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Palynological evidence sheds new light on the age of the Liuqu Conglomerates in Tibet and its geological significance

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The Liuqu Conglomerates consist of a suit of terrestrial molasse deposits formed in a foreland basin of the Himalaya-Tibet orogenic belt before the collision of India and Eurasia. These deposits record considerable geological information regarding the late tectonic evolution of the Neotethyan ocean. The palynological study of interlayers of mudstone and mud-sandstones indicates an Oligocene age. The palynological assemblage consists mainly of deciduous broad-leaved angiosperms, with some coniferous gymnosperms and evergreen broad-leaved angiosperms. The deposits reflect a broad-leaved deciduous forest or mixed with conifer-broad-leaved forest ecotypes, showing a warm-temperate or temperate zone climatic environment. This work provides significant new information about the tectonic evolution, paleogeography, and paleoenvironment of southern Tibet during the Cenozoic.

Southern Tibet, Yalung Zangpo suture zone, Liuqu Conglomerates, palynological assemblage, Oligocene

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Uplift of the Tibetan Plateau has resulted from the Indian plate subducting beneath the Eurasian plate, followed by the closure of the Neotethys, collision of India against Eurasia, and crustal shortening. The Yalung Zangpo ophiolite belt represents the remnant crust of the Neotethys, and the belt associated with a Mesozoic-Cenozoic volcano-sedimentary formation on both sides of the belt constitutes the Yalung Zangpo suture zone, which is a complex tectonic zone resulting from the evolution of the Neotethys during the Late Triassic to Paleogene and the collision between the Indian plate and the Eurasian plate [1–23]. The sedimentary layers within the Yalung Zangpo suture zone contain a vast amount of information regarding India-Eurasia convergence and collision history.

At least two types of clast-dominated molasse formations can be recognized along the Yalung Zangpo suture zone in southern Tibet [24]. One of them crops out on the north side of the Yalung Zangpo suture zone, and includes marine and terrestrial molasse deposits. The marine deposits include the uppermost Cretaceous-Eocene Quxia and Jialazi groups [25–28]. The terrestrial deposits are represented by the Gangrinboche Conglomerates, consisting of the Kailas, Qiuwu, Dazhuka, and Luobusha groups of uppermost Oligocene to lower Miocene affinity [24, 29–32]. The other one crops out on the south side of the Yalung Zangpo suture zone or amongst the Yalung Zangpo suture zone, and also includes marine and terrestrial molasse deposits. Here, the marine deposits are represented by the upper Paleogene to

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lower Eocene Gyachala and Zheya groups [16, 33, 34]. This study focuses on the Liuqu Conglomerates [29, 35], which belong to the terrestrial deposits. Aitchison et al. [36] reported that multiple subduction systems are preserved within the Yalung Zangpo suture zone. These could represent several subduction-collision events. The molasse formations described above are related to these subduction-collision events. Further, at least one intra-oceanic island arc system existed within the Neotethys, and the island arc systems accreted to the passive Indian margin prior to its collision against Eurasia [37]. Recent studies interpreted the Liuqu Conglomerates to have developed in association with an early collision event between the Indian plate and an oceanic arc system inside the Neotethys [21–24, 35–37]. A suite of molasse sediments formed in a foreland basin after island arc-continent collision, thus recording considerable geological information regarding the upper period of Neotethyan evolution.

Geologists have spent considerable time and effort investigating the age of the Liuqu Conglomerates. Guo [38] first found some plant impression megafossils in the 1960s and 1970s within the conglomerates at the north of Gelongpu village in Lhatse County, and identified them as an Upper Cretaceous flora. Tao [39, 40] reported tropical and subtropical plant impression megafossils in the 1980s from the Liuqu Conglomerates near the Gongqiongla Village in Lhatse County, and identified them as a middle to upper Eocene flora. On the basis of stratigraphic relationships, Davis et al. [35] inferred indications that the conglomerates formed in the Paleogene. Geologists from the Institute of Geological Survey of Tibet Autonomous Region[1)] collected *Miscellanea* sp. (foraminifera) at Gadui during their geological survey. A scientist from Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences identified these and thought the age to be Paleocene. Researchers from the Institute of Geological Survey of Hubei Province[2)] reported some plant impression megafossils and a small number of gastropod and bivalve fossils in the Liuqu Conglomerates at Gelongpu village of Lhatse County, which belong to the Paleocene-Eocene. Fang et al. [41, 42] reported finding more than 10 species of angiosperm leaf impressions, which they identified as a middle to upper Eocene flora. Yin et al. [29] concluded that the age span of the Liuqu Conglomerates should be between the middle-late Eocene and the Miocene based on the analysis and comparison of plant megafossils.

