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Dinosaur eggshell assemblage from Japan reveals unknown diversity of small theropods

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ABSTRACT

The Lower Cretaceous (Albian) Sasayama Group in the Hyogo Prefecture of southwestern Japan has yielded various vertebrate fossils, including skeletal remains of dinosaurs, anurans, lizards, and mammals, and recently eggshell fragments. Here we report on numerous fossil eggshells from the bone-bearing Kamitaki locality in Tamba City, which represents a diverse dinosaur eggshell assemblage. Of the more than 90 eggshell fragments recovered, five different types were identified, including eggshells that likely belong to a variety of theropods (*Nipponoolithus ramosus* oogen. et oosp. nov., *Elongatoolithus* sp., *Prismatoolithus* sp., and Prismatoolithidae indet.) and at least one ornithopod (*Spheroolithus* sp.). All eggshells are relatively thin, and a new derived estimation method correlating egg mass with eggshell thickness indicates that they are among the smallest (28–135 g) theropod eggs known, likely laid by small bodied forms. The eggshell assemblage from this locality suggests that a diverse small dinosaur fauna, consisting primarily of theropods, nested in the region, a diversity yet to be evidenced from skeletal remains in Japan.

1. Introduction

Dinosaur remains are rare in Japan, although there has been a rapid increase in discoveries in recent years (Kobayashi et al., 2006). Since 1978, about 20 dinosaur-bearing localities have been found, which have yielded mainly isolated bones and teeth (for review see Kobayashi et al., 2006), with the exception of a few partial skeletons (Kobayashi and Azuma, 2003; Ohashi and Barrett, 2009; Azuma and Shibata, 2010; Saegusa and Ikeda, 2014; Shibata and Azuma, 2015). Although dinosaur skeletal remains have been the subject of detailed descriptions (Azuma and Currie, 2000; Kobayashi and Azuma, 2003; Azuma and Shibata, 2010; Saegusa and Ikeda, 2014; Shibata and Azuma, 2015), other fossils that potentially belong to non-avian dinosaurs, such as eggshells, have been mentioned only briefly (Azuma, 2003; Hirayama et al., 2003) and have yet to be described. In this paper, we provide the first description of a dinosaur eggshell assemblage from Japan from a new locality in the Sasayama Group in the Hyogo Prefecture.

In 2006, a fossil vertebrate locality, herein referred to as the Kamitaki locality, was discovered in exposures of the Lower Cretaceous Sasayama Group in the southeastern area of Tamba City, eastern Hyogo Prefecture, southwestern Japan (Fig. 1). This locality has since yielded skeletal remains of anurans, lizards, and non-avian dinosaurs (i.e., a basal hadrosaurid, ankylosaur, titanosauriform sauropod, tyrannosauroid, therizinosauroid, and indeterminate theropods) (Saegusa and Ikeda, 2014), as well as numerous fossil eggshells. The eggshell fragments ($n > 90$) were collected from a relatively small area (11×10 m) in a bonebed layer that contains articulated anuran skeletons, as well as isolated bones and/or teeth of the aforementioned dinosaurs. The bone layer is contained within a reddish mudstone, interpreted to be a floodplain deposit (Saegusa and Ikeda, 2014). The layer is stratigraphically located in the lower part of the 'Lower Formation' of the Sasayama Group (Fig. 1a, b), which is composed of conglomerates,

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sandstones, mudstones, and contains several intercalated tuff beds (Yoshikawa, 1993). Radiometrically-dated tuff beds in the lower parts of the 'Lower Formation' and 'Upper Formation' constrain the age of the locality between 112.1 ± 0.4 Ma and 106.4 ± 0.4 Ma, indicating an early Albian age (Kusuhashi et al., 2013).

1.1. Institutional abbreviations

HEC, Hirsch Egg Catalogue, University of Colorado Museum, Boulder, Colorado; MNHAH, Museum of Nature and Human Activities, Hyogo, Japan; NMMNH, New Mexico Museum of Natural History and Science, Albuquerque, New Mexico; UCM, University of Colorado Museum, Boulder, Colorado; YPM-PU, Princeton University collection at Yale Peabody Museum, New Haven, Connecticut.

2. Materials and methods

More than 90 eggshell fragments were recovered from the Kamitaki locality via manual excavation of the rocks within the site. For this study, 72 eggshells that have been prepared were studied. These were initially categorized into different types, based on outer surface morphology, with the use of binocular microscopes (Leica M80 and Nikon SM2100). The microstructure of each type of eggshell was examined using scanning electron microscopy (SEM; on FEI Quanta FEG 250 and Hitachi TM-1000) and polarized light microscopy (PLM; on Leica DM2500P) in order to confirm the classification and to describe the eggshell. Radial thin sections of each eggshell type were made for observation under PLM. Photomicrographs were captured digitally and processed with Adobe Photoshop CS5. The eggshell thickness was measured using a digital micrometer Mitutoyo CPM30-25 MJ (precision = 2 μm), a digital caliper Mitutoyo CD-15PX (precision = 0.02 mm), or from digital images of radial thin sections in Photoshop. Descriptive terminology follows Mikhailov (1991).

