversion using simulated annealing (Maver and Rasmussen, 1995; Husse and Feary, 2005).

In this study, there is only one well (C0020) close to the 2D seismic profile and no well in 3D seismic survey area (Figure 2.1). Therefore, pseudo-well data was extracted from the acoustic impedance results of 2D seismic line (OKSR02-7) at the intersection between 3D and 2D seismic line (CDP 21610 of the 2D seismic line), and was used for acoustic impedance inversion of 3D seismic data (Figures 2.1 and 2.6). This allowed us to tie the acoustic impedance data from IODP Site C0020 along 2D seismic line (ODSR02-7) into the METI 3D seismic volume (Figure 2.7). Because of similar source characteristics of 2D and 3D seismic data, the error of applying acoustic impedance inversion with pseudo-well information could be small. By using this pseudo-well information with the METI 3D seismic data, 3D acoustic impedance model of coal-bearing formation was estimated (Figure 2.7).

2.4.1.2 Chaos, ant-tracking, and envelope

Chaos attribute is a measure of the lack of organization in the dip and azimuth estimation method (Pigott et al., 2013; Koson et al., 2014). Here, chaos can be used to illuminate faults and discontinuities. Zones of maximum chaoticness indicate the discontinuities such as faults, fractures, and angular unconformities, while zones of minimum chaoticness correspond to bed continuity (Koson et al., 2014; Pigott et al., 2013). In this study, the chaos was used as input data in order to employ ant-tracking attribute (see below).

Ant-tracking is an algorithm that extracts continuous features to facilitate fault or fracture identification. This attribute is an extension to the heuristic ‘ant system’ algorithm developed from observations of ant colonies and proposed as a viable new approach to stochastic combinatorial optimization (Dorigo et al., 1996). The method uses the principles of “swarm intelligence” to find and enhance fault structure from spatial discontinuity and allows automatic fault extraction from the output ant-track attribute volume. In the ant attribute algorithm, large numbers of electronic ants are distributed in the seismic volume allowing them to move along faults and emitting pheromones which shows the result of fault zones very sharp and detailed. This approach has several important parameters, such as initial ant boundary, ant-track-derivation, ant-step size, illegal steps allowed, legal steps required, and stop criteria (Table 1). “Initial ant boundary” defines number of voxel radius territories that each agent searches and “ant-track deviation” is a parameter to control the maximum allowed deviation from a local maximum while tracking. “Ant-track step size” defines the number of voxels an ant agent advances for each increment within its searching step. “Illegal steps allowed” defines how many steps an agent’s track can continue without finding a local maximum. “Legal steps required” controls how connected a detected edge must be to help distinguish an edge from un-oriented noise. “Stop criteria” refers to the percentage of illegal steps allowed throughout an entire search space. In this study, different parameters are tested and the best parameters are chosen (Table 1). After seismic conditioning (structural smoothing) was applied to reduce noise and enhanced the spatial discontinuities via chaos, the ant-tracking volume (fault surface extraction) was generated.

Table 2.1 Ant-tracking parameters

	Initial ant boundary	Ant-track deviation	Ant step size	Illegal step allowed	Legal step required	Stope criteria
Cross-line dip attribute	7	2	3	1	3	5
Similarity attribute	15	2	3	1	3	5
Most-positive curvature attribute	7	2	3	1	3	5

Envelope attribute or reflection strength is important in detecting bright spots caused by gas accumulations and detecting major lithological changes that are caused by strong energy reflections and sequence boundaries (Figures 2.8 -2.14; e.g., Taner et al., 1979; Tsuji et al., 2012). The envelope attribute ($E(t)$) can be computed as a modulus of complex trace, thus this attribute is independent of the phase or polarity of the seismic data, both of which affect the apparent brightness of a reflection. The recorded seismic trace $f(t)$ can be thought of as a real part of the complex trace $F(t)$, which also has an imaginary part $g(t)$ that can be derived through the Hilbert transform.

$$F(t) = f(t) + i \cdot g(t) = E(t) \cdot e^{i\theta(t)} \quad (2-4)$$

$$E(t) = \sqrt{f^2(t) + g^2(t)} \quad (2-5)$$

$$\theta(t) = \arctan(g(t)/f(t)) \quad (2-6)$$

where $\theta(t)$ is the instantaneous phase, which computed as the argument of the complex trace. The advantage of using this attribute instead of the original seismic trace values is that it is independent of the phase or polarity of the seismic data, both of which affect the apparent brightness of a reflection.

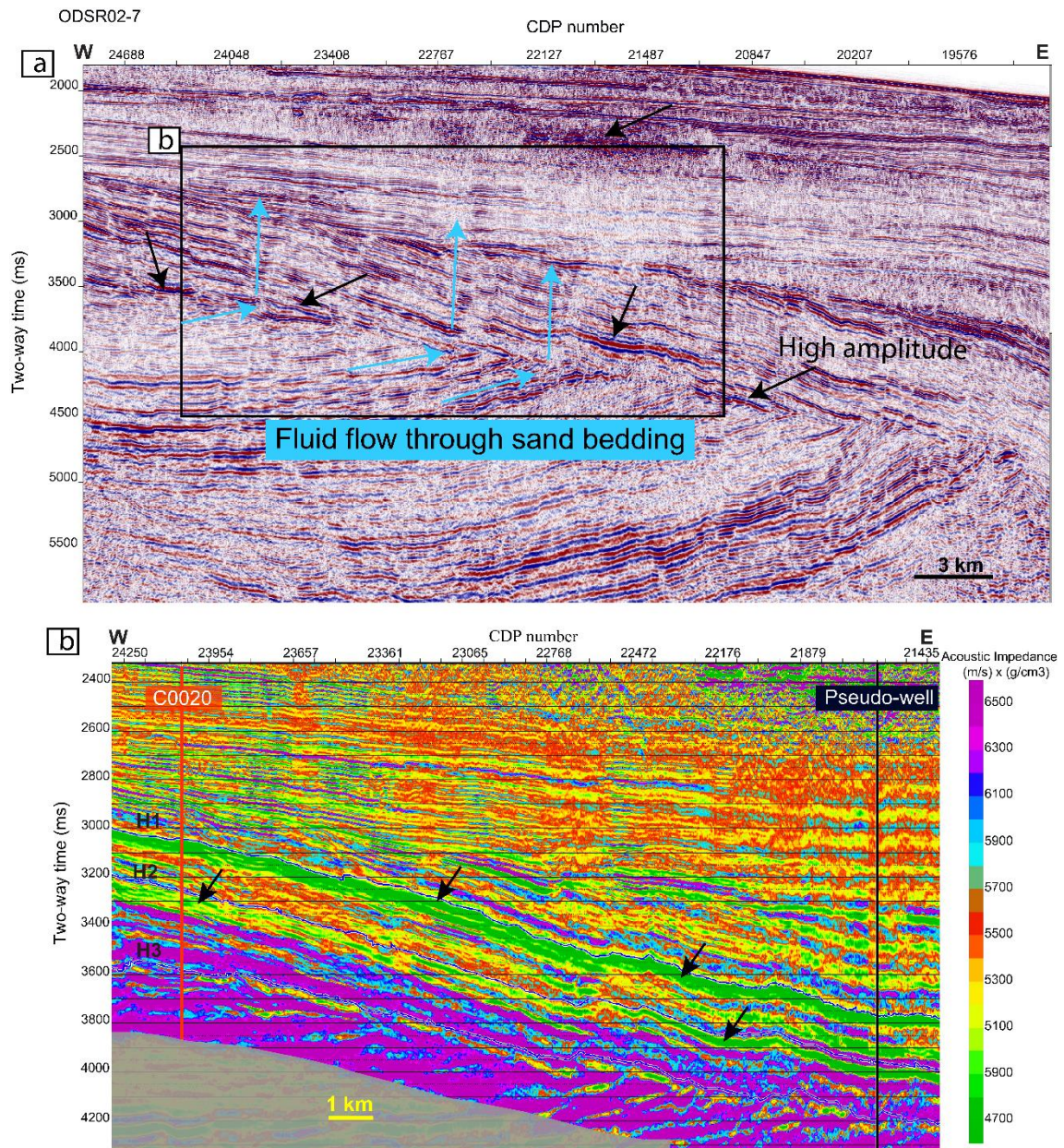


Figure 2.6 (a) Seismic profile ODSR02-7. Blue arrows indicate interpreted fluid migrated pathway through porous formations and faults. Black arrows indicate strong reflection interpreted as gas-bearing sediments. Black rectangle refers to the acoustic impedance profile displayed in panel (b). (b) Acoustic impedance of seismic line ODSR02-7. Vertical black line indicates the pseudo-well that extracted at CDP 21610. Black arrows indicate low acoustic impedance for coal-bearing formation. H1, H2, and H3 are the horizontal interpretation.

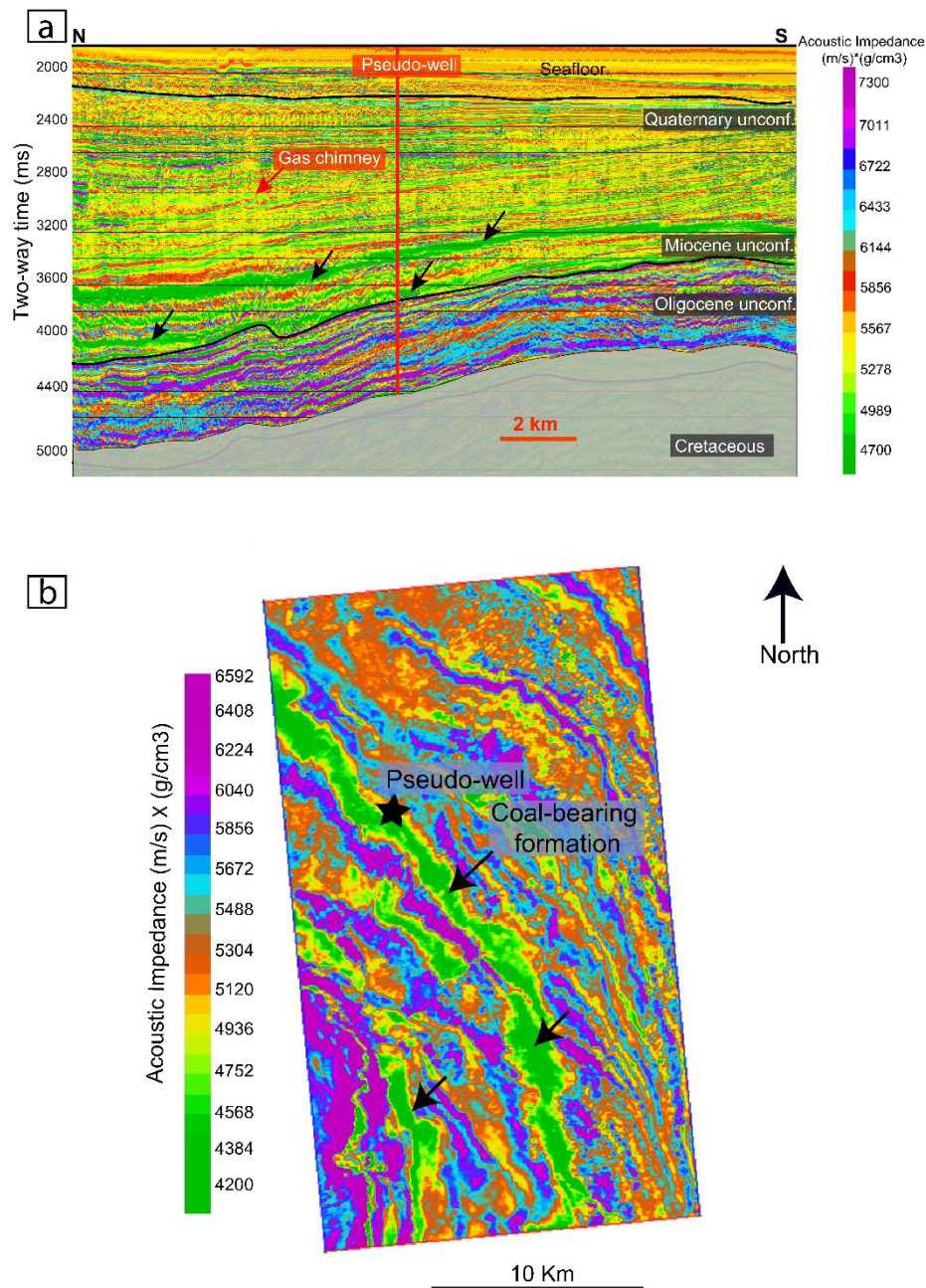


Figure 2.7 (a) Acoustic impedance profile of the METI 3D seismic volume. (b) Time-slice of acoustic impedance volume at 3150 ms TWT. Black arrows indicate low acoustic impedance for coal-bearing formations. Black star shows location of pseudo well, and pseudo-well shows in red line.

2.5 Results and interpretation

2.5.1 Coal-bearing formation

Because the lateral distribution of coal-bearing formations in the Sanriku-Oki forearc basin cannot be determined from seismic reflection profiles alone, we used acoustic impedance profiles. An inverted acoustic impedance profile of part of east–west 2D seismic line ODSR02-7 (Figure 2.6b), which crosses IODP Site C0020, shows two intervals of low acoustic impedance compared with clastic sediments, which interpreted to represent coal-bearing formation (Figure 2.6b). These appear to be continuous in the time window from 3.0 to 3.4 s two-way traveltime (TWT) (Figure 2.6b). Furthermore, the distribution of coal beds in the METI 3D seismic survey volume was investigated by considering a horizontal time slice extracted from the entire 3D acoustic impedance volume within a 10 ms time window centred at 3.15 s TWT (Figure 2.7b). The coal-bearing formations (or coal dominant formations) appear as bands of relatively low acoustic impedance of ~ 4200 to $5200 [(m/s) \times (g/cm^3)]$ within the time slice. The acoustic impedance values obtained in the time slice were consistent with sonic and density log data for coal seams penetrated at IODP Site C0020 (Figure 2.4).

Although Inagaki et al. (2016) identified several coal seams in Unit III (Figure 2.4), only the two major coal-bearing formations could identify in acoustic impedance inversion data (green in Figures 2.6b, 2.7a, 2.7b) because the isolated coal seams were too thin to be resolved by the low-frequency seismic data. The acoustic impedance data for the two major coal dominant formations (Figure 2.7b) indicate only small lateral variations of thickness, which suggests that they likely extend continuously across the entire forearc basins in north-eastern Japan (Oda, 2003; Koide and Kuniyasu, 2006; Osawa, 2002). Furthermore, the higher acoustic impedance of the fine-grained clastic sediments (shales, siltstones, and shaly sandstone) recognized there by Inagaki et al. (2016) and Glombitza et al. (2016) likely represent the top and bottom of the coal formations. Thus, the continuity of the low acoustic impedance bands representing the major coal dominant formations can be used to map their distribution within the entire

METI 3D seismic volume.

The coals in Unit III (Figure 2.4) were deposited in tidal flats, channels, wetlands, and fluvial environments (back marshes and swamps) during the late Oligocene to early Miocene. Subsequent subsidence of the forearc basin led to the deposition of a thick overlying sequence of deep marine sediments (Taira et al., 2005; Oda et al., 2003; Noda et al., 2013; Inagaki et al., 2012; Takano, 2017). The total organic carbon content of the coals ranges from 9.9 to 40.9 wt.% (Inagaki et al., 2013), which makes them excellent hydrocarbon source rocks (Peters and Cassa, 1994). Vitrinite reflectance values of 0.2–0.4 and maximum burial temperatures of 400–440 °C indicate that the organic matter in the coals is in a thermally immature to early mature state for gas generation (Inagaki et al., 2013). The type II/III kerogens of these coals and their medium to high hydrogen index indicate that they are more likely to produce hydrocarbon gas than oil (Osawa, 2002; Oda et al., 2003), which is supported by the presence of methane and other hydrocarbon gases, as well as N₂, O₂, H₂, and CO, in the coal-bearing formations at Site C0020 (Inagaki et al., 2012).

The hydrocarbon gases discovered in the forearc basins of north-eastern Japan have been formed by biogenic processes in coals or coaly shales since the Oligocene (Osawa, 2002; Oda et al., 2003; Inagaki et al., 2012; 2013). Therefore, the Unit III coals in the Sanriku-Oki forearc basin are regarded to be the likely source rocks for the natural gas discovered there. However, Cretaceous to Palaeogene (lower to middle Eocene) coal-bearing formations deposited in bay to braided-fluvial environments are a potential alternative source rock for hydrocarbon gas in this area (Takano and Tsuji, 2017). Vitrinite reflectance and well log data from the nearby MITI Sanriku-Oki well site (Figure 2.1) indicate the presence of mature coal beds in these deep formations (Osawa et al., 2002). Because drilling at IODP Site C0020 did not reach these formations, and because of the low resolution of the available seismic data, the Cretaceous to Palaeogene coal-bearing formations cannot be identified by acoustic impedance inversion data.

2.5.2 Bottom simulating reflector (BSR)

A high-amplitude but distinctly low continuity BSR, subparallel to and of opposite polarity to the seafloor reflector, was identified on seismic profiles in the Sanriku-Oki forearc basin (black arrow in Figures 2.2; 2.3, and 2.8-2.13). The BSR is recognized in the shallow section of the seismic profiles (2.4 to 2.6 s TWT) with a roughly N–S-trending horizontal distribution (parallel to trench) over a distance of ~30 km within the study area (2.2; 2.3, and 2.8-2.13). The BSR is clearly observed within the Quaternary succession of the basin and appears to follow the top of a sequence of Quaternary slump deposit (slump D), but is disrupted by a gas chimney extending from the Miocene unconformity to the Quaternary unconformity (Figures 2.2). The BSR exhibits all of the diagnostic characteristics of a seismic reflector at the base of the gas hydrate stability zone, or the top of the free-gas zone beneath gas hydrates (Bale et al., 2014; Taira et al., 2005; Baba and Yamada, 2004; Hyndman and Spence, 1992; Mackay et al., 1994; Kvenvolden, 1998; López and Ojeda, 2006). The Sanriku-Oki forearc basin lies on the continental slope at water depths of around 1180 mbsf in a region where the geothermal gradient is 24 °C/km and the seafloor temperature is 3.6 °C (Inagaki et al., 2013; Tanikawa et al., 2016); these characteristics suggest that the subsurface environment would sustain the accumulation of gas hydrate (Kvenvolden, 1998). These conditions are also similar to those of the methane hydrate stability zone in the Guajira basin offshore from Northern Colombia (López and Ojeda, 2006), the Kumano forearc basin in the Nankai Trough (Yamano et al., 1982; Chhun et al., 2017; Miyakawa et al., 2014), the Cascadia accretionary prism (Davis and Villinger, 1990), and the Fiordland continental margin in New Zealand (Townend, 1997). Moreover, in the study area, the spatial distribution of the BSR appears to be associated with the presence of gas chimneys, slump deposits (Figure 2.15), and an underlying basement high (Figures 2.2, 2.3, 2.16 and 2.25). The slump deposits could provide much pore space (high porosity) for hydrate and gas accumulation.

2.5.3 Distribution of free gas

The particular seismic characteristics of sediments charged with free gas in the Sanriku-Oki forearc basin is high amplitude reflection anomalies beneath and subparallel to the BSR (Figures 2.8-2.14). The presence of free gas underlying the BSR was supported by amplitude envelope analysis, which showed a wide distribution of high amplitude reflectors that are probably representative of free gas (red in Figures 2.8-2.14). These high-amplitude anomalies are visible in Quaternary sediments immediately below the BSR from 2.5 to 2.9 s TWT (~400 -800 m depth range) and over about 30 km along a N-S trend in the horizontal direction. Similar high-amplitude anomalies associated with gas-charged sediments have been observed in the South China Sea (e.g., Sun et al., 2012) and in the Nankai Trough (e.g., Taladay et al., 2017).

Core samples from the Quaternary succession recovered at IODP Site C0020 are composed mainly of alternating beds of mud and sand with thin intercalations of volcanic tephra and locally developed gravel or sand layers (Inagaki et al., 2012). The Quaternary sand facies there is a candidate reservoir rock for accumulations of natural gas. In addition, the core samples of slump sequence at Hidaka sedimentary basin (a northward continuation of Sanriku-Oki; Figure 2.1) consists of sandy layers with dark olive clayey silt intercalations with porosity range from 52 -72 % (Noda et al., 2013). These suggest that slump sequences can be a good reservoir for hydrocarbon. The overlying gas hydrate layer would provide an impermeable seal, preventing or at least inhibiting the escape of free gas and other fluids to the surface (Chhun et al., 2017) and resulting in lateral up-dip migration of the gas through porous strata and its subsequent accumulation in porous slump deposits (alternating facies of mud and sand) underlying the BSR (Figures 2.2, 2.3, and 2.8-2.17). The alternating of mud and sand and thrusting in slump sequences may constitute a good fluid migration system for promoting the accumulation of free gas (Yu et al., 2014). Seismic profiles from the Sanriku-Oki forearc basin clearly show high-amplitude reflections, primarily within the slump sequences of the Quaternary succession, which appear to be the focal points for accumulations of free gas (Figures 2.2, 2.3, and 2.8-2.14). Bangs et al. (1993) reported that even small amounts of free gas (1–2%) in sediments can cause anomalously high amplitude reflections.

Inagaki et al. (2012) inferred that most of the natural gas in study area is of biogenic origin because the temperature in the coal-bearing formations (50 °C) would sustain microbial life. If the timing of the biogenic (microbial) formation of hydrocarbon gases in Oligocene to Miocene coal seams (Inagaki et al., 2012; Gross et al., 2015) or Cretaceous or Eocene sediments (Osawa et al., 2002; Taira et al., 2005) coincides with the availability of appropriate migration pathways, upward migration of those gases to form a gas hydrate layer and accumulation of free gas in the forearc basin is possible. The source rocks for the gas hydrate and free gas would most likely be from deeply buried coal beds, which has high concentrations of organic carbon in order to generate significant volumes of hydrocarbon gas. Moreover, iodine concentrations and radioisotopic compositions of pore water from below the base of the gas hydrate layer at IODP Site C0020 show that the pore water is older than the host sediments, which suggests that the gas accumulations are the result of long-term migration from the deep biogenic sources (Tomaru et al., 2009).

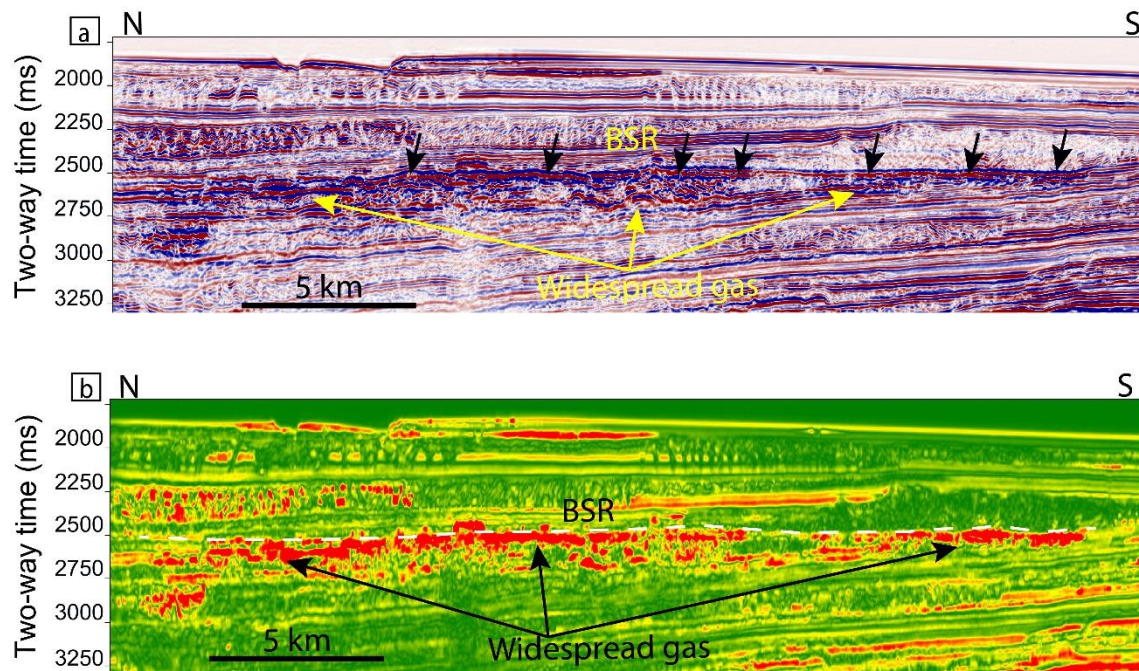


Figure 2.8 (a) Seismic profile (in line A) for N-S direction showing BSR and free gas bearing sediment. Black arrows indicate BSR. Yellow arrows indicate high amplitude of free gas. (b) Result of envelope attribute emphasizing spatial gas distribution. White dash line shows widespread BSR. Black arrows indicate widespread of free gas zone below BSR (red area).