However, no one has studied mudstone interlayers within the Liuqu Conglomerates using palynological analysis. Previous age assignments were based primarily on plant impression fossils. Wei et al. [43] obtained abundant, well-preserved spore and pollen fossils for the first time, and briefly discussed paleovegetation. This paper focuses on sedimentary age, paleoenvironment and tectonic significance, which provide important evidence on the age and depositional environments of the conglomerates. Compared to plant megafossils, the palynology offers certain advantages in determining the Cenozoic paleoclimate and identifying ages, partly because palynological records in sediments are relatively continuous [44]. Furthermore, palynological assemblage in sedimentary rocks reflects the regional paleovegetation during that geological epoch, as fossil spores and pollens can fill gaps in the incomplete record of plant megafossils (resulting from limited preservation). Continuous floral records can clarify the paleoclimatic and paleoenvironmental changes of a source area, because palynology offers a real index that reflects the paleoclimate, paleogeography, and paleoenvironment. On the other hand, evolutionary biology and floral characteristics can confirm the ages of terrestrial sedimentary strata, and these have important significance for studying the uplift of the Tibetan Plateau.

1 Geological setting

The Liuqu Conglomerates are located amongst the Indian, Bainang and Dazhuqu terranes and distributed in southern Tibet near Xigaze, cropping out discontinuously at Liuqu, Gadui, Qumei, and Bainang counties, along the Yalung Zangpo suture zone. The conglomerates extend for more than 150 km from west to east. Their width varies between hundreds of meters to kilometers, occupying a total area of about 30 km^2 (Figure 1).The field section we investigated extends south-north across the Requ River (28°08′41″N, 88°07′34″E). The segment of the section on the river's south bank is very short, but that along the north bank of the river extends 3.5 km up valley, northward to the ophiolite belt (at 4670 m, Figure 2). At the northern margin of the Liuqu Conglomerate belt, ophiolitic mafic-ultramafic slabs of Dazhuqu terranes have been thrust southward, generally over the Liuqu Conglomerate beds at a high-angle (Figure 2(a)). Upper Triassic epimetamorphic blocks (Xiukang Group) within Paleogene mélange (Yamdrok mélange) are thrust northward with a dip angle near 70° over the Liuqu Conglomerates at the south end of the section (Figure 2(e)). This exposure of the Liuqu Conglomerates dips mostly to the north (Figure 2(c)). Open folds can be seen locally, and the main layers lie in a normal sequence. A typical open syncline can be seen stretching to the east and west in the northern section (upper part). The opposite two limbs of the syncline dip between about 15° and 30° (Figure 2(b)). The uppermost layer of the conglomerates outcrops in the synclinal core. The north limb of the syncline (the northernmost part of the section) becomes more vertical and even over-

1) Institute of Geological Survey of Tibet Autonomous Region. Report of regional geological survey in Xigaze (1/250000) (in Chinese). 2002.
2) Institute of Geological Survey of Hubei Province. Report of regional geological survey in Lazi County (1/250000) (in Chinese). 2003.

