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Eocene–Oligocene glaciation on a high central Tibetan Plateau

Guoqing Xia1,2, Chihua Wu1,2,*, Ahmed Mansour3,4, Xin Jin1, Haisheng Yi1, Gaojie Li5, Qiushuang Fan1,2, Zhiqiang Shi1, Julian B. Murton6, Junling Pei7,* and Juan Pedro Rodríguez-López2,6,8

1State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China
2Plateau and Global Desert Basins Research Group (PAGODA), Institute of Sedimentary Geology, Chengdu University of Technology, Chengdu 610059, China
3School of Geoscience and Technology, Southwest Petroleum University, Chengdu 610500, China
4Geology Department, Faculty of Science, Minia University, Minia 61519, Egypt
5College of Resources and Environmental Engineering, Mianyang Normal University, Mianyang 621000, China
6Permafrost Laboratory, Department of Geography, University of Sussex, Brighton BN1 9QJ, UK
7Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China
8Department of Geology, Faculty of Science and Technology, University of the Basque Country (UPV/EHU), Ap. 644, E-48080 Bilbao, Spain

ABSTRACT

The nature of glaciation (bipolar vs. unipolar) during the Eocene–Oligocene transition (EOT) remains unresolved. Here, we report the occurrence of frost marks, ice-rafted debris (IRD), and glendonites from the Upper Eocene to Lower Oligocene Niubao Formation (Fm.) deposited in a proglacial lake above glaciolacustrine conglomerates and diamicritic facies in the Lunpola Basin, central Tibetan Plateau (CTP). Magnetostatigraphy dates these cryospheric deposits to ca. 36.2–31.8 Ma, synchronous with a stratigraphic interval containing IRD offshore of SE Greenland and in the Barents, Chukchi, and Laptev Seas, suggesting a strong continental-oceanic coupling. Our results provide robust continental evidence for intermittent cryospheric processes in the midlatitude Northern Hemisphere during the late Eocene and EOT. The global cold snap EOT-1 influenced already glacierized high-altitude mountains, lowering equilibrium line altitudes (ELAs) of glaciers and leading to local development of ice fields, ice caps, and valley glaciers with proglacial lake systems, such as the one recorded in the Niubao Fm. The record of IRD, glendonites, and frost marks before the onset of EOT-1 points to an active cryosphere on a plateau already elevated by ca. 36.2 Ma.

INTRODUCTION

During the Cenozoic, widespread mountain glaciations on Earth are thought to have occurred no earlier than the Miocene and Pliocene (Hutchinson et al., 2021), with the Eocene–Oligocene transition (EOT) characterized by unipolar glaciation restricted to Antarctica (Zachos et al., 2001). However, increasing evidence from the EOT indicates that polar ice also existed in the Northern Hemisphere (e.g., Tripati et al., 2020), and therefore for evaluating the occurrence of glaciations during the EOT.

Here, we report the occurrence of frost marks, glendonites, and ice-rafted debris (IRD) from the Niubao Formation (Fm.) in the Lunpola Basin, central Tibetan Plateau (CTP). Their age is constrained between 36.2 and 31.8 Ma by magnetostratigraphy and radiochronologic dating. These ice-related structures in the midlatitudes of the Northern Hemisphere record terrestrial cryospheric processes during the EOT. This new finding reveals an active continental cryosphere with plateau glaciation in central Asia.

GEOLOGIC BACKGROUND AND LITHOSTRATIGRAPHY

The ice-related structures were observed at section 382 (32.034°N, 89.154°E) beside the Zagya Zangbo River, north of Selin Co (lake), in the Lunpola Basin (Fig. 1; Figs. S1A and S1B) to further constrain *paleomagnetic sampling was performed at section 382 (32.034°N, 89.154°E) beside the Zagya Zangbo River, north of Selin Co (lake), in the Lunpola Basin (Fig. 1; Figs. S1A and S1B) to further constrain

CHRONOSTRATIGRAPHY

The age of the studied section is well-constrained by magnetostatigraphy and radiochronology. Han et al. (2019) obtained an absolute U-Pb age of 35.31 ± 0.93 Ma from zircon in a tuff 108 m above the base of section 382 (Fig. 1C), producing a general chronologic framework. For the present study, detailed paleomagnetic sampling was performed at mostly 0.2–0.7 m intervals through section 382 (Fig. 1; Figs. S1A and S1B) to further constrain

