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Magnetostratigraphic study of the potash-bearing strata from drilling core ZK2893 in the Sakhon Nakhon Basin, eastern Khorat Plateau

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ABSTRACT

The Khorat Plateau holds one of the world's largest potash deposits. Although many attempts have been made, the age of the potash-bearing strata remains poorly determined. Here, we report a high resolution magnetostratigraphic study of a 595.4 m-deep potash bearing borehole (ZK2893) in the southeast Sakhon Nakhon Basin in central Laos. This borehole penetrated the whole potash-bearing Nong Boua Formation and reached the underlying sandstone beds of the Nam Noy Formation. A total of 500 (383 level) cubic paleomagnetic samples were collected. *k*-T curves and hysteresis loops revealed that hematite and magnetite were the main magnetic carriers and were likely of detrital origin, as indicated by microscopic and Electron Microprobe Analysis (EMPA) examinations. Progressive thermal and alternating field (AF) demagnetization isolated 229 valid characteristic remnant magnetizations (ChRMs), which showed a normal and antipodal distribution of the inclination data. Both the microscopic and EMPA examinations and inclination-only analysis suggest primary magnetizations of the ChRMs, yielding nine normal and seven reversed polarity zones. Combined with regional palynological, isotopic and sedimentologic evidence, the obtained polarity zones were best correlated to the geomagnetic polarity time scale of Gradstein et al. (2012) (GPTS2012), yielding magnetostratigraphic ages of > 63.5 Ma to ~92 Ma for the potash-bearing Nong Boua Formation and ~85 Ma for the potash bed in its lower salt unit.

1. Introduction

The Maha Sarakham Formation (MSF) in the Khorat Plateau holds prospective reserves of K_2O over 26.6 billion tons (Liu et al., 2015). It is one of the largest potash deposits in the world (Hite and Japakasetr, 1979; Fan, 2000), where the world largest one in Saskatchewan, Canada has 66.5 billion tons of K_2O (Liu et al., 2015). The formation of the potassic salt has been proposed in an inland sea or lagoon environment (Thiramongkol, 1978), a hypersaline and landlocked lake within an arid continent desert (Booth and Sattayarak, 2011), or a shallow saline-pan environment (Tabakh et al., 1999; Hansen et al., 2016). One of the main reasons for such large debates is that there lacks well age constraints for the potash-bearing sedimentary sequence.

Since Gardner et al. (1967) first named the formation, originally assigning it to be Late Cretaceous to Eocene sequence, numerous scientists have attempted to more specifically identify the stratigraphic age and the time of potash formation (e.g., Harris, 1977; Maranate, 1982; Pisutha-Arnond et al., 1986; Qu et al., 1998; Hansen et al., 2002, 2016; Feng et al., 2005; Racey and Goodall, 2009; Zhong et al., 2012). However, the stratigraphic age of this formation remains highly debated, ranging from Early Cretaceous to Eocene (Table 1). For example, preliminary paleomagnetic studies (Maranate, 1982; Maranate and Vella, 1986) yield a poorly constrained Late Cretaceous or Tertiary age for the formation; the Ostracoda and Charophyta assemblages from the mudstone layers of the formation indicate a Paleocene age (Feng et al., 2005); palynological assemblages suggest an Albian to Cenomanian age (Harris, 1977; Racey and Goodall, 2009) or Turonian to Santonian age (Zhong et al., 2012; Qin et al., 2013); geochemical studies of $\delta^{34}S$ analyses of the evaporitic anhydrites and their correlation with the world marine evaporate sulphur age curve provide a Cenomianage for the MSF (Pisutha-Arnond et al., 1986); and multiple isotopic approaches of Rb/Sr, K/Ar and $^{87}Sr/^{86}Sr$-composition indicate a Cenomanian formation of the carnalites in the potash unit (Hansen et al., 2002) and Santonian to Campanian age for the middle salt unit (Hansen

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Table 1
Summary of previous chronological results obtained for the potash-bearing strata in the Khorat Plateau.

Location	Formation	Sample Source	Dating Method	Ages (Ma) E2 E1 K2 K1 34 50 60 70 80 90 100 110 120 140	Reference
Maha Sarakham NE Thailand	Maha Sarakham		Stratigrahpic contact relationship		Gardner et al., 1967
Vientiane area Laos	Thangon	Mudstone units	Ostracoda and Charophyta assemblage		Feng et al., 2005
Phu Horm, NE Thailand	Maha Sarakham	Interbeded mudstones and siltstones	Palynology		Harris, 1977; reinterpreted by Racey and Goodall, 2009
Khammouane, Laos	Nong Boua	Greyish green mudstone above the potash layer			Zhong et al., 2012
Khammouane, Laos	Nong Boua	Cinerous mudstone units			Qin et al., 2013
Bamnet Narong area, NE Thailand	Maha Sarakham	evaporitic anhydrite beds	$\delta^{34}S$ correlation with the world marine evaporites sulphur age curve		Pisutha-Arnond et al., 1986
Bamnet Narong area, NE Thailand	Maha Sarakham	Carnalites of the potash unit	Rb/Sr		Hansen et al., 2002
Bamnet Narong area, NE Thailand	Maha Sarakham	Clay above the potash unit	K/Ar		Hansen et al., 2016
Bamnet Narong area, NE Thailand	Maha Sarakham	Anhydrite of the Middle Salt Unit	$^{87}Sr/^{86}Sr$		
Nakhon Phanom, NE Thailand	Maha Sarakham	Translucent to clear salt	Paleomagnetism		Manarate, 1982
	Maha Sarakham		Paleomagnetism		Manarate and Vella, 1986

The question mark "?" represents questionable results.

et al., 2016).