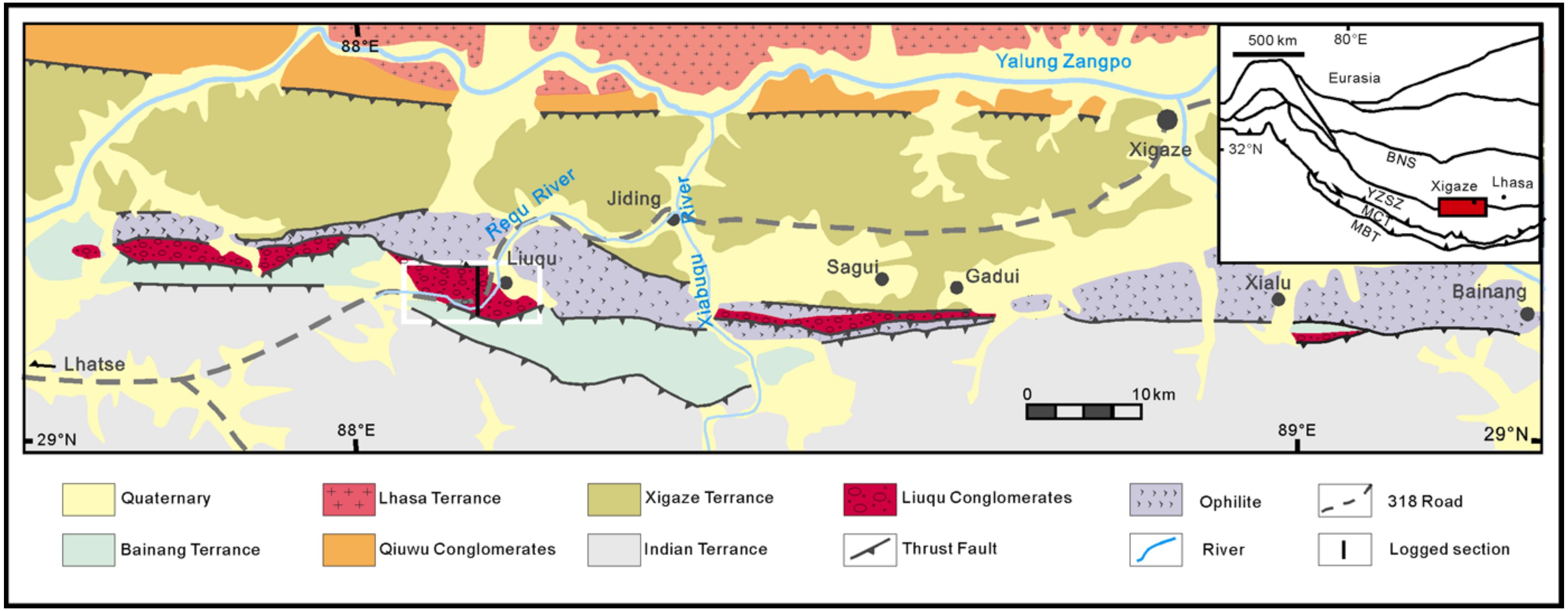

Figure 1 Geological sketch map of the Liuqu Conglomerates indicating the position of major tectonic features and locations mentioned in this paper. The Liuqu Conglomerates crop out intermittently along the YTSZ. Revised from Davis et al. [35] and Aitchison et al. [21, 37]. MBT=main boundary thrust of the Himalayas, MCT=main central thrust of the Himalayas, YZSZ=Yalung Zangpo suture zone, BNS=Bangong-Nujiang suture zone.

