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

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（地震探査データを用いた資源貯留層の定量評価手法の開発：デジタル岩石物理と地震波属性の利用）

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論 文 内 容 の 要 旨

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 CO_2 into reservoirs at the continental margin (CO_2 geological storage), CO_2 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 ~2.5–2.9 s two-way traveltime (~400–800 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.