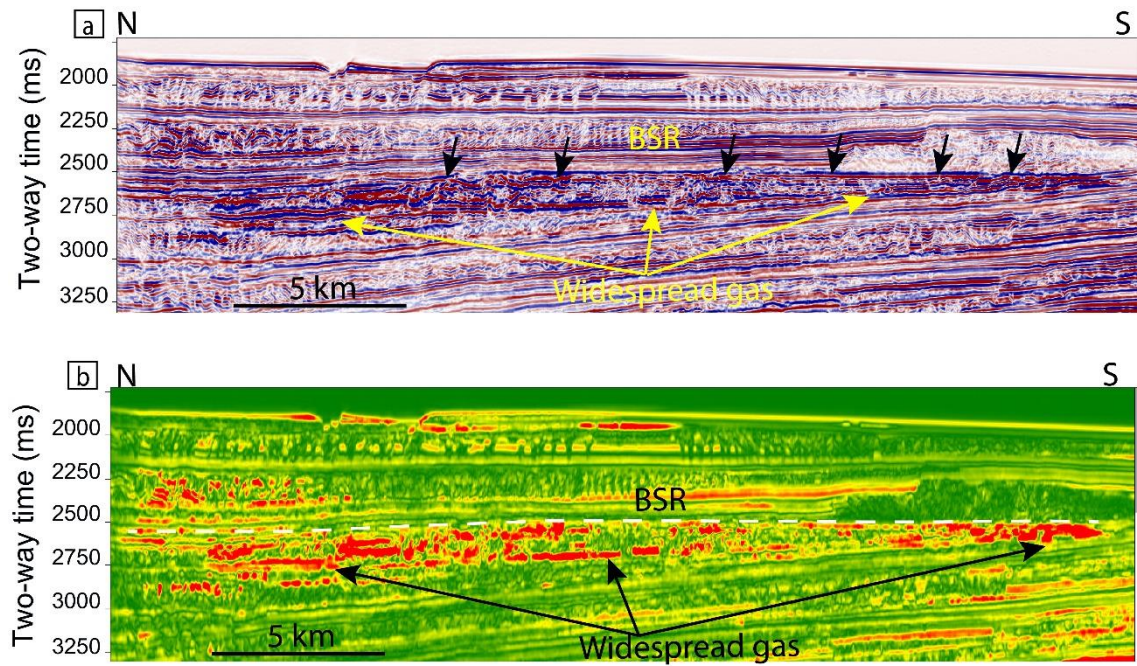


Figure 2.9 (a) Seismic profile (in line B) for N-S direction showing BSR and free gas bearing sediment. Black arrows indicate BSR. Yellow arrows indicate high amplitude of free gas. (b) Result of envelope attribute emphasizing spatial gas distribution. White dash line shows widespread BSR. Black arrows indicate widespread of free gas zone below BSR (red area).

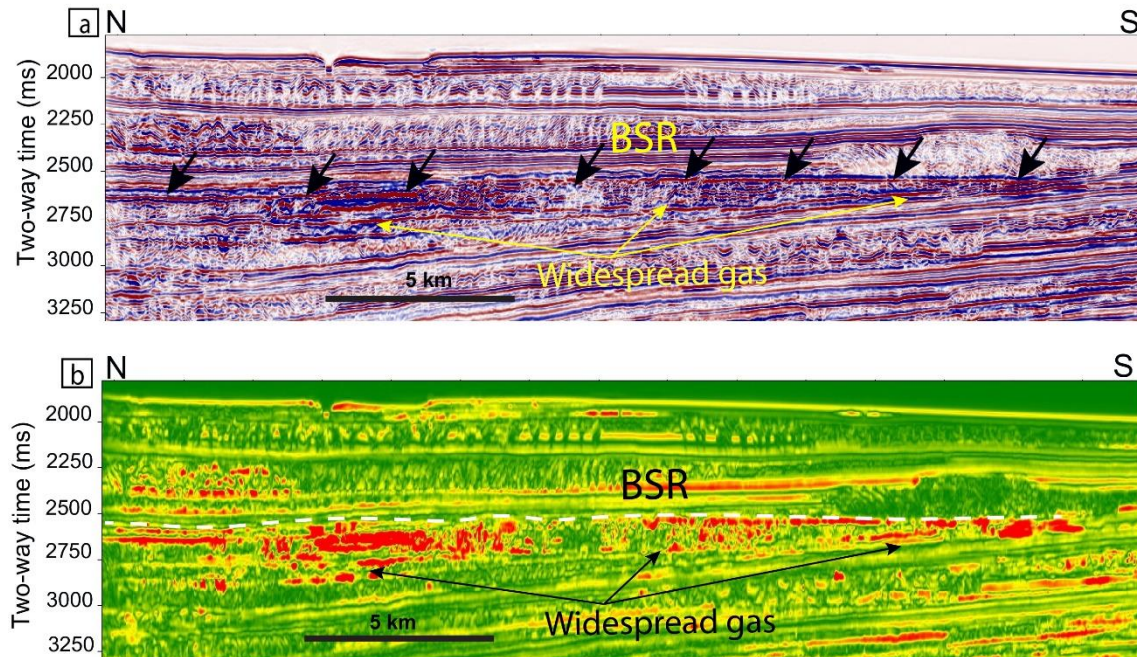


Figure 2.10 (a) Seismic profile (in line C) for N-S direction showing BSR and free gas bearing sediment. Black arrows indicate BSR. Yellow arrows indicate high amplitude of free gas. (b) Result of envelope attribute emphasizing spatial gas distribution. White dash line shows widespread BSR. Black arrows indicate widespread of free gas zone below BSR (red area).

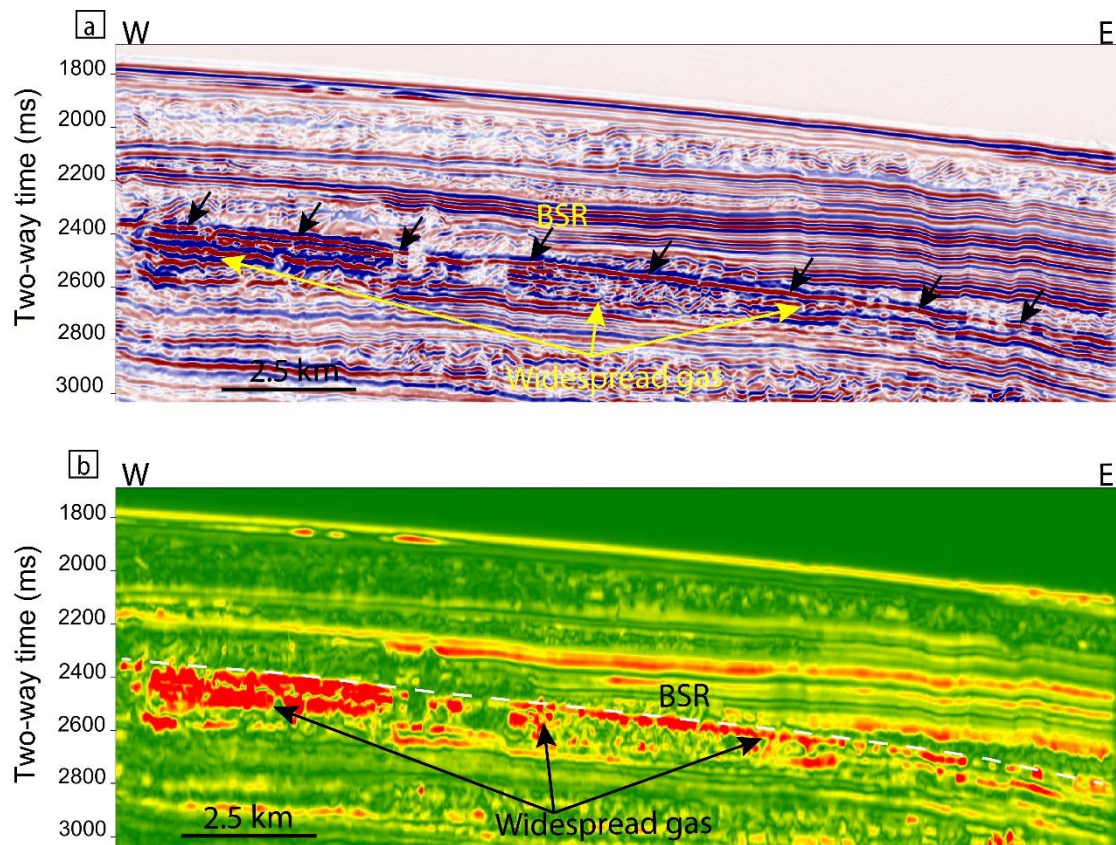


Figure 2.11 (a) Seismic profile (Cross line A) for E-W direction showing BSR and free gas bearing sediment. Black arrows indicate BSR. Yellow arrows indicate high amplitude of free gas. (b) Result of envelope attribute emphasizing spatial gas distribution. White dash line shows widespread BSR. Black arrows indicate widespread of free gas zone below BSR (red area).

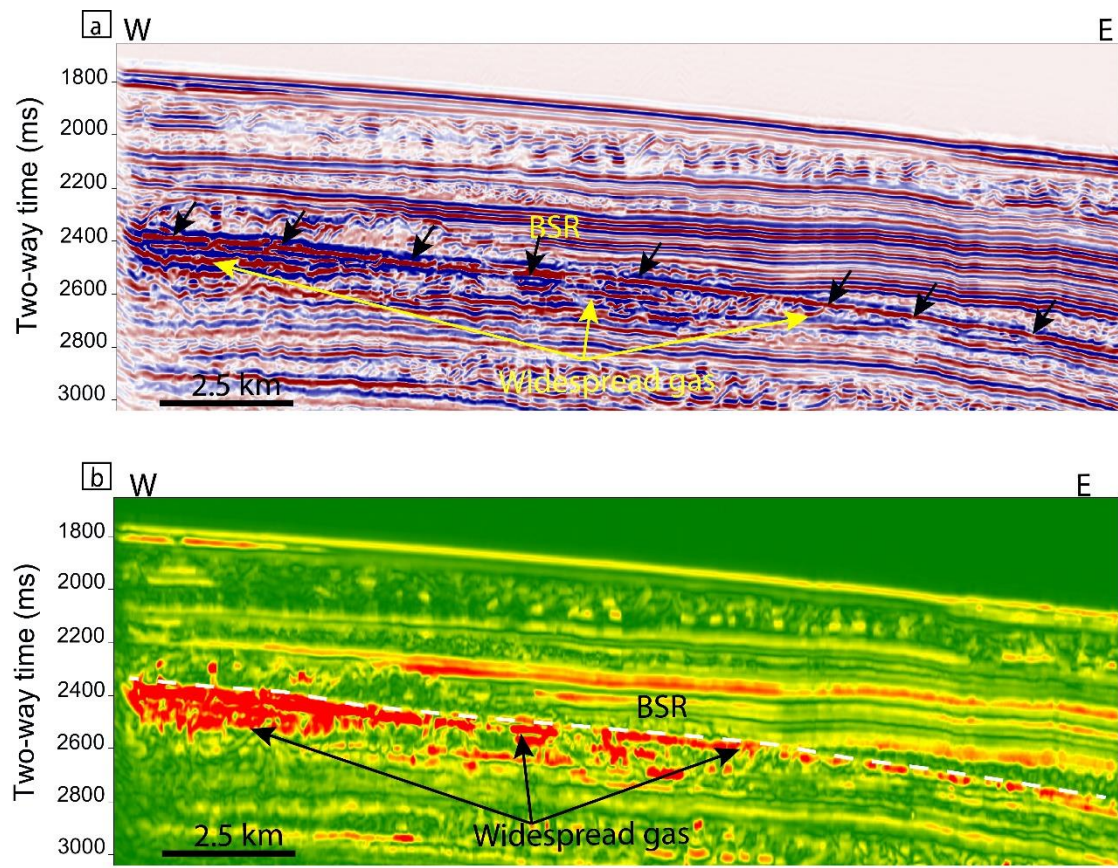


Figure 2.12 (a) Seismic profile (Cross line B) for E-W direction showing BSR and free gas bearing sediment. Black arrows indicate BSR. Yellow arrows indicate high amplitude of free gas. (b) Result of envelope attribute emphasizing spatial gas distribution. White dash line shows widespread BSR. Black arrows indicate widespread of free gas zone below BSR (red area).

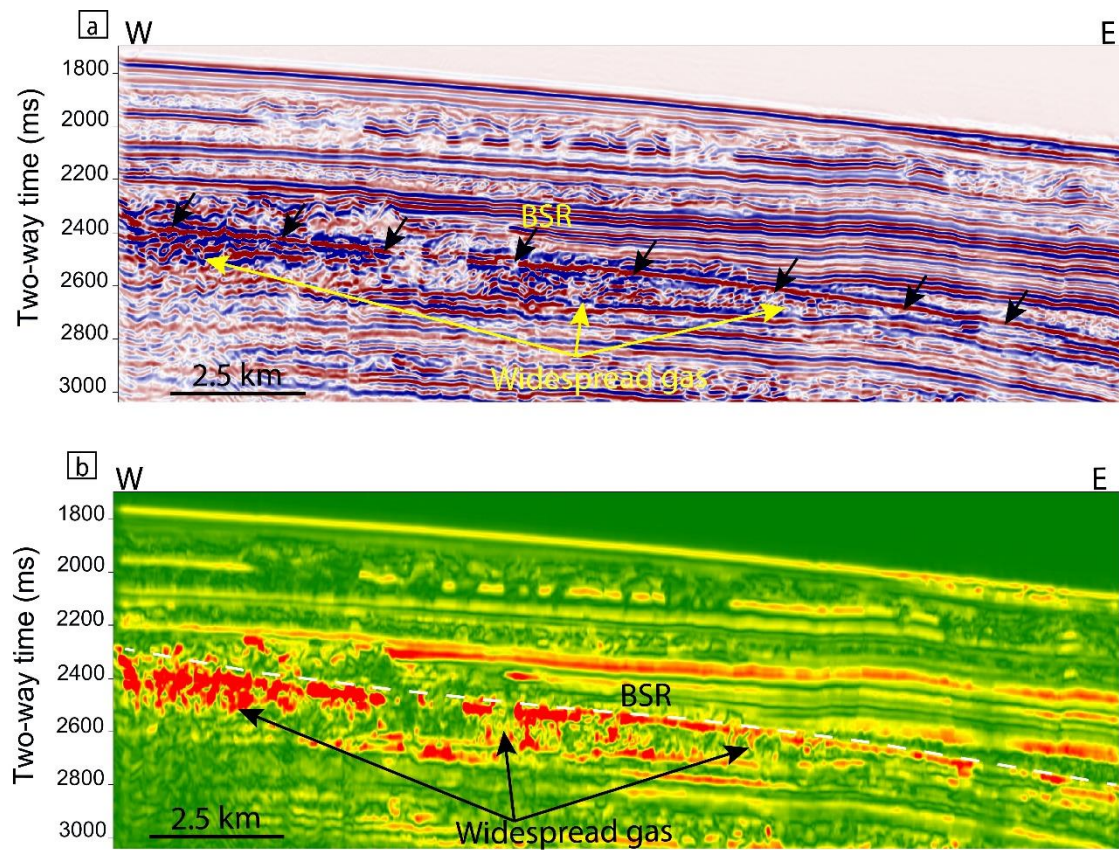


Figure 2.13 (a) Seismic profile (Cross line C) for E-W direction showing BSR and free gas bearing sediment. Black arrows indicate BSR. Yellow arrows indicate high amplitude of free gas. (b) Result of envelope attribute emphasizing spatial gas distribution. White dash line shows widespread BSR. Black arrows indicate widespread of free gas zone below BSR (red area).

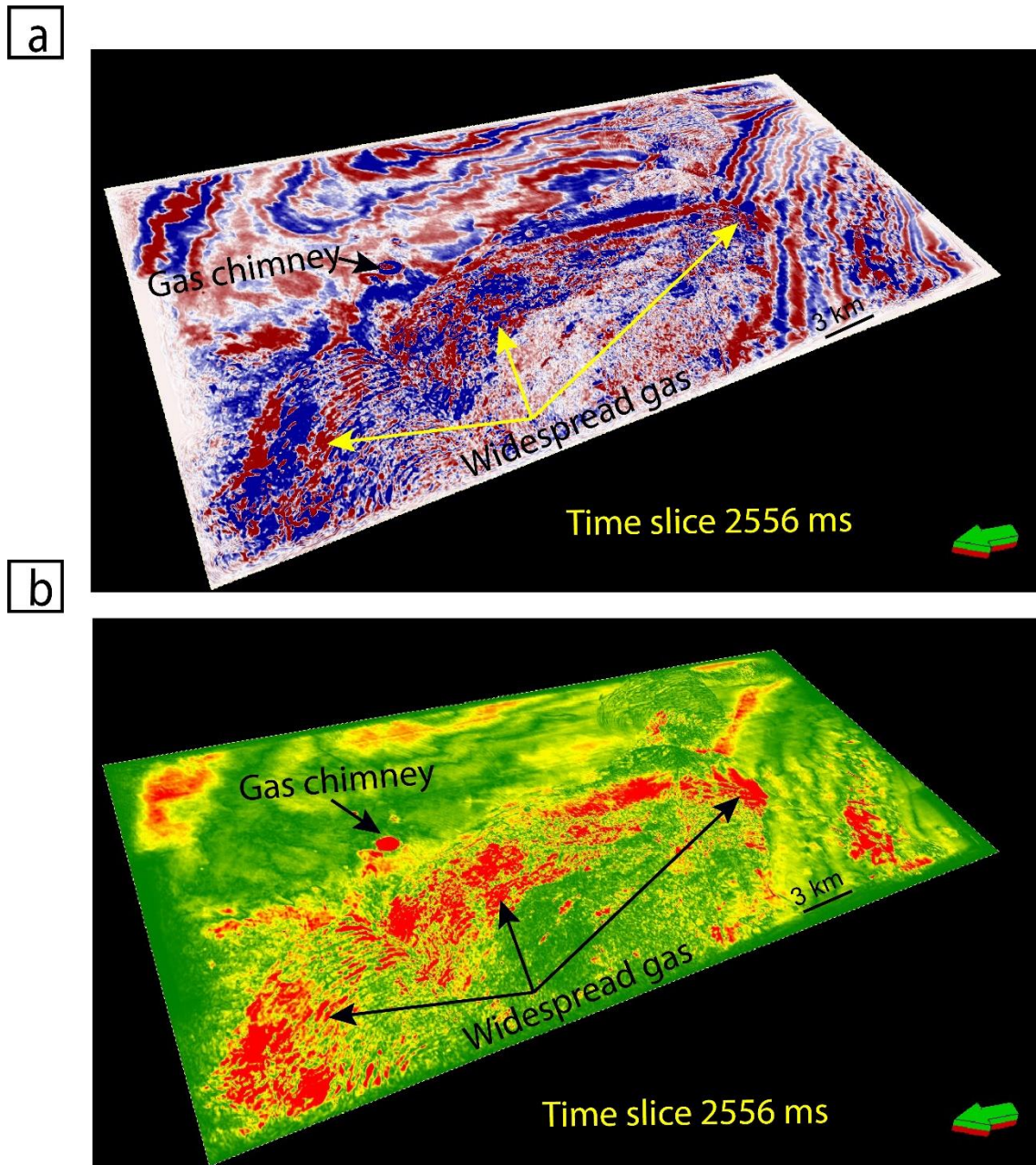


Figure 2.14 (a) Time-slice of (2556 ms TWT) 3D seismic profile showing gas chimney and free gas bearing sediment. (b) Time-slice of (2556 ms TWT) 3D envelope volume showing free gas-bearing sediments.

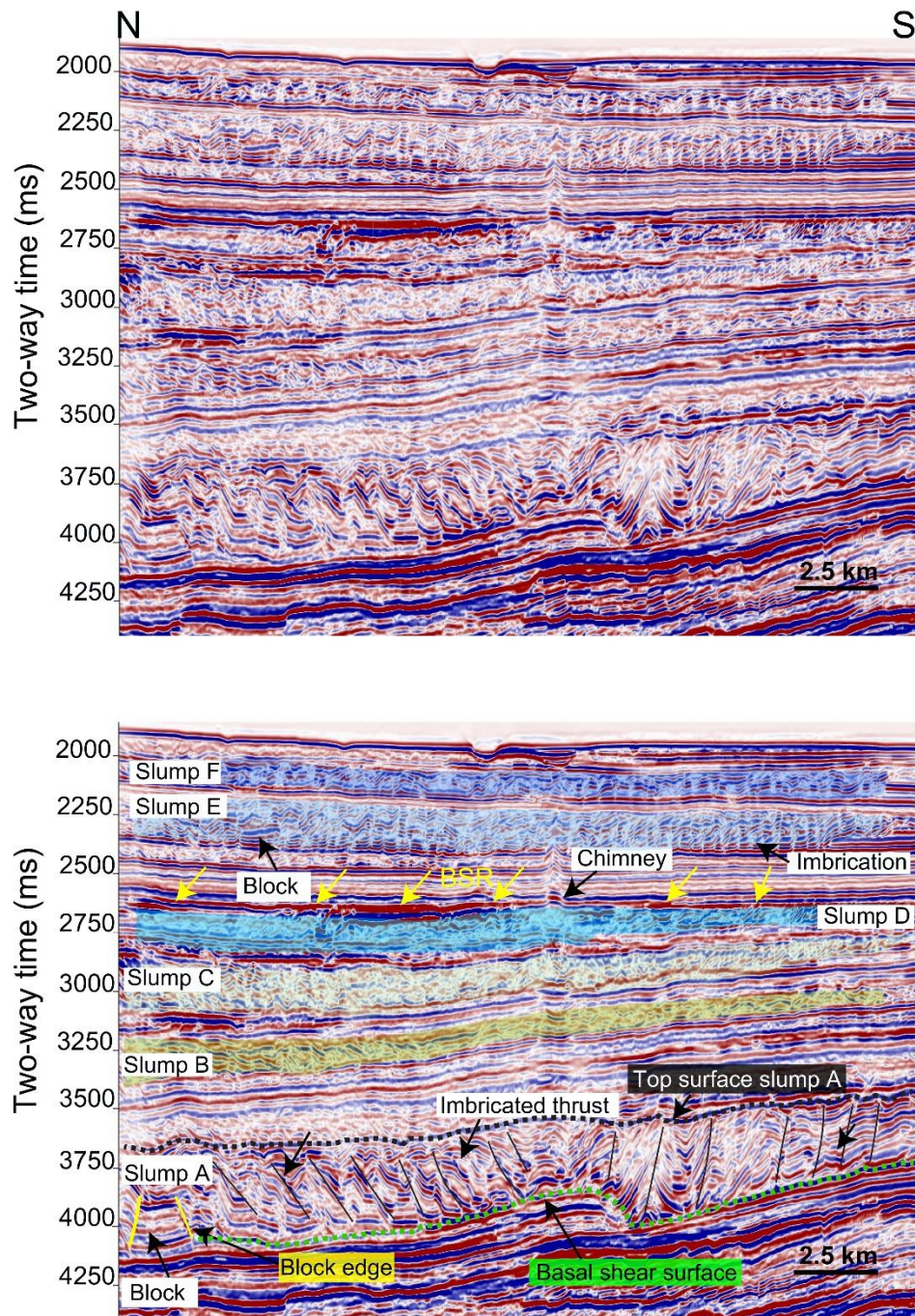


Figure 2.15 Seismic reflection profiles across Sanriku-Oki forearc basin with and without geological interpretation. The profiles for N-S direction, extracted from the METI 3D seismic volume. Various features of slumps observed on the METI 3D seismic profiles. Six slump sequences were observed on seismic profiles. The slumps often show imbrication and chaotic structures.

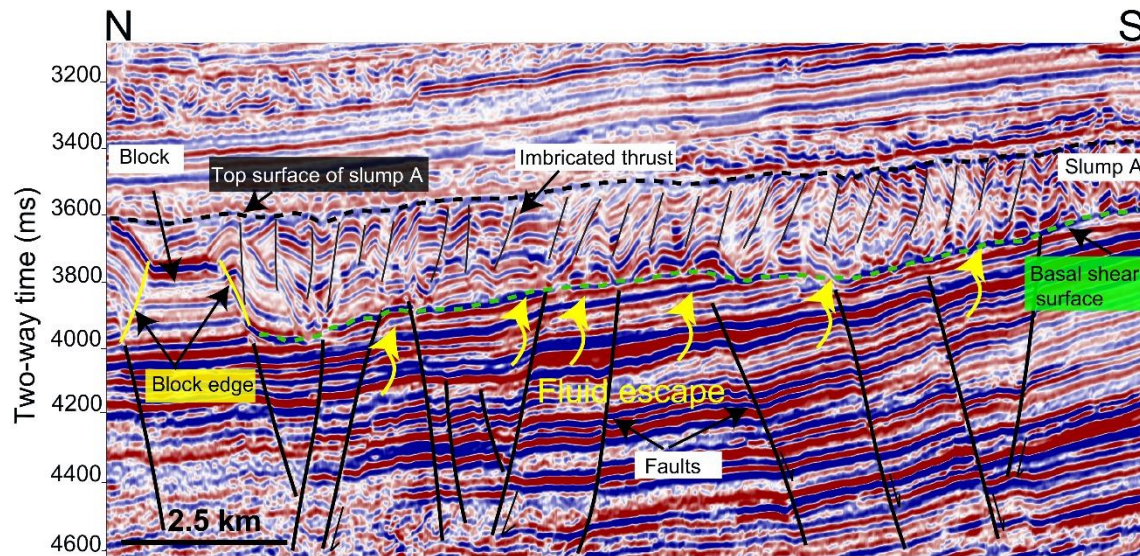


Figure 2.16 Enlarged seismic profile for slump A (Figure 2.15). Slump A was developed above fault block. Yellow arrows indicated fluid escaped from deeper formation, which could induce the slumping.

