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Vibrational spectroscopic characterization of mudstones in a hydrocarbon-bearing depression, South China Sea: Implications for thermal maturity evaluation

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ABSTRACT

A better understanding of mineral transformations in sedimentary rocks and the controls on thermal maturity have become essential in the petroleum exploration industry in recent years. The Fushan Depression is an important hydrocarbon-bearing depression in South China Sea, which can be subdivided into three structural zones: the western, central and eastern zones. In this study, a series of mudstone samples selected from 13 drilling cores with depths ranging from 2100 to 3800 m were studied using infrared reflectance spectroscopy and X-Ray Powder Diffraction (XRD) methods. And another 10 samples have been chosen for vitrinite reflectance measurement so as to investigate the ability of using infrared spectroscopy for thermal maturity evaluations. The infrared spectra results show that quartz and silicates (e.g. illite, kaolinite, smectite) are the dominant minerals in all samples. The semi-quantitative XRD analysis reveals a clear trend in illite content as the eastern zone (mean 80.81%) > the western zone (mean 73.52%) > the central zone (mean 55.04%) as well as a contrary trend in kaolinite content. This study documents that the peak height and position of Si–O antisymmetric stretching bands at ~1025 cm^{-1} and ~1000 cm^{-1} have a significant correlation with the degree of kaolinite illitization, suggesting that the utility of infrared spectroscopy is a valuable tool for the study of thermal maturity in sedimentary basins. The infrared spectra and XRD results together with vitrinite reflectance data indicate that the thermal maturity in the eastern zone is anomalously high, followed by the western zone, and that in the central zone is lowest. The igneous intrusion in the eastern zone has a significant impact on thermal maturation, resulting in high degree of kaolinite illitization. By contrast, the abundance in kaolinite in the central zone represents relatively low degree of kaolinite illitization, which should be attributed to shallow burial depth.

1. Introduction

The mineralogical composition of mudstone is controlled mainly by provenance, depositional environments and burial history and igneous intrusion [1,2]. As these factors can vary significantly both temporally and spatially, mudstone compaction trends will also vary [3]. The identification of the principal clay-mineral species (i.e. kaolinite, smectite, illite and chlorite) in sedimentary rocks is extremely important in both mineralogical and thermal maturity studies [4,5], because when sandstones and mudstones are buried, diagenetic mineral transformations occur in response to the increased temperatures and pressures.

In hydrocarbon bearing sedimentary basins, a better understanding of thermal maturity history has become essential in petroleum exploration for evaluating a source rock's potential to generate oil or gas. One of the most common and important reactions in mudstones occurring in response to the increased temperatures and pressures is the dioctahedral smectite to illite conversion through illite–smectite mixed-layer minerals [6,7]. And the other significant reaction is the illitization of kaolinite [5,8,9]. Although vitrinite reflectance is the most widely used indicator to assess the degree of thermal maturity of sedimentary basins [10], this analyze approach is not readily available because it is cost-intensive and time-consuming [11]. Moreover, some mudstones contain little or no vitrinite for measurement.

In the last decades, spectroscopic methods such as infrared reflectance spectroscopy have been applied as a field-based technique to study alteration mineral assemblages widely, because it is simple,

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rapid, nondestructive and safer than conventional method. Although extensive studies have been performed on the spectroscopy of marine and lake sediments in recent years, most of the studies were conducted on sandstone reservoirs [5,12,13]. By contrast, relative limited studies have rarely reported mineral transformations in mudstones from hydrocarbon-bearing fields and their implications for thermal maturity history using infrared spectroscopy.

With an increasing demand for petroleum resources in China, the Fushan Depression in the Beibuwan Basin has recently become a focal point for intensive petroleum exploration in South China Sea [14,15]. The transfer zone in the central zone subdivides the depression into two sags including the Bailian Sag in the east and the Huangtong Sag in the west (Fig. 1). The gray and black mudstones in the lower Eocene Liushagang Formation are considered as the main source rocks [14,15]. Hydrocarbon exploration in this depression revealed that the eastern zone is a typical gas-bearing field related to extremely high thermal maturity [14]. However, it cannot be explained by normal geothermal gradients which could not produce so high maturity/palaeotemperature at the current burial depth (less than 4000 m). Furthermore, in contrast to the eastern zone, the western zone where the burial depth is over 4500 m is an oil-bearing field with lower level of thermal morality. It seems that the source rocks in the eastern zone are characterized by anomalous thermal maturity. But no target work has been undertaken to investigate the spatial differences in thermal maturity, and the formation mechanism of anomalous thermal maturity in the eastern zone is poorly known.

