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Reconstruction of Late Cretaceous coastal paleotemperature from halite deposits of the Late Cretaceous Nongbok Formation (Khorat Plateau, Laos)

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Abstract

Cretaceous evaporites of the Maha Sarakhan Formation in Thailand (e.g., the Nongbok Formation, Laos) have been studied for almost a century as the huge potash deposits in the world. The consistently high local paleotemperatures should lead to huge salt deposits during the evaporation process. Primary fluid inclusions in halite can provide surface brine water temperatures directly and quantitatively. Until now, there have been no data published from paleotemperature of primary fluid inclusions of Cretaceous halite. The non-marine halite from the Cretaceous Nongbok Formation (Laos) precipitated from shallow brine waters with temperatures of 17.7–42.3 °C.

Keywords: Fluid inclusions; Halite; Homogenization temperature; Cretaceous

1. Introduction

Evaporite deposits are important sources of paleoclimate information. This is because salt minerals are very sensitive to the local climate (Roberts and Spencer, 1995; Lowenstein et al., 1998; Benison and Goldstein, 1999; Satterfield et al., 2005; Ge et al., 2007; Liu et al., 2007; Meng et al., 2011a,b, 2013; Zambito and Benison, 2013). Although many different methods can be used to reconstruct temperature, such as palynology, isotopes and mineralogy (Zheng et al., 1998; Tong et al., 2002; Knauth and Lowe, 2003; Knauth, 2005), most of these are indirect and only semiquantitative. However, primary fluid inclusions in halite can provide direct, quantitative paleotemperature data. Specifically, the "cooling nucleation method" used to determine the homogenization temperature from primary fluid inclusions reflects the surface brine water temperature. The primary fluid inclusions in halite deposits formed below 60 °C often are all-liquid fluids at room temperature. So cooling below −10 °C to −30 °C can nucleate vapor bubbles artificially in primary liquid inclusions but cannot change the original size of fluid inclusions so that homogenization temperatures can be obtained (Benison, 1995; Roberts and Spencer, 1995). This approach obtains direct paleotemperature data because primary fluid inclusions in halites formed in surface or shallow brines record the temperature during formation, which is similar to the local air temperature (Lowenstein et al., 1998; Benison and Goldstein, 1999; Satterfield et al., 2005; Ge et al., 2007; Liu et al., 2007; Meng et al., 2011a,b, 2013; Zambito and Benison, 2013). Primary fluid inclusions in halite may occur as two crystal types: cumulate crystals formed in the surface brine and chevron crystals formed in the very shallow brine. Cumulate halite crystals can preserve a direct record of surface temperatures, which are comparable with air temperatures (Roberts and Spencer, 1995). Chevron crystals form beneath shallow brines (always less than 2 m deep and usually less than 0.5 m) (Warren, 2006), as a result of competitive growth (Dellwig,

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1955; Handford, 1982; Roedder, 1984). Both of cumulate and chevron halite crystals have inclusion-rich growth bands and clear, inclusion-poor growth bands (Lowenstein et al., 1998; Benison and Goldstein, 1999; Satterfield et al., 2005; Ge et al., 2007; Liu et al., 2007; Meng et al., 2011a,b, 2013). As a result, they record bottom water temperatures similar to the surface brine temperature (Lowenstein et al., 1998; Meng et al., 2011b) and, by extension, air temperatures. Therefore, both cumulate and chevron fluid inclusions from halite act as proxies for the local air temperature.

These methods have been applied to ancient evaporites including the Precambrian, Permian, Silurian, Eocene, and modern age deposits. However, until now there have been no data published from primary fluid inclusions in the Cretaceous halites (Lowenstein et al., 1998; Benison and Goldstein, 1999; Ge et al., 2007; Liu et al., 2007; Meng et al., 2011a,b, 2013). There are very few Cretaceous halite deposits in the world compared with the number of Neoproterozoic–Cambrian and Triassic-Jurassic salt deposits (Knauth, 2005). Many of the existing Cretaceous halite deposits can be found in the Khorat Plateau of Laos and Thailand. The aim of the research presented here was to determine surface temperatures at the time of deposition of the Cretaceous Nongbok formation by means of measurement of homogenization temperatures in primary fluid inclusions in halite crystals formed in shallow brine. These are the first quantitative surface paleotemperature data reported from the Cetaceous halite deposits.