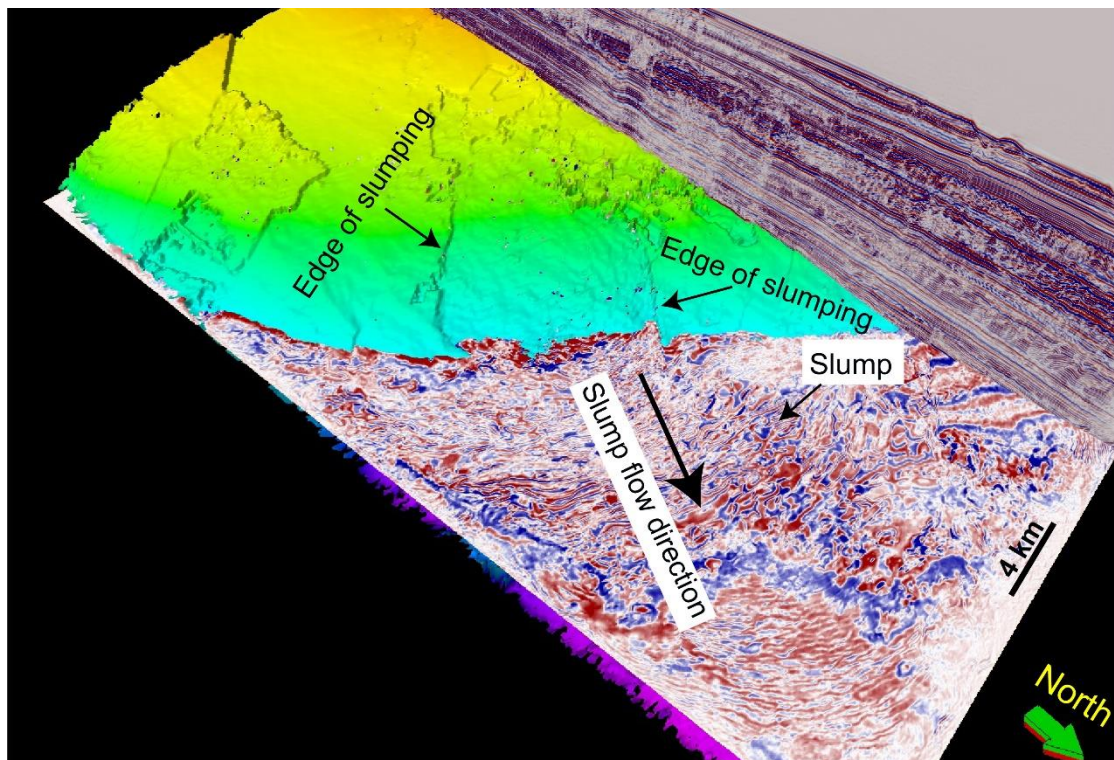


Figure 2.17 3D geometry of base of slumping direction unit (horizon) showing the slumping direction. The general flow direction is SW to NE.

2.6 Discussion

2.6.1 *Migration pathways for hydrocarbon gas accumulation*

Hydrocarbon gases in the Sanriku-Oki forearc basin migrated upward from biogenic sources (Inagaki et al., 2012) through favoured conduits (e.g., faults, fractures, and chimneys) to accumulate in Quaternary reservoirs. Here, I discuss the tectonic events and forearc basin configuration that controlled the migration and accumulation of hydrocarbon gases in the basin.

2.6.1.1 *Normal faults*

Our application of the ant-tracking algorithm and chaos attribute to the part of the METI 3D seismic volume that corresponds to the Cretaceous to Quaternary sequences (below the gas accumulation zone) revealed details of the complex patterns of faults and fractures there (Figures 2.18-2.21). Many steeply dipping normal faults were identified within the sedimentary successions of Cretaceous to Oligocene age; these faults were consistent with those author interpreted on the seismic reflection profiles (Figures 2.22 and 2.23). Most of the faults strike either NW–SE or N–S and are associated with the subsidence that typically occurs in forearc basins (Xie and Heller, 2009). The average rate of subsidence in the Sanriku-Oki forearc basin during the late Oligocene and early Miocene was ~100m/Ma (Takano, 2017; Regalla et al., 2013) and may have been a consequence of abrasional basal erosion of upper plate material at the plate interface during subduction (von Huene and Lallemand, 1990; Takano, 2017). The resultant dynamic changes in the geometry of the upper plate and the shallow part of the downgoing slab created the accommodation space required for forearc basin subsidence. Regalla et al. (2013) and Tsuji et al. (2013) proposed that the subsidence was contemporaneous with the onset of extension in the upper plate. Subsidence of the forearc basin was also associated with the increasing rate of convergence of the two tectonic plates in response to eastward motion of Honshu that was initiated during opening of the Japan Sea (Regalla et al., 2013). Thus, it is likely that the abovementioned extensional stress was the cause of the normal faulting in the Cretaceous to Oligocene successions in the forearc basin.

Moreover, the results of ant-tracking (Figures 2.20-2.22) show a detailed network of planar faults accompanied by many small-offset faults, which were unable to recognize during our manual interpretation of seismic profiles. These normal faults works as fluid pathways as well as hydraulic boundaries (e.g., Jia et al., 2016).

2.6.1.2 Gas chimneys

Gas chimneys provide a pathway for vertical upward migration of fluids. On inline seismic profiles from the METI 3D data volume (Figures 2.2 and 2.15), the author interpreted a vertically elongated feature in the Miocene to Quaternary succession, above the coal-bearing formations and the faulted block sequence, to represent a gas chimney (Figures 2.3 and 2.25). This feature is in the north-eastern part of study area between ~2.4 and 3.6 s TWT (giving a height of ~1.2 km) and is ~600 m wide. It cuts across horizontally stratified reflections in the Miocene to Quaternary sequence and manifests as a narrow vertical zone of distorted seismic reflections (Figure 2.3). The gas chimney in the Sanriku-Oki forearc basin have formed above potential source rock (coal layers) and near the edges of areas of slumping in sediments overlying the Miocene unconformity (Figures 2.24- 2.26). Because the fluid trapped beneath the low-permeable formation migrates lateral up-dip direction along the formation and escapes upward from the edge of layer structure (i.e., edge of slumping area), due to collapse of low-permeable seal layer (Figures 2.25 and 2.26).

2.6.1.3 Slump structures

The METI 3D seismic volume revealed six relatively low-amplitude sequences characterized by imbricate faulting and chaotic slump structures (slump sequences A to F; Figures 2.15 and 2.16). Here we note 5 dominant slumping sequences, but several minor slumping occurs between the dominant sequences (e.g., above the top surface of slump A in Figure 2.16). These sequences are extensively distributed in the north-eastern part of the study area (Figure 2.17), particularly within the Miocene to Quaternary sedimentary succession. The overall flow direction of slump sequences is from SW to NE (Figure 2.17). Here, two scenarios for deposition of the slump sequences are proposed: (1) They formed in areas of normal faulting (slump sequence A) and (2) they formed in

fault-free sequences (slump sequences B to F).

In slump sequence A on N-S seismic profiles (Figures 2.15 and 2.16), the imbricate thrust north of the gas chimney dip to the south, whereas those south of the chimney dip north. In three dimensionally, the imbricate thrust north-east of gas chimney dip to south-east, whereas those south-east of gas chimney dip to north-east. The author observed that the early Miocene slump sequence A has both the greatest lateral extent and the greatest thickness among the six slump sequences (Figure 2.15). It is thicker at the northern end of the profile shown in Figure 2.15 (3.6 to 4.1 s TWT; ~500 m thick) and thinner in the south (3.0 to 3.1 s TWT; ~100 m thick), with a lateral extent of ~25 km (Figures 2.15 and 2.16). The basal shear surface (base of slump sequence) of the slump sequence A is clearly identified on seismic profiles (Figures 2.15 and 2.16). It appears as a discontinuous, moderate-amplitude reflector showing basal erosion scours; it also truncates normal faulting in the underlying Cretaceous sequence (Figures 2.15 and 2.16). As previously mentioned, these normal faults extend from within the Cretaceous section to the base of slump sequence A (early Miocene); thus, they were likely an important control on the development of slump sequence A. Moreover, activity on these faults probably generated the structural high in Cretaceous rocks underlying the gas chimney and could have triggered large-scale instability in the overlying strata (Figure 2.16). Indeed, location of basal shear surface of slump A is influenced by normal fault movements in the deeper formation (see Figure 2.16). These seismic characteristics are similar to those attributed to mass transport deposits associated with growth faulting in the Taranaki Basin, New Zealand (Panpichityota et al., 2017). Furthermore, the subsidence event in Miocene could contribute the slope failure and gravitational deformation in form of submarine slumping in Sanriku-Oki, particularly slump A. Similar features were observed in other forearc basin (e.g., Lin et al., 2010; Lamarche et al., 2008).

Within the study area, slump sequences B to F appear to be restricted to the Late Miocene to Quaternary sequences shallower than the region of the interpreted fault and lack the clear imbricate faulting observed in slump sequence A (Figure 2.15). However, high pore pressures in this sequence may have created a film of pressure compartment

(Morita et al., 2012; Kokusho, 2000), which caused the lubrication to enhance the slumping. Rapid sedimentation rates in the Sanriku-Oki forearc basin from Cretaceous to Palaeogene time may have resulted in overpressured fluids being trapped in the sediments (Flemings et al., 2008; Shipp et al., 2011; Tsuji et al., 2008); these could have contributed to slumping and the development of the gas chimney. Moreover, the Sanriku-Oki forearc basin is within a tectonically active region characterized by frequent large earthquakes (Tanioka and Satake, 1996; Kanamori, 1971). Large earthquakes can instantaneously generate high pore pressures, even at large distances from the source fault (Nimiya et al., 2017); such elevated pore pressures may have triggered slumping along low-dip sequence even if the area is far from the source fault (Tsuji et al., 2017). The oscillating ground motions of earthquakes can cause cyclic horizontal and vertical shear stresses, thereby increasing the gravitational force applied to sediments and leading to slumping (Leynaud et al., 2004; Strasser et al., 2007). Slump sequence D shows as flat and high amplitude beneath BSR, this suggests that the accumulation of hydrocarbon gas causes anomalously high reflection strength on seismic profiles (Figs. 2.2, 2.8-2.13, and 2.15). Kret et al., (2018) indicated that slump sequence in the high reflection strength beneath the BSR has low seismic velocity due to the presence of gas as well as high pore pressure. These suggest that the elastic moduli of slump sequence D are changed by gas accumulation and results as flat and high amplitude overprinting the original slump structure.

2.6.2 Fluid flow features as a function of coal-bearing formation

Coal seams are common in the Cretaceous to Palaeogene successions of the Sanriku-Oki forearc basin (Osawa et al., 2002; Inagaki et al., 2012). The forearc basin was characterized by Takano (2017) as a shelved and benched forearc basin in which uplift of the trench slope break resulted in the emergence of a ridge along the eastern margin of the basin that provided a barrier to the open sea conditions trenchward of the basin. Thus, the forearc basin was overfilled to produce an aggradational sequence of coal-bearing bay to fluvial sediments. Based on the vitrinite reflectance, these coal seams are thermally more mature than those deposited during the Oligocene and early Miocene (coals in Unit III; the high total organic carbon content (40 to 60%) and organic type II/III, the coals are considered to be potential source rocks for hydrocarbon gases (Osawa et al., 2002, Takano

et al., 2017). Takano and Tsuji (2017) noted that the Cretaceous to Palaeogene succession contains many palaeochannels and coal-bearing fluvial sediments, thus providing potential for both source and reservoir rocks. The author suggests that high-amplitude reflections on our seismic profiles from Cretaceous to Oligocene sediments (Figures 2.2, 2.3 and 2.6a) might represent hydrocarbons entrapped within sandy palaeochannels. Moreover, author suggests that highly porous lithological boundaries (Figure 2.6a) and numerous normal faults in these formations have provided upward migration pathways for hydrocarbon gases generated in the deep Cretaceous to Palaeogene sedimentary sequences (blue arrow in Figure 2.6a) and their accumulation within the porous Quaternary slump sequences. Similar features observed in seismic sections have been identified as gas-charged sediments and fluid migration paths in other regions (e.g., Lower Congo Basin; Gay et al., 2006). Due to lack of dipping faults in shallower Miocene to Quaternary sedimentary sequences, the migration of hydrocarbon gases through slump sequences (i.e., thrust, edges of slumping) also plays important role in this sedimentary interval (Figure 2.15, 2.16, 2.27, and 2.28). The permeable zone of internal slump sequences (i.e., thrust) allows fluids flow through slump layers and leakage upward at the up-dip edges of slumping (Gamboa and Alves, 2015; Gamboa et al., 2011).

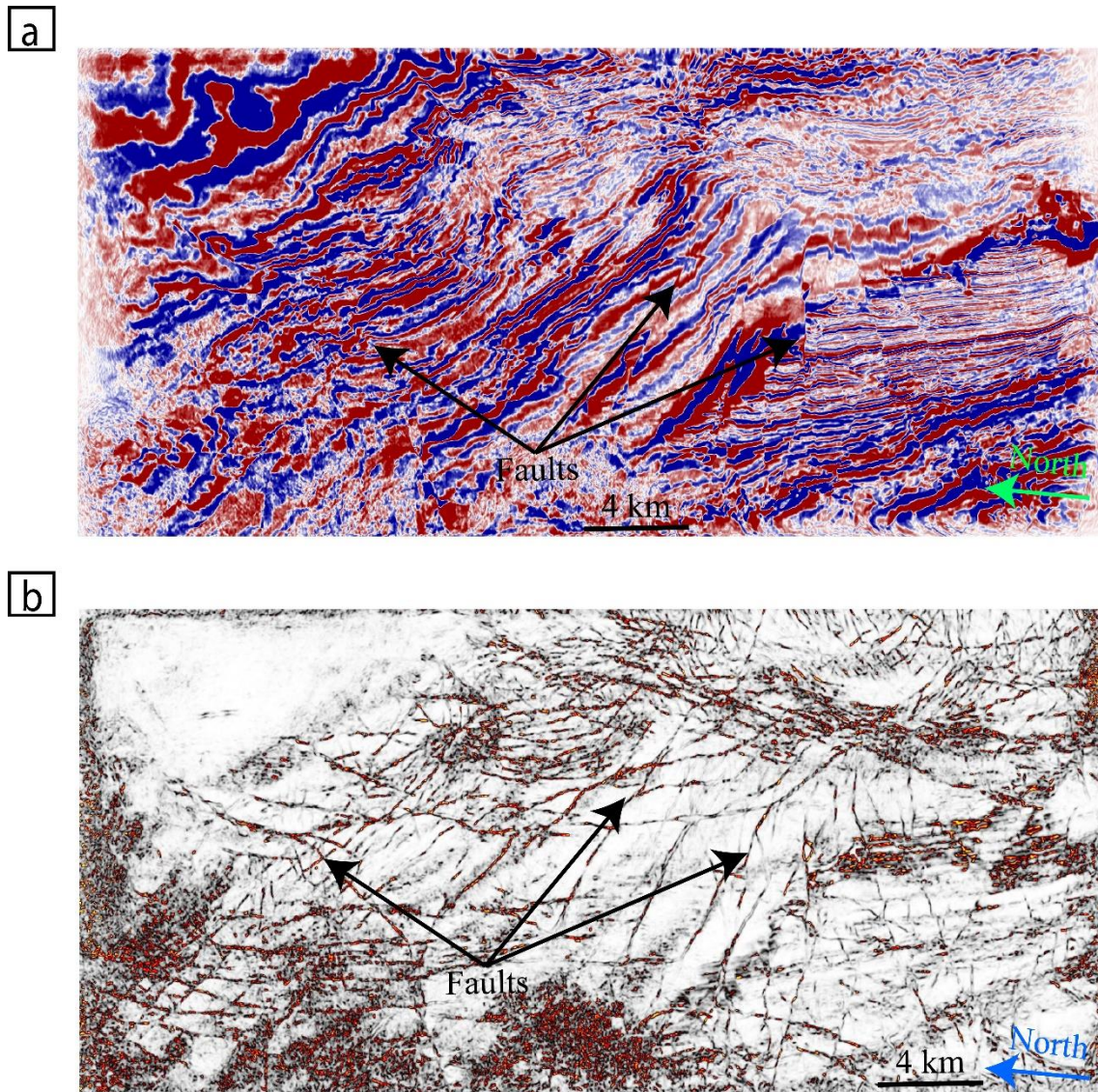


Figure 2.18 (a) Plan-view of seismic profiles and (b) chaos attribute (4200 ms TWT), which shows detailed of faults of Oligocene formation.

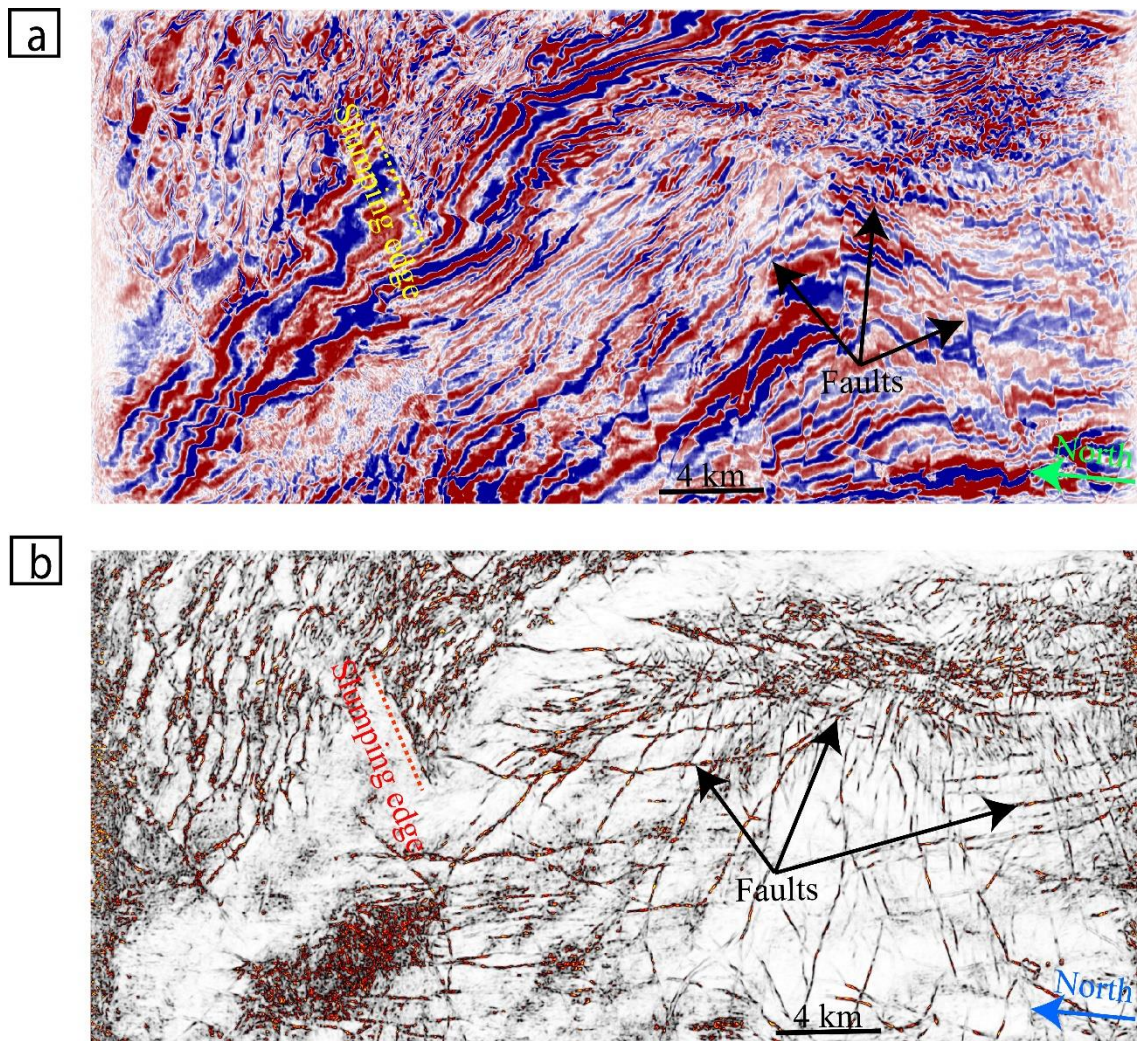


Figure 2.19 (a) Plan-view of seismic profiles and (b) chaos attribute (3932 ms TWT), which shows lower slumping boundary and detailed of faults of Miocene formation

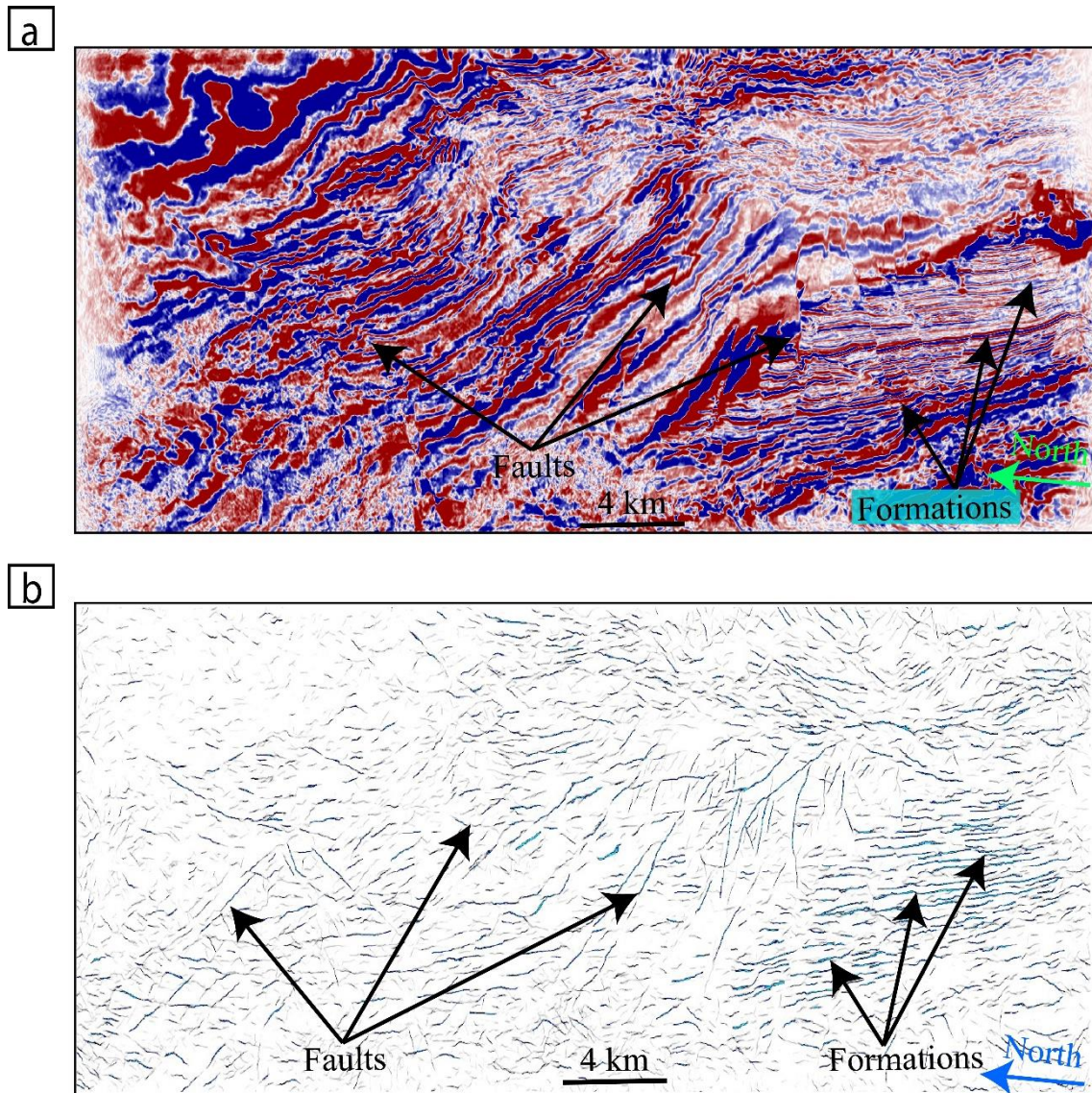


Figure 2.20 (a) Plan-view of seismic profiles and (b) ant-tracking attribute (4200 ms TWT). Faults and fractures of Oligocene formation enhanced on the ant-tracking profile.

