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Late Triassic volcanic activity in South-East Asia: New stratigraphical, geochronological and paleontological evidence from the Luang Prabang Basin (Laos)

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ABSTRACT

In South-East Asia, sedimentary basins displaying continental Permian and Triassic deposits have been poorly studied. Among these, the Luang Prabang Basin (North Laos) represents a potential key target to constrain the stratigraphic and structural evolutions of South-East Asia. A combined approach involving sedimentology, palaeontology, geochronology and structural analysis, was thus implemented to study the basin. It resulted in a new geological map, in defining new formations, and in proposing a complete revision of the Late Permian to Triassic stratigraphic succession as well as of the structural organization of the basin. Radiometric ages are used to discuss the synchronism of volcanic activity and sedimentation.

The Luang Prabang Basin consists of an asymmetric NE-SW syncline with NE-SW thrusts, located at the contact between Late Permian and Late Triassic deposits. The potential stratigraphic gap at the Permian–Triassic boundary is therefore masked by deformation in the basin. The Late Triassic volcaniclastic continental deposits are representative of alluvial plain and fluvial environments. The basin was fed by several sources, varying from volcanic, carbonated to silicic (non-volcanic). U–Pb dating of euhedral zircon grains provided maximum sedimentation ages. The stratigraphic vertical succession of these ages, from ca. 225, ca. 220 to ca. 216 Ma, indicates that a long lasting volcanism was active during sedimentation and illustrates significant variations in sediment preservation rates in continental environments (from ~100 m/Ma to ~3 m/Ma). Anhedral inherited zircon grains gave older ages. A large number of them, at ca. 1870 Ma, imply the reworking of a Proterozoic basement and/or of sediments containing fragments of such a basement. In addition, the Late Triassic (Carnian to Norian) sediments yielded to a new dicynodont skull, attributed to the Kannemeyeriiform group family, from layers dated in between ~225 and ~221 Ma (Carnian).

1. Introduction

During the Palaeozoic, the opening of the Palaeotethys and the Mesotethys on the India–Australian margin of Gondwana drove the separation of the continental blocks, North China, South China, Indochina, Simao and Sibumasu (e.g. Burrett, 1974; Şengör, 1979; Metcalfe, 1988, 2002, 2011). Then, during the Permian and Triassic periods, these blocks collided with Laurasia, leading to the closure of the Palaeotethys (e.g. Metcalfe, 2011). While different models exist to explain the timing of the Palaeotethys closure and the locations of the resulting suture zones (e.g. Lepvrier et al., 2008; Sone and Metcalfe, 2008; Cai and Zhang, 2009), the sedimentary basins recording this history remain poorly studied. For example, Feng et al. (2005) published a stratigraphic correlation between Triassic

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sediments from Thailand and southern China but also pointed out the lack of reliable data in Laos.

Studies of the Luang Prabang Basin in northern Laos (Counillon, 1896; Saurin, 1962; Bercovici et al., 2012) demonstrated that this area recorded the continental Permian and probably Triassic geological history. The basin can therefore be used to better understand the geological history of this eastern Tethysian domain and to fill the gap pointed out by Feng et al. (2005). In addition, some studies suggest that a NNE-SSW suture zone (or major fault) divides the Indochina Block (e.g. Lepvrier et al., 2008; Metcalfe, 2011). The cartographic trace of this suture zone is inferred in the vicinity of the Luang Prabang Basin. Therefore, the Luang Prabang area represents a potential key target to constrain the stratigraphic and structural evolution of the Indochina Block.

The first mention of vertebrate fossils in the Luang Prabang Basin (Fig. 1A and B) dated back to the 19th century when Counillon (1896), recorded dicynodont remain from the continental deposits of the Purple Claystones Formation, north of the Mekong River (Fig. 1C). Repelin (1923) first attributed the fossil to the genus *Dicynodon*. Latter, it was attributed to the genus *Lystrosaurus* by Woodward (1932) before to be reattributed to the genus *Dicynodon* by Piveteau (1937a, 1937b, 1938) and Battail (2009). Accordingly, this formation was attributed to the Late Permian (Battail, 1997, 2009; Steyer, 2009). A recent work has shown the volcaniclastic character of the corresponding deposits, where volcanic fragments were reworked in an alluvial environment (Bercovici et al., 2012). Nevertheless, the overall structures and ages of the formations described in the latest geological map of the area (Saurin, 1962) are still a matter of debate. Moreover, the evolution of the sedimentary succession is partly understood to the north of the Mekong River for the Late Permian (Bercovici et al., 2012; Fig. 1D) but is still unknown to the south. This new study concerns the entire Late Permian to Late Triassic successions and was thus carried out on both sides of the Mekong River. The aim of this study is therefore to give new insights into the sedimentary context, the age of the series, and on the structure of the basin using a combined approach involving sedimentology (facies and petrographical analyses), palaeontology, geochronology (U–Pb dating on zircon) and structural analysis. The results were used to propose a new geological map and a synthetic log for the Permian and Triassic successions in the Luang Prabang Basin. They also illustrate the particular usefulness of this type of combined approach to demonstrate the synchronism of volcanic activity and sedimentation in tuffaceous rocks (tuffites), in which volcaniclasts are reworked.

