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Age constraint on Burmese amber based on U–Pb dating of zircons

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ABSTRACT

Amber from northern Myanmar has been commercially exploited for millennia, and it also preserves the most diverse palaeobiota among the worlds' seven major deposits of Cretaceous amber. Recent estimated ages vary from Albian to Cenomanian, based on palynology, an ammonoid, and Mesozoic insect taxa preserved within the amber. The burmite-bearing rock is sedimentary and consists mainly of rounded lithic clasts (0.03 ~ 0.15 mm in diameter), with minor fragments of quartz and feldspar. Among the lithic clasts are mostly volcanic rocks. Zircons separated from the amber matrix form two groups: Group-I zircons are overgrown and have variable CL patterns, experienced slight geological disturbances after they formed, and their Ion microprobe $^{206}Pb/^{238}U$ ages fall into a very narrow range of ~102 Ma–~108 Ma; Group-II zircons are typical magmatic ones with rhythmically flat zones, inferred to be derived from volcanic rock clasts, and yielded a concordia $^{206}Pb/^{238}U$ age of 98.79 ± 0.62 Ma. The dating on Group-I zircons is only for their interiors, thus hiding what age excursion might come from the overgrowth. Considering the nearshore marine environment and 1-m thickness of the burmite-bearing sediments, and the syn- and post-eruption deposition of volcanic clasts, the age of 98.79 ± 0.62 Ma therefore can be used as a maximum limit for the burmite (either at or after), establishing an earliest Cenomanian age for the fossilized inclusions. The age also indicates that volcanic eruption occurred at 98.79 ± 0.62 Ma in the vicinity of the Hukawng Valley.

1. Introduction

Amber from northern Myanmar, called Burmese amber or merely "burmite", is the only Cretaceous amber deposit in the world that is exploited commercially, as well as the first to have been studied scientifically. The history of its use has been reviewed by Zherikhin and Ross (2000), Grimaldi et al. (2002), Cruickshank and Ko (2003), and Ross et al. (2010). Briefly, burmite had been used primarily in carvings for at least two millennia by Chinese people, for which the material is ideally suited (Grimaldi, 1996). The deposits in the Kachin state, northern Myanmar, are productive (an estimated 83 tons were exported between 1898 and 1940), and some amber pieces are very large (the largest is 15 kg, in the Natural History Museum, London). Moreover, colours vary from a transparent yellow to a highly desirable deep red (Figs. 1–3), the amber resists fracturing and is relatively hard (1.2 times harder than Baltic amber), and it receives a glassy polish. Burmite mining lapsed from just before the independence of Burma from Britain in 1947, and did not resume until the late 1990s. The greatest value of burmite, however, is scientific.

Amber in general preserves biological inclusions with microscopic fidelity, so as a mode of fossilization it is unparallelled for phylogenetic and palaeontological studies of Cenozoic and late Mesozoic terrestrial life forms (Grimaldi and Engel, 2005). Amber from the Cretaceous is further significant since it coincides with the radiation of the angiosperms and major tectonic shifts in continental positions, and precedes the famous end-Cretaceous impact event. Of the seven major deposits of amber from the Cretaceous Period (Table 1), Burmese amber contains probably the most diverse palaeobiota. For example, approximately 228 families of organisms (primarily arthropods) have been reported from burmite, compared to a range of 68–125 families recorded thus far in the other six major amber deposits. Only the much larger, commercially exploited deposits from the Miocene of the Dominican Republic and Mexico, and the Eocene Baltic amber have yielded more families and species. Interestingly, burmite contains an

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Fig. 1. A photograph of rough and semi-polished pieces of burmite.

exceptional diversity and abundance of the most diverse order of insects, the Coleoptera (16% of all studied inclusions, representing more than 40 families, vs. 2–8% and around a dozen families in the other Cretaceous ambers).

Fig. 2. A modern carving of burmite showing a small bunch of fruit with leaves: the interesting thing about the carving is that in the centre of each piece of fruit is a spider; the carver made a special effort to frame each spider.

Among the more significant records of organisms in burmite is the only Mesozoic fossil of the phylum Onycophora ("velvet worms") (Grimaldi et al., 2002), as well as the oldest definitive Mesozoic records of mosquitoes, family Culicidae (Borkent and Grimaldi, 2004), and the insect orders Embiodea (Engel and Grimaldi, 2006), Strepsiptera (Grimaldi et al., 2005a, b), and Zoraptera (Engel and Grimaldi, 2002) (Fig. 4). Oddly, burmite also preserves the youngest records of several archaic insect groups, notably *Postopsyllidium* of the hemipteran family Protopsyllidiidae (previously known from the Permian–Jurassic) (Grimaldi, 2003), and *Parapolycentropus*, of the scorpionfly family Pseudopolycentropodidae (Triassic–Barremian) (Grimaldi et al., 2005a) (Fig. 4).

Fig. 3. Yellow-orange portions of burmite tightly attached to reddish brown ones, with thin, white calcite veinlets cutting through it. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Major deposits of fossiliferous Cretaceous amber.