Egg mass for the different types of Kamitaki eggshells was estimated using eggshell thickness. Although eggshell thickness of non-avian dinosaurs has been regressed against egg mass previously, only poor to moderate correlations resulted (Deeming, 2006), perhaps due to the small sample size ($n = 8$ for theropods

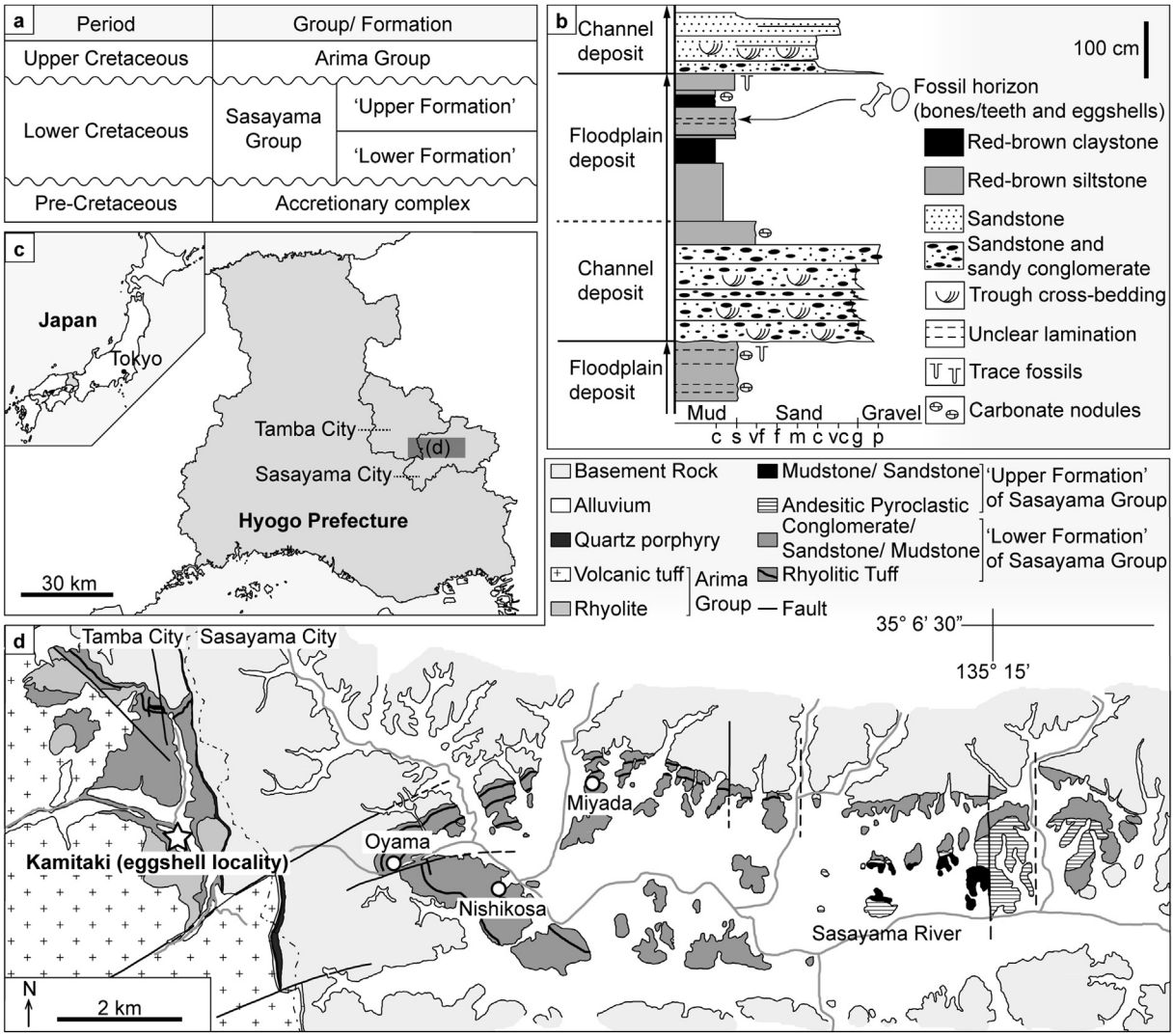

Fig. 1. Stratigraphic position and locality maps of the Kamitaki eggshell site in Hyogo Prefecture, Japan. (a) Stratigraphic position of the 'Lower Formation' of the Sasayama Group (modified from Kusuhashi et al., 2013). (b) Stratigraphic section at the Kamitaki eggshell site (modified from Saegusa et al., 2010). (c) Geographical location of Tamba and Sasayama cities in eastern Hyogo with location of eggshell locality (grey area). (d) Location of eggshell locality (star) (modified from Yoshikawa, 1993 and Saegusa and Ikeda, 2014).