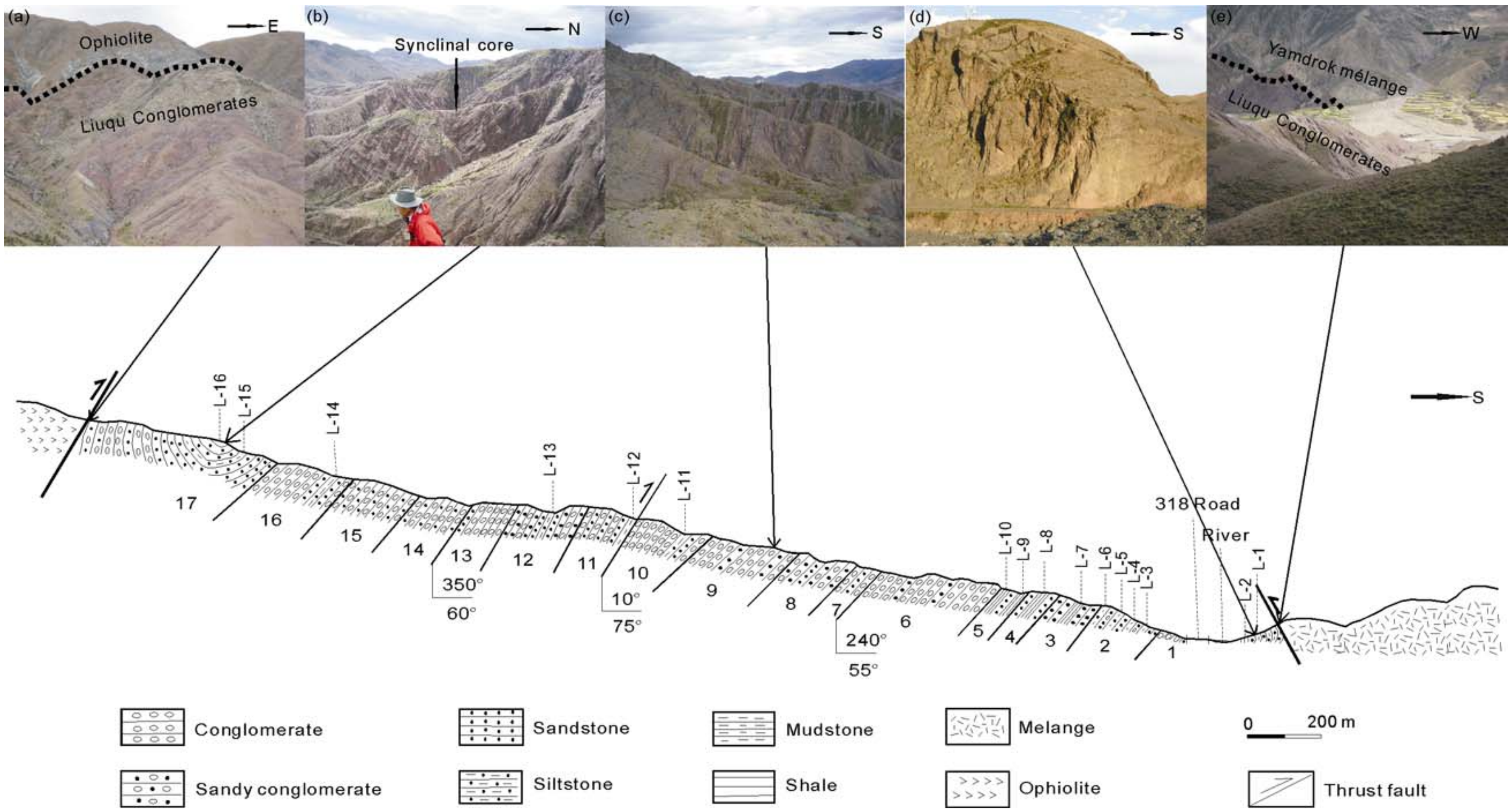

Figure 2 Section from which palynological assemblage was recovered, showing the stratigraphy and lithology of the Liuqu Conglomerates and the locations of the samples. (a) Thrust fault between the ophiolite belt and the Liuqu Conglomerates; (b) synclinal core in the upper part of the Liuqu Conglomerates; (c) photograph taken looking east from another ridge in the middle part of the Liuqu Conglomerates; (d) muddy siltstone; (e) thrust fault between the Yamdrok mélange and the Liuqu Conglomerates.

turned locally at a south-directed drag thrust. The main clastic beds of the Liuqu Conglomerates include mottled conglomerates, purple red sandy conglomerates, and red sandstone intercalated with muddy sandstones and silty mudstones. Thin gray-green muddy sandstones (Figure 2(d)) and the silty mudstones are distributed through the bottom and upper layers.

Davis et al. [35] describe the regional tectonic background for the Liuqu Conglomerates, indicating that they were deposited in an oblique-slip basin within both terrestrial and sub-aqueous settings between the northern edge of the Indian continent and an island arc of Late Jurassic to Cretaceous age within the Neotethys. Sedimentary rhythm displays an upward thinning on the whole. The sedimentary facies of the Liuqu Conglomerates change clast type, grain size and depositional style abruptly, indicating that the suite of conglomerates was deposited rapidly and during a short period [35]. The overall lithologies of the Liuqu Conglomerates are coarse, so we only collected 16 samples in the thin interlayers across the whole section (Figure 2).

2 Discussions

All 16 samples contain abundant spores and pollens. Fifty-two genera were identified and 200–300 grains were counted within each sample. The major floral components are shown in a spore and pollen percentage diagram (Figure 3). Figure 4 shows photographs of some of the dominant genera. Detailed data see Wei et al. [43].

2.1 Geological age

Angiosperm pollen grains dominate the palynological assemblage from the Liuqu Conglomerates, and the angiosperm pollens are characterized by abundant porate pollens, such as Betulaceae, Juglandaceae, Fagaceae, Ulmaceae and Tiliaceae. These pollens are common worldwide in Cenozoic. Betulaceae plants, which are panarctic, were widely distributed in the middle-late Paleogene strata, especially in the late Paleogene [45]. Zhang [46] summarized earlier results, showing that Juglandaceae pollens appeared with modern forms, and occurrences of *Juglanspollenites* and *Platycaryapollenites* began to increase after the late Eocene. The *Momipites* includes mainly *Momipites coryloides* that lived between Paleocene and Miocene. They were common during middle-late Paleogene and prospered in the late Paleogene [47]. Large forms dominate the Ulmaceae pollens, and the *Ulmipollenites minor* and *Ulmoideipites*, which were prevalent during early Paleogene, are absent in these beds. This palynological assemblage described above rules out the possibility that the Liuqu Conglomerates formed in the Late Cretaceous or Paleocene, because of the absence of Cretaceous features (such as Aquilapollis and Normapolles) that were common during early Paleogene. The assemblage includes sporadic occurrences of typical subtropical and tropical angiosperm pollens that were widespread during early-middle Paleogene, but their genera are relatively abundant. Because of plant continuity, typical subtropical and tropical angiosperms that were widespread during early-middle Paleogene could appear sporadically in Oligocene. Based on the above analyses, temperate zone broad-leaved deciduous angiosperms (such as Betulaceae, Juglandaceae, Fagaceae, Ulmaceae) dominated the paleovegetation of the Liuqu Conglomerates sedimentary interval. Thus, the age of the Liuqu Conglomerates in this section should be regarded as late Paleogene.

The gymnosperm pollens consist predominantly of conifer pollens (such as *Pinuspollenites*, *Abiespollenites*, *Cedripites* and trace numble of *Tsugaepollenites*), and bisaccate pollens dominate the gymnosperm pollens. Furthermore, *Pinus* pollens dominate the conifer pollens in this assemblage. Conifer pollens account for an average of over 22.48% of the total number of spores and pollens in this assemblage, showing that conifers proliferated at that time. This assemblage contains a number of *Abiespollenites* that did not appear until Oligocene in the lower Ganchaigou Formation of the Qaidam basin in China [45]. We also found sporadic *Tsugaepollenites*, which only appeared sporadically in the Oligocene and commonly until the Miocene [32, 45, 48]. Thus, we assign the Liuqu Conglomerates to the Oligocene.