Deposit(s)	Age	Method(s)	Botanical origin	References
Taimyr, Siberia; Agapa	Late Cenomanian	Palynology	??	1, 2
Taimyr, Siberia; Yantardakh	Santonian	Palynology	??	
W. Canada; Foremost Fm.	78 Ma	Radiometric	Cupressaceae	3, 4, 5, 6
W. Canada; Horseshoe Canyon Fm.	Late Campanian	Palynology		
New Jersey; Raritan Fm.	Turonian	Palynology	Cupressaceae	7, 8, 9
Charente-Maritime, France	Late Albian–early Cenomanian	Palynology	Araucariaceae/Cheirolepidiaceae	10, 11, 12
Northern Myanmar	Late Albian/early Cenomanian/ 98.8 ± 0.62 Ma	Ammonoid insects palynology radiometric	?Araucariaceae/Pinaceae/ Cupressaceae	13, 14, 15, 16, herein
Álava, Spain; Escucha Fm.	Early Albian	Ammonoids palynology	Cheirolepidiaceae/?Araucariaceae	17, 18, 19
Lebanon; various outcrops	Mainly Barremian–early Aptian	Palynology	Cheirolepidiaceae/?Araucariaceae	20, 21

References: 1, Zherikhin and Sukacheva, 1973; 2, Zherikhin and Eskov, 1999; 3, McAlpine and Martin, 1969; 4, Pike, 1995; 5, McKellar et al., 2008; 6, McKellar and Wolfe, 2010; 7, Grimaldi et al., 1989; 8, Grimaldi et al., 2000; 9, Grimaldi and Nascimbene, 2010; 10, Perrichot, 2005; 11, Perrichot et al., 2007; 12, Perrichot et al., 2010; 13, Zherikhin and Ross, 2000; 14, Grimaldi et al., 2002; 15, Ross et al., 2010; 16, Cruickshank and Ko, 2003; 17, Alonso et al., 2000; 18, Delclòs et al., 2007; 19, Peñalver and Delclòs, 2010; 20, Azar, 2000; 21, Azar et al., 2010.
"??" as undetermined or unknown; "?" as possibly.

Parapolycentropus is remarkable for the loss of the hind wings, specialized antennae, and long, styletiform proboscis, convergently resembling a mosquito. Burmite also preserves early, primitive species in groups that are highly social today, notably Formicidae (ants) and Isoptera (termites) (Engel and Grimaldi, 2005; Engel et al., 2007). One of these presumably social insects is *Haidomyrmex* (Dlussky, 1996), arguably the most peculiar ant known (Fig. 4).

Despite its scientific significance, precise dating of Burmese amber has been elusive. For the first 80 years of its scientific study, burmite was widely considered to be Eocene–Miocene in age, although Cockerell (1917) insightfully considered a Cretaceous age based on the insect inclusions. When Alexandr Rasnitsyn of the Palaeontological Institute in Moscow examined the burmite collection in the Natural History Museum, London in 1995, he noticed the presence of some Cretaceous insect groups in this amber, notably Serphitidae and the extinct subfamily of ants Sphecomyrminae (Zherikhin and Ross, 2000). This and other evidence established a Cretaceous age for the material, corroborated by expanded studies of myriad arthropod taxa in the NHML and AMNH collections (Grimaldi et al., 2002). Based on 21 insect taxa found within various stages of the late Mesozoic as well as in Burmese amber, a Cenomanian age was hypothesized by Grimaldi et al. (2002). Cruickshank and Ko (2003) reviewed the geology of the burmite deposits, based on published and original observations, and reported an ammonite specimen taken 2 m above an amber bed at the principal mine at Noije Bum, identified as *Mortoniceras*, which has a stratigraphic range of Middle–Upper Albian (Wright et al., 1996). Cruickshank and Ko (2003) cited unpublished reports by E.H. Davies (Branta Biostratigraphy Ltd.) of the fossil pollen, spores, and dinoflagellates, which further indicated an age of the sediments and thus the amber as "most likely Albian to early Cenomanian". The late Albian age proposed by Cruickshank and Ko (2003) is widely cited in original and review papers on burmite (e.g., Ross et al., 2010, and references therein).

2. Amber/geological samples

Cruickshank and Ko (2003) described and mapped the locality of the amber mines that are the primary sources of the collections in the Natural History Museum, London and the American Museum of Natural History, New York. Chhibber (1934) listed 13 amber outcrops in the valley, some of which are outside the mine area described by Cruickshank and Ko (2003). Briefly, the mines are located in the Hukawng Valley (Hukawng Basin) of Kachin State, northern Myanmar, and specifically on Noije Bum, a hill that rises some 250 m above a broad alluvial plain that lies between two rivers, Idi Hka and Nambyu Hku. Noije Bum is narrow, approximately 5 km long with a north–south orientation, located approximately at 26°15′N, 96°34′E, some 18 km south-west of the town of Tanai. The amber mines are located at the north end of Noije Bum.

More than 10 kg of amber plus matrix from amber mines near the Tanai Village were purchased from a Myanmar miner by one of us (GHS). Samples consisted of amber pieces with attached sedimentary matrix surrounding them. The amber pieces varied from several cm to more than 15 cm in maximum dimension. Most unbroken pieces had shapes like a disk, lens, or flattened ball with aspect ratios ranging from 2 to ∼10, whereas a few were ellipsoidal or irregular. Orientation of the amber generally had the flattest surfaces parallel to bedding of the sedimentary host. The amber had two main, contrasting colours: the majority are typically reddish brown, while a minor proportion are yellow-orange, similar to the observations of Cruickshank and Ko (2003). Occasionally, individual yellow-orange portions were tightly attached to reddish brown ones (Fig. 3). In these samples, thin, white calcite veinlets were common, running perpendicular to the major plane of the amber discs, thus cross-cutting them and the bedding. The veinlets were <1 mm–∼5 mm in width. The concentration of the veinlets varies greatly from essentially absent to as much as 10% vol. veinlets, similar to the description by Cruickshank and Ko (2003).

