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Diagenesis of magnetic minerals in a gas hydrate/cold seep environment off the Krishna–Godavari basin, Bay of Bengal

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ABSTRACT

We carried out detailed magnetic measurements of the core (MD161/8) located in the vicinity of Site NGHP-01-10, where ~128 m of hydrate is confirmed by drilling/coring, to understand the diagenesis of magnetic minerals in a gas hydrates/cold seep environment. The rock magnetic measurements along with SEM–EDS and XRD analyses show a zone of reduced magnetic susceptibility (*zone 2*) where most of the magnetic minerals are dissolved. The enhanced concentration of chromium reducible sulfur (CRS) in this zone suggests an intense pyritization process while isotopically depleted authigenic carbonates indicate sulfate reduction via anaerobic oxidation of methane (AOM). Therefore, the dissolution of magnetic minerals is attributed to the HS^- released during AOM that has resulted in the reduction in the magnitude of magnetic parameters. Within zone 2, a zone of enhanced susceptibility (*zone 2a*) is observed between 17.68 and 23.6 mbsf, and is located beneath the present day sulfate–methane transition zone (SMTZ). The frequency-dependent magnetic susceptibility and low temperature magnetic measurements suggest the abundance of fine grained superparamagnetic (SP) sized ferrimagnetic particles. The SEM–EDS and XRD analyses show the presence of greigite which occurs in interstices between the pyrite crystals. Such occurrence of greigite in sediments has important implications in the interpretation of paleomagnetic records. We evaluated the likely mechanism for the greigite formation in KG offshore basin and our data suggest that the formation of greigite may be related to either paleo-SMTZ or anaerobic oxidation of pyrite. It is unlikely that the formation of greigite can be explained by the downward diffusion of sulfide below the current depth of SMTZ. However, further investigations are required to ascertain the mechanism for the formation and preservation of greigite.

1. Introduction

The reductive dissolution of iron oxides and authigenic formation of magnetic minerals have been studied extensively in marine sediments as they have important implications for the interpretation of environmental and paleomagnetic records (e.g., Snowball and Thompson, 1990; Verosub and Roberts, 1995). In marine environment, iron and sulfur cycles are mostly mediated microbially by degradation of organic carbon (Froelich et al., 1979). Under suboxic conditions, authigenic magnetite of biogenic origin is commonly found at the top of the iron reduction zone (Lyle, 1983; Petersen et al., 1986; Karlin et al., 1987). Under anoxic conditions, the detrital iron-bearing minerals react with the hydrogen sulfide (HS^-) which is produced during anaerobic reduction of sulfate to form pyrite (FeS_2) (Karlin and Levi, 1983; Karlin and Levi, 1985; Canfield and Berner, 1987; Karlin, 1990; Leslie et al., 1990). As a precursor to pyrite, metastable greigite (Fe_3S_4) is formed during the pyritization process (Berner, 1984; Wilkin and Barnes, 1997; Hunger and Benning, 2007). If the pyritization process is incomplete either due to the limited concentration of hydrogen sulfide or enrichment of reactive iron, the intermediate ferrimagnetic iron sulfide (greigite) may be preserved in the marine sediments (Kao et al., 2004; Rowan and Roberts, 2006). Several studies have documented the presence of greigite formed due to sulfate reduction either by oxidation of organic matter (Liu et al., 2004) or anaerobic oxidation of methane (AOM) (Housen and Musgrave, 1996; Kasten et al., 1998; Jørgensen et al., 2004; Liu et al., 2004; Neretin et al., 2004; Horng and Chen, 2006; Larrasoaña et al., 2006; Musgrave et al., 2006).

Greigite, a ferrimagnetic mineral capable of acquiring stable remanent magnetization, has received considerable attention due to its implications in paleomagnetic records (Jiang et al., 2001; Kao et al., 2004; Roberts et al., 2005; Rowan and Roberts, 2006; Larrasoaña et al., 2007). The greigite lattice is similar to that of magnetite with higher coercivity, lower susceptibility and saturation magnetization (Roberts, 1995). According to the steady-state diagenetic model (e.g., Berner, 1984), greigite is formed shortly after deposition and therefore accurately records the geomagnetic field at the time of its formation (Tric et al., 1991; Roberts and Turner, 1993). However, recent studies have

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shown that the presence of authigenic SP/SD greigite can significantly overprint the paleomagnetic records (Kasten et al., 1998; Jiang et al., 2001; Jørgensen et al., 2004; Liu et al., 2004; Neretin et al., 2004; Roberts and Weaver, 2005; Fu et al., 2008; Rowan et al., 2009). The processes for the formation of authigenic SP/SD greigite are not well studied in different geological environments. Therefore, we carried out detailed magnetic measurements along with SEM–EDS and XRD analyses on a long sediment core (~30 m) in which the evidence of paleo-cold seep activity has been reported (Mazumdar et al., 2009). The core was collected onboard R/V *Marion Dufresne* (MD161/8) in the Krishna-Godavari (KG) offshore basin using a Giant Calypso piston corer with a PVC liner of 10 cm inner diameter at a water depth of 1033 m (Latitude = 15° 51.8624′N and longitude = 81° 50.0692′E, Fig. 1A). The magnetic measurements vis-à-vis the geochemical and sedimentological data were analyzed to understand the effect of cold seep processes on the magnetic minerals.

