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Quantitative temperature records of mid Cretaceous hothouse: Evidence from halite fluid inclusions

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ABSTRACT

Quantitative temperature reconstructions for the mid Cretaceous are still rare although its typical greenhouse climate is regarded as one of the best analogues for future global warming. For the first time, mid Cretaceous temperatures were quantitatively reconstructed based on homogenization temperatures (Th) of halite fluid inclusions from the Lower Member of the Nong Bok Formation in the Thakhek mining area, Laos. Petrological features and primary textures of halite indicate a shallow water setting during halite formation that allows the use of homogenization temperatures as air temperature proxy. Obtained homogenization temperatures mainly range from 30 to 50 °C, probably representing local air temperature conditions of Laos during the mid Cretaceous. The determined temperatures are relatively similar to temperatures in many modern and ancient evaporative settings. The maximum homogenization temperature (Th_{Max}) for the Nong Bok Formation of 62.1 °C is significantly higher than existing mid Cretaceous paleotemperature records from both continental and marine sediments and comparable with the temperature records from the contemporaneous Mengyejing Formation of Yunnan, Southern China. The correspondence of the temperature records from Laos and Yunnan implies that very high temperature conditions prevailed in the region. Our results and other reconstructed very high temperatures from potash deposits (e.g., 59 °C for the Silurian Michigan Basin and 58 °C for the Quaternary Lop Nur region) suggest that extremely high temperatures probably had an important impact on the formation of the large potash deposits of the world. However, more studies are needed to improve our understanding of the detailed and quantitative relationships between temperature conditions and potash formation.

1. Introduction

Detailed research of good analogues of past greenhouse climates is essential for the reliable prediction of future environmental and climate changes on a warming Earth. Ancient greenhouse conditions are poorly understood especially in terms of the rates and magnitudes of climate change. The Cretaceous period, typified as long-term "greenhouse state" (Bice et al., 2006), attracted studies of various scientific communities in the past decades including research on abrupt climate change events such as oceanic anoxic events (OAEs; Schlanger and Jenkyns, 1976; Leckie et al., 2002; Jenkyns, 2003) and oceanic red beds (ORBs; Hu et al., 2005, 2006, 2012a, 2012b; Wang et al., 2005, 2009), Large Igneous Provinces (LIPs; Larson, 1991) and carbonate platform drowning events (Schlager, 1989). More importantly, the Cretaceous can also represent a model for a return to greenhouse climate as atmospheric CO_2 concentrations continue to rise during the twenty-first century (Jenkyns, 2003; Hay, 2011).

Multi-proxy records and climate simulations show that the Cretaceous period underwent different stages of climate change (Huber et al., 2002; Friedrich et al., 2012; Wang et al., 2013), and especially the mid Cretaceous apparently experienced the highest temperatures in the past 100 Ma (Pearson et al., 2001; Norris et al., 2002; Wilson et al., 2002; Friedrich et al., 2012). Exceptionally high temperatures during mid Cretaceous have been revealed by several geological lines of evidence such as extreme warmth of tropical sea surface temperatures (SSTs) above 35 °C that are at least ~7–8 °C warmer than today (Pearson et al., 2001; Norris et al., 2002; Wilson et al., 2002), warm deep-ocean temperatures in the southern high latitudes and the Pacific Ocean that reached up to 20 °C (Friedrich et al., 2012), and atmospheric CO_2 levels estimated to have been several times higher than those prior to the Industrial Revolution (Bice and Norris, 2002; Huber et al., 2002; Y.D. Wang et al., 2014).

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Despite the efforts of mid Cretaceous climate reconstructions, a number of uncertainties and deficiencies still exist. For example, compared to the well-known marine climate system, the Cretaceous continental climate is still poorly understood (Hasegawa, 1997, 2003; Grocke et al., 1999; Heimhofer et al., 2005), possibly reflecting the fact that terrestrial records tend to be fragmentary in nature and isolated in both space and time (Parrish, 2001). On the other hand, paleoclimate proxy data such as stable oxygen isotopes, TEX_{86}, tree rings, pollen, and leave-stomata inferred P_{CO2} reconstructions are often fragile to diagenetic alteration or only provide indirect and qualitative information. Quantitative and direct temperature records for mid Cretaceous climate reconstructions are still rare. Therefore, for a more accurate and comprehensive understanding of climate states during the mid Cretaceous, studies of continental climate records and quantitative temperature inferences are clearly required.

Salt minerals hold great potential for climatic reconstruction due to their sensitivities to climatic conditions (Roberts and Spencer, 1995; Benison and Goldstein, 1999). In particular, primary fluid inclusions within salt minerals are remnants of hydrosphere and atmosphere, and, therefore, can yield detailed information about water temperatures, water chemistries and even atmospheric conditions under which evaporites formed (Roberts and Spencer, 1995; Lowenstein et al., 1998; Benison and Goldstein, 1999). Compared with climate proxy data obtained through other ways, homogenization temperatures of halite fluid inclusions that formed at the Earth's surface especially in a shallow water environment can serve as indictor of water temperatures and approximate air temperature without corrections for substantial pressure, and provide a more direct and quantitative temperature record. It is thus widely used for temperature reconstruction of both the modern and past continental and oceanic systems (e.g. Lowenstein et al., 1998; Meng et al., 2011a,b). The core ZK2893 in the Thakhek mining area in Laos reveals continuous salt sediments of mid Cretaceous age. A large number of well-preserved primary fluid inclusions and other primary textures of halite samples suggest a saline-pan setting during halite deposition that provides a unique opportunity for using the homogenization temperatures as surface water temperature or approximate air temperature proxy. We therefore report for the first time mid Cretaceous air temperatures derived quantitatively from homogenization temperatures of halite fluid inclusions of the Nong Bok Formation in the Thakhek mining area (Laos). These new direct and quantitative paleo-temperature reconstruction results represent significant paleoclimate data that supplement the knowledge of Cretaceous climate conditions and promote our understanding of 'greenhouse' climate systems in general.