3. Petrography of amber-bearing matrix

The rock matrix containing amber is a greyish to bluish-green volcanoclastic to mudstone, consistent with the description by Cruickshank and Ko (2003) that the amber is located in the finer facies of sedimentary rocks they encountered at Noije Bum. On close inspection, the rocks consist of sub-millimetre black, yellow, grey and light green clasts. Thus it is understandable why Chhibber (1934) described the rocks as appearing blue in colour, while Cruickshank and Ko (2003) said that they are more nearly medium green, greyish green, or rarely blue-green. The rock is poorly consolidated, such that it can be readily broken with bare hands. Petrologically, these are clastic sedimentary rocks ranging from fine sandstones to shale. The amber discs lie parallel to the bedding planes of finer sediment.

Thin sections of the amber-bearing rock were made for petrographic observations and electron microprobe analyses. The rocks consist of clasts with incipient rounding, from 0.03 mm to

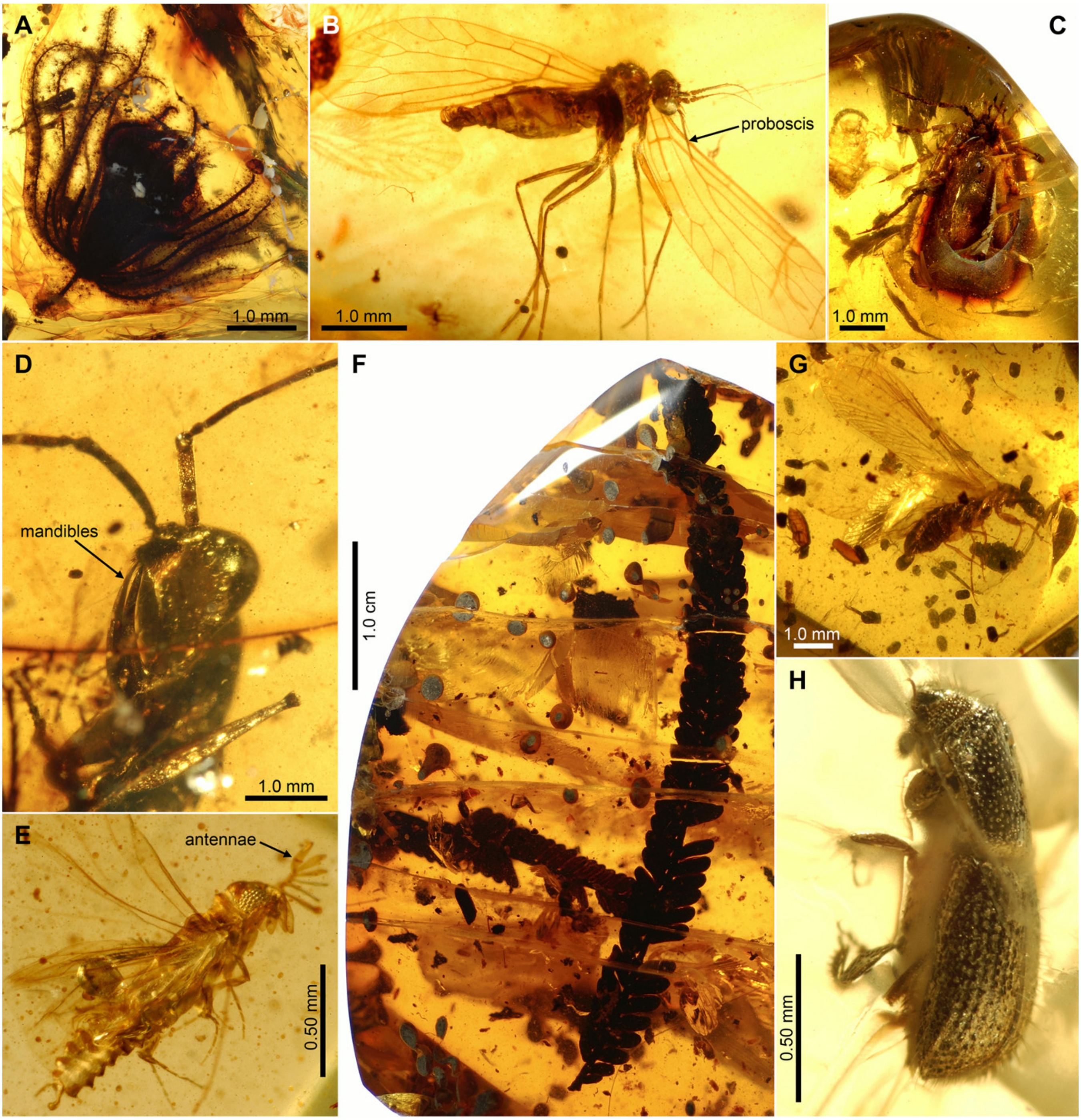

Fig. 4. Inclusions in Burmese amber of exemplar organisms. A, unusual, undescribed flower with numerous tentacular bracts covered in trichomes; AMNH BU-FB36. B, undescribed male of the bizarre, mosquito-like scorpionfly *Parapolycentropus burmiticus* Grimaldi and Rasnitsyn; AMNH BU-FB1. This species is the latest occurrence of the Mesozoic family Pseudopolycentropodidae, and the family is a stem group to modern scorpionflies. C, undescribed, bloated tick (Ixodidae: Argasidae), James Zigras collection. D, dealate specimen of the bizarre, basal ant *Haidomyrmex* sp. (Hymenoptera: Formicidae: Sphecomyrminae) – huge, sickle-shaped mandibles pivoted vertically, rather than laterally as in modern ants; AMNH BU-FB80. E, *Cretostylops engeli* Grimaldi, the Cretaceous member of the parasitoid order Strepsiptera; AMNH BU-FB31. F, two leafy shoots of the "dawn redwood" *Metasequoia*, a possible source of the Burmese amber; AMNH BU-229. G, early, basal termite, *Dharmatermes avernalis* Engel, Grimaldi, and Krishna (Isoptera); AMNH BU-FB77. H, *Microborus inertus* Cognato and Grimaldi (Coleoptera: Scolytinae), AMNH BU-1607, one of only two bark beetles known from the Cretaceous. Bark beetles have devastating impacts on modern conifer forests.