According to previous studies, herbaceous species (such as Chenopodiaceae, Compositae, Gramineae, Cyperaceae) commonly began to appear in Paleogene, but initially only in trace amounts. They did not prosper until Miocene. These herbaceous pollens appear sporadically in this assemblage, in particular, Compositae and *Artemisiaepollenites* of Compositae. Compositae and *Artemisiaepollenites* of Compositae are generally regarded as important evidence for separating the Oligocene from the Miocene, because the former only emerged sporadically during Oligocene and the latter did not appear until Miocene. The several Compositae pollens in this assemblage all belong to the early *Echitricolporites* pollens of Compositae, and *Artemisiaepollenites* pollens of Compositae are absent. The earliest Cyperaceae pollen was found in the middle Eocene [49], but it began to prosper in the Neogene. Herbaceous pollens do not have dominant representations and do not occur with more evolved types in this assemblage. The distributions of these herbaceous plants and pollens over time can be treated as markers for determining and dividing the age of strata. The discussion above demonstrates that the age of Liuqu Conglomerates should not fall into Miocene and Eocene, but into Oligocene.

During the same geological interval, the regional paleovegetation and paleoclimate should have been similar and comparable to analogous geographic areas. According to previous studies, northwestern and southwestern China held broad-leaved deciduous forest or mixed conifer-broad-

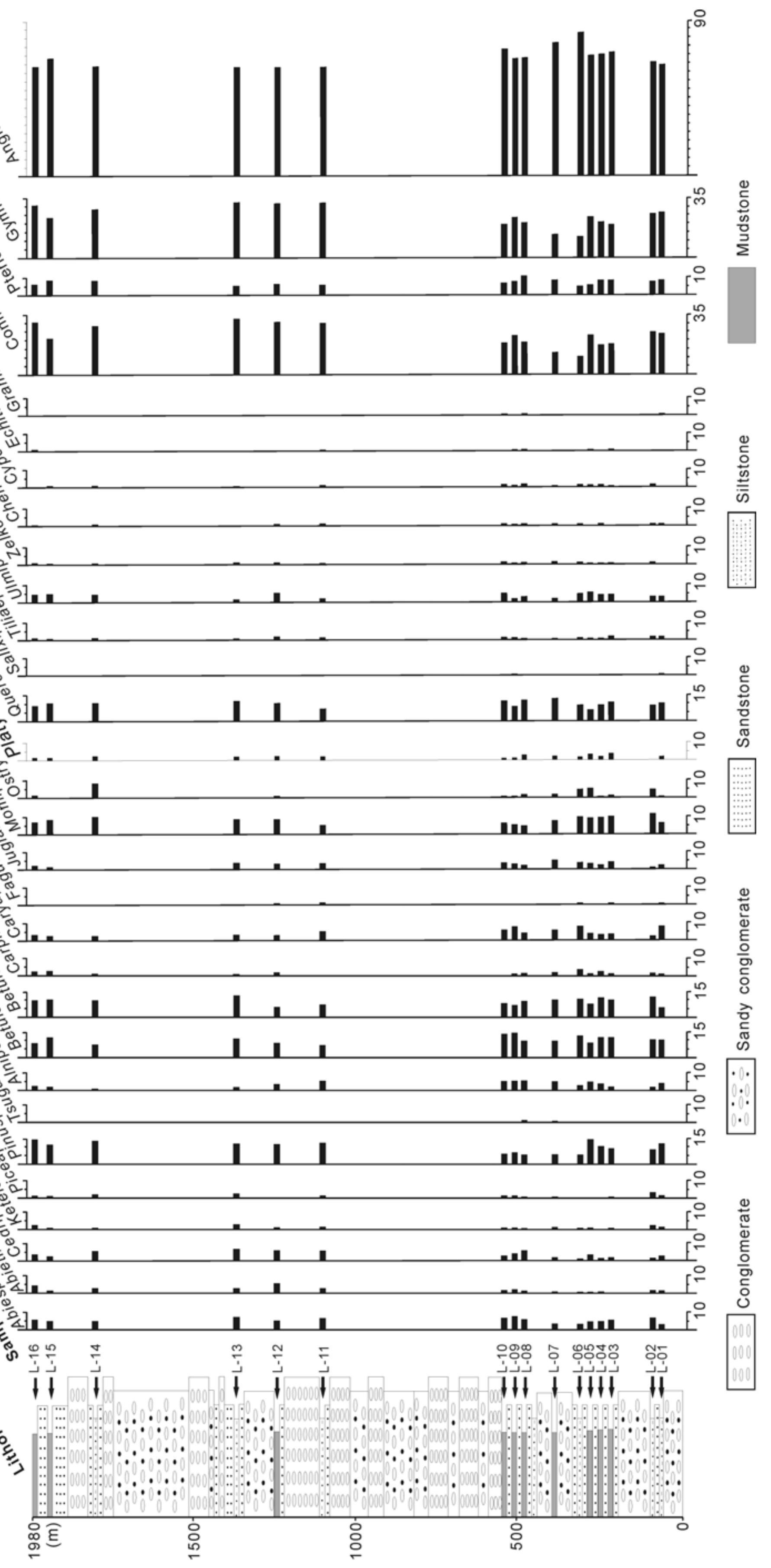

Figure 3 Spore and pollen diagram showing the percentage abundances of the major floral components within the Liuqu Conglomerates.