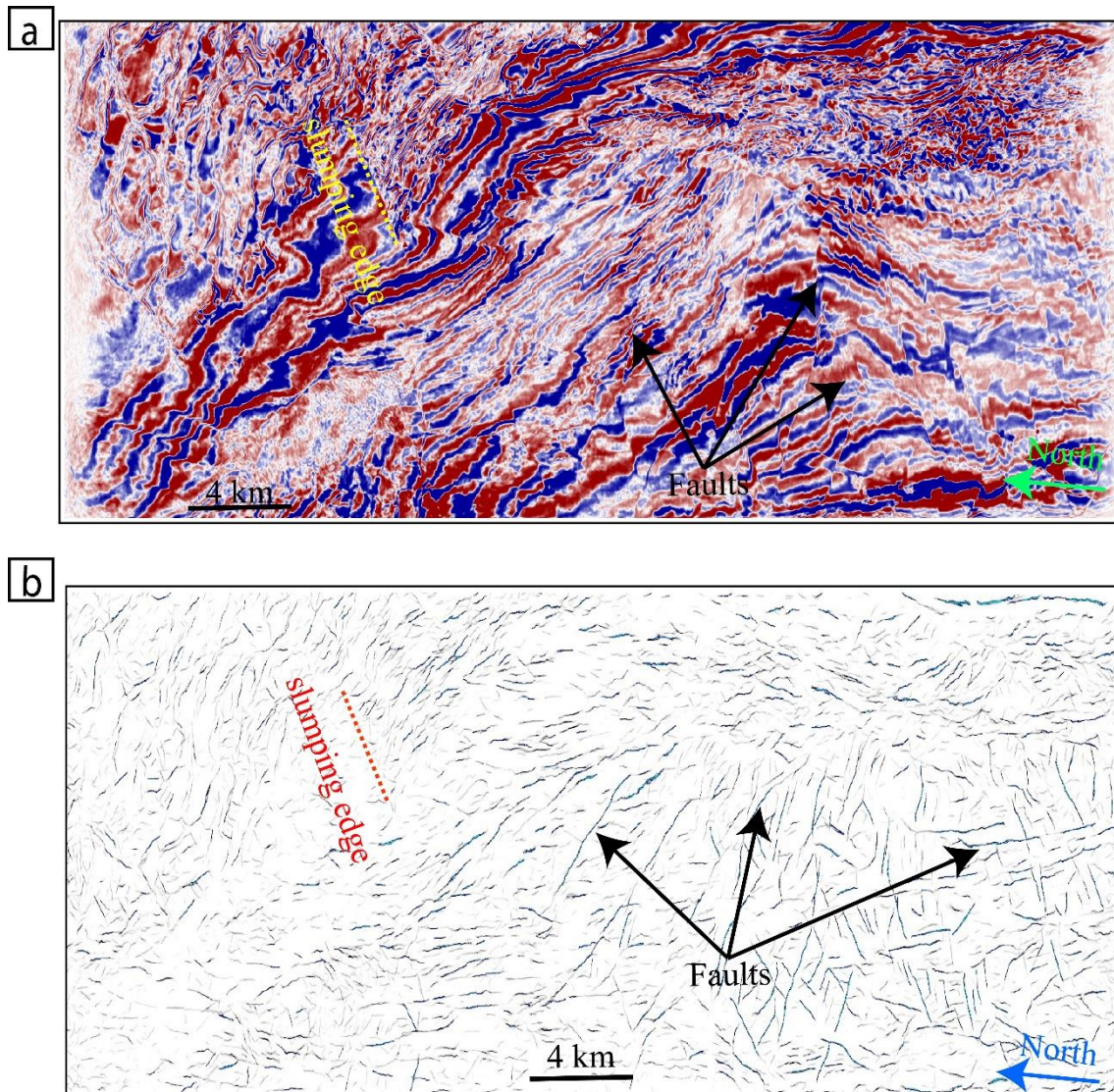


Figure 2.21 (a) Plan-view of seismic profiles and (b) ant-tracking attribute (3932 ms TWT), which shows lower slumping boundary. Faults and fractures of Miocene formation enhanced on the ant-tracking profile.

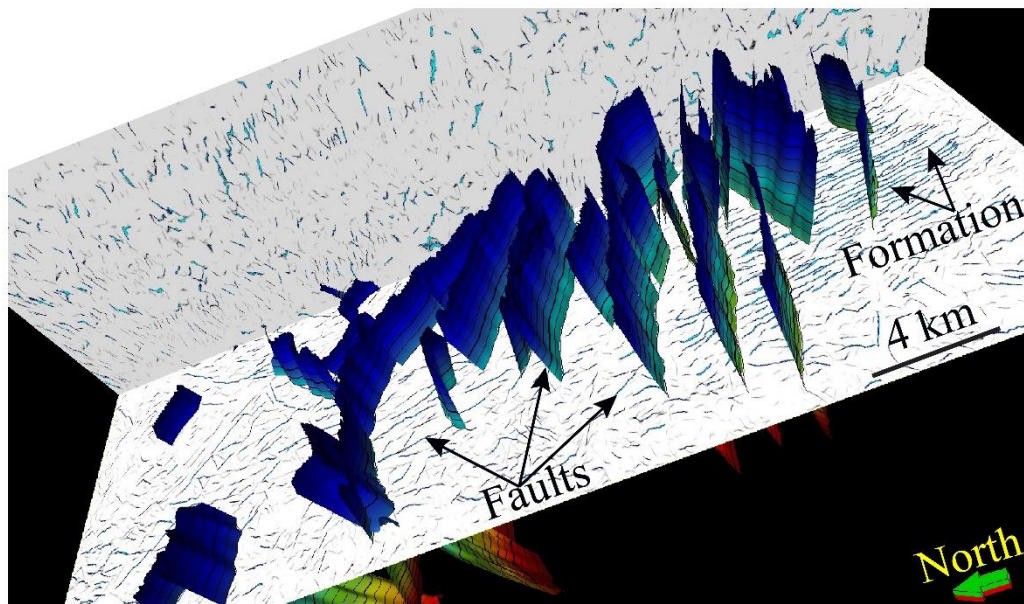


Figure 2.22 3D geometry of normal faults and fracture enhanced on the ant-tracking profile. Dominant normal faults strike NW-SE.

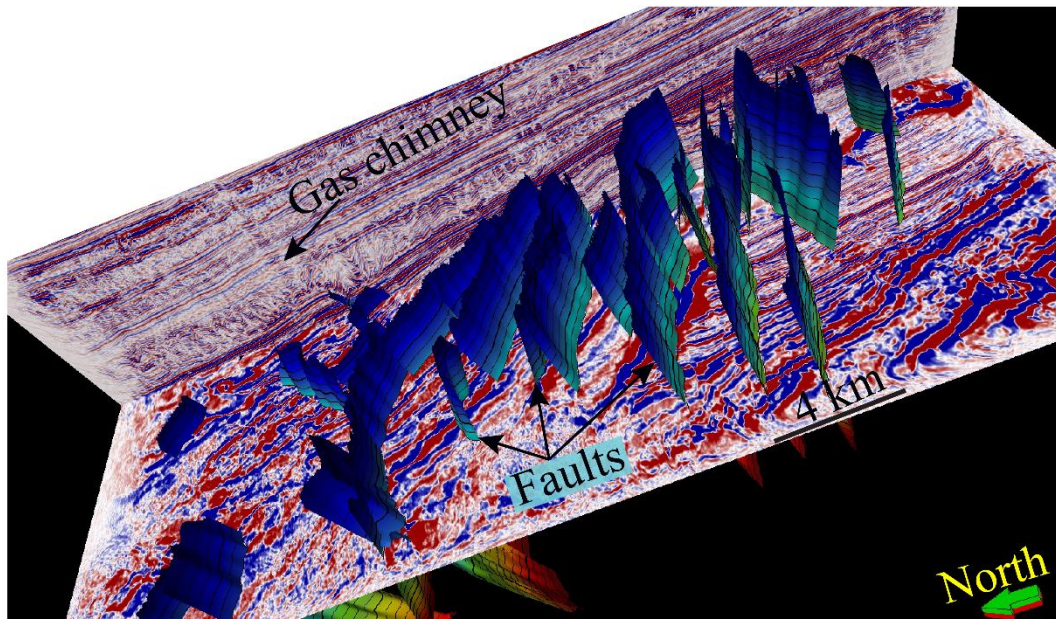


Figure 2.23 3D geometry of normal faults extracted from the METI 3D seismic volume. Dominant normal faults strike NW-SE.

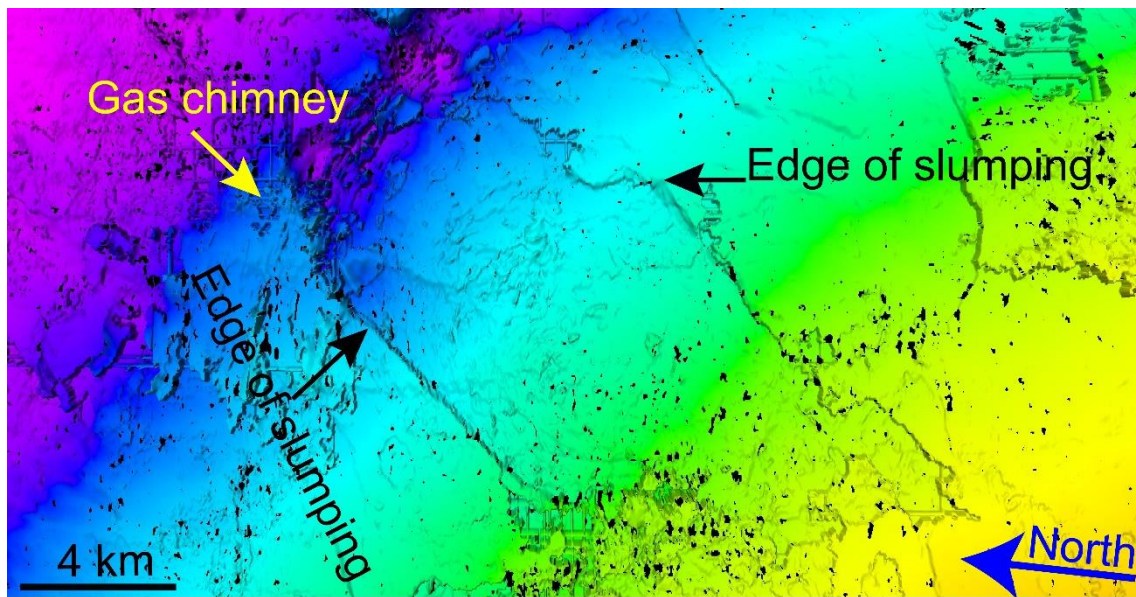


Figure 2.24 Plan-view of slumping boundary. Red arrow indicates lower slumping boundary, black arrow shows upper slumping boundary, and yellow arrow indicates location of chimney.

2.6.3 Influence of faults, slumping, and chimney on hydrocarbon migration and accumulation

The base of the interpreted gas chimney is in Miocene strata at the edge of slump sequence A, where slumping and fracturing has caused intense deformation of the sediments (Figures 2.25 and 2.26). The sequence directly beneath the gas chimney can accumulate hydrocarbons from surrounding formation because the shape of this formation at edge of slumping is shallower than the surrounding area (Figures 2.2 and 2.25). Local concentrations of hydrocarbons can increase fluid advection and initiate the development of a gas chimney (Løseth et al., 2009). The contrasting dips of thrusts in slump sequence A on either side of the gas chimney (Figure 2.15 and 2.16) suggests that localized extension occurred in the sequence beneath the chimney (Figure 2.25). Therefore, the presence of faults, the high permeable zone of the slumping edges and the localized extensional regime allowed overpressured fluids to escape from deep Cretaceous biogenic sources. Similar gas chimneys that cut across the slump sequences have been identified in the Hidaka trough, northern Japan (Noda et al. 2013).

The 3D seismic data provided evidence of gas pockets in the south-eastern part of our study area (Figures 2.27 and 2.28). The gas pockets stand out as narrow anomalously high amplitude reflections that occur locally within individual slump units and at the edges of slump sequences. Edges of slumping are defined as margin or scarp marking the upslope limit of the slump sequence (Figures 2.26-2.28). These edges are indicative of a local extensional failure surface and works as sharp boundary between porous slumping formation and stratified formation. They propagate along strike of slump sequence and generally parallel to the dip slope because of the effect of gravity on the sediment mass (Bull et al., 2009). Most of these boundaries were conspicuous both on seismic sections, in plan-view and time slices (Figures 2.19, 2.21, 2.24, and 2.26-2.28). In-plan view (Figure 2.24), the edges of slump sequences appear to be continuous planar features that might provide fluid migration paths. The internal structure of slump sequences, such as thrusts (Figures 2.15, 2.16, and 2.19), might also provide potential routes for percolation of fluids and their accumulation in porous sedimentary succession. Thus, hydrocarbon gases can propagate vertically through slumps or along edge of blocks, thrust, and

fractures, and horizontally along sheared beds. Figures 2.24 and 2.26 illustrate distinctive northern and southern edges of slump sequence A, both of which may have provided conduits for migration of hydrocarbon gases. Thus, the author suggests that the slump sequences provided an important control for the accumulation of gas pockets in the Sanriku-Oki forearc basin.

Seismic data indicate that there are more gas accumulations in the north-east of the study area (Figures 2.8-2.10, 2.14, and 2.25). In response to subsidence during the Miocene, the Sanriku-Oki forearc basin transitioned from a shelved and benched type forearc basin to a slope type forearc basin (Takano, 2017; Takano et al., 2013), which suggests that the mud and sand facies sediments deposited there from both the open sea and from landward were thicker than those in south-east of the study area. The thick sequences of Quaternary and Miocene sediments with a high proportion of slump units and sand facies in the north-east of the study area (Figures 2.15 and 2.25) may also have contributed to migration pathways and the accumulation of hydrocarbon gases there, as demonstrated in the North Sea by Shanmugam et al. (1996). It is clear that faults and gas chimneys influenced the migration of hydrocarbons in the north-east of the study area. The major faults there cut potential source rocks underlying the gas chimney. In contrast, in the south-eastern part of the study area (within the 3D seismic volume), there is absent of gas chimney and consists of only normal faults in the Cretaceous to Palaeogene successions, which perhaps provides an explanation for the limited migration and accumulation of hydrocarbon gases in the south-east.

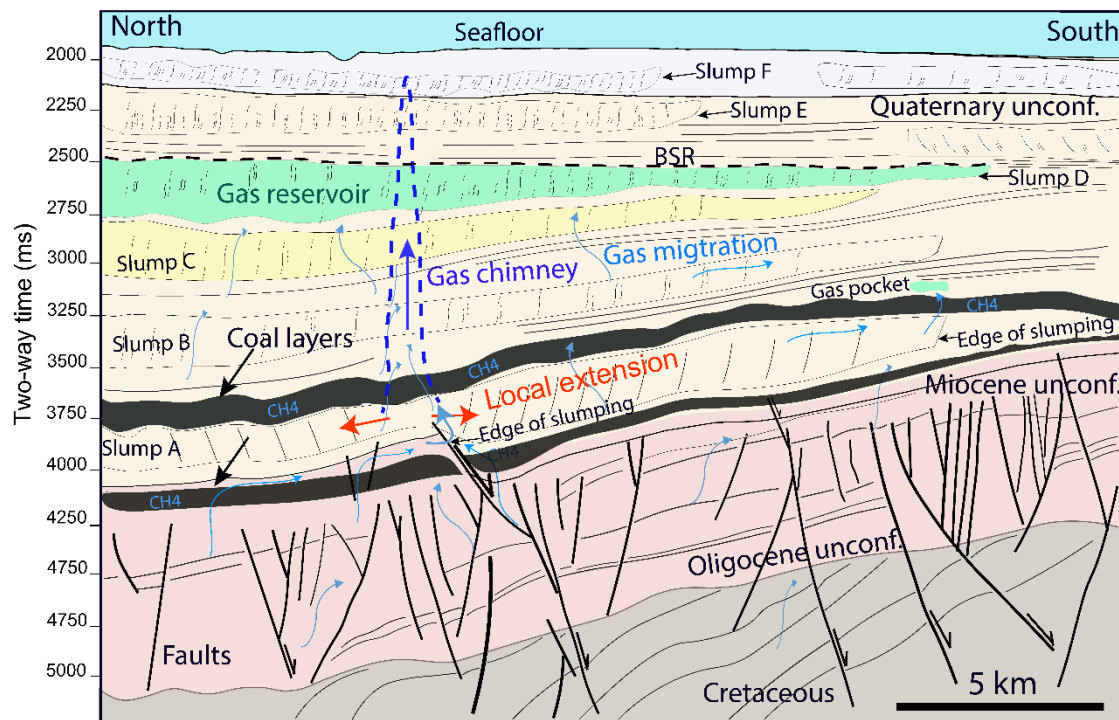


Figure 2.25 Schematic image of hydrocarbon gas system and formation in Sanriku-Oki forearc basin (N-S profile).

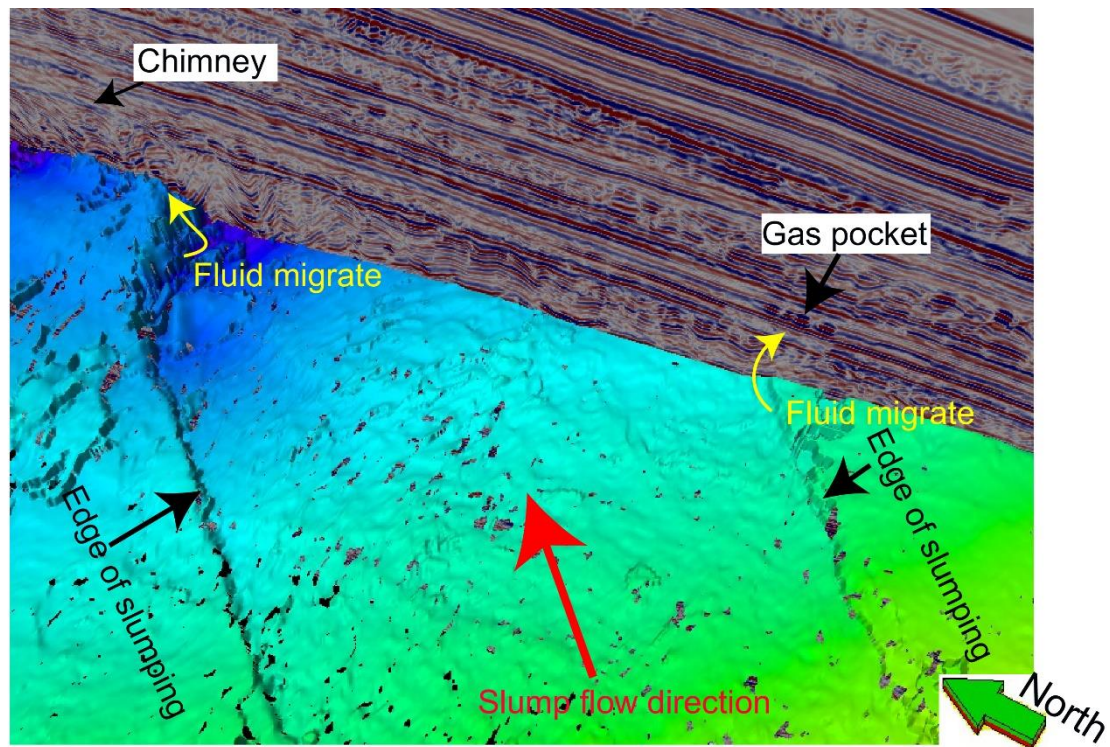


Figure 2.26 3D view of slumping boundaries. Yellow arrows indicate interpreted fluids migration.

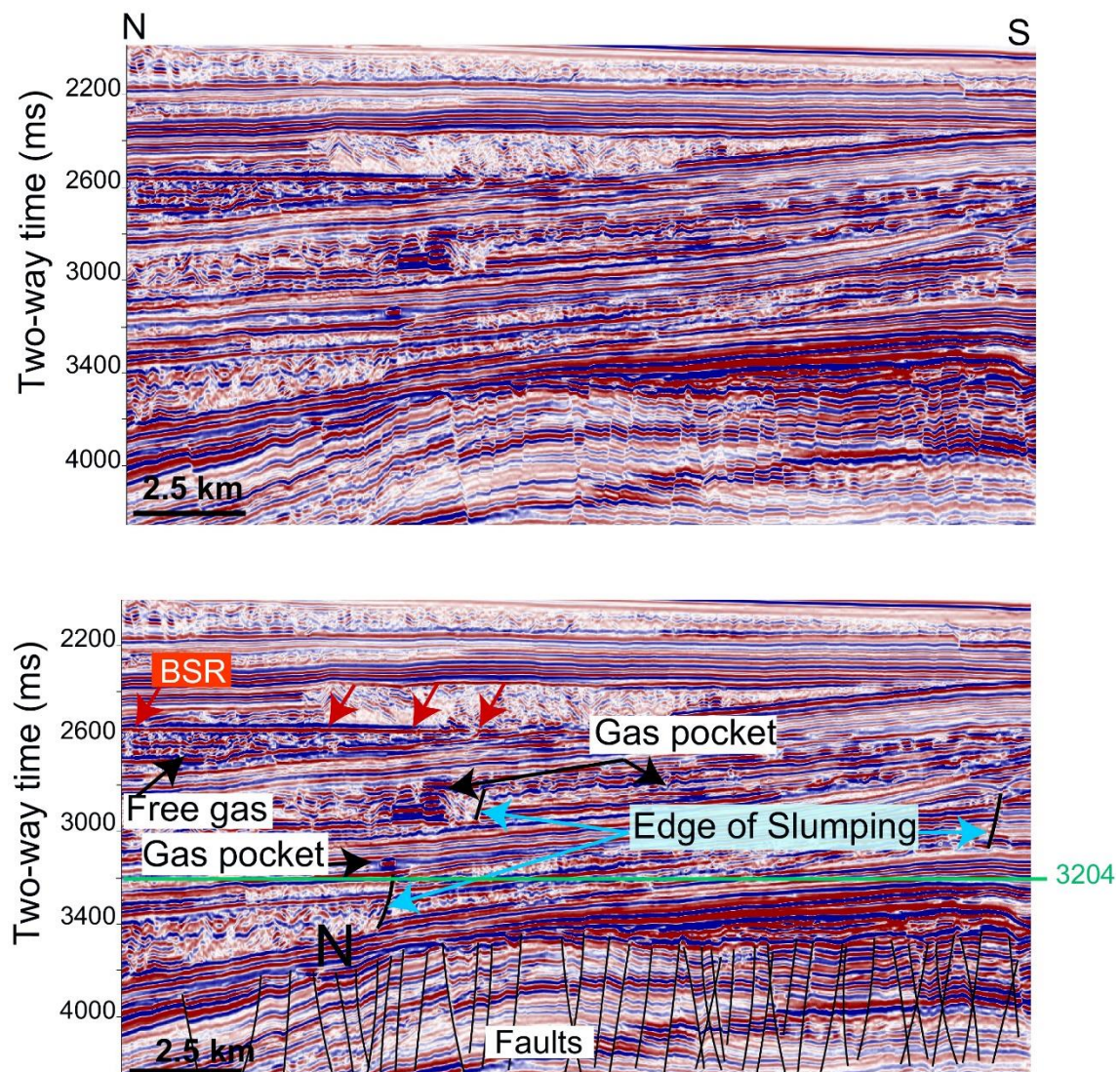


Figure 2.27 Seismic reflection profiles across Sanriku-Oki forearc basin with and without geological interpretation. Seismic profile showing the relationship between gas pockets, slumping boundaries (blue arrows), and fault block (black lines). Green line indicates the time slice beneath gas pocket at 3204 ms TWT, which shows in panel (2.28).

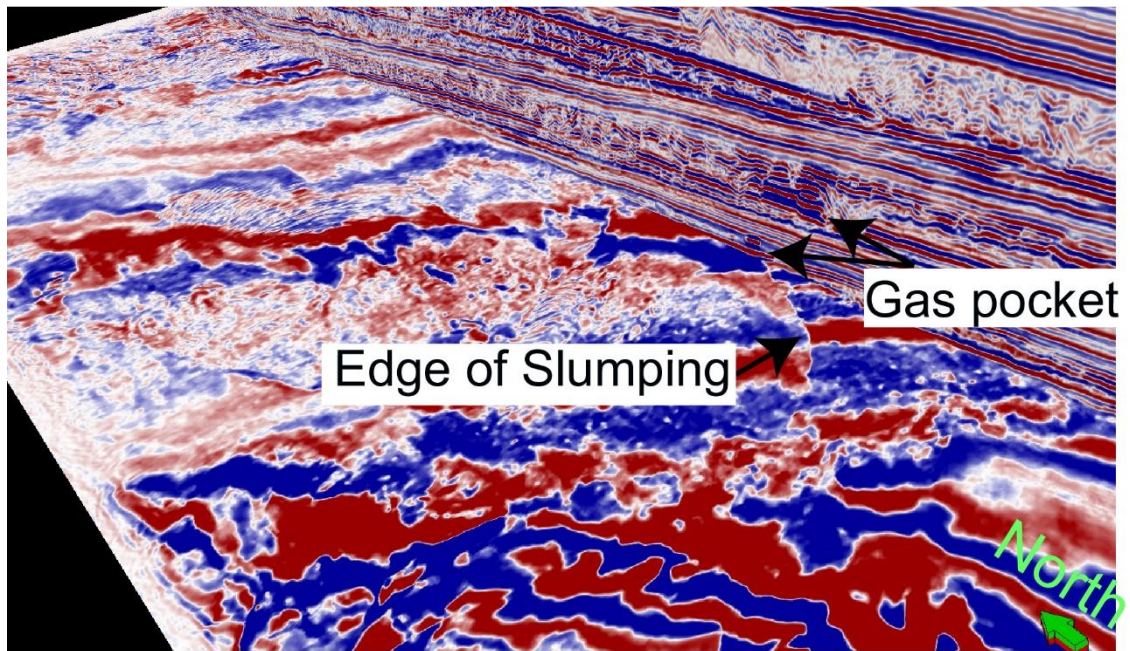


Figure 2.28 Time-slice images of gas pockets and slumping boundary were extracted from the green lines in panel (2.27)

2.7 Conclusions

Seismic attributes analysis were used to identify potential source rocks, gas-bearing sediments, and hydrocarbon migration pathways in the Sanriku-Oki forearc basin. Our main findings are summarized below.