0.15 mm in diameter (Fig. 5) in a finer unconsolidated matrix of clay, calcite and pyrite. The clasts are predominately lithic fragments, with minor crystal fragments of quartz and feldspar. Most lithic clasts belong to volcanic rock, whilst other lithic clasts, such as chert, quartzite, micritic limestone, serpentinite, and actinolite schist described by Cruickshank and Ko (2003) were not frequently observed. The volcanic fragments consist of phenocrysts of plagioclase, quartz and K-feldspar, and glassy matrix. The plagioclase phenocrysts are primarily andesine (Table 2), which combined with the other igneous clasts suggests the rock is dacitic

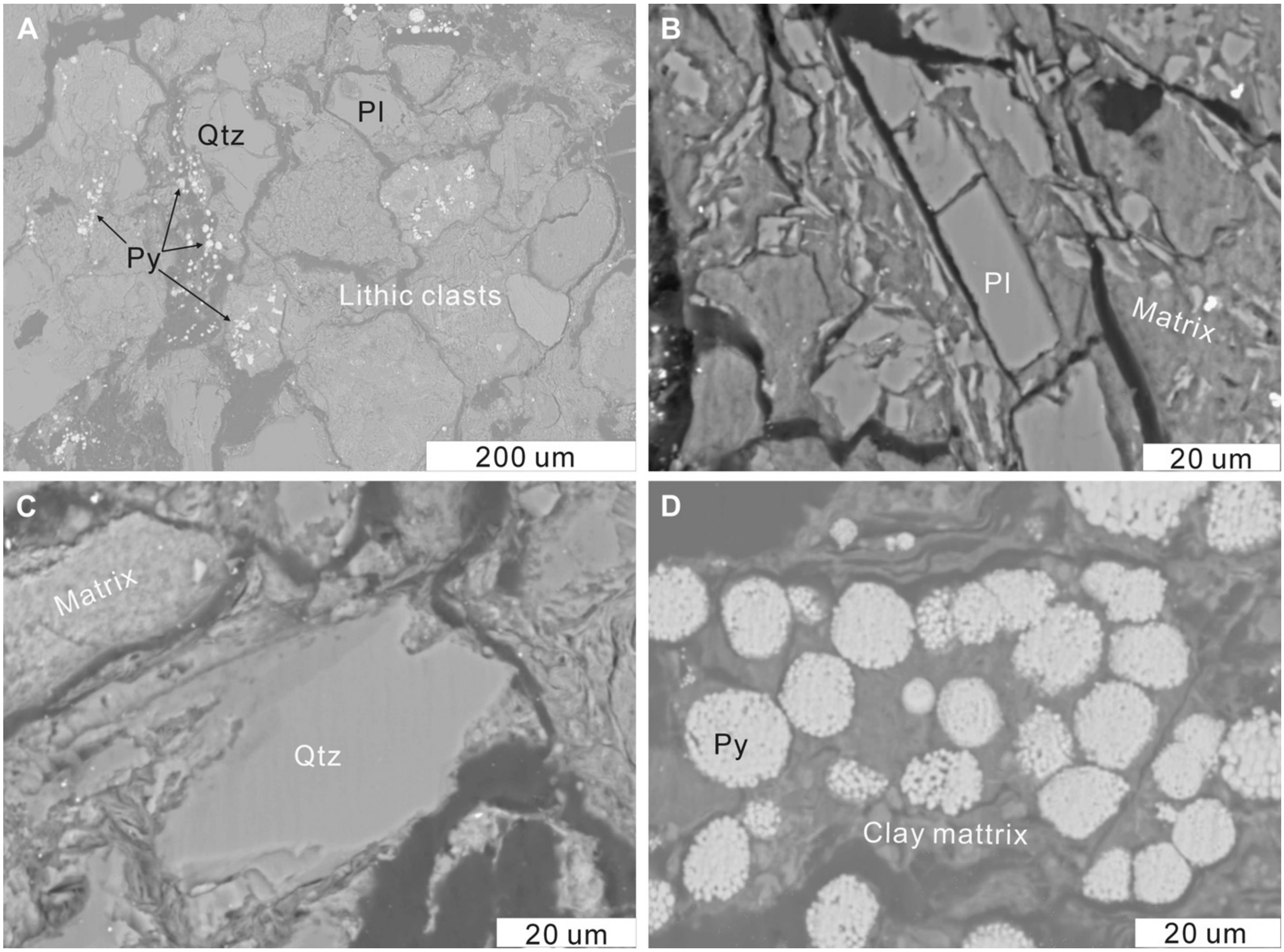

Fig. 5. Backscattered electronic images of amber-contained host rocks: A, lithic clasts, crystals of plagioclase, quartz with later-stage pyrite framboids are main component of the host rock. B, close-up of a lithic clast, consisting of plagioclase and glass matrix. C, close-up of another lithic clast, consisting of quartz and glass matrix. D, close-up of a later-stage pyrite framboids with clay matrix.

Table 2
Chemical compositions of plagioclases.