The Sakhon Nakhon basin is located in the northern part of the Khorat Plateau. This and the Khorat basins once formed one large unified basin during the potassic salt deposition and were separated since the Early Paleocene Phu Phan range uplift (Hansen et al., 2016) (Fig. 1). The potash-bearing sequences include three shallow and hemi-deep lake evaporitic-clastic cycles. Although the thicknesses of both clastic and salt units are significantly varied throughout the Khorat Plateau, they are comparable between the two sub-basins (Hite and Japakasetr, 1979; Tabakh et al., 1999; Suwanich, 2007; Hansen et al., 2016). The Thakhet area in the southeast Sakhon Nakhon basin (Fig. 1) contains large potash deposits. It has typical potash-bearing sequences. The large numbers of boreholes and a few pollen biostratigraphic studies make these deposits an ideal place for our detailed geochronology study.

Magnetostratigraphy has been widely and successfully utilized in ascertaining the depositional age of the long sequence strata elsewhere around the Tibetan Plateau (e.g., Benammi et al., 2002; Fang et al., 2003, 2005, 2007, 2016; Zhu et al., 2005, 2008; Coster et al., 2010; Hasegawa et al., 2010). To ascertain the depositional age of the potash-bearing strata and investigate the potash resources in the Thakhet area, we collaborated with the SINA-AGRI Mineral Resources Co. Ltd. and drilled a 595.4-m-long borehole (designated ZK2893) through the potash bearing strata of the Nong Boua Formation in the Thakhet area (Fig. 1) in the year of 2011. In this paper, we present a detailed magnetostratigraphic study of this core and attempt to establish an age constraint for the potash-bearing strata and the potash bed. Rock magnetic analyses of *k*-T curves and hysteresis loops and Microscopic and EMPA analyses are used to identify the magnetic carrier minerals. Both the inclination histogram distribution and reversals test are utilized to evaluate the reliability of the characteristic magnetizations. By integrating regional palynological, isotopic and sedimentologic evidence, the polarity zones obtained are properly correlated to the geomagnetic polarity time scale of GPTS2012.

2. Geological setting and sampling

The Khorat Plateau with an area of over 170,000 km^2 is located in the central part of the Indochina Terrane. It is separated from the surrounding terranes by the Song Ma Suture, Dian Bian Phu Fault and Nan-Uttaradit Suture (Metcalfe, 1996, 2006, 2011, 2013) (Fig. 1). The nearly *E*-W trending Phu Phan uplift range divides the Khorat Plateau into two depositional basins: the Khorat Basin in the south and the smaller Sakhon Nakhon Basin in the north (Hite, 1974; Hite and Japakasetr, 1979; Suwanich, 1986; Lovatt-Smith et al., 1996).

Each of the basins has a developed, wide-distributed and correlative potash-bearing sedimentary sequence. Although they sedimentologically refer to the same strata, the sequence is known as the Maha Sarakham Formation in Thailand, Thangon Formation in Vientiane area and as the Nong Boua Formation in the provinces of Khammouane-Savannakhet of Laos. Because our study is located in Khammouane Province, we refer to the strata as the Nong Boua Formation. Borehole data reveal that this formation has a thickness ranging from ~250 m to over 1000 m throughout the Khorat Plateau (Hite and Japakasetr, 1979; Hansen et al., 2016), which generally unconformably overlies the Nam Noy Formation of the Khorat Group (Utha-Aroon, 1993; Tabakh et al., 1998; Zhong et al., 2012; Qin et al., 2013). The complete lithostratigraphy of the Nong Boua Formation includes three shallow and hemi-deep lake evaporitic-clastic cycles, which can be listed in ascending stratigraphic order as the basal anhydrite, lower salt, lower clastic, middle salt, middle clastic, upper salt and upper clastic units (e.g., Hite and Japakasetr, 1979; Tabakh et al., 1999; Suwanich, 2007; Hansen et al., 2016).

The ZK2893 core was obtained at N17°11.11′ and E104°49.37′ in the Nong Boua depression of the southeast Sakhon Nakhon Basin, east of the Khorat Plateau (Fig. 1). The location lies to the south of the Thakhek City, which is the capital of Khammouane Province, Laos (Fig. 2), where the potash-bearing strata are almost horizontal. The borehole penetrated the whole potash-bearing Nong Boua Formation and reached the underlying sandstone beds of the Nam Noy Formation (known as the Khok Kruat Formation in Thailand). A 595.4-m-long core