2. Geological setting

The Khorat Plateau, part of the Indochina Terrane in Southeast Asia, is located in northeastern Thailand and central Laos. The plateau is divided by the Phu Pan Anticline into the Khorat Basin in the south and the Sakon Nakhon Basin in the north (Fig. 1). The plateau is bounded to the west by the Nan Suture, the Sukhothai Arc and Sibumasu Terranes, and to the north by the Song Ma Suture and the South China Terrane (Sone and Metcalfe, 2008; Metcalfe, 2011). In the early Late Triassic, the Sibumau Terrane collided with the continental Sukhothai Arc of western Indochina, the local manifestation of the closing of the Paleo-Tethys Ocean (Sone and Metcalfe, 2008). Following the collision Khorat basins on the Khorat Plateau are formed (Metcalfe, 1988). Subsequently, the non-marine Khorat Group and a Cretaceous evaporite sequence, known as the Maha Sarakhan Formation in Thailand, and the Nongbok Formation in Laos were deposited. These strata today form part of the Khorat Plateau: the nonmarine Khorat Group and the later evaporite-bearing Maha Sarakhan Formation (Thailand) were deposited (Fig. 2; El Tabakh et al., 1999). This formation is called the Nongbok Formation in Laos. During the Early Paleocene, 3000 m of Khorat Group sediments were removed by erosion and the NW–SE trending Phu Phan Anticline in the central Khorat Plateau formed (Cooper et al., 1989; Mouret, 1994).

Because they include one of the largest potash deposits in the world (Fan, 2000), the evaporites of the Maha Sarakhan Formation (Thailand) have been studied for almost a century. These deposits contain few fossils, so their geological age is

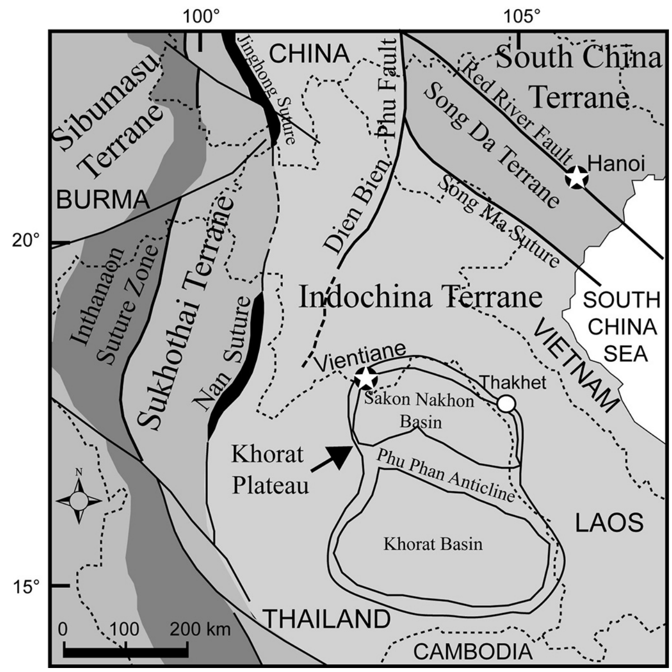

Fig. 1. Tectonic subdivisions of the Khorat Plateau and its adjacent regions (after Sone and Metcalfe, 2008).

difficult to determine and the data are still debated. According to early palynological studies, these evaporites were formed in the Middle Cretaceous (Harris, 1977). More recently, it was suggested that these evaporites are middle–late Albian to Cenomanian (Sattayarak and Polachan, 1990). Hansen et al. (2002) dated the middle salt layer within the Maha Sarakhan Formation at Bamnet Narong (Thailand) potash and rock salt deposits using K-Ar and Rr-Sr and suggested an age of ≈95 Ma (Cenomanian). Recent palynological studies of interbedded clastic sediments in Laos indicated these evaporites were deposited between the Turonian and the Santonian (Late Cretaceous; Fig. 2) (Qin et al., 2013). These evaporite cycles lack basal marine carbonate units, and contain tachyhydrite, sylvite, and carnallite (Horita et al., 2002). Therefore, some studies suggested these evaporites had a non-marine origin or some hydrothermal contribution (Hite and Japakasetr, 1979; Hardie, 1990; Garrett, 1996; El Tabakh et al., 1999, 2003); however, geochemical evidence indicated that they probably originated from seawater (Hite and Japakasetr, 1979; Tan et al., 2010; Zhang et al., 2013). Sulfur isotopes show that the source of sulfate in the evaporitic anhydrite is predominantly marine ($\delta^{34}S = 14.3–17.7‰$ from evaporitic anhydrites), but non-marine in anhydrite from siliciclastic sediments ($\delta^{34}S = 6.4–10.9‰$ from nonmarine siliclastic anhydrites; El Tabakh et al., 1999). Therefore the depositional environment appears to have oscillated between marine and non-marine, as is likely in a coastal evaporite basin. Br contents in the lower halite of the Maha Sarakham evaporites ranges from 70 ppm to 400 ppm (base to top), which imply the evaporative brine evolution from marine water (El Tabakh et al., 1999).

Since 2007, geological exploration for potash deposits has been carried out in the Dongtai mining area (Thakhet, Laos;