leaved forest including many broad-leaved deciduous angiosperms (such as Betulaceae, Juglandaceae, Fagaceae, Ulmaceae) and more of coniferous gymnosperms during Oligocene, reflecting a relatively warm or temperate and humid climate. Similar paleovegetation and paleoclimate also appear in the depositional record of the Liuqu Conglomerates, consistent with an Oligocene age for these conglomerates. Oligocene palynological assemblages are rich in China, and the representative palynological assemblages in eastern and southern China come from Dainan Formation in Jiangsu [50], Linjiang Formation of Qingjiang Basin in Jiangxi [51], lower part of Qianjiang Formation of Jianghan Basin in Hubei [52], Weizhou Formation of Leizhou Peninsula in Guangdong [53], Fuping Formation of Baise Basin in Guangxi [54], and Huayong Formation of Sanshui Basin in Guangdong [55]. Common characteristics of the above-mentioned palynological assemblages are as follows: Broad-leaved deciduous plant pollens play an important role in these assemblages, and sometimes gymnosperm pollens are dominant; conifer and Taxodiaceae pollens dominate the gymnosperm pollens; tropical and subtropical angiosperm pollen are frequent. This indicates that eastern and southern areas of China are warmer and more humid than Liuqu during Oligocene. Unique geomorphologic feature may have appeared during Oligocene, resulting in the differences between the above-mentioned palynological assemblages and the palynological assemblage of Liuqu Conglomerates. The paleovegetation and paleoclimate of the Liuqu Conglomerates closely resemble the Oligocene paleovegetation and paleoclimate of the Qinghai-Tibet Plateau and its surrounding areas, such as the lower Ganchaigou Formation in the Qaidam basin of Qinghai Province [45], the lower Lunpola Group in the Lunpola basin of northern Tibet [56], and the Wanbaogou Group in the western part of the Eastern Kunlun orogenic belt [48]. The palynological assemblage of lower Ganchaigou Formation in the Qaidam basin is dominated by angiosperm pollens such as *Quercoidites*, *Meliaceoidites* and Betulaceae type pollens, conifer saccate pollens account for more than 27.97% of the total number, and *Piceapollis* is about 13.67% of the total number; *Tsugaepollenites* and *Abiespollenites* begin to appear; *Ephedripites* occurs in relative abundance, about 13.81%; and Herbaceous pollens do not form dominant representations [45]. The palynological assemblage of Wanbaogou Group in the western part of the Eastern Kunlun orogenic belt is dominated by angiosperm pollens (about 68%), followed by gymnosperm pollens (about 26%) and pteridophyta spores (about 6%); the broad-leaved deciduous plant pollens dominated the angiosperm pollens by a large percentage of *Caryapollenites* (12%) and followed by *Ulmipollenites*, *Betulaceoipollenites* and *Momipites*; the gymnosperm pollens consist mainly of conifer pollens (about 20%) and *Ephedripites* (about 7%) [48]. The above mentioned two palynological assemblages have a high representation of *Ephedripites*, indicating that the climates of the two areas are relatively drier than this area during that time. The palynological assemblage of lower Lunpola Group in the Lunpola basin is characterized by conifer saccate pollens, which account for more than half of the total number; the angiosperm pollens consist mainly of *Salixipollenites*, Betulaceae and Juglandaceae type pollens [56]. The palynological assemblage of lower Lunpola Group has a larger percentage than this assemblage, maybe because Liuqu Conglomerates were located at low latitude during that time.

A global cooling event took place at the Eocene-Oligocene transition [57, 58], and set the stage for further changes in early Oligocene [59]. The influence of this global event on paleovegetation showed the gradual decrease of tropical and subtropical elements and the increase of cooler elements [60, 61–63]. Northern Hemisphere temperature gradually decreased during Oligocene, evidenced by the fossil records in North America, Europe, and Asia. The Oligocene palynological assemblages of some areas of the world were dominated by temperate broad-leaved deciduous forest and conifer, such as lignite layers in Germany [64], Himachal Pradesh in India [65], and Hokkaido in Japan [66].

The foregoing analysis demonstrates that the Liuqu Conglomerates consists of Oligocene deposits. We did not find the bottom of this section, and thus we do not rule out the possibility that the Liuqu Conglomerates include the Eocene deposition. The top of this section is a syncline core, and likewise we do not rule out the possibility that the Liuqu Conglomerates include the Miocene deposition.