- Acoustic impedance inversion of 3D seismic data showed that coal-bearing formations are widely distributed in Late Oligocene to Early Miocene sedimentary rocks; the coal-bearing formation were interpreted to be one of potential source formations for hydrocarbon gases.
- A widespread free gas zone was identified in Quaternary porous slump units below the BSR that has a similar horizontal distribution to the BSR. Several gas pockets were identified in the south-eastern part of study area that were spatially associated with the margins of Quaternary slump sequences. The largest potential gas accumulations were in the north-east of study area where the most intense slumping and faulting was evident and gas chimneys were developed.
- Major NW-striking faults that cut Cretaceous to Miocene strata provided migration pathways for hydrocarbon gases from deep Cretaceous–Palaeogene source rocks to Miocene formation.
- Gas chimneys that extend from just above potential source rocks to the Quaternary sequences were identified in the north-east of the study area. The base of the gas chimney was at the edge of a slump sequence (a local extension area). Gas chimneys and slump thrusting were the main controls for vertical migration of fluids from Miocene formation to Quaternary reservoir rocks.

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Chapter 3

Rock Evolution Process Using Digital Rock Physics

3.1 Introduction

Digital rock physics approach is used to further quantify the physical and fluid flow properties and heterogeneity of reservoir rocks. In this approach, high-resolution images of the pore or fracture and mineral grains (e.g., mineral precipitation) are obtained and processed, and reservoir properties are evaluated by numerical simulation of the physical processes of interest at the pore scale. Because intensive geophysical surveys are conducted in Nankai Trough (Figure. 3.1a) and the consolidated rocks there are suitable for characterizing rock evolution process. Therefore, the seismic velocity (V_P and V_S), elastic moduli and digital rock in this area can be used to evaluate rock evolution process in the plate subduction zone. In this study, I apply digital rock physics to the Nankai Trough area.

The active seismogenic fault in the Nankai Trough is caused by the subduction of the Philippine Sea Plate beneath south-western Japan at a rate of $\sim 4.1\text{--}6.5$ cm/y at an azimuth of 300 to 315 (e.g. Seno et al., 1993; Miyazaki and Heki, 2001) (Figure 3.1a). The plate boundary fault poses a constant threat to the densely populated coastal cities of south-west Japan in the form of potential massive earthquakes and tsunamis. Ando (1975) and Kumagai (1996) reported that the plate interface was the origin of great interplate earthquakes recurring in the region over the last 1000 years. The 1944 Tonankai and the

1946 Nankai earthquakes were the latest of these events. Many previous studies described the seismogenic fault in order to reveal the earthquake generation mechanisms in this plate interface. In particular, characterization of the pore pressure could help to understand the coseismic rupture propagation (e.g. Park et al., 2014; Kamei et al., 2012; Tsuji et al., 2014a; Kimura et al., 2012; Kodaira et al., 2004; Moore and Saffer, 2001; Scholz, 1998; Tobin and Saffer, 2009). Previous studies also investigated the effect of crack-filling minerals that control earthquake generation in subduction zones worldwide (e.g. Audet and Burgmann, 2014).

Because of recent developments in imaging rock internal structures, high-resolution 3D digital rock models of fault rocks with crack-filling minerals can be constructed. By applying numerical simulations to these rock models, we can obtain the elastic and hydrologic properties of the rock (e.g. Jiang and Tsuji, 2016; Yamabe et al., 2016; Andra et al., 2013; Saenger et al., 2011; Saenger, 2008; Saenger et al., 2004; Tsuji et al., 2016). Using the digital rock approach, the crack-filling materials can be changed to analyse their influence on rock seismic velocities.

The coseismic fault in the Nankai subduction zone is too deep to obtain core samples via drilling; hence, a numerical rock model based on microcomputed tomography (micro-CT) images of core samples cannot be obtained. Therefore, core samples from the Nobeoka Thrust were used to simulate the characteristics of the Nankai seismogenic fault. The Nobeoka Thrust is an ancient plate boundary fault that outcrops on Kyushu Island, south west Japan (Figure 3.1a). This thrust has been inactive in the recent geological past and has maintained a deep setting in the seismogenic zone (e.g. Kondo et al., 2005; Research Group for Active Faults of Japan, 1991). The Nobeoka Thrust and the coseismic plate boundary fault have similar lithologies and elastic properties (Tsuji et al., 2006). Several previous studies have described and compared the characteristics of the ancient and modern seismogenic faults (e.g. Hamahashi et al., 2013). For example, the Nobeoka Thrust formed at depths of 11 km beneath the sea floor (e.g. Kondo et al., 2005), which is similar to the depth of the modern Nankai seismogenic fault (e.g. Park et al., 2002; Kamei et al., 2012, 2013).

In this study, digital rock models of the Nobeoka core samples were constructed based on micro-CT images in order to estimate the effective P- and S-wave velocities (V_P and V_S) and their ratio (V_P/V_S). V_P and V_S were estimated from numerical simulations of seismic wave propagation through the digital rock models. In the numerical simulation, the effects of the crack-filling materials on the effective velocities were investigated by replacing cracks and veins with various elastic materials such as air, water, calcite and quartz. The resulting velocities were then compared with those from field seismic data in the Nankai Trough (i.e. V_P and V_S of the seismogenic fault).

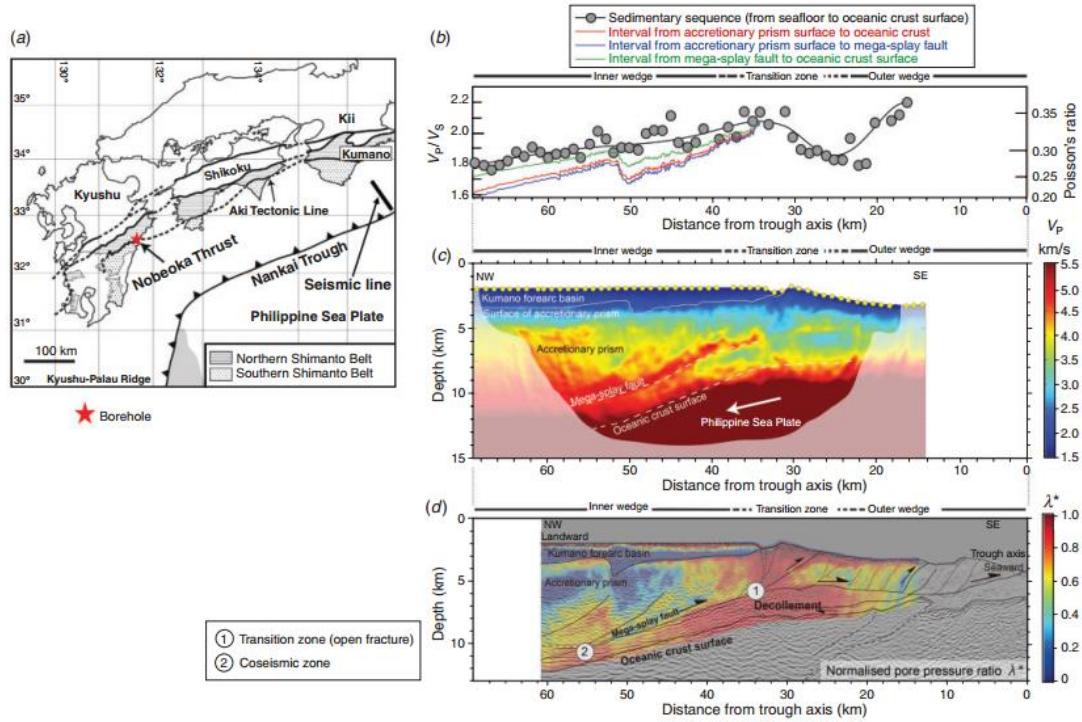


Figure 3.1 (a) Location of the Nankai Trough, Nobeoka Thrust and a seismic line off Kumano (modified from Kondo et al., 2005). (b) V_p/V_s above the subducting oceanic crust surface (within the sedimentary sequence) estimated from P-to-SV converted waves (grey circles; Tsuji et al., 2011). The green line indicates V_p/V_s of the underthrust sequence (from the mega-splay fault to the crust surface). The red line indicates V_p/V_s within the accretionary prism (from the accretionary prism surface to the oceanic crust). The blue line indicates V_p/V_s within the accretionary prism (from the accretionary prism surface to the mega-splay fault) (Tsuji et al., 2014a). (c) V_p obtained by waveform tomography analysis (Kamei et al., 2012, 2013). (d) Normalized pore pressure ratio overlaid on the seismic reflection profile of Nankai Trough (Tsuji et al., 2014a). Colour scale indicates the normalized pore pressure ratio λ^* . $\lambda^* = 1$ indicates lithostatic pressure and $\lambda^* = 0$ indicates hydrostatic pore pressure.

3.2 Geological setting

The Nobeoka Thrust is a major fault that separates the northern and southern Shimanto Belts of a Cretaceous–Tertiary accretionary complex in Kyushu, south-west Japan (Figure 3.1a). It extends for more than 800 km in the Shimanto Belt and is parallel to the modern Nankai Trough. Vitrinite reflectance data indicates that both the hanging wall and footwall of the Nobeoka Thrust experienced heating to maximum temperatures of $\sim 320^{\circ}\text{C}$ and $\sim 250^{\circ}\text{C}$, respectively (Kondo et al., 2005). The thrust was drilled by the Nobeoka Drilling Project 2011, and the drill hole was located ~ 200 m north of an outcrop where intensive field surveys such as physical property measurements had been previously conducted (Kondo et al., 2005; Tsuji et al., 2006). The length of the drilled core sample is ~ 250 m, consisting of ~ 40 m of hanging wall and ~ 210 m of footwall (Hamahashi et al., 2013). Both the hanging wall and footwall rock have the same shale and sandstone-dominant protolith; however, the hanging wall exhibits a penetrative plastic deformation, while the footwall exhibits a brittle, cataclastic melange-like deformation. Three types of mineral veins are well developed, especially in the damaged footwall: tension crack-filling veins, fault-filling veins and post-melange veins (Kondo et al., 2005). The matrix minerals are mostly calcite, plagioclase, illite, chlorite and quartz (Fukuchi et al., 2014), while the veins are rich in calcite, ankerite and minor quartz (Yamaguchi et al., 2011). While the foliation is well developed in the hanging wall side, the foliation in the footwall is unclear (Tsuji et al., 2006).

3.3 Data and methods

The sequence of processes from rock digitization to seismic velocity calculation is illustrated in Figure 3.2. In this study, I have used three core samples obtained from the footwall of the Nobeoka Thrust at distances of 44.25, 36.4 and 3.4 m from the fault core. To obtain the digital images, the samples were scanned by X-ray micro-CT with a resolution (pixel size) of 10 mm (Figure 3.3). Although the original size (grid number) of the scanned images was 1024 x 1024 x 1024 pixels, 500 x 500 x 500 pixels (white square in Figure 3.3) were extracted from the undisturbed central part of the original 3D pixel images for our analysis (Figure 3.4).

3.3.1 Phase classification

Because the CT values are proportional to the density of the material, the measured CT values were converted into density values as follows:

$$\rho(x, y, z) = \alpha CT(x, y, z), \quad (1)$$

where $\rho(x, y, z)$ and $CT(x, y, z)$ represent the density and the CT values at the grid point (x, y, z) , respectively. The proportionality constant α was determined using the following equation:

$$\alpha = \frac{CT_{ave}}{\rho_{ave}} \quad (2)$$

where CT_{ave} is the CT value averaged over $500 \times 500 \times 500$ pixels and ρ_{ave} is the averaged density ($\rho_{ave} = 2.6 \text{ g/cm}^3$) of the core samples from the Nobeoka thrust measured in the laboratory by Tsuji et al. (2006).

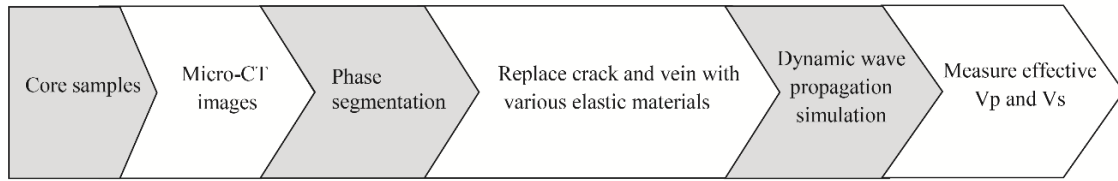


Figure 3.2 Procedure for estimating the effective velocity from core samples using the digital rock approach.

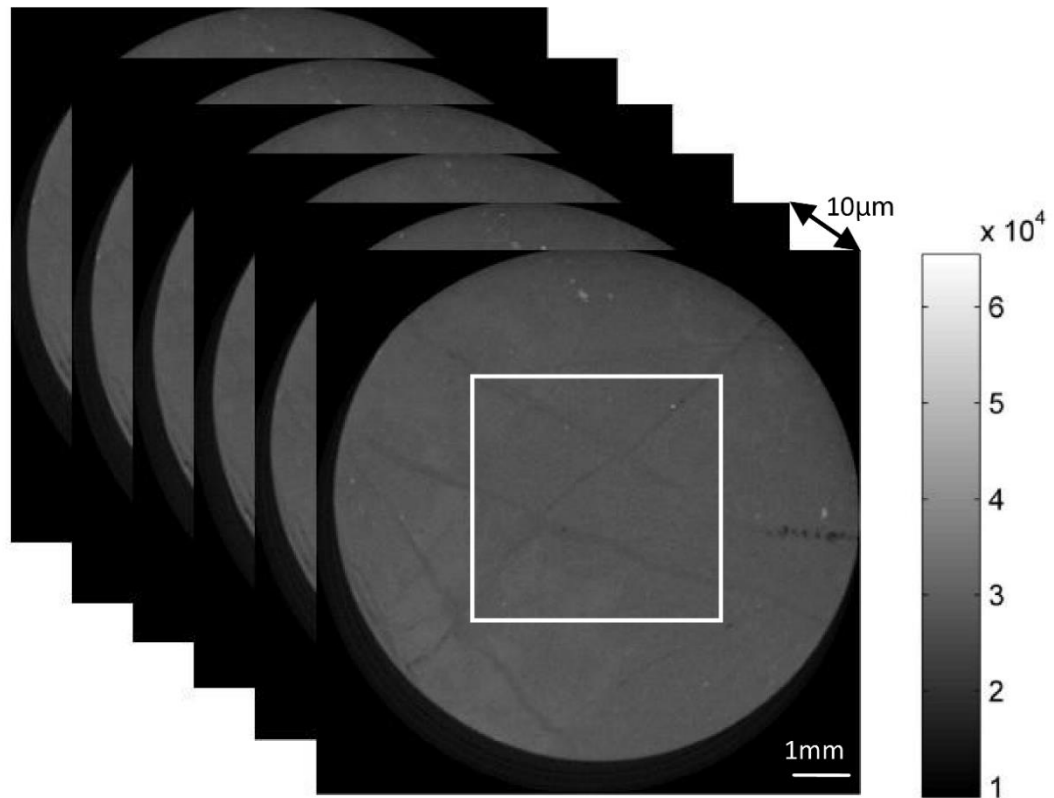


Figure 3.3 Example of micro-CT scanned images. The white square outlines the area (500 x 500 grid points) extracted for the digital rock model construction. The grey scale represents the CT values.

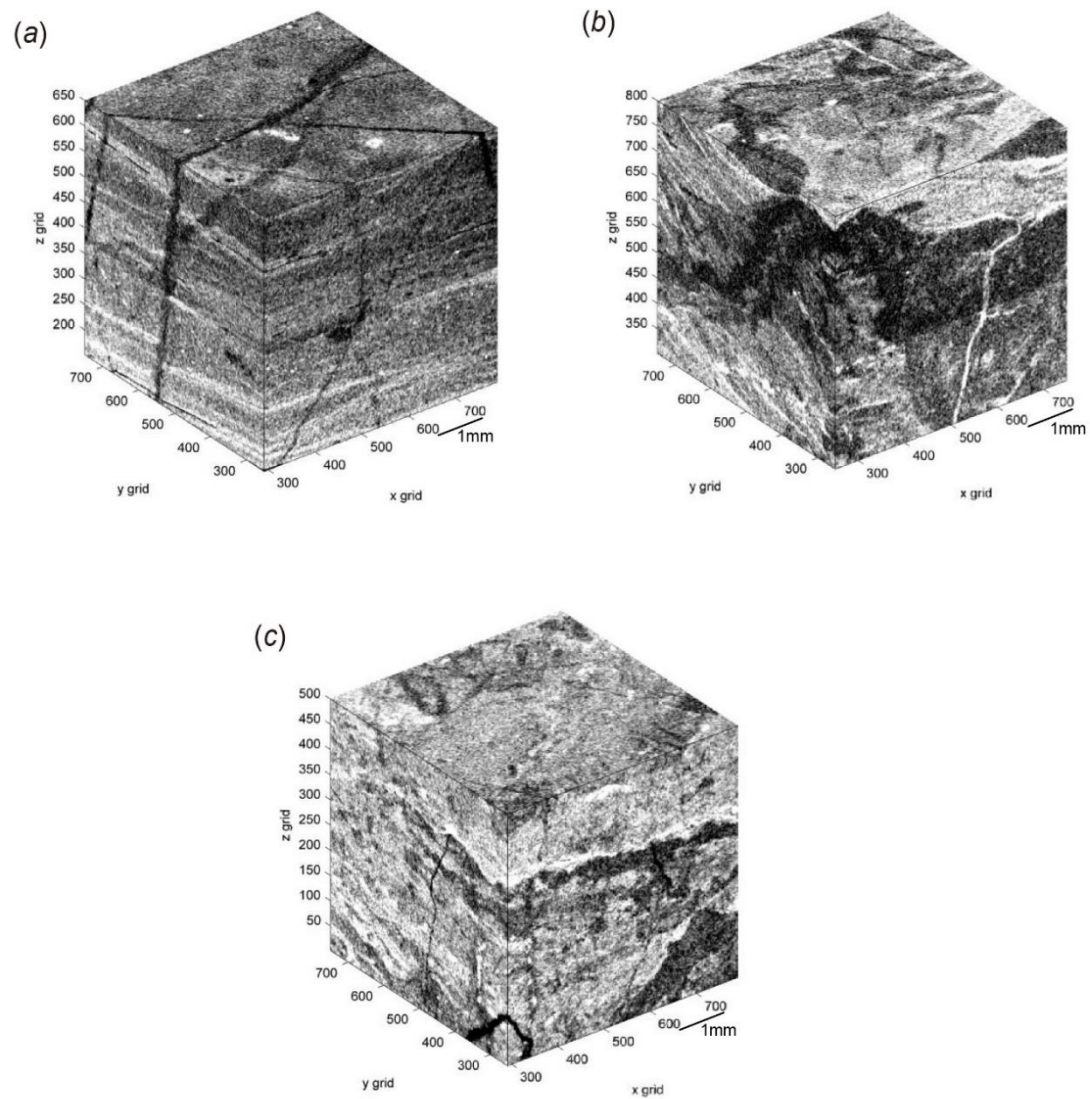


Figure 3.4 3D digital rock models of three rocks: (a) Model 1, (b) Model 2 and (c) Model 3. The white tone represents the higher CT values.

The material at each grid point was then classified as grain, crack or vein based on porosity value and visual inspection (Figure 3.5a, c, e). Following Jiang and Tsuji (2015), the author sets the threshold density between the cracks (pores) and the grains as 2.35 g/cm^3 based on porosity from logging data (Hamahashi et al., 2015) and core samples (Tsuji et al., 2006) (Figure 3.5b, d, f). Veins (crack minerals such as calcite, ankerite and quartz; Yamaguchi et al., 2011) were identified by using the density of 2.85 g/cm^3 as the threshold between veins and grains based on visual inspection (white in Figure 3.5b, d, f). The volumes of cracks and veins are shown in Table 3.1. These veins were open cracks prior to mineral infilling. The seismic velocities in the three models were calculated using dynamic wave propagation simulations with the cracks and veins replaced by various elastic materials (Figures 3.6 -3.11).

3.3.2 Elastic parameters for each phase

To perform wave propagation simulations, the elastic parameters need to be assigned for each grid cell. Assigning an exact value for the elastic parameters for grains is one of the challenging issues in digital rock physics (Madonna et al., 2012). A homogeneous grain needs to be assumed at each grid point, although it may contain unresolved micro-cracks. As a result, if the elastic parameters of the major mineral are used for each grain, effective velocities calculated from digital rock models are higher than the laboratory measurements (e.g. Madonna et al., 2012).

Table 3.1 The volume percentages of cracks and veins for Models 1, 2, and 3.

Models	Crack (%)	Vein (%)
Model 1	15.97	1.43
Model 2	13.33	4.95
Model 3	8.68	4.91

Here, the results of laboratory measurements of Nobeoka footwall samples under a confining pressure of 55 MPa in dry conditions (Tsuji et al., 2006) are used to define V_P and V_S for grains and to consider the effect of velocity reduction due to unresolved micro-cracks. Since the laboratory experiment used highly consolidated outcrop samples containing a lot of veins, the grain density was assumed to be 2.64 g/cm³, which is smaller than the laboratory value. While varying the V_P and V_S values assigned to the grains, the effective velocities calculated by seismic wave propagation simulation (details are shown in the next section) were compared with the results of the laboratory measurement ($V_P = 4180$ m/s, $V_S = 2750$ m/s). Model 3 was used as the 3D digital rock model because its porosity is close to that of the laboratory data (Tsuji et al., 2006). The author varied V_P and V_S for the grain material in the range of 3750–4500 m/s and 2500–3000 m/s (step size 250 m/s), respectively. The elastic parameters of air was assigned for cracks (i.e. simulating a dry condition) and those of calcite for veins. As a result, the grain velocities were determined to be $V_P = 4250$ m/s and $V_S = 2750$ m/s because the corresponding effective velocities are most consistent with the laboratory results.

To investigate the influence of crack-filling materials on effective velocities, the identified cracks and veins were replaced, shown as dots in Figure 3.18, with the commonly accepted elastic parameters for air, water, calcite and quartz (Mavko et al., 1998). The cracks and veins were also replaced with 11 cases of elastic materials with different values of elastic moduli and densities (k , m and ρ) (Table 3.2 and Figure 3.18). The density values for these cases satisfy the Gardner relation (e.g. Gardner et al., 1974). For reference (i.e. non-crack models), the effective velocities for homogeneous models were computed by using the elastic parameters of grains defined above.

Table 3.2 Elastic moduli for filling the crack and pore space

Conditions	Bulk modulus (k) GPa	Shear modulus (μ) GPa	Density (ρ) g/cm ³
Dry	0.00131	0	0.00119
Water	2.2	0	1
Quartz	37	44	2.65
Calcite	74.8	30.6	2.76
Case 1	30	30	2.62
Case 2	40	35	2.69
Case 3	50	30	2.7
Case 4	45	25	2.66
Case 5	30	20	2.56
Case 6	10	15	2.39
Case 7	40	10	2.54
Case 8	60	37	2.76
Case 9	35	5	2.48
Case 10	10	45	2.62
Case 11	45	70	2.67

3.3.3 Effective velocity measurements by seismic wave simulation

Once the elastic parameters for the 3D digital rock models are given, the effective seismic velocities can be estimated by seismic wave propagation simulation. To perform the simulation, the author employed the finite-difference method using a rotated staggered grid (Saenger et al., 2000), which is effective for 3D digital rock models (e.g. Yamabe et al., 2016; Andra et al., 2013; Saenger et al., 2011; Saenger, 2008; Saenger et al., 2004; Madonna et al., 2012). The rotated staggered grid approach is stable for seismic wave propagation modelling in a medium containing sharp interfaces such as the solid-void interface in this study. The top and bottom layers of the digital rock models were set as homogeneous layers (Yamabe et al., 2016) with constant elastic properties ($V_P = 4250$ m/s, $V_S = 2750$ m/s and density = 2.64 g/cm³). To avoid artificial reflection from the boundaries, the absorbing boundary condition of Cerjan et al. (1985) was applied. A plane P- or S-wave was generated by applying a plane source at the lower part of each model

(Figures 3.6 -3.11). A Ricker wavelet was used as the source function with a central frequency of 3 MHz. The seismic waveforms were received at two horizontal planes (151×151 pixels) placed at the upper and lower parts of the digital rock models (Figures 3.12-3.17). The received signals were horizontally averaged. V_P and V_S of the digital rock models were calculated based on the time delay of the observed peak amplitude of the two averaged waveforms (Figures 3.12 -3.17).

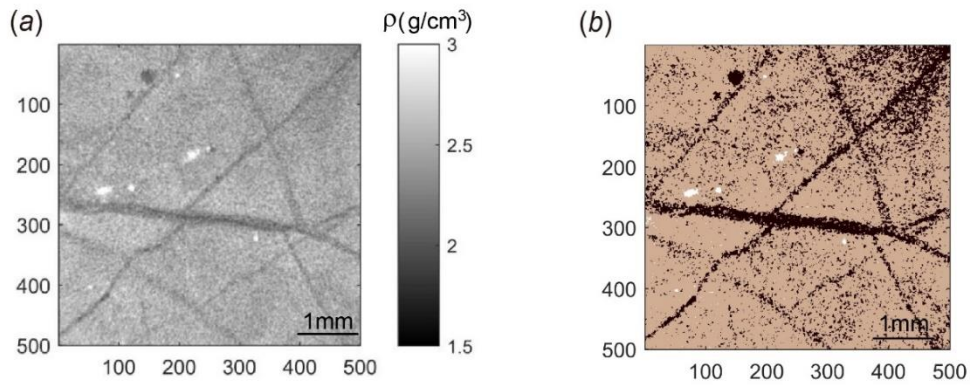
3.4 Results and interpretation

The effective velocities in the three rock models were calculated for the various crack-filling materials, including the non-crack case. From these results, the diagram of estimated velocities (i.e. V_P , V_S and V_P/V_S) was constructed for different elastic moduli (k and m) (Figure 3.18).