2. Study area

2.1. Geologic setting

The Khorat Plateau covers an area of 170,000 km^2 in the Esarn region in northeastern Thailand and central Laos (El Tabakh et al., 1999). As part of the Indochina terrane, tectonically, the plateau is bounded by the Nan Uttaradit Suture, Sukhothai Arc and Sibumasu Terranes to the west, and by the Song Ma Suture and the South Terrane to the north (Sone and Metcalfe, 2008; Metcalfe, 2011). The Mesozoic–Cenozoic deposition in the Khorat Plateau is closely related to the evolution of Tethys Ocean. Following the closure of the Palaeo-Tethys Ocean by the early late Triassic as a result of the collision of the Sibumau Terrane with the terrestrial Sukhothai Arc of western Indochina (Sone and Metcalfe, 2008), the late-stage tectonic relaxation or extension led to the formation of a half-graben basin. Nonmarine red beds of the Khorat Group with up to 5 km thickness were deposited in the basin (El Tabakh et al., 1999).

The overlying Nong Bok Formation in Laos, also known as the Maha Sarakhan Formation in Thailand is characterized by evaporite sequences with average thickness of 250 m and maximum thickness of 1.1 km in the center of the Khorat Basin (El Tabakh et al., 1999). These evaporites have been dated by palynological means (Sattayarak et al., 1991; Smith et al., 1996; Racey and Goodall, 2009) and isotopic evidence (Hansen et al., 2002), as Albian to Cenomanian (roughly 112–93 Ma). Detailed petrological and sedimentological analyses demonstrated that the evaporitic rocks formed in a large isolated inland basin (Utha-Aroon, 1993; El Tabakh et al., 1999), that probably encountered marine flooding (Zhang et al., 2013; L.C. Wang et al., 2014; Wang et al., 2015). During the early Paleocene, the continuing collision and resulting uplift caused the erosion of ca. 3000 m thick sediments of the Khorat Group and the formation of the NW–SE trending Phu Phan anticlinorium in the central part of the Khorat Plateau (Cooper et al., 1989; Mouret, 1994). The Phu Phan anticline in northeastern Thailand divides the plateau into two basins, the Sakon Nakhon Basin to the north and the Khorat Basin to the south.

The Thakhek mining area in Laos is located at the northeastern margin of the Sakon Nakhon Basin (Fig. 1). No significant fault has been observed in the area. The ZK2893 core with a length of about 600 m was recovered from the southeast of the Thakhek mining area (17°11′N, 104°49′E). The strata of the ZK2893 core consist of evaporitic–clastic sediments of the Lower and Middle Members of the mid Cretaceous Nong Bok Formation and Quaternary unconsolidated reddish and greenish silty–clayey sediments. The sediments between the Nong Bok Formation and the Quaternary deposits are lacking in core ZK2893 and other drill cores in Laos probably due to erosion in the late uplift phase of the plateau (Zhang et al., 2013).

2.2. Lithology and stratigraphy of core ZK2893

The lithology of core ZK2893 consists of two distinct evaporitic–siliciclastic cycles which represent the Lower and Middle Members of the Nong Bok Formation which are widely distributed throughout both the Sakon Nakhon Basin and the Khorat Basin. These members are mainly composed of evaporites separated by siliciclastic redbeds (Fig. 2).

The Lower Member is made up of basal anhydrite unit, the overlying halite unit including an anhydrite marker layer, potash unit and the topmost clastics unit. The basal anhydrite unit represents the base of the Nong Bok Formation throughout the whole plateau (El Tabakh et al., 1999), underlain by the Khorat Group sandstones. The anhydrite unit mainly occurs in form of laminar and nodular anhydrite, with nodular-mosaic or 'chicken-wire' texture. The overlying halite unit is about 190 m in thickness and usually exhibits individual halite beds of cm-scale thickness. Sporadically, anhydrite or gypsum beds occur as fine stringers or crumbs in the halite unit. Generally, two types of halite were observed in the lower member. One is characterized by cleaner halite with purer and more transparent halite crystals but less fluid inclusions. The other one is typified by smoky or milky halite within which well-preserved chevron halite occurs. In some cases, the latter type is stained by mud or fine siltstones. The potash unit overlying the halite unit hosts potash minerals mainly including sylvite, carnallite and tachyhydrite, and borate minerals (Hite and Japakasetr, 1979). The potash unit is capped with red clastic unit which is dominated by mudstones with disrupted and chaotic textures. The Middle Member of the Nong Bok Formation in core ZK2893 shares similar lithologic features with the Lower Member, except the absence of the potash unit.

3. Materials and experimental method

3.1. Materials

Halite samples were collected from the Lower Member of the Nong Bok Formation in core ZK2893, with stratigraphic levels at 586.29, 583.59, 572.66, 572.26, 563.16 and 394.14 m, respectively (Fig. 2). Halite samples mainly consist of transparent and gray or white halite with an admixture of anhydrite nodules and mud patches. Transparent halite