2.2 Paleoenvironments

The palynological assemblage dominated by temperate zone broad-leaved deciduous pollens, such as Betulaceae, Juglandaceae, Fagaceae and Ulmaceae, which indicate that paleoclimate is relatively warm and humid during Oligocene. The angiosperm pollens such as *Taxodiaceaepollenites* and *Sabalpollenites* disappear, which reflects hot and humid climate. Tropical and subtropical components, such as *Cupuliferoipollenites*, *Engelhardtioidites*, *Myrtaceidites*, *Rhoipites*, *Pterocaryapollenites*, *Nyssapollenites*, only have a trace number. *Abiespollenites, Piceapollis, Cedripites, Tsugaepollenites* are temperate alpine coniferous forest pollens and are common, indicating a relatively cold and humid climate. High pollen percentages of *Abiespollenites* and *Piceapollis* indicate a cold and humid climate [67]. This assemblage has a trace number of classic arid components, such as Ephedraceae, Chenopodiaceae and Compositae, which indicates the climate is not dry. The palynological assemblage shows that the paleovegetation of the Liuqu Conglomerates during that time consists mainly of deciduous broad-leaved angiosperms, such as Betulaceae, Juglandaceae, Fagaceae, Ulmaceae and Tiliaceae, with some coniferous gymnosperms and a small proportion of evergreen