Points	P2	P4	P7	P8	P9
SiO_2	61.37	62.43	53.76	56.41	55.59
TiO_2	0.12	0.10	0.13	0.02	0.03
Al_2O_3	24.70	22.96	28.18	25.93	26.18
FeO	0.90	1.11	0.87	0.37	0.40
MgO	0.02	0.19	0.14	0.03	0.01
MnO	0.00	0.03	0.00	0.00	0.00
CaO	6.67	5.06	11.54	7.79	8.25
Na_2O	7.62	7.42	4.64	7.09	6.25
K_2O	0.54	1.35	0.18	0.54	0.54
Total	101.94	100.65	99.43	98.18	97.25
Si	2.69	2.77	2.45	2.58	2.57
Ti	0.00	0.00	0.00	0.00	0.00
Al	1.28	1.20	1.51	1.40	1.43
Mg	0.00	0.01	0.01	0.00	0.00
Ca	0.31	0.24	0.56	0.38	0.41
Mn	0.00	0.00	0.00	0.00	0.00
Fe	0.03	0.04	0.03	0.01	0.02
Na	0.65	0.64	0.41	0.63	0.56
K	0.03	0.08	0.01	0.03	0.03
O	8.00	8.00	8.00	8.00	8.00
Name	Pl	Pl	Pl	Pl	Pl

to andesitic (Fig. 5B), although a spectrum from rhyolite to basalt is possible. The quartz and feldspar crystal fragments show resorption features (e.g., irregular shapes) and have internal cracks (Fig. 5A, C). Pyrite is common between and within the clasts in the rocks, occurring as spherical aggregates of discrete micro-crystallites known as framboids ($\sim$0.5 μm in diameter, with the aggregate size ranging from 5–15 μm) (Fig. 5A). These are similar to descriptions of framboids by Ohfuji and Rickard (2005) and Wilkin and Barnes (1997). The sedimentary texture is immature, as evidenced by poor size sorting and only incipient rounding of clasts, indicating a short distance of transport by water currents. As Cruickshank and Ko (2003) described, the cement is coarse crystalline calcite, and the rock effervesces vigorously in dilute hydrochloric acid.

Zircons were selected from the rind of matrix that surrounded the unprocessed amber. The rock matrices were washed away by brushing after immersion in a container of clean water. The washed matrix was then gathered for zircon separation following the conventional procedure (crushing, sieving, gravity separation, magneto-dynamic separation, Wilfley table and then picking out under a binocular microscope) at the Langfang lab, Hebei Geology and Resource Bureau. Zircons are mostly euhedral, 80–200 μm long with aspect ratios ranging from $\sim$1.2 to $\sim$2.5.

4. Methods and results

The selected zircons were then cast in a transparent epoxy mount together with the standard zircon Plešovice. Cathodoluminescence (CL) imaging of zircon grains employed a scanning electron microscope (LEO1450VP with MiniCL instrument) at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). Backscattered electron (BSE) images and mineral compositions of the rock matrices were obtained using a JXA-8100 Electron Microprobe Analyzer (EMPA) at IGGCAS with a voltage of 15 kV, a beam current of 10 nA and a spot size less than 10 μm (Shi et al., 2011). EMPA standards include the following minerals: andradite for Si and Ca, rutile for Ti, corundum for Al, hematite for Fe, eskolaite for Cr, rhodonite for Mn, bunsenite for Ni, periclase for Mg, albite for Na, K-feldspar for K. Chemical compositions of feldspars in burmite-bearing rock are given in Table 2.

Measurements of U, Th and Pb were conducted using the Cameca IMS-1280 ion microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing. Operating and data process procedures were similar to those described by Li et al. (2009) and Shi et al. (in press), and are only briefly given here. U–Th–Pb ratios were determined relative to the standard zircon Plešovice ($^{206}Pb/^{238}U$ age of 337.3 Ma) (Sláma et al., 2008), analyses of which were interspersed with those known grains. A long-term uncertainty of 1.5% (1 RSD) for $^{206}Pb/^{238}U$ measurements of the standard zircons was propagated for the unknowns (Li et al., 2010). Absolute abundances of U/Th were determined relative to the standard zircon 91500 (Wiedenbeck et al., 1995) on other mounts. The mass resolution used to measure Pb/Pb and Pb/U isotopic ratios was 5400 during the analyses. Measured compositions were corrected for common Pb using non-radiogenic ^{204}Pb. SIMS U–Pb zircon data are presented in Table 3. Uncertainties of the individual analysis are reported at a 1σ level; mean ages for pooled U/Pb and Pb/Pb analyses are quoted with 95% confidence intervals. Data reduction was carried out using the Isoplot/Ex v. 2.49 programs (Ludwig, 2001).

There are two groups of zircons based on CL imaging and U–Pb ages. All zircons with overgrowth features are within Group-I. These have variable overgrowths either as a layer on grain rims (Fig. 6, zircon with point 7) or as patchy zones cutting the previous ones (Fig. 6, zircon with points 2, 4, 5, 6, 18 and 31). U–Pb ages of interiors fall into a narrow interval of 102–108 Ma. The dating on Group-I zircons is only for their interiors, thus obscuring what age excursion might come from the overgrowth. In this case, the most likely event to have occurred was the eruptions that may have exposed these zircons and which had previously been sealed in an earlier crystallized rock. Group-II zircons do not have overgrowths, show only rhythmic zoning, typical of a magmatic origin (Fig. 6) and make up about 80% of all the sampled zircons. Twenty-five SIMS analyses of Group-II zircons formed a cluster and yielded a concordia age of 98.79 ± 0.62 Ma (Fig. 7, points 9, 10 and 14 are excluded because of possible deviations during analysis). The

Table 3
SIMS zircon U–Th–Pb analyses of the Myanmar amber matrix.