In the current study, more than 20 mudstone samples, selected from different sites of the Fushan Depression, South China Sea were analyzed using infrared reflectance spectroscopy and X-Ray Powder Diffraction (XRD) techniques. This work aims to examine the changes in the mineralogical composition of the mudstones, and investigates their potential in evaluating thermal maturity through spectroscopic method. The present work focused not only on qualitative identification of mineral species but also semi-quantitative determination of variations in the relative abundances of major clay minerals in the altered sequence. Combined with limited vitrinite reflectance data and our previous sedimentary analysis results, this study intends to assess the effectiveness of the portable infrared spectroscopic method as an operational geothermal exploration tool, and to investigate the controlling factors in the variations in thermal maturity within the hydrocarbon-bearing depression.

2. Experimental and methods

2.1. Materials

A series of selected mudstone samples were collected from exploration cores at depths between 2100 m and 3800 m from the Fushan

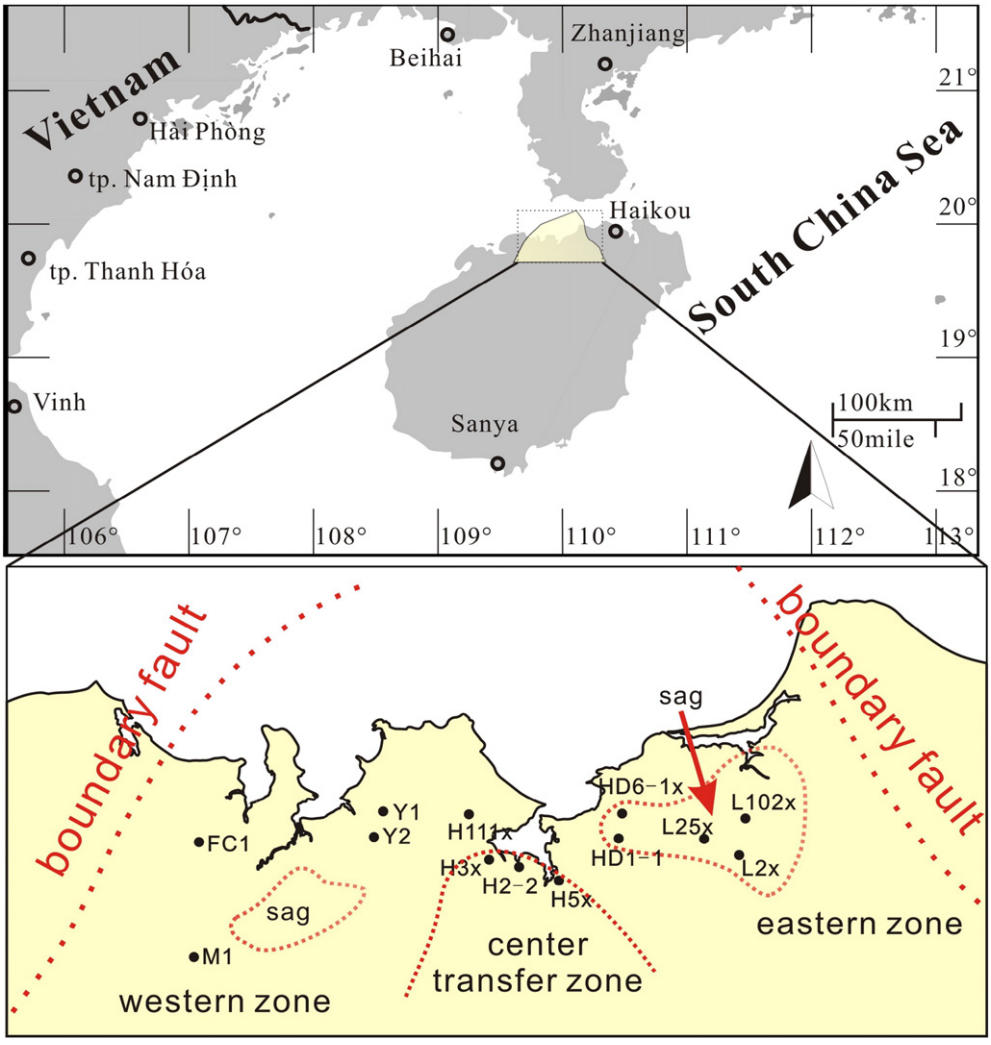

Fig. 1. Map showing the locations of mudstone samples in the Fushan Depression, South China Sea. The Fushan Depression can be subdivided into three structural zones: the western zone, the central zone and the eastern zone.