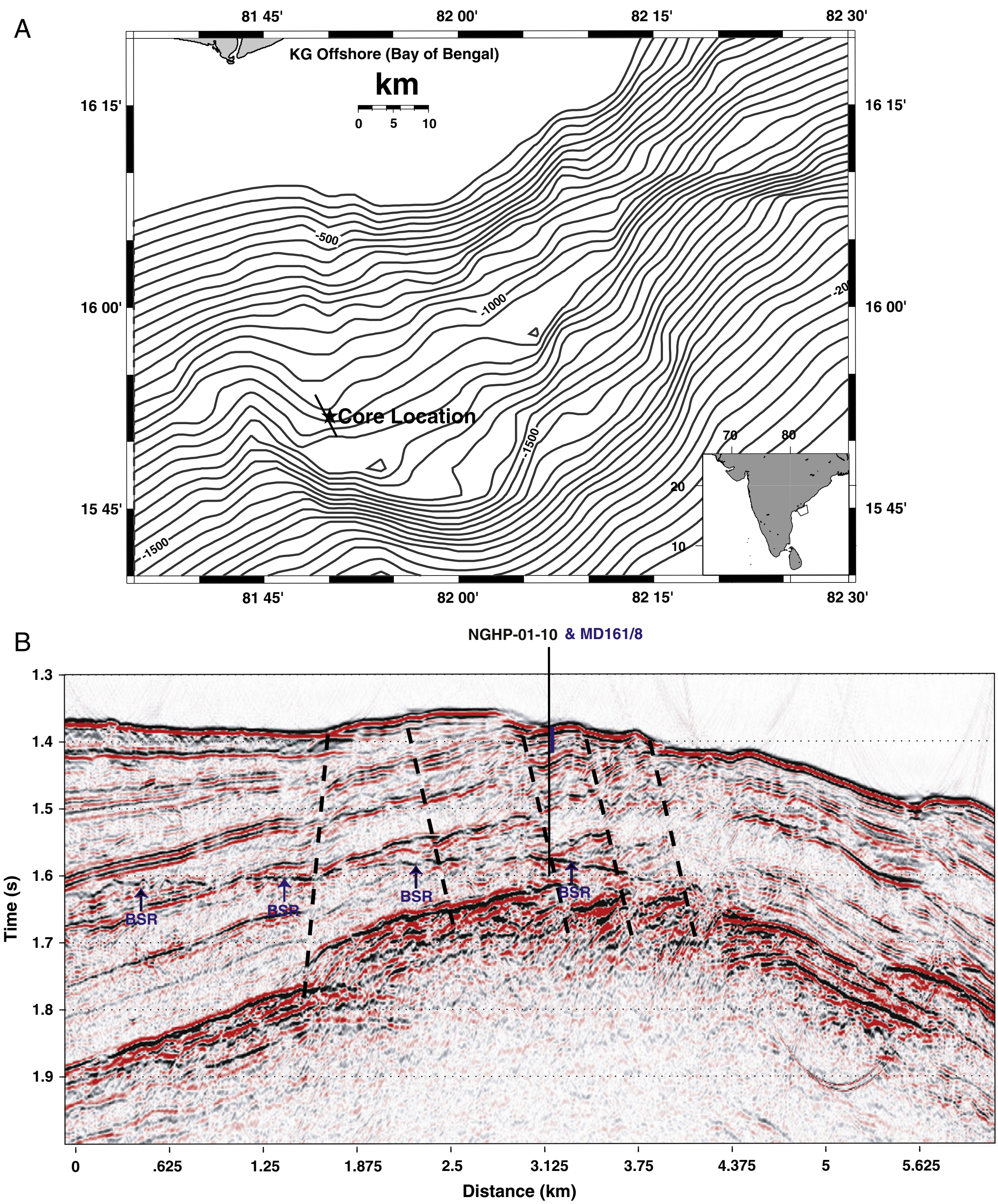

Fig. 1. A) Location map of the study area in Krishna Godavari offshore basin, eastern continental margin of India. The star denotes the location of the studied core obtained onboard R/V *Marion Dufresne* (MD161). The inset shows the zoom out of the study area. The contour interval is 50 m. B) Seismic section across the studied core highlighting the presence of a BSR. The thick black line indicates the length of the core NGHP-01-10 and the blue lines indicate the length of the core MD161/8.