1Supplemental Material. Analytical methods and description of the measured section, with figures and supporting data. Please visit https://doi.org/10.1130/G51104.1/GEOL.S.22304125 to access the supplemental material, and contact editing@geosociety.org with any questions.

the chronology. Stepwise thermal demagnetization was applied to two sets of specimens (286 in total) from the samples. Well-defined characteristic remanence magnetization (ChRM) directions were recognized in 192 samples (Fig. S2). Based on virtual geomagnetic pole (VGP) latitudes, five pairs of normal (N1–N5) and reversed (R1–R5) magnetic polarity intervals were observed (Fig. 1). Constrained by the radiochronologic dating by Han et al. (2019), the observed magnetic polarities were correlated with chrons C16r to C12n of the Geologic Time Scale 2012 (GTS2012; Gradstein and Ogg, 2012), yielding an age range of ca. 36.7–30.6 Ma for the studied section, constraining the occurrence of ice-related structures to ca. 36.2–31.8 Ma (Fig. 1).

CRYOGENIC STRUCTURES

Three groups of cryogenic structures occur in the middle unit of the Niubao Fm.: (1) frost marks, (2) ice-rafted debris (IRD), and (3) glendonite pseudomorphs after ikaite. Frost marks on bedding planes are the most common, characterized by radiating, dendritic, and feather-like shapes typical of ice crystals (Figs. 2A, 2B, 2E, and 2F). The marks have straight and sharp margins, straight to slightly curved lineations, and radiate outward from nuclei. They are geometrically similar to modern frost structures (Figs. 2C, 2D, and 2G). The Eocene frost marks are typically 2–5 cm long (≤50 cm) and 2–5 mm wide, often linked. They branch into each other with a recurrent pattern and a uniform angle (<30°) between branches. Host dolomite facies are fine grained (<10 μm grain size; Figs. S3A and S3B) and appear to lack evidence for significant recrystallization. The intermittent occurrence of frost marks on bedding planes indicates that the Lunpola lake basin experienced strong seasonal temperature variations and winters characterized by water temperatures below 0 °C (Girard et al., 2015).

IRD features appear as angular and sub-rounded droppstones (outsized clasts) encased in laminated sediments, at both outcrop (Figs. 3A–3C) and petrographic scale (Figs. 3D–3F). The clasts deform the underlying sediments, showing bending, rupture, and penetration structures at their base and drape and onlapping structures at their top (Figs. 3D–3F). The clasts are widely scattered in the laminated sediments and associated with glendonites. Disruption of the lower contact and onlapping geometries of laminations suggest that the clasts sank to the lake bottom, deforming underlying sediments (Rogov et al., 2021), and were subsequently draped by laminated sediments. The outsized clasts are thus interpreted as droppstones that sank from drifting ice floes and icebergs into the lake bottom (Rodríguez-López et al., 2021). The droppstones show vertical to steeply dipping orientation of their long axes with respect to bedding planes (Figs. 3A–3C), like other IRD worldwide (Rodríguez-López et al., 2016, 2021; Le Heron et al., 2021).

Glendonites occur mostly as euhedral blocky carbonate crystals or aggregates with pyramidal faces, with a displacive growth form in the laminated sediments (figs. 2H–2N). Crystal size is 0.1–1.5 mm, and, in cross section, the shape is blocky or rhombic. Penetrative, blocky twins
are common, with obtuse angles (95°–125°) (Fig. 2I). Sedimentary laminae curve around the structures as they do around authigenic phosphatic nodules, suggesting that glendonite precursors formed during early diagenesis, prior to sediment compaction. Cathodoluminescence images show that the glendonites have been diagenetically altered (Figs. 2K–2N; Figs. S3C and S3D), preserving secondary porosity (Fig. S3C) due to dehydration and volumetric reduction during the conversion of ikaite to more stable polymorphs (Mikhailova et al., 2021). Natural ikaite forms between –2°C and +7°C (Vickers et al., 2022). The occurrence of glendonites after ikaite in sediments hosting frost marks and IRD indicates that freezing temperatures occurred intermittently during deposition of the Niubao Fm.