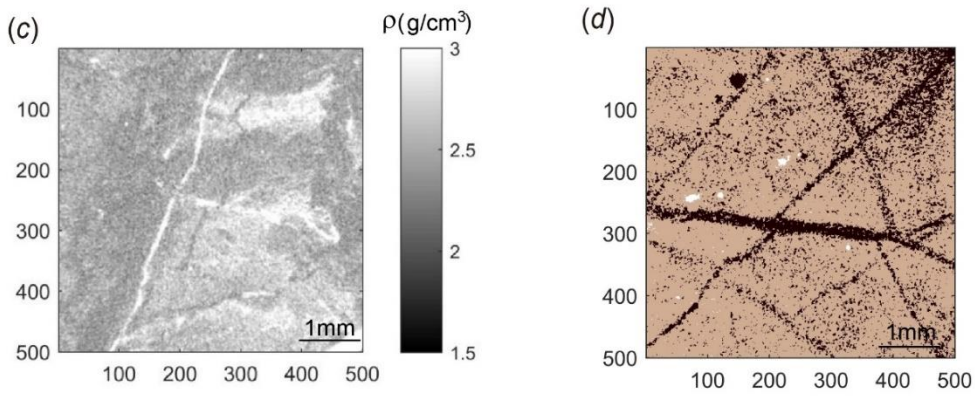
3.4.1 *Effect of crack-filling materials on seismic velocities*

For the water-saturated case in Model 1, V_P and V_S decreased significantly by $\sim 9\%$ and $\sim 12\%$, respectively, compared to the non-crack case (Figure 3.18a, b). The V_P/V_S value in the water-saturated case (~ 1.60) is higher than in the non-crack case (~ 1.56). In contrast, velocities for the crack-filling minerals increased $\sim 4\%$ (V_P) and $\sim 5\%$ (V_S) for quartz, and $\sim 5\%$ (V_P) and $\sim 3\%$ (V_S) for calcite, compared to the non-crack case. The V_P/V_S value for the quartz-filled case decreased $\sim 0.21\%$ compared with the non-crack case and increased $\sim 2\%$ for the calcite-filled case (Figure 3.18c). The V_P/V_S value for the quartz-filled case (~ 1.55) was lower than that of the water-saturated case (~ 1.60), while the V_P/V_S value for the calcite-filled case (~ 1.59) was similar to the water-saturated case. The V_P and V_S for dry case (Figure 3.18) decreased $\sim 9\%$ and $\sim 11\%$, respectively, and its V_P/V_S increased $\sim 2\%$ compared with non-crack model.

Model 1



Model 2



Model 3

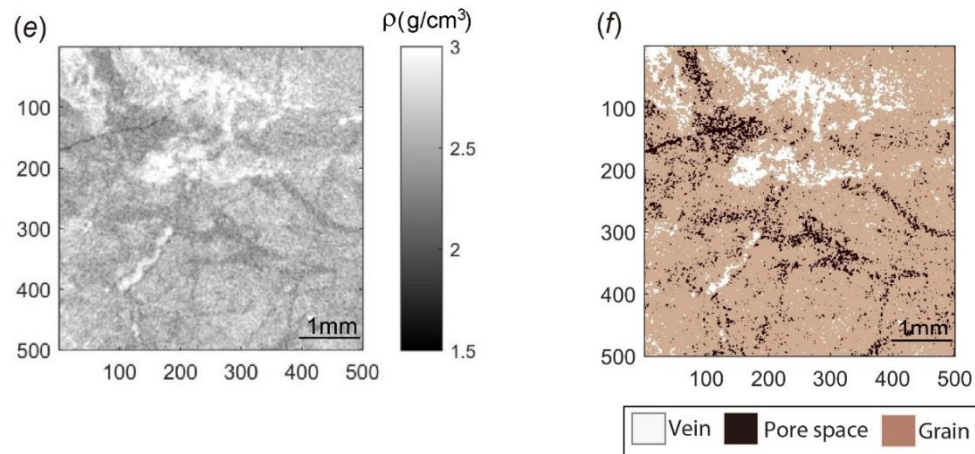


Figure 3.5 Numerical data showing grains, cracks and veins. (a) The density distribution of the original rock texture; the black and white tones represent the lower and higher density values, respectively. (b) Grains (brown), cracks (black) and veins (white) for Model 1. (c), (d) and (e), (f) are the same as (a), (b) but for Models 2 and 3, respectively. The numbers on the horizontal and vertical axes indicate pixel numbers of the 3D digital model.

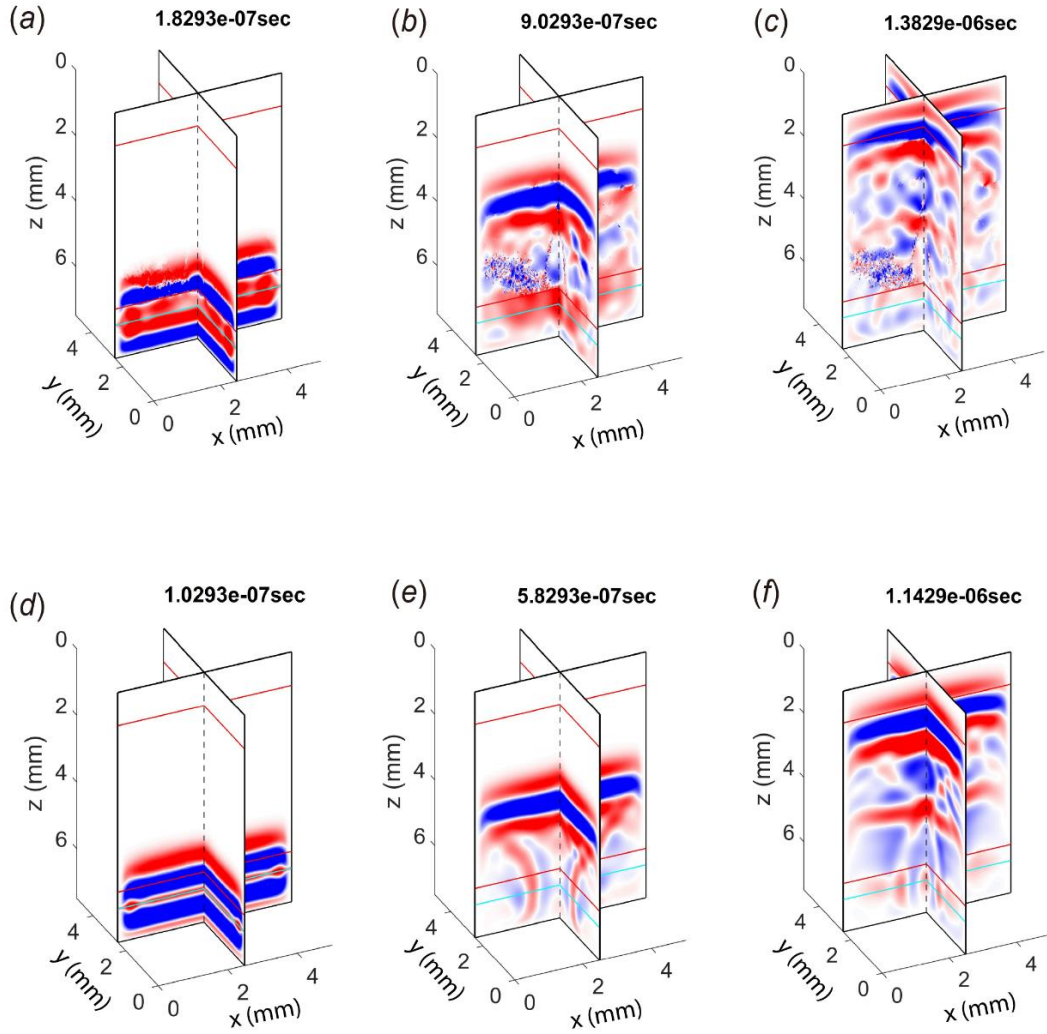


Figure 3.6 Example snapshots of dynamic wave propagation simulations for V_p estimation in digital rock (Model 1), with the cracks and veins replaced by (a)–(c) water and (d)–(f) quartz. The two magenta lines (top and bottom of model) represent the receiver arrays and the cyan line (bottom) indicates the location of the plane wave sources. Red and blue shading indicate the positive and negative amplitudes of the particle velocity field, respectively. A scattered wave field in (b) and (c) caused by water in the cracks and veins was observed. The origin of time was defined when the peak of the source wavelet passes the inlet side (cyan line) of the digital rock model.

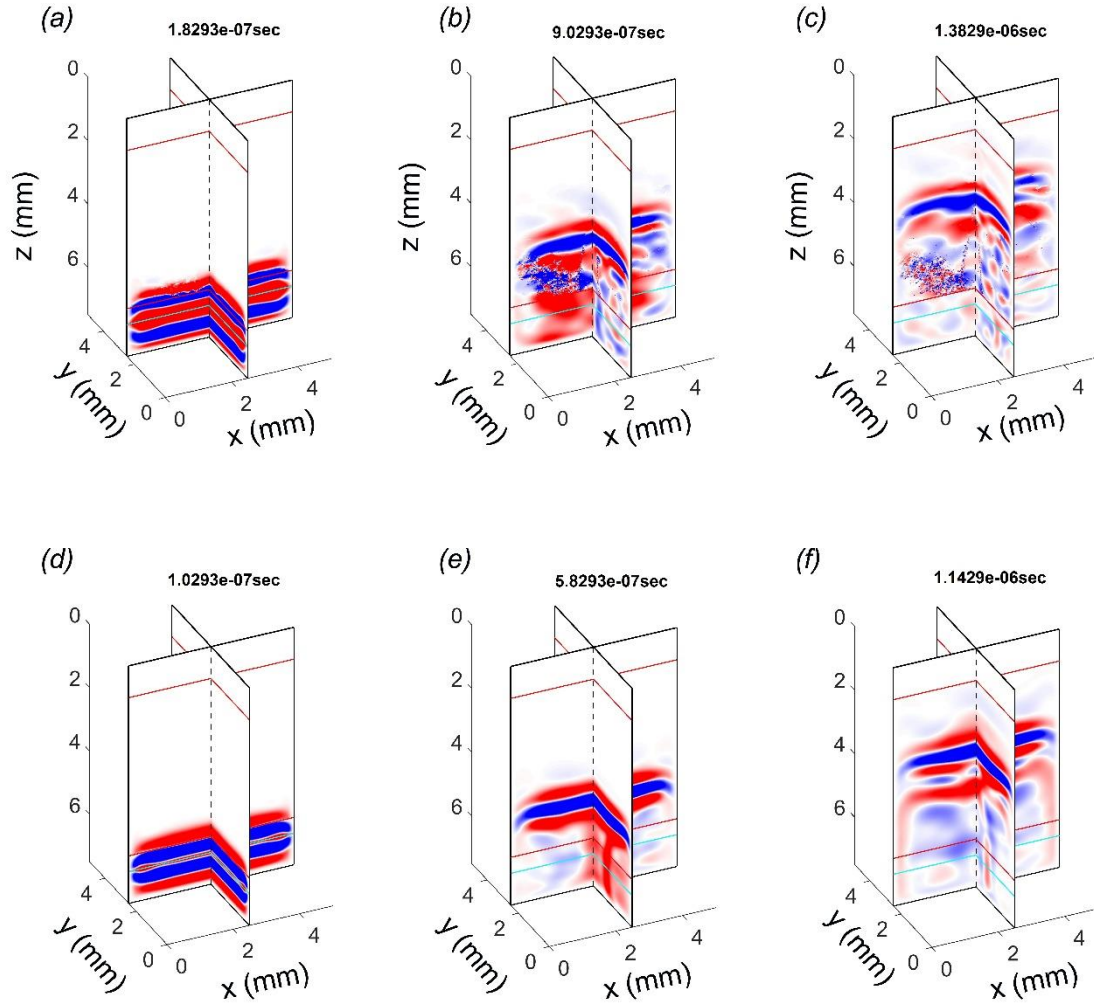


Figure 3.7 Example snapshots of dynamic wave propagation simulations for V_s estimation in digital rock (Model 1), with the cracks and veins replaced by (a)–(c) water and (d)–(f) quartz. The two magenta lines (top and bottom of model) represent the receiver arrays and the cyan line (bottom) indicates the location of the plane wave sources. Red and blue shading indicate the positive and negative amplitudes of the particle velocity field, respectively. A scattered wave field in (b) and (c) caused by water in the cracks and veins was observed. The origin of time was defined when the peak of the source wavelet passes the inlet side (cyan line) of the digital rock model.

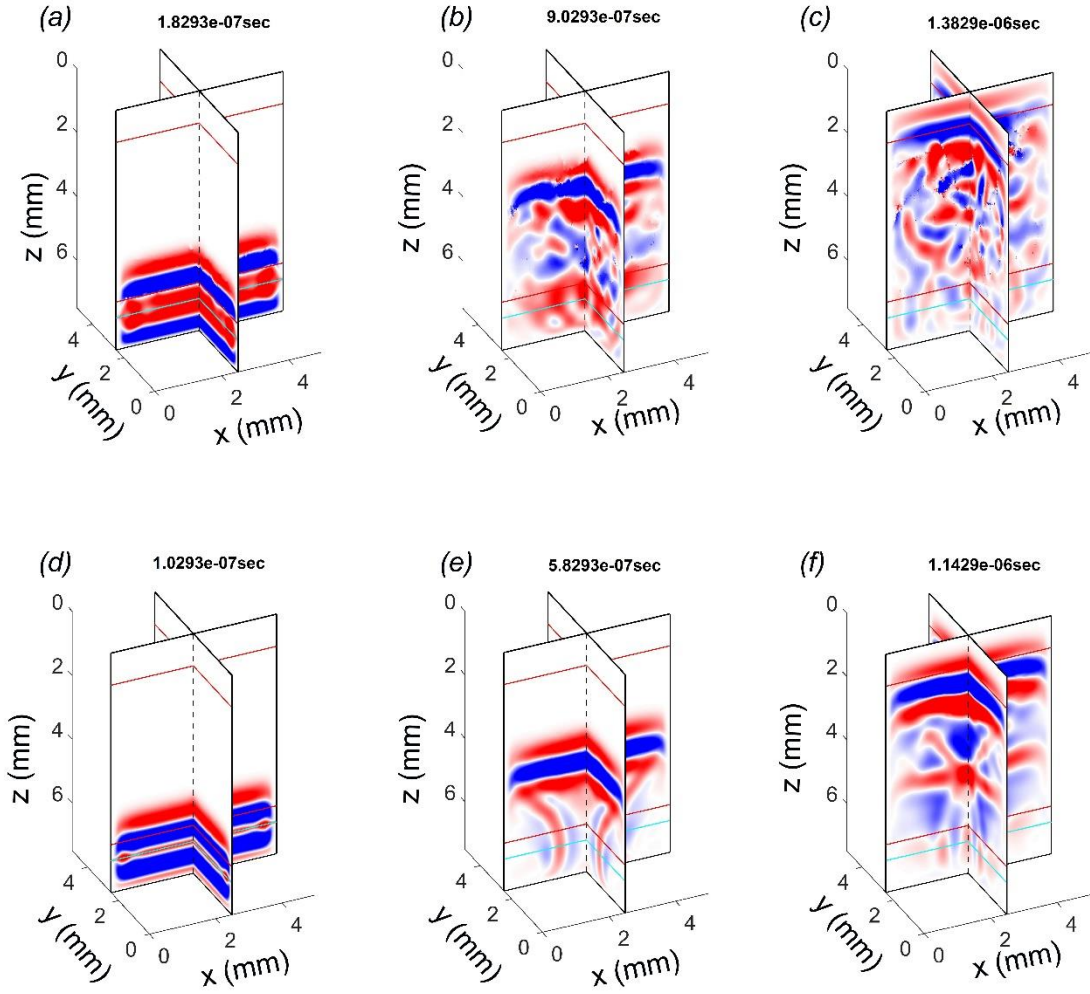


Figure 3.8 Example snapshots of dynamic wave propagation simulations for V_p estimation in digital rock (Model 2), with the cracks and veins replaced by (a)–(c) water and (d)–(f) quartz. The two magenta lines (top and bottom of model) represent the receiver arrays and the cyan line (bottom) indicates the location of the plane wave sources. Red and blue shading indicate the positive and negative amplitudes of the particle velocity field, respectively. A scattered wave field in (b) and (c) caused by water in the cracks and veins was observed. The origin of time was defined when the peak of the source wavelet passes the inlet side (cyan line) of the digital rock model.

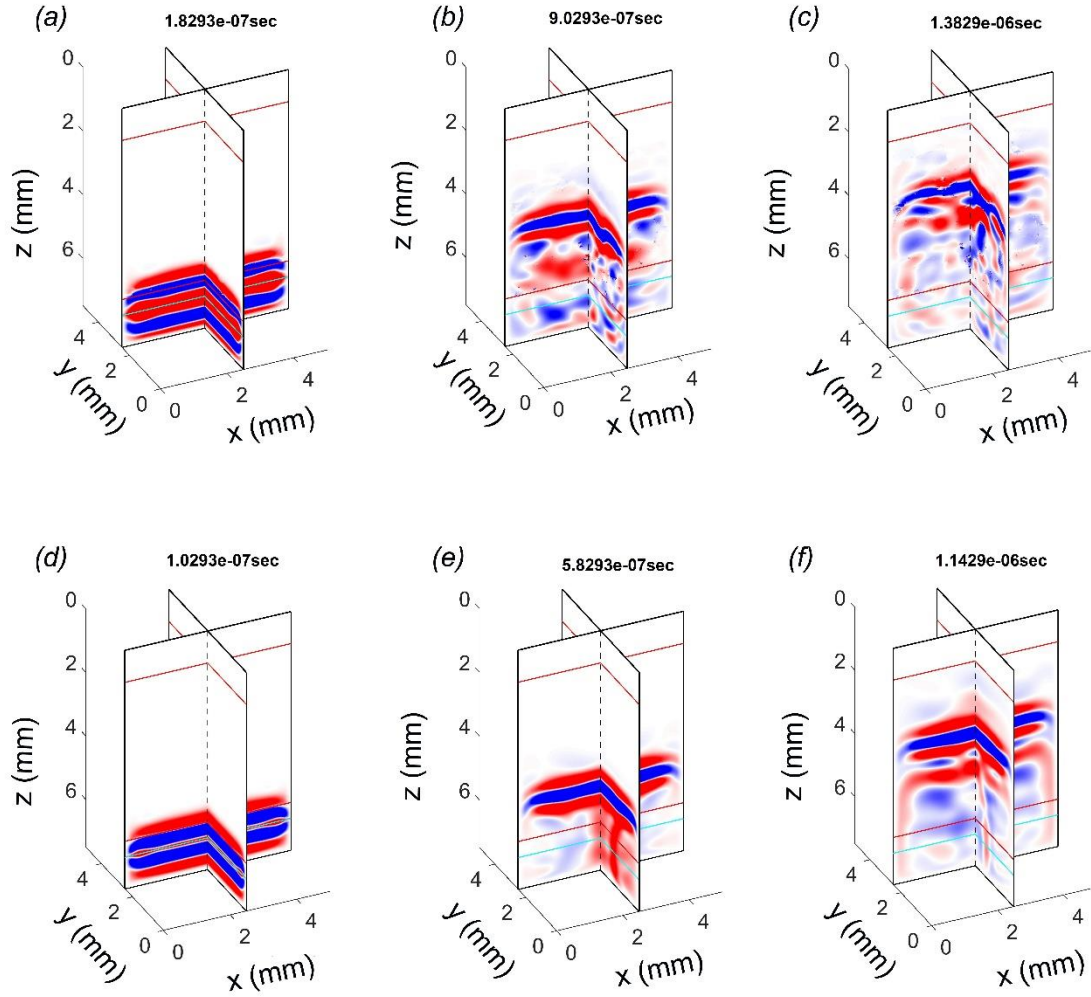


Figure 3.9 Example snapshots of dynamic wave propagation simulations for V_s estimation in digital rock (Model 2), with the cracks and veins replaced by (a)–(c) water and (d)–(f) quartz. The two magenta lines (top and bottom of model) represent the receiver arrays and the cyan line (bottom) indicates the location of the plane wave sources. Red and blue shading indicate the positive and negative amplitudes of the particle velocity field, respectively. A scattered wave field in (b) and (c) caused by water in the cracks and veins was observed. The origin of time was defined when the peak of the source wavelet passes the inlet side (cyan line) of the digital rock model.

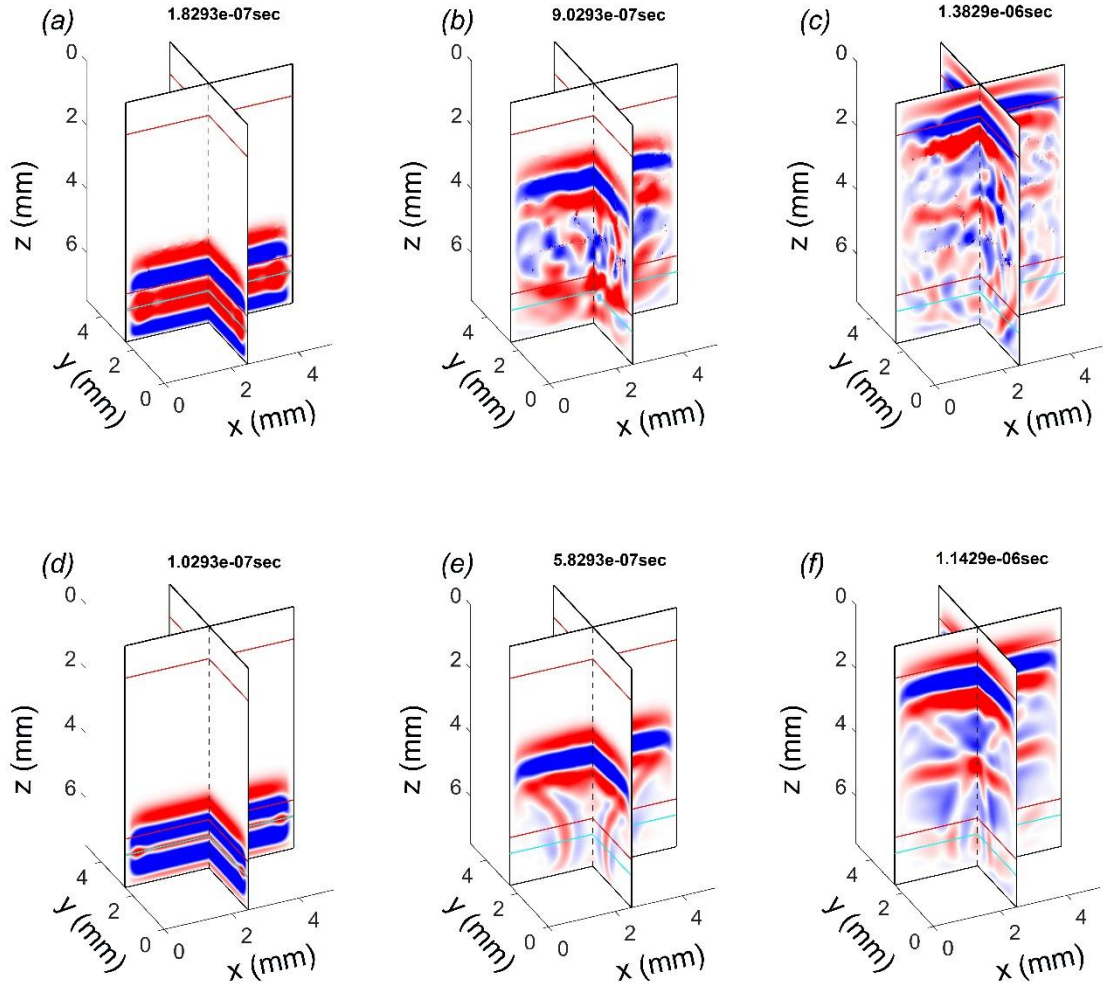


Figure 3.10 Example snapshots of dynamic wave propagation simulations for V_p estimation in digital rock (Model 3), with the cracks and veins replaced by (a)–(c) water and (d)–(f) quartz. The two magenta lines (top and bottom of model) represent the receiver arrays and the cyan line (bottom) indicates the location of the plane wave sources. Red and blue shading indicate the positive and negative amplitudes of the particle velocity field, respectively. A scattered wave field in (b) and (c) caused by water in the cracks and veins was observed. The origin of time was defined when the peak of the source wavelet passes the inlet side (cyan line) of the digital rock model.