Spot[b]	Type	U (ppm)	$\frac{Th}{U}$	f_{206}[a] (%)	$\frac{^{207}Pb^*}{^{206}Pb^*}$	±1σ (%)	$\frac{^{207}Pb^*}{^{235}U}$	±1σ (%)	$\frac{^{206}Pb^*}{^{238}U}$	±1σ (%)	ρ[b]	$t_{207/206}$ (Ma)	±1σ	$t_{207/235}$ (Ma)	±1σ	$t_{206/238}$ (Ma)	±1σ
01	II	191	0.74	{0.00}	0.0467	2.8	0.1004	3.2	0.0156	1.6	0.49	33.1	65.1	97.1	2.9	99.8	1.5
02	I	176	0.47	{0.11}	0.0479	2.7	0.1124	3.1	0.0170	1.6	0.49	92.4	63.3	108.1	3.2	108.8	1.7
03	II	386	1.04	{0.06}	0.0473	2.1	0.1004	2.6	0.0154	1.5	0.59	65.8	48.6	97.1	2.4	98.4	1.5
04	I	281	0.59	{0.11}	0.0473	2.7	0.1075	3.1	0.0165	1.5	0.50	64.4	62.1	103.7	3.0	105.4	1.6
05	I	419	0.52	{10.33}	0.0543	10.0	0.1202	10.1	0.0161	1.5	0.15	382.9	209.4	115.2	11.0	102.7	1.5
06	I	633	0.81	{0.06}	0.0475	1.6	0.1048	2.2	0.0160	1.5	0.70	74.2	36.8	101.2	2.1	102.3	1.5
07	I	505	0.64	{0.37}	0.0491	2.1	0.1118	2.6	0.0165	1.5	0.58	151.1	48.7	107.6	2.7	105.7	1.6
08	II	668	0.68	{0.23}	0.0470	2.8	0.0955	3.2	0.0147	1.5	0.48	50.2	64.8	92.6	2.8	94.2	1.4
09	II	309	0.48	{0.25}	0.0467	2.9	0.0935	3.3	0.0145	1.6	0.48	33.1	67.9	90.7	2.9	92.9	1.5
10	II	356	0.48	{0.17}	0.0475	2.0	0.1021	2.6	0.0156	1.5	0.60	76.3	47.9	98.7	2.4	99.7	1.5
11	II	387	0.53	{0.21}	0.0477	2.5	0.1044	2.9	0.0159	1.5	0.53	86.0	57.8	100.8	2.8	101.4	1.5
12	I	381	0.69	{0.17}	0.0466	2.7	0.1089	3.1	0.0169	1.5	0.50	28.9	62.7	104.9	3.1	108.3	1.7
13	II	375	0.47	{0.25}	0.0478	2.9	0.0985	3.2	0.0149	1.5	0.47	89.4	66.5	95.4	3.0	95.6	1.4
14	II	211	0.46	{0.17}	0.0470	2.8	0.0944	3.2	0.0146	1.5	0.47	50.3	65.7	91.6	2.8	93.2	1.4
15	II	431	0.55	{0.28}	0.0481	2.8	0.1041	3.2	0.0157	1.5	0.48	106.4	65.3	100.5	3.1	100.3	1.5
16	II	506	0.51	{0.12}	0.0478	1.9	0.1017	2.5	0.0154	1.5	0.61	88.1	45.6	98.4	2.3	98.8	1.5
17	II	279	0.41	{0.08}	0.0485	3.5	0.1029	3.8	0.0154	1.5	0.40	125.8	79.6	99.5	3.6	98.4	1.5
18	I	678	0.66	{0.05}	0.0482	1.5	0.1068	2.1	0.0161	1.5	0.71	109.3	35.2	103.0	2.1	102.7	1.5
19	II	523	0.60	{0.31}	0.0484	1.7	0.1024	2.3	0.0153	1.5	0.67	119.2	39.7	99.0	2.2	98.2	1.5
20	II	577	0.55	{0.08}	0.0469	1.8	0.1005	2.4	0.0155	1.5	0.64	44.5	43.2	97.2	2.2	99.4	1.5
21	II	410	0.55	{0.20}	0.0467	2.8	0.0976	3.2	0.0152	1.5	0.48	33.5	65.4	94.6	2.9	97.0	1.5
22	?	139	0.43	{0.30}	0.0485	3.5	0.1073	3.8	0.0161	1.6	0.41	122.3	79.5	103.5	3.7	102.7	1.6
23	II	284	0.96	{0.16}	0.0480	3.1	0.1042	3.5	0.0157	1.6	0.46	98.5	71.9	100.6	3.4	100.7	1.6
24	II	557	0.55	{0.27}	0.0472	2.2	0.1023	2.7	0.0157	1.5	0.57	61.3	51.2	98.9	2.5	100.5	1.5
25	II	778	0.86	{0.22}	0.0466	2.2	0.0965	2.7	0.0150	1.5	0.56	30.2	52.7	93.5	2.4	96.0	1.4
26	II	289	0.48	{0.00}	0.0491	2.7	0.1052	3.1	0.0155	1.5	0.49	153.6	62.5	101.5	3.0	99.3	1.5
27	II	386	0.66	{0.12}	0.0476	2.3	0.0985	2.7	0.0150	1.5	0.56	78.0	52.7	95.4	2.5	96.1	1.5
28	II	441	0.61	{0.11}	0.0471	2.4	0.1001	2.9	0.0154	1.5	0.53	56.2	57.1	96.9	2.7	98.5	1.5
29	II	376	0.60	{0.13}	0.0466	2.3	0.1015	2.9	0.0158	1.7	0.60	29.3	54.7	98.2	2.7	101.0	1.7
30	II	387	0.59	{0.12}	0.0479	2.3	0.1010	2.8	0.0153	1.6	0.57	94.7	52.7	97.7	2.6	97.8	1.5
31	I	162	0.49	{0.28}	0.0481	2.9	0.1121	3.3	0.0169	1.5	0.46	102.7	67.4	107.9	3.4	108.1	1.6
32	II	345	0.65	{0.24}	0.0477	2.1	0.1002	2.6	0.0153	1.5	0.59	82.7	48.3	97.0	2.4	97.6	1.5
33	II	249	0.40	{0.38}	0.0474	2.4	0.1003	2.9	0.0153	1.5	0.54	71.4	56.4	97.0	2.6	98.1	1.5
34	II	404	0.35	{0.14}	0.0482	2.2	0.1034	2.7	0.0156	1.5	0.57	111.0	50.9	99.9	2.5	99.5	1.5
35	II	310	0.32	{0.66}	0.0480	2.2	0.1033	2.7	0.0156	1.5	0.58	99.9	50.6	99.8	2.5	99.8	1.5