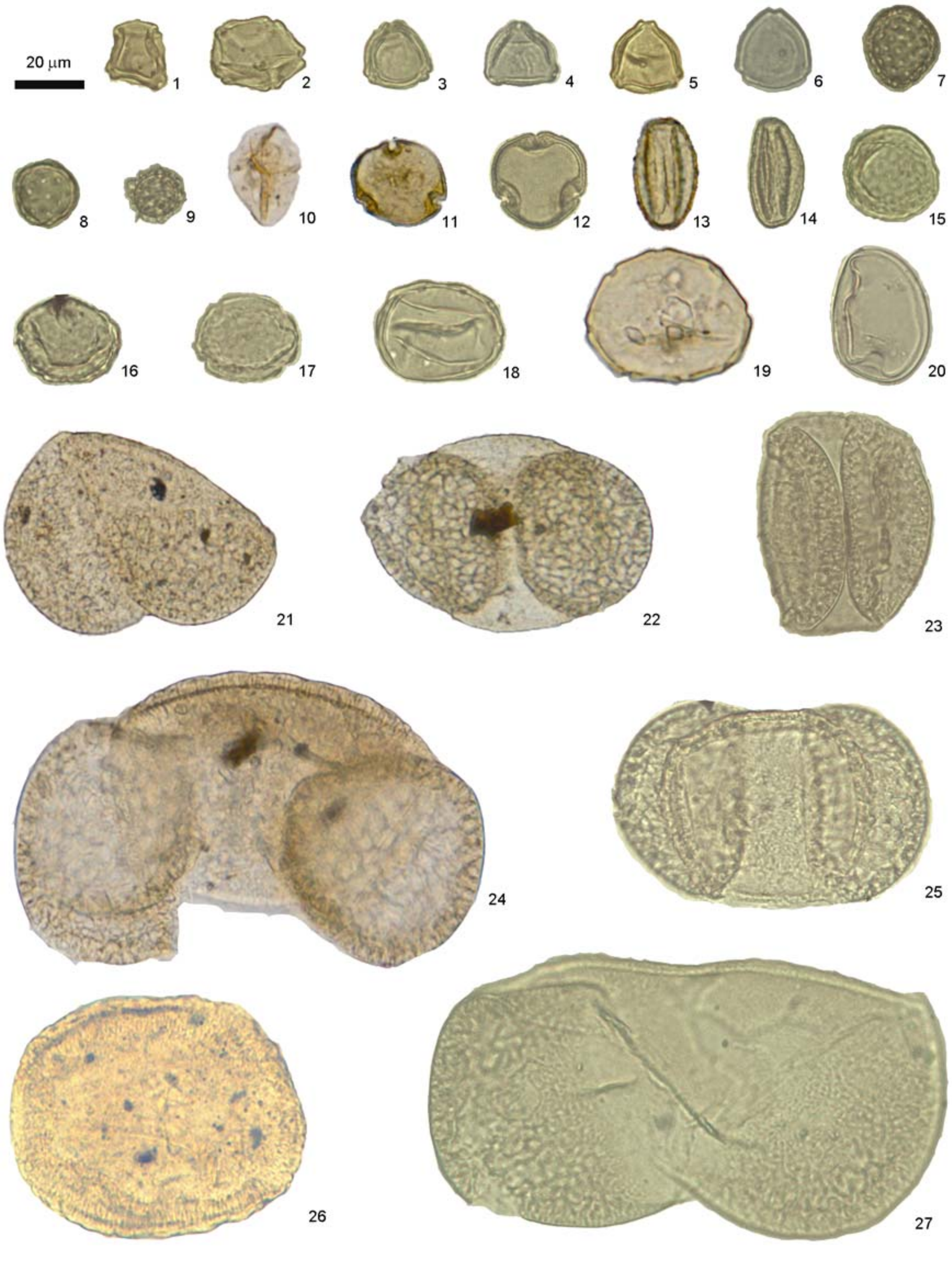

Figure 4 Representative photographs of spore and pollen grains from the Liuqu Conglomerates in Southern Tibet, China. 1 *Alnipollenites metaplasmus* (Potonie) Potonie, 1960; 2 *Alnipollenites verus* (Potonie) Potonie, 1960; 3 *Betulaceoipollenites bituitus* (Pot.) Potonie, 1960; 4 *Betulaepollenites microrugusus* Song et Zhu, 1985; 5 *Ostryoipollenites* sp.; 6 *Momipites coryloides* Wodehouse, 1933; 7, 8 *Chenopodipollis* spp.; 9 *Echitricolporites minor* Song et Zhu, 1985; 10 *Graminidites* sp.; 11, 12 *Tiliaepollenites* spp.; 13 *Quercoidites cf. densus* (Pflug) Song et Zheng, 1978; 14 *Quercoidites henrici* (Pot.) Pot., Thoms. et Their., 1950; 15, 16 *Ulmipollenites* spp.; 17 *Zelkovaepollenites thiergarti* Nagy, 1969; 18 *Juglanspollenites* sp.; 19 *Juglanspollenites rotundus* Ke et Shi, 1978; 20 *Cyperaceaepollis* sp.; 21 *Cedripites* sp.; 22, 25. *Pinuspollenites* spp.; 23 *Abietineaepollenites* sp.; 24 *Abiespollenites sibiriciformis* (Zakl.) Krutzsch, 1971; 26 *Tsugaepollenites viridifluminipites* (Wodehouse) Potonie, 1958; 27 *Piceapollis praemarianus* Krutzsch, 1971.

broad-leaved angiosperms, such as *Caryapollenites*. The palynological assemblage generally shows warm and relatively humid climate or temperate and relatively humid climate, and a warm-temperate or temperate zone climatic environment.

Pinaceae grows in high altitude, and averaged up to 22.48% in this assemblage, indicating Tibet already uplifted and alpine coniferous forest grew in Tibet during that time. The temperate zone broad-leaved deciduous forest (Betulaceae, Juglandaceae, Fagaceae and Ulmaceae) grew in the lowland and hills, while trace number of tropical and subtropical trees (Aquifoliaceae and Myrtaceae) were mixed in the forest. The understory, including ferns and a small number of shrubs and herbs, grew in the lowland. The palynological assemblage from the Liuqu Conglomerates reflects a broad-leaved deciduous forest or mixed with conifer-broad-leaved forest ecotype, and the understory includes ferns and a small number of shrubs and herbs.

3 Geological significances and conclusions

Reinvestigating the age of the Liuqu Conglomerates within the Yalung Zangpo suture zone can provide significant information for studying the collision between the Indian and the Eurasian plates. The Gangrinboche Conglomerates were formed during the latest Oligocene-early Miocene [21, 32]. Because the Gangrinboche Conglomerates and the Liuqu Conglomerates obviously were formed during different geological periods, this implies that they resulted from two separate subduction-collision events, further confirming that more than one subduction system once existed within the Neotethys. Our investigation of the Liuqu Conglomerates cannot constrain the initial time of the collision between the Indian and the intra-Neotethyan arc. However, the deposits investigated can provide strong evidence that the collision had already happened. The absence of materials derived from north of the Yalung Zangpo suture suggests that the basins in which the Liuqu Conglomerates were deposited formed prior to the main continent-continent collision between the Indian and the Eurasian plate and the final closure of the Neotethys [35]. Based on studies of the Paleocene to early Eocene marine Gyachala Formation along the southern side of the Yalung Zangpo suture zone in southern Tibet, Li and Wan [68] and Li et al. [34] concluded that the closing of the Neotethys occurred after the Priabonian of late Eocene. The final India-Eurasia collision should then have occurred prior to the latest Oligocene-early Miocene, according to studies of the Gangrinboche Conglomerates [21]. From the above analyses, the India-Eurasia continent continent collision should not have occurred earlier than Oligocene, which basically is consistent with the view that the continent-continent collision began at about 34 Ma, based on studies of the relative positions of the Indian continent and the sedimentary records in southern Tibet [22].

Based on the analyses on the palynological assemblage of the Liuqu Conglomerates, we conclude that: (1) The Liuqu Conglomerates consist of the Oligocene deposits. (2) The palynological assemblage shows that the Oligocene paleovegetation of the Liuqu Conglomerates consisted of warm-temperate zone or temperate zone broad-leaved deciduous forest or mixed conifer-broad-leaved forest, including a large number of temperate zone deciduous broad-leaved angiosperms, a number of coniferous gymnosperms, and a small proportion of evergreen broad-leaved angiosperms.

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