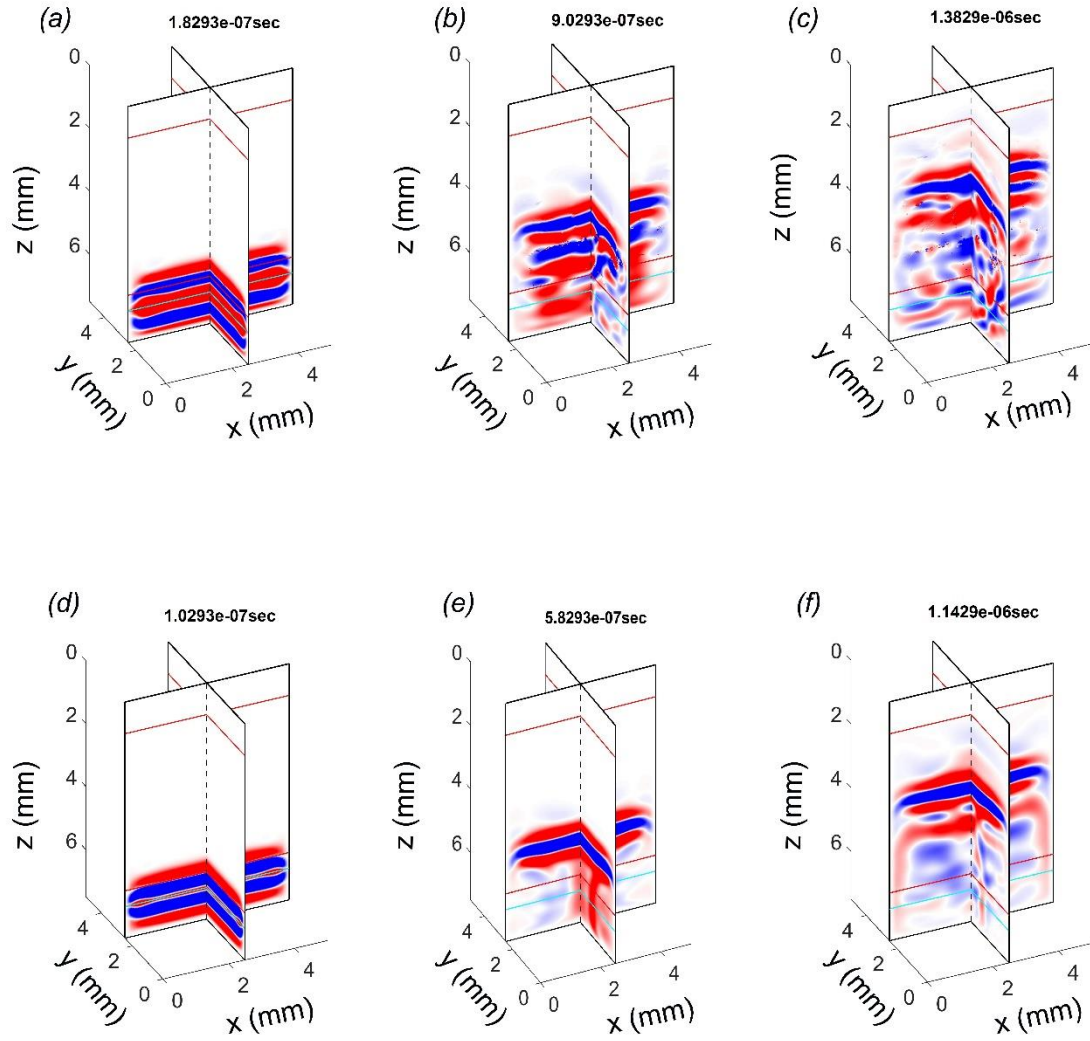


Figure 3.11 Example snapshots of dynamic wave propagation simulations for V_s estimation in digital rock (Model 3), with the cracks and veins replaced by (a)–(c) water and (d)–(f) quartz. The two magenta lines (top and bottom of model) represent the receiver arrays and the cyan line (bottom) indicates the location of the plane wave sources. Red and blue shading indicate the positive and negative amplitudes of the particle velocity field, respectively. A scattered wave field in (b) and (c) caused by water in the cracks and veins was observed. The origin of time was defined when the peak of the source wavelet passes the inlet side (cyan line) of the digital rock model.

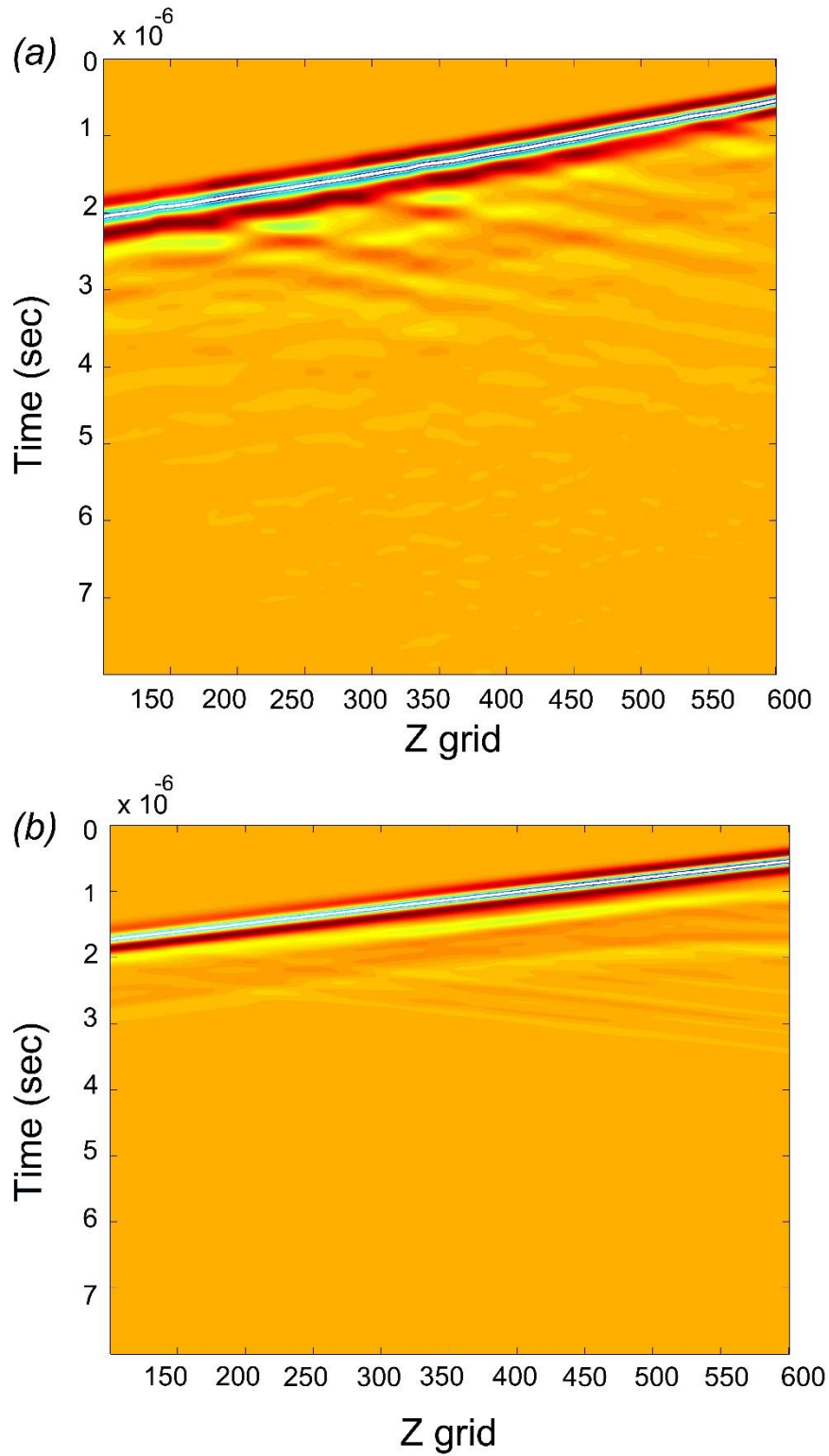


Figure 3.12 V_p waveforms for V_p estimation in digital rock Model 1, with the cracks and veins replaced by (a) water and (b) quartz.

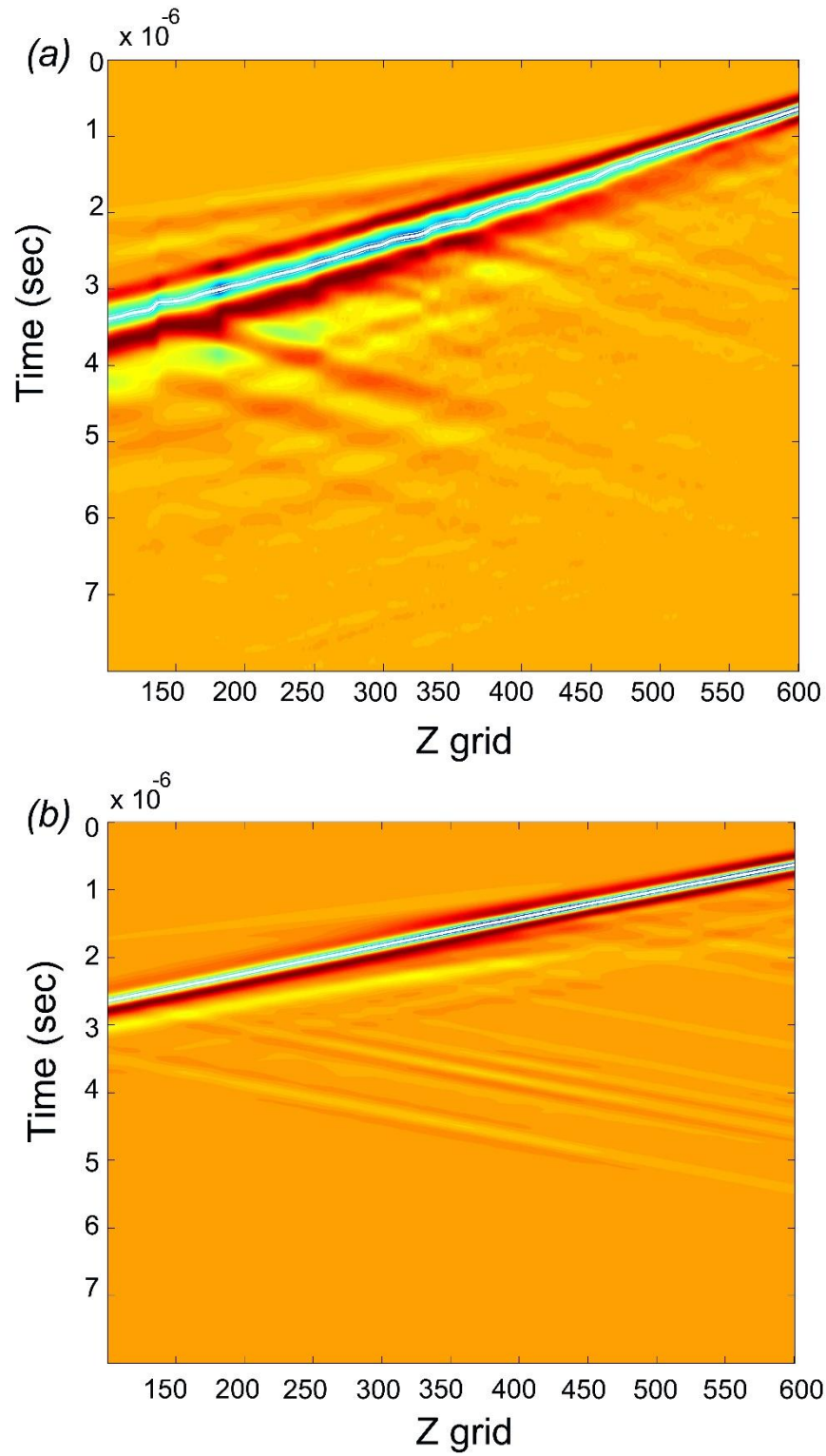


Figure 3.13 V_s waveforms for V_s estimation in digital rock Model 1, with the cracks and veins replaced by (a) water and (b) quartz.

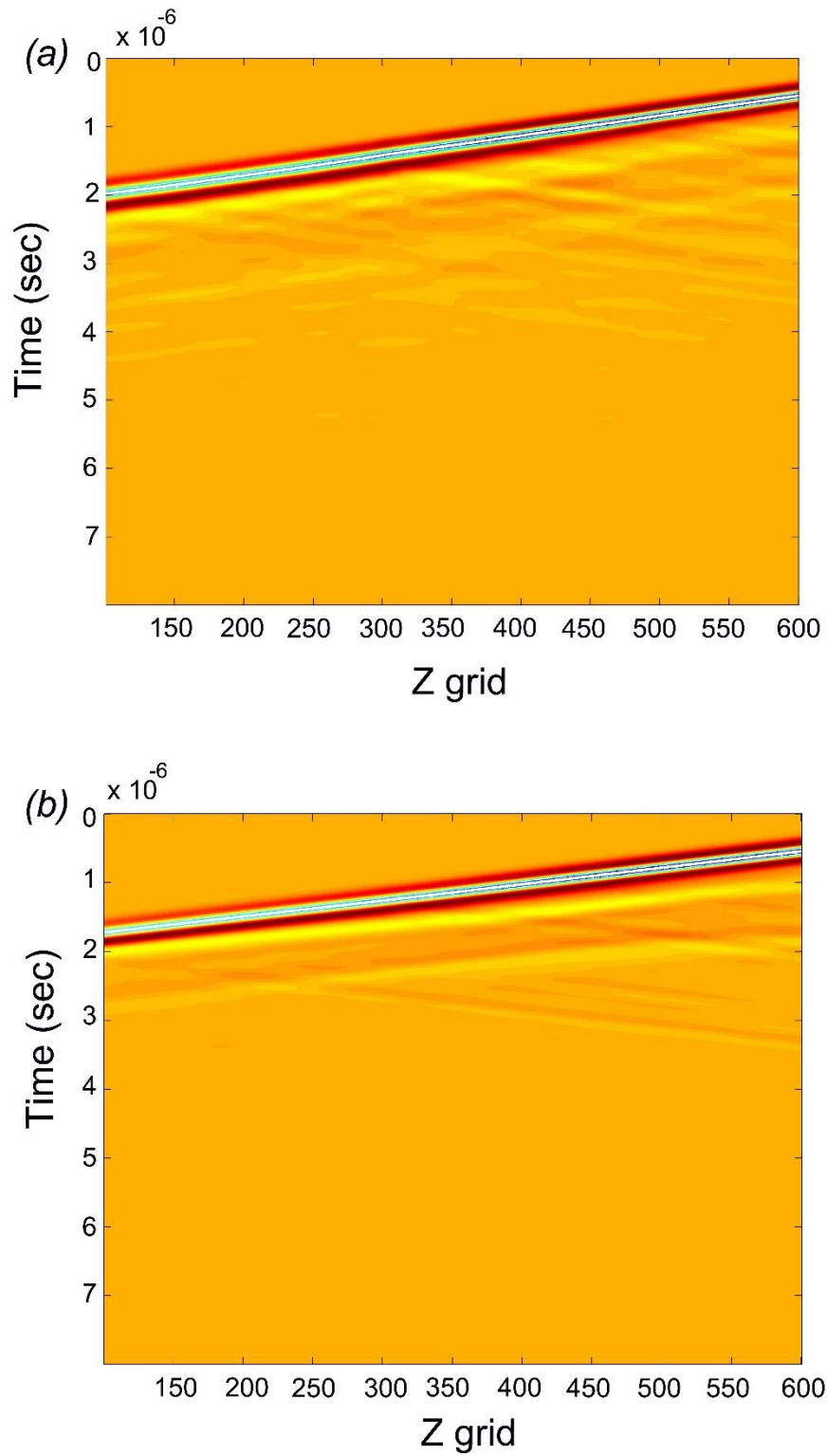


Figure 3.14 V_p waveforms for V_p estimation in digital rock Model 2, with the cracks and veins replaced by (a) water and (b) quartz.

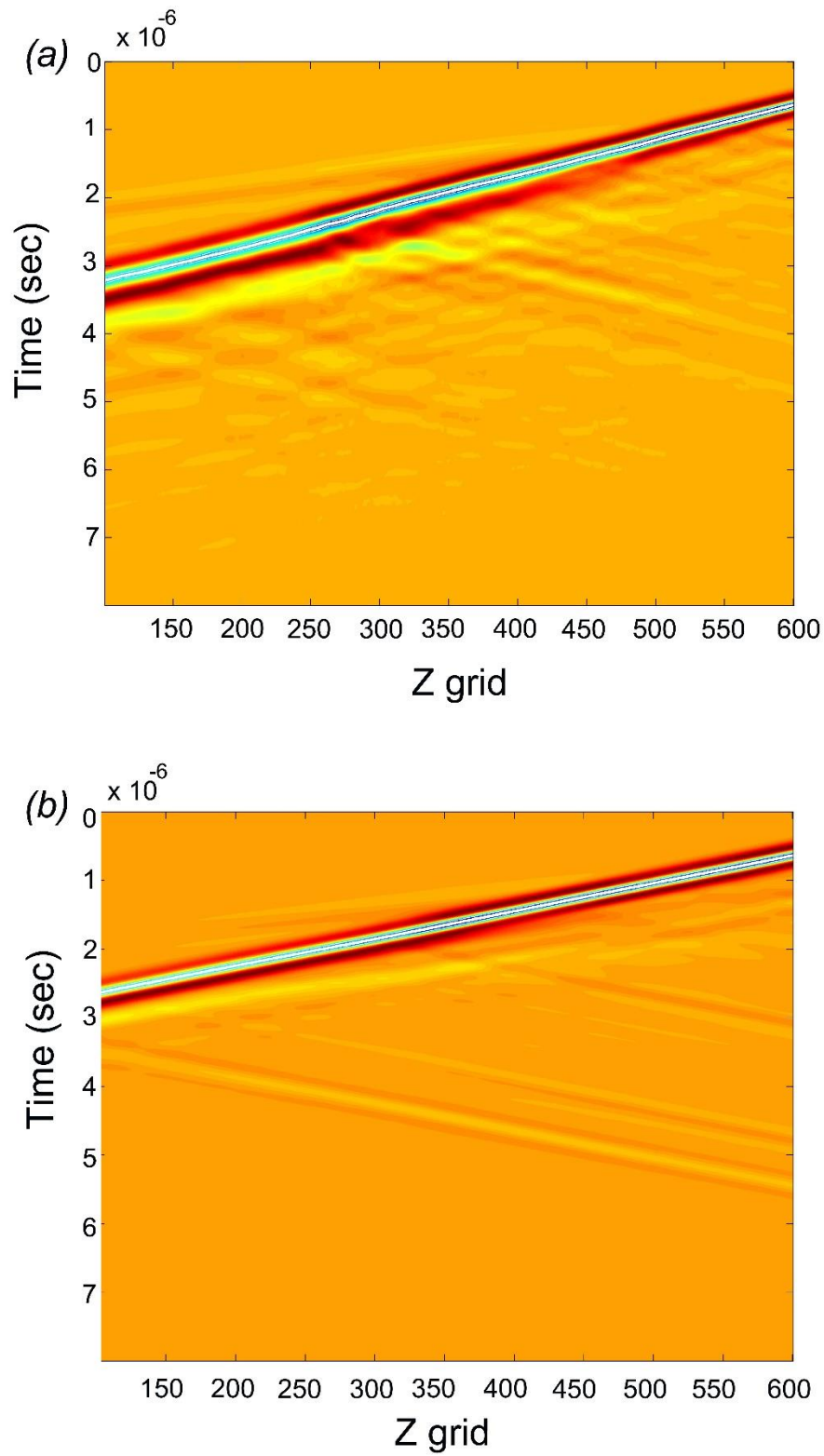


Figure 3.15 V_s waveforms for V_s estimation in digital rock Model 2, with the cracks and veins replaced by (a) water and (b) quartz.

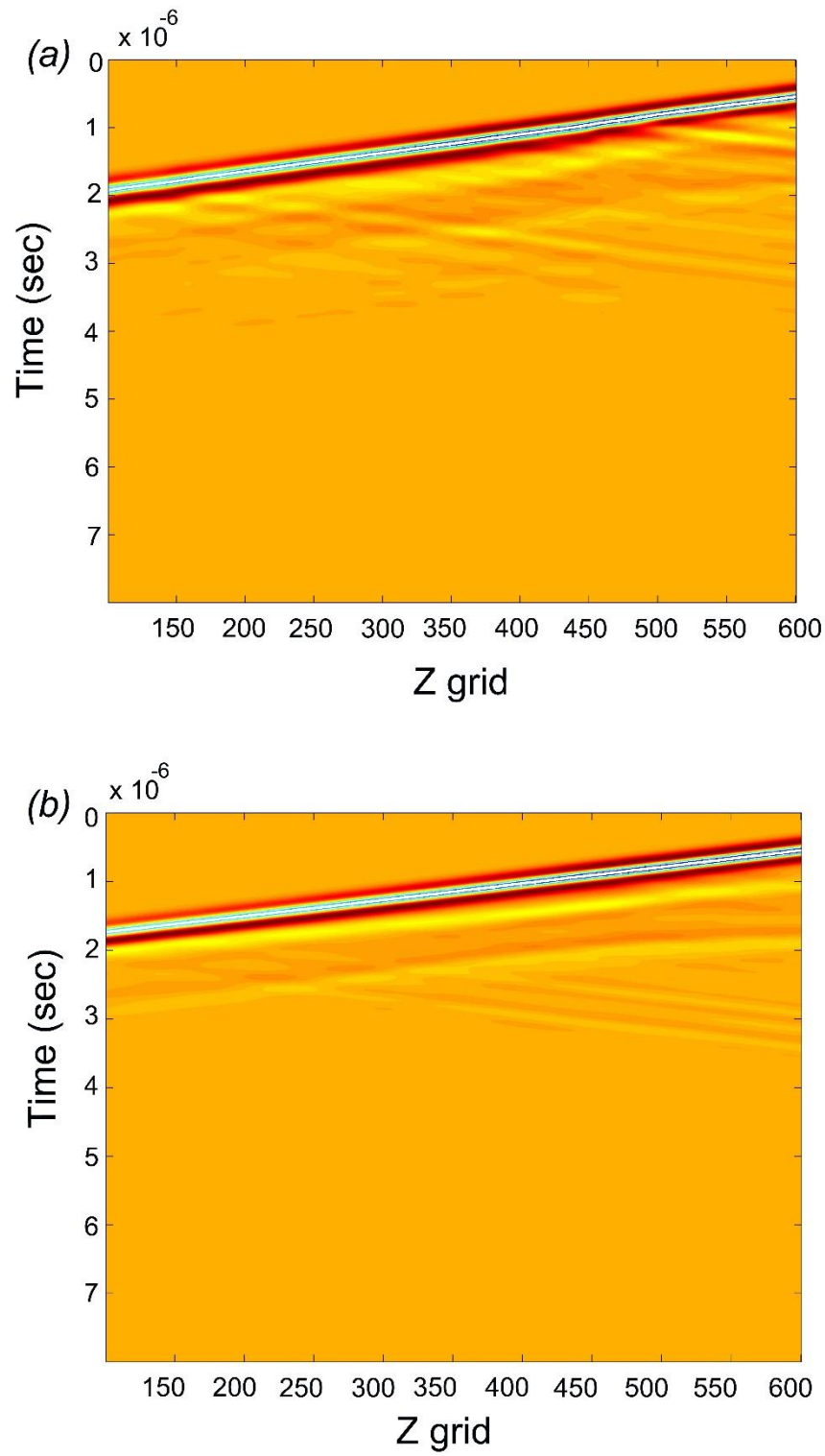


Figure 3.16 V_P waveforms for V_P estimation in digital rock Model 3, with the cracks and veins replaced by (a) water and (b) quartz.

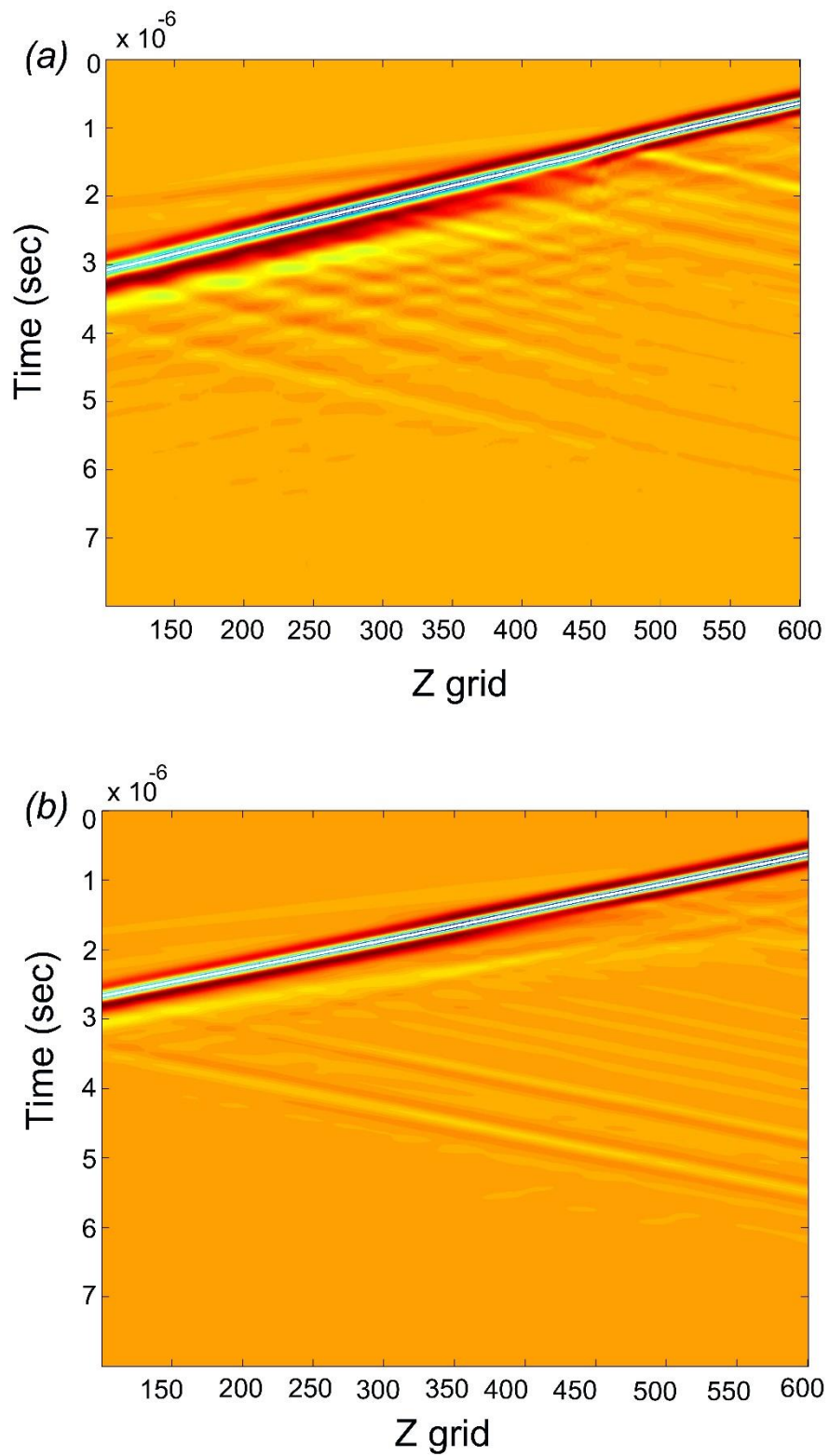


Figure 3.17 V_s waveforms for V_s estimation in digital rock Model 3, with the cracks and veins replaced by (a) water and (b) quartz.