*Denotes radiogenic

[a] f_{206} is the percentage of common ^{206}Pb in total ^{206}Pb.

[b] Error correlation between $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$.

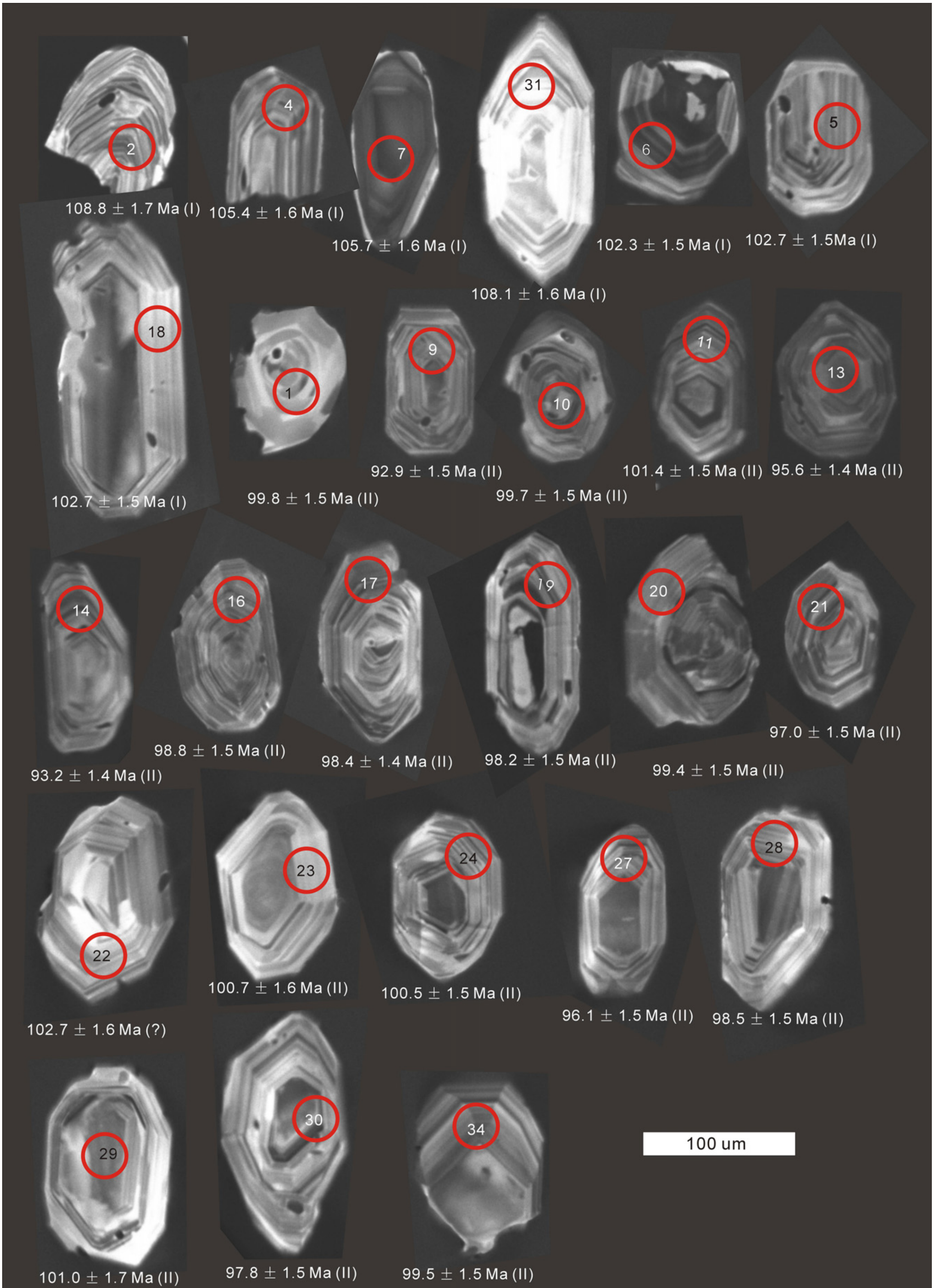

Fig. 6. Cathodoluminescence images of zircon grains from the rock matrixes of the Myanmar amber. The marked SIMS spot numbers, Group type and ^{204}Pb-corrected ^{206}Pb/^{238}U ages correspond to those in Table 3.