2. Geological setting

The first description of the sedimentary successions in the Luang Prabang Basin was provided by Counillon's (1896) study to the north of the Mekong River (Fig. 1C). This author produced the first geological map (1:60,000) of the area, where he described five lithological "zones" that are now defined as formations (Bercovici et al., 2012). In 1962, Saurin published a smaller scale (1:500,000) geological map in which most of the geological contacts were redrawn after Counillon (1896). On his map, Saurin (1962) drew an anticline. The five formations recognized from the southeast to the northwest (Fig. 1C) are listed in Table 1.

(1) The Marine Limestones Formation ("Zone des Calcaires", Fig. 1C) contains rare fossils of marine affinity (Counillon, 1896): brachiopods (*Rhynchonella* sp., *Spiriferina* sp.) and bivalves (*Avicula* sp.). The occurrence of ammonites (*Discophyllites* sp., *Tibetites* sp.) attributes a Norian (Late Triassic) age (Fromaget, 1929; Saurin, 1962).

(2) The Red Claystones Formation ("Zone des Argiles rouges", Fig. 1C and D) is attributed to an alluvial plain environment (Bercovici et al., 2012). Reptile remains were found in this formation by Counillon (1896), but they were too fragmentary to be identified and useful for biostratigraphy (Battail, 2009). Therefore, the age of this formation is unclear. It is considered as Permian or Triassic (Battail, 2009), whereas Saurin (1962) described this formation as middle Indosinias (i.e. Upper Triassic to Middle Jurassic).

(3) The Limestones and Sandstones Formation ("Zone des Calcaires et Grauwackes", Fig. 1C and D), contains fine-grained calcareous sandstones with numerous marine organisms (brachiopods, ammonoids, bivalves, gastropods and bryozoans). According to Bercovici et al. (2012), this formation was deposited in a coastal environment, preserving both continental plants and marine organisms. Saurin (1962) described this formation as lower Indosinias (i.e. Pennsylvanian and Permian). However, the basal part is constituted of sandstone containing an ammonoid identified as a *Pseudotirolites* sp. (Brayard, Burgundy University, pers. com., 2011), which suggests a late Changhsingian (Late Permian) age. It is overlain by a 2 m-thick layer of black claystones that contains numerous plant debris, such as *Lobatannularia* and *Gigantopteris*, bracketing its age between the Middle to the Late Permian (Bercovici et al., 2012). The structural and stratigraphic relationships of this formation with the Purple Claystones Formation remain unknown at this stage.

(4) The Purple Claystones Formation ("Zone des Argiles violettes, Fig. 1C and D), where abundant cranial and postcranial of *Dicynodon* therapsids (Counillon, 1896; Battail, 2009) and at least one carnivorous chroniosuchid anthracosaur amphibian were found (Steyer, 2009; Bercovici et al., 2012), is mainly composed of purple claystones interstratified with conglomeratic and sandstone levels. The conglomerates contain limestone pebbles with abundant marine fauna that correspond to late Early – Middle Permian ages in Laos (Saurin, 1956; Fontaine, 2002) or to Pennsylvanian – Middle Permian deposits in Thailand and Vietnam (Thanh and Khuc, 2006). This formation is characteristic of braided rivers within an alluvial environment constituted by playa-lake, floodplain or pound with volcanic fragments (feldspars and rocks, Bercovici et al., 2012). The first authors who worked on this formation (Repelin, 1923; Piveteau, 1937a, 1937b, 1938) attributed it to the Triassic, based on what was then known about the age of the *Dicynodon* genus, while Saurin (1962) attributed this formation to the middle Indosinias (i.e. Upper Triassic to Middle Jurassic). However, current data on the stratigraphic distribution of these dicynodonts favour a Late Permian age (Battail, 2009).

(5) The Grey Sandstones Formation ("Zone des Grès gris", Fig. 1C) mentioned by Counillon (1896) was never really described. This formation likely corresponds to the "Anthracolitic" (i.e. Carboniferous, stratigraphically below the lower Indosinias) on Saurin's (1962) map.

3. Methods

3.1. Fieldwork and mapping

In order to propose an updated geological map for the Luang Prabang area, approximately 100 localities were studied from a structural, sedimentological, petrographical, palaeontological and, geochronological point of view. In addition, the south of the