3.4.2 Effect of heterogeneous texture on seismic velocity

The texture of Model 3 is more massive than the textures of Models 1 and 2 (Figure 3.4 and Table 3.1), with ~1% to ~3% fewer cracks and veins than in Models 1 and 2, respectively. The total amount of cracks and veins in Model 1 is between that of Models 2 and 3, but the variation of the velocities in Model 1 is greater than in Models 2 and 3. This is because the distribution of the cracks differs between the models: the crack in Model 1 runs across the whole length of the rock model (Figure 3.4a). Although the models have different heterogeneous textures and the absolute values of the effective estimated V_P , V_S and V_P/V_S differed (Figure 3.18), similar trends in the elastic moduli were observed for the different crack-filling materials.

3.5 Discussion

3.5.1 Classification on V_P/V_S and V_P diagram

Here, I discuss the velocity variation of the digital rock models influenced by crack-filling materials. The velocity of the non-crack model was used as the reference velocity (pink circles in Figure 3.18). Based on the results of the three rock models (Figure 3.4), the effective velocity variation diagram showing the relation between V_P and V_P/V_S was constructed (see Figure 3.19). The velocities can be classified into three zones: (1) quartz-rich, (2) water-saturated open fracture, and (3) calcite-rich.

The high V_P and low V_P/V_S results of the quartz-filled crack model define the quartz-rich zone. Additionally, there are several elastic materials with similar V_P and low V_P/V_S values (Figure 3.19 and green circles in Figure 3.18) that can be also classified within the quartz-rich zone. The water-saturated open fracture zone is characterized by the lower V_P and higher V_P/V_S water-filled crack features (Figure 3.19 and red circles in Figure 3.18).

The elastic materials that have high V_P and V_P/V_S values, similar to those of the

calcite-filling model (Figure 3.19 and blue circles in Figure 3.18), are grouped in the calcite-rich zone. In reservoir characterization, this diagram can help evaluate the crack-filling mineral in the rock based on V_P and V_P/V_S measurements.

3.5.2 Evolution process of the Nankai seismogenic fault

Here, the fracture-filling materials are investigated in the (1) transition zone from aseismic to coseismic regimes and (2) deeper coseismic zone in the Nankai seismogenic fault off Kumano (see Figure 3.1d). The V_P and V_P/V_S values of the Nobeoka Thrust determined from the digital rock models (Figure 3.18) are compared with those calculated from seismic data at the Nankai seismogenic fault (Figure 3.1b, c; Kodaira et al., 2004; Kamei et al., 2012; Tsuji et al., 2011).

3.5.2.1 The transition zone from aseismic to coseismic regimes

The transition zone is located between the inner and outer wedges, ~35 km landward from the trough axis (Figure 3.1d) and ~6 km below the seafloor in the Nankai Trough off Kumano (e.g. Moore and Saffer, 2001). This zone is also considered to be the up-dip limit of the coseismic plate boundary fault. The seismic data indicates that the transition zone has low V_P and high V_P/V_S (Figure 3.1b, c; Tsuji et al., 2011; Kamei et al., 2012, 2013, 2014; Tsuji et al., 2014a). This trend is consistent with the water-saturated open fracture zone in the $V_P - V_P/V_S$ diagram (Figure 3.19), suggesting that the transition zone has high pore pressure that supports open cracks and/or fractures (Figure 3.20). Furthermore, the clay minerals may dehydrate and release water into the fractures, particularly during the smectite-to-illite transition process (e.g. Moore and Vrolijk, 1992; Saffer and Tobin, 2011; Tsuji et al., 2008; Screatton et al., 2002). The smectite to-illite transition occurs at temperatures between ~100 °C and 150 °C and releases a significant amount of water into the pore space (Moore and Saffer, 2001). This temperature range is similar to that at the transition zone studied here (Hyndman et al., 1995). Furthermore, Martin et al. (2010) showed that a lateral fault developed at the transition zone, which can generate intensive fracturing in the region (Tsuji et al., 2014b). These interpretations suggest that water-filled fractures may be dominant in the transition zone (Figure 3.20).

A transition zone containing water-rich fractures supported by high pore pressure will strongly influence the mechanical properties of a seismogenic fault (e.g. Moore and Saffer, 2001; Tobin and Saffer, 2009; Wang and Hu, 2006). The high-pressure conditions may be associated with slow-slip earthquakes generated in the transition zone (Figure 3.20; e.g. Obara and Ito, 2005; Obana and Kodaira, 2009; Tsuji et al., 2014a).

3.5.2.2 The deeper coseismic zone

The coseismic zone is in the inner wedge, ~50 km landward from the trough axis (see Figure 3.1d) (e.g. Park et al., 2002) at a depth of ~6–15 km below the seafloor (Moore and Saffer, 2001). From the seismic data, this zone has high V_P and low V_P/V_S (Figure 3.1b, c; Kodaira et al., 2004; Tsuji et al., 2011). This trend agrees with the quartz-rich zone in Figure 3.19. The result of this study is also consistent with the low V_P/V_S values observed at the Cascadia subduction zone by Audet and Burgmann (2014). Quartz mineralization can occur in the subduction zone, particularly as a result of precipitation of fluid-dissolved silica derived from the progressive dehydration of the downgoing slab (e.g. Audet and Burgmann, 2014). The quartz enrichment in this coseismic zone may also be related to temperature because the pressure solution and quartz cementation processes occur in this zone at temperatures above 150 °C (Moore and Saffer, 2001). Under similar conditions, Moore and Allwardt (1980) assumed that pressure solution and quartz veins can develop in an accretionary prism at temperatures of ~100 °C to 200 °C, and become dominant features in rock deformed above 200 °C (DiTullio et al., 1990; Fisher and Byrne, 1992). Based on thermal modelling (Hyndman et al., 1995), the temperature at the true up-dip limit corresponds to ~200 °C; therefore, quartz mineralization in the fractures increases at the coseismic zone, which causes the closure of cracks. Moreover, slip-weakening behaviour occurs in the quartz-precipitated zone where the friction coefficient (dynamic friction) of the quartz veins is strongly lessened (e.g. Di Toro et al., 2004; Goldsby and Tullis, 2002), increasing the possibility of a great earthquake occurring in the coseismic zone (Figure 3.20).

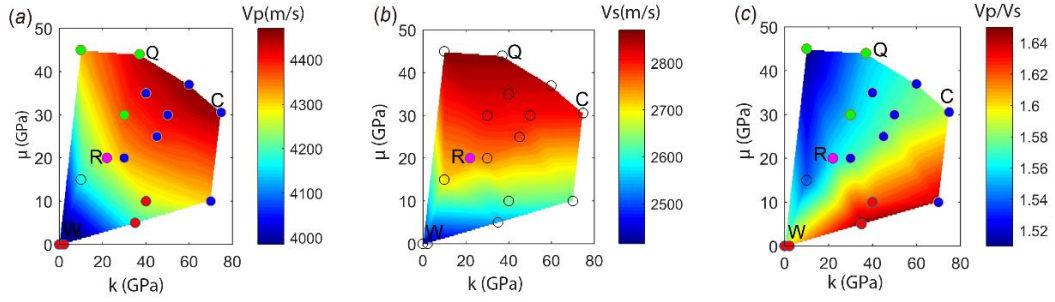
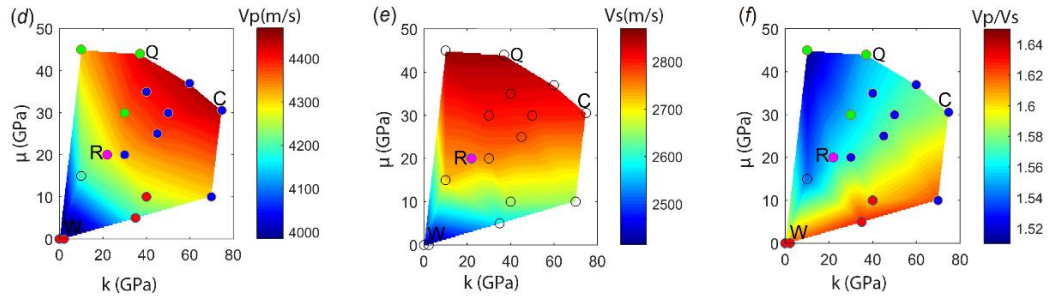
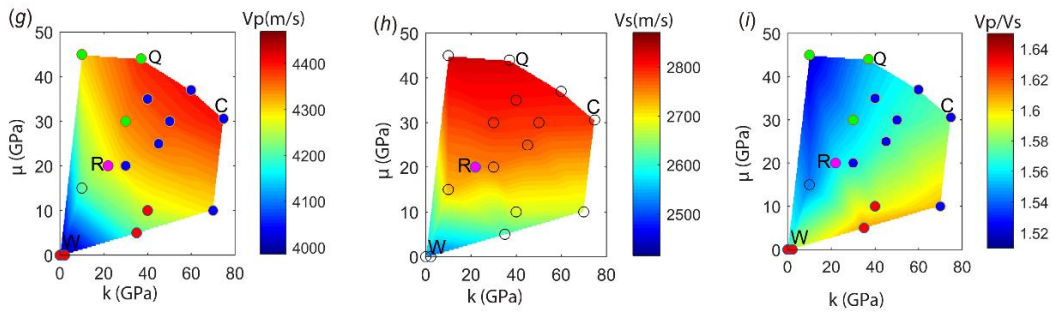
Model 1

Model 2

Model 3


Figure 3.18 Effective seismic velocities calculated from digital rock models (Models 1, 2, and 3) for different crack-filling materials. Horizontal and vertical axes show the bulk and shear moduli of the crack filling materials, respectively. (a, d, g) Effective V_P of different crack-filling materials for Models 1, 2 and 3, respectively. (b, e, h) Effective V_S of different crack-filling materials for Models 1, 2 and 3, respectively. (c, f, i) Effective V_P/V_S of different crack-filling materials for Models 1, 2 and 3, respectively. Circles indicate the elastic moduli of the crack-filling minerals or materials. Q, C, and W indicate the quartz-, calcite- and water-filled cracks, respectively. R represents the velocity of the non-cracked rock.

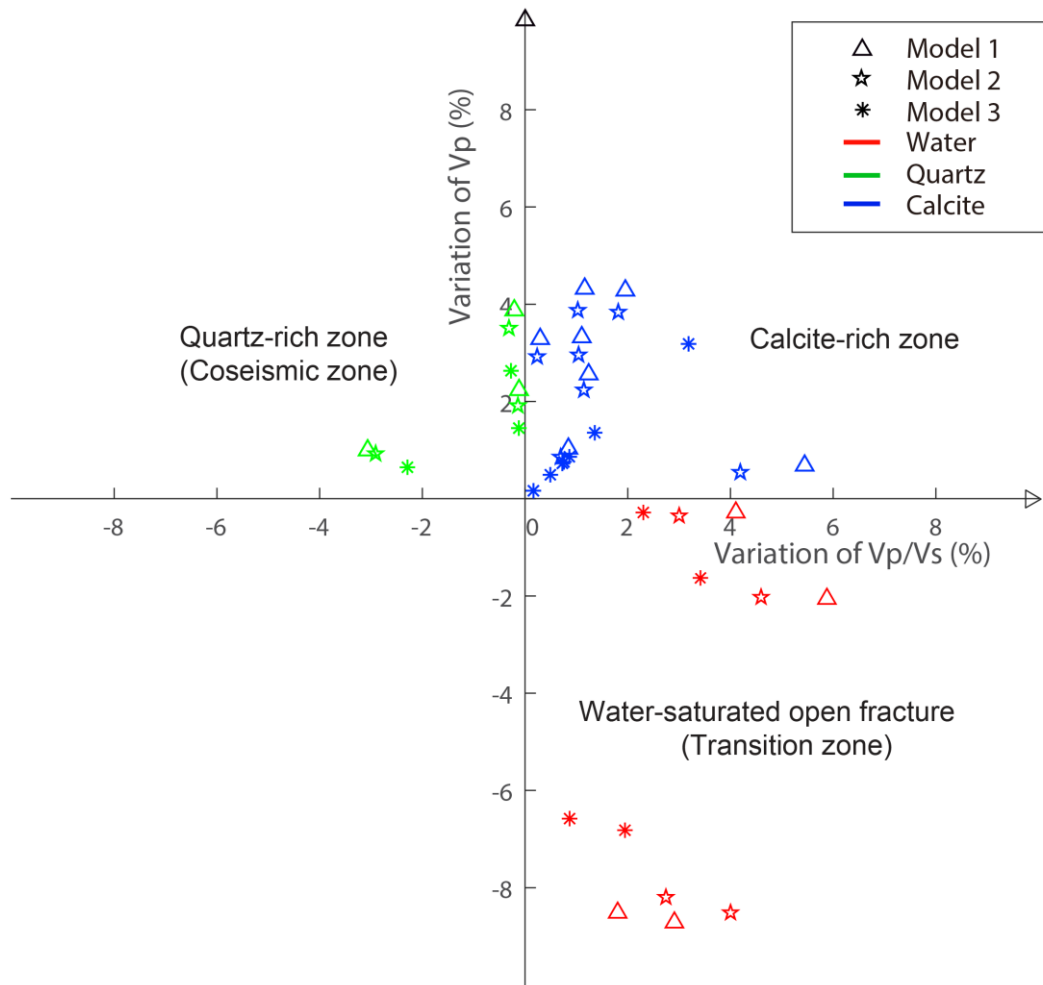


Figure 3.19 Variation of V_P and V_P/V_S for the three rock models with different crack-filling materials (quartz, calcite and water). Based on the velocity relationships, three zones of crack-filling materials are defined as quartz-rich zone, calcite-rich zone and water-saturated zone.

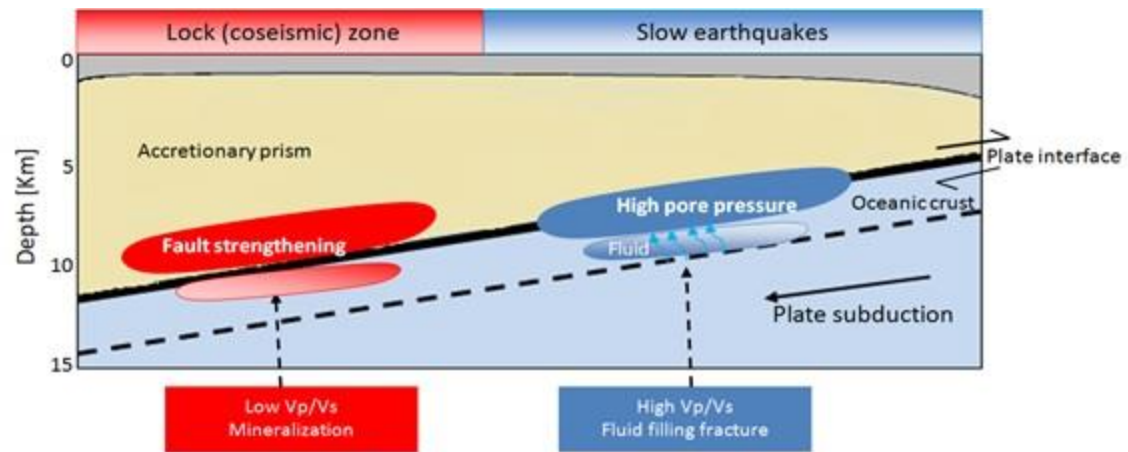


Figure 3.20 Schematic section of Nankai Trough. Red zone indicates coseismic area or great earthquake zone, which consists of mineralization (quartz) and low V_P/V_S . Blue zone shows slow earthquake area, which has high pore fluid pressure and high V_P/V_S .

3.6 Conclusion

The evolution process of the Nankai seismogenic fault off Kumano was identified by using 3D digital rock models. The dynamic wave propagation simulations were applied to digital rock models of Nobeoka core samples and constructed a diagram of estimated V_P and V_S for three models, applying different crack-filling materials to each model. Based on these results, the relationship between V_P and V_P/V_S for the three models was derived, and the variation of these velocities on the relationship was divided into three zones: the quartz-rich, water-saturated open fracture and calcite-rich zones. The transition zone between the outer wedge and inner wedge of the Nankai seismogenic fault (~6 km below seafloor) has low V_P and high V_P/V_S values consistent with water-saturated open fracture zone. Thus, the rock in this transition zone may have high pore pressure, supporting open fractures. The coseismic zone of the Nankai seismogenic fault (~615 km below seafloor) has high V_P and low V_P/V_S values that correspond to quartz rich zone, suggesting that this zone may have quartz-rich fractures.

This approach can be used in many geo-engineering studies (e.g. geothermal reservoir characterization; hydrocarbon reservoir characterization, and CO₂ injection monitoring) and can consider heterogeneous natural pore geometry for seismic velocity calculation, although conventional rock physics typically assumes simplified pore space, such as a crack. Therefore, using a digital rock physics approach, we could accurately evaluate the elastic properties of heterogeneous rock.

3.7 References

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Chapter 4

Conclusions

4.1 Conclusions

Hydrocarbon in the marine sediments have attracted great attention for contributing the world potential energy resources. Because the complex and deep of this hydrocarbon reservoir, geologists and geophysicists need key technologies or method to challenge with this concern. In this dissertation, quantitative seismic interpretation (i.e., seismic attributes and digital rock physics analysis) has been emphasized for quantitative hydrocarbon characterization. This work is useful for both geologists and geophysicists to perform seismic reservoir characterization in a more geologically feasible way. The main achievements are summarized as follows:

In Chapter 2, the main purpose is to characterize hydrocarbon reservoir, migration pathways, and sources in Sanriku-Oki basin, Japan. Hydrocarbon sources (coal-bearing formations) have been successfully mapped by using acoustic impedance inversion attribute with pseud-well information. This new approach indicates that pseudo-well approach is very useful for hydrocarbon reservoir characterization and lithologies identification even in limited well area. Moreover, other seismic attributes including envelope, chaos, and ant-tracking are employed for characterizing hydrocarbon migration route and accumulation. The results reveal that geological structures of plate subduction zone (i.e., slumping and fault) largely influence hydrocarbon gases migration and accumulation in basin. Gas hydrate and free gas are widely distributed in the porous slump units. In addition, gas chimneys and gas pockets are spatially associated with fluid flow

through the permeable of lithology boundaries and edge of slumping sequence. Particularly, free gas highly accumulated in the north-east of basin where there are successive slump sequences and gas chimneys. The implications obtained in this study are not solely related to the Sanriku-Okii forearc basin, but they can extend to other hydrocarbon reservoir in plate convergent margins.

In Chapter 3, the digital rock physics modelling has been applied to quantify reservoir rocks. Digital rock physics were employed to the Nankai Trough area in order to evaluate rock evolution process. The subduction zone (or accretionary prism) is suitable location to characterize rock evolution process, because the rock is gradually consolidated from trench to landward area. The results demonstrate that rock heterogeneity or crack-filling materials influence on seismic velocities (V_P and V_P/V_S). Water-filled crack model highly decreased the seismic velocity and increased V_P/V_S . The V_P/V_S of the quartz-filled crack model was lower than that in the water-saturated case and in the calcite-filled rock model. In addition, the diagram of seismic velocities for elastic moduli (bulk and shear moduli) was constructed. The result of seismic velocities in this study has been well consistent with field seismic estimation. Because this approach is also available for gas characterization within pore space (Yamabe et al., 2016), I could use digital rock approach to well understand reservoir parameters and heterogeneous natural pore structures. The inference can be used not only hydrocarbon reservoir characterization, but in other geo-engineering and seismology fields.

4.2 Future implications and vision

Concerning hydrocarbon reservoir in slump sequences, I suggest for further deep investigation on hydrocarbon gases saturation by using automatic velocity analysis (Chhun et al., 2017). Moreover, I will be able to investigate on large-scale nature of marine slump sequences, including their phenomenon and characteristic (i.e., porosity, permeability) because slump units can be played both roles as reservoir rock and seal competence for hydrocarbon gases accumulation (Sun et al., 2017; Arfai et al., 2016). In addition, as marine slump is associated with interstitial fluid motion, it could cause the

instability of gas hydrate and free gas formation and generate gas leaking on seafloor, which induced to marine geological hazards.

Regarding digital rock physics, dynamic wave propagation modelling can be applied on heterogeneous rock. This digital rock physics approach will be applied to Sanriku-Oki area, such coal-bearing formation (Figure 4.1) in order to characterize the reservoir properties and investigate the influence of gases on seismic velocities. Furthermore, I suggest to further investigate the effect of rock heterogeneity on seismic velocities by using homogenous rock and changing the direction (i.e., anisotropy) of seismic wave propagation modelling. Then, I may be able to predict how large of heterogeneous texture influence on seismic velocities.

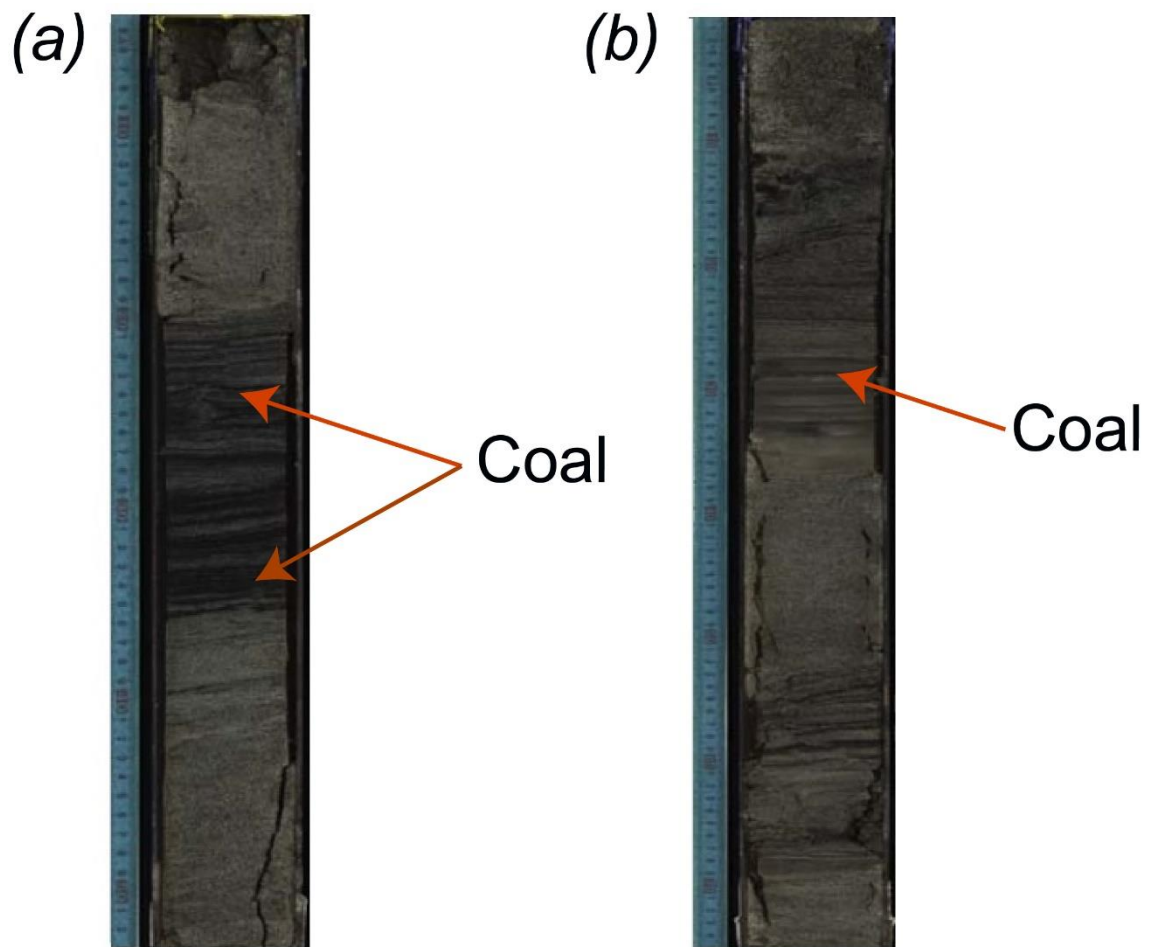


Figure 4.1 Core samples of IODP Site C0020 for formation Unit III (Phillips et al., 2017). (a) Sample from interval of 1937.45-1937.95 meter below seafloor (mbsf). (b) Sample from interval of 1940.15 -1940.84 mbsf. Red arrows indicate coal formations.

4.3 References

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