**ICE-CONTACT FAN CONGLOMERATES AND DIAMICTITES**

The lower unit of section 382 consists of decameter-thick conglomerates containing striated clasts, as well as interbedded diamicrite facies with dropstones (Figs. 3G–3I), indicating deposition by proglacial or subglacial processes in an ice-contact, coarse-grained fan (e.g., Bache et al., 2012). Striated clasts (Figs. 3J–3O) suggest gravitational redeposition of subglacial till blocks (Ezpeleta et al., 2020) transported by subglacial melt streams to the proglacial lacustrine ice-contact fan. Calving at the glacier ice front discharged icebergs carrying till and generated dropstones in the coarse-grained proximal proglacial lake facies. The dropstones are identified by the occurrence of plastic deformation beneath some blocks in the conglomerates (Figs. 3H–3I) (e.g., Le Heron et al., 2021). The occurrence of diamicite facies associated with ice-contact fan conglomerates is a common facies association in proglacial lakes (Sutherland et al., 2019). Diamicite facies containing dropstones like those observed in Figures 3A–3C are interbedded with conglomerates from Paleozoic analogues in Brazil (Bache et al., 2012) and glacilacustrine moraines in the central Tien Shan, eastern Kyrgyzstan (Häusler et al., 2014).

**DISCUSSION AND CONCLUSIONS**

**Eocene–Oligocene Glaciation**

The EOT involved a major environmental and climatic change that lasted for ~790 k.y., leading to the first major glaciation in...
Antarctica and to a global cooling event from a largely ice-free greenhouse to an icehouse world (Zachos et al., 2001; Hren et al., 2013). Although it is generally believed that the Paleogene cryosphere was related to a unipolar Antarctic glaciation, our data from continental facies of central Tibet indicate plateau glaciers during the Eocene. Our results are based on 19 stratigraphic occurrences of ice-related structures (frost marks and IRD) and cold-water–related authigenic minerals (glendonites after ikaite) recovered from the 156-m-thick interval. Freezing conditions prevailed at least seasonally, leading to an exceptional record of dropstones produced by melting ice floes and icebergs on the lake and by the growth of ikaite in the lacustrine sediments of a proglacial environment. Paleomagnetic dating of the host strata indicates that these cryospheric deposits formed at 36.2–31.8 Ma, synchronous with an interval of sea ice and IRD accumulation offshore of SE Greenland and in the Barents, Chukchi, and Laptev Seas (Fig. 4) (Tripati and Darby, 2018).

Paleogene Uplifted Central Tibetan Plateau
The timing and magnitude of the uplift of the CTP are controversial (Fig. S4). The first estimate of the paleoelevation of the Lunpola Basin, ~4.5 km above sea level (asl) at >35 Ma, came from pedogenic carbonate δ18O data (Rowley and Currie, 2006). A high elevation (~3 km asl) during the Eocene–Oligocene (45 and 30 Ma) for the proto-Tibetan Plateau in the CTP region has also been proposed (Wang et al., 2008; Spicer, 2017). Our previous studies indicated an active Cretaceous plateau cryosphere (Wu and Rodrí¬
frozen conditions in the Tibetan EOT higher and making the minimum altitude needed for western Pacific Ocean (Straume et al., 2022), higher than present, reaching stages after the global events EOT-1 and Oi-1. We also found evidence of dropstones during the global cold snap EOT-1 suggesting glacier calving. We also found evidence of winter freezing, and the occurrence of cool waters in the lake for at least five stages before the EOT-1, and two glacial cooling—which lasted only 790 k.y. (Hutchinson et al., 2021)—but also by the altitude that the plateau had already reached. Thus, we argue that the CTP had reached a high paleo-altitude by 36.2 Ma, controlling the altitudinal distribution of ELAs and Cenozoic glaciers. The interval recorded in the Lunpola Basin by ice-related structures likely involved cooling—which lasted only 790 k.y. (Hutchinson et al., 2021)—but also by the altitude that the plateau had already reached. Thus, we argue that the CTP had reached a high paleo-altitude by 36.2 Ma, controlling the altitudinal distribution of ELAs and Cenozoic glaciers. The interval recorded in the Lunpola Basin by ice-related structures likely involved a topographic transition from an intramontane basin surrounded by prominent mountain ranges to a plateau terrain.

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REFERENCES CITED

GEOLOGY | Volume XX | Number XX | www.gsapubs.org


Qu, Y.G., Wang, Y.S., and Duan, J.X., 2011, Report of 1,250,000 regional geological survey in Duoba area: Wuhan, China University of Geosciences Press.


Straume, E.O., Nummellin, A., Gaina, C., and Nisanciglu, K.H., 2022, Climate transition at


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