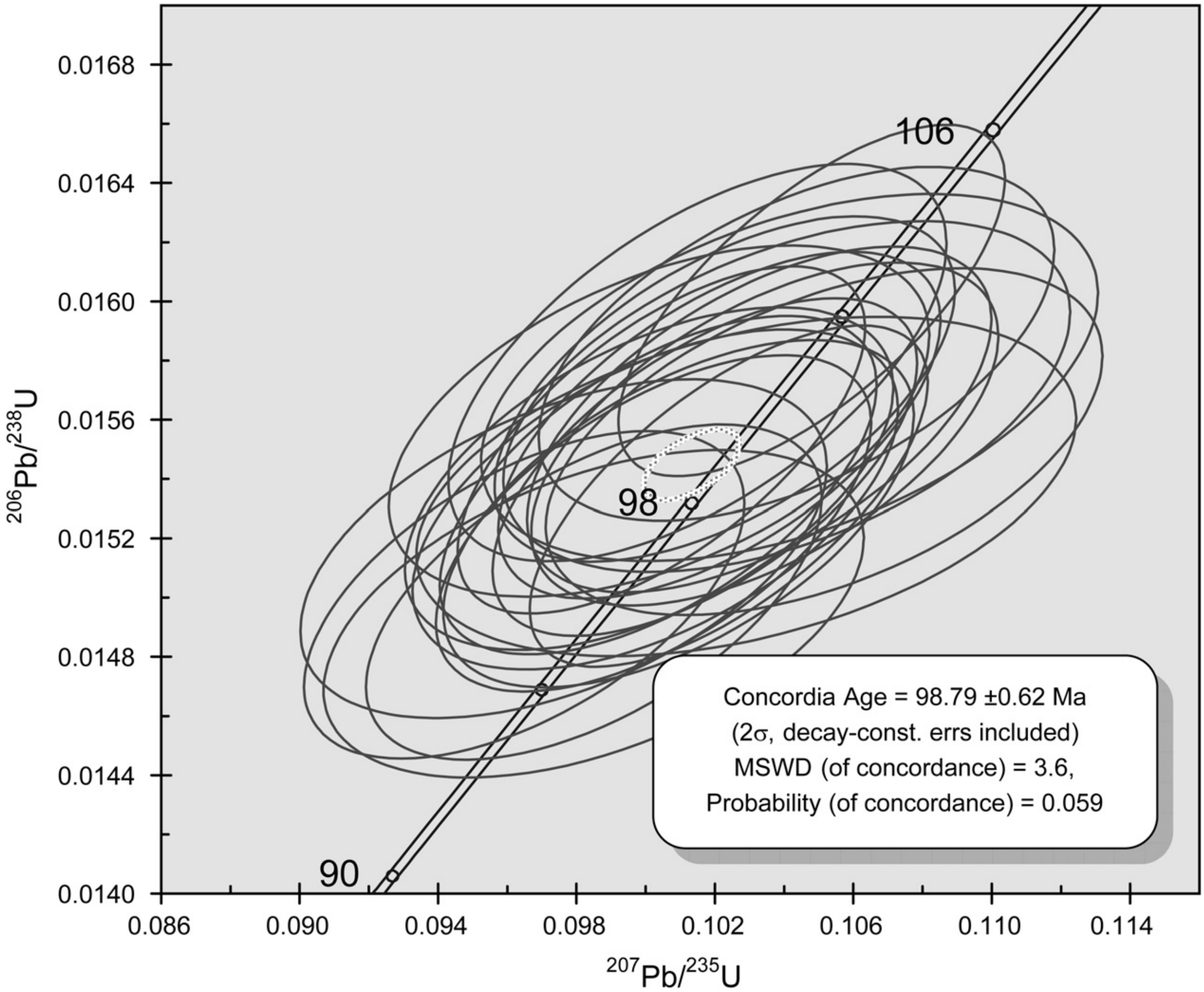

Fig. 7. Concordia diagrams of SIMS U–Pb analytical results on the Group-II zircons.

dating on Group-II zircons represents formation age while volcanic rocks were erupted.

5. Discussion and conclusions

As the zircons are from sedimentary rocks, the depositional age cannot be older than the youngest ages of Group-II zircons (i.e., 98.79 ± 0.62 Ma). There are two possible interpretations: either the depositional age is essentially the same as the Group-II zircons, implying that the volcaniclastics were airfall which immediately became sediments, or the zircons did not become sediment until some unspecified time later. Petrographic observations do not help in resolving between the two possibilities.

It is unlikely that Burmese amber is much older than the sediments in which they were buried, for several reasons. First, survival of fragile, runnel-shaped pieces of burmite (Cruickshank and Ko, 2003) suggests quick burial without either lengthy resin ageing or lifetime in the sedimentary environment. Second, in a nearshore marine, estuarine or lagoonal environment (Cruickshank and Ko, 2003) dominated by volcanic ejecta and ash for the amber-bearing sediments, deposition of the ~1-m section needed to be geologically rapid and not erased by more mature sedimentary processes or high energy reworking. We suggest that the confluence of amber and volcaniclastics may represent a volcanic event that provided the means for fast burial and preservation of amber and accompanying organic matter. Therefore, the age of the volcanic lithic components should be regarded as the age of the amber, particularly considering the errors in the age determination. Thus the Myanmar amber was probably formed at (but not earlier than) ~98.79 ± 0.62 Ma, in the earliest Cenomanian. There are slight differences in the dating of the Albian/Cenomanian stratigraphic boundary. Obradovich (1993), for example, placed it at 98.5 Ma, based on Ar–Ar dating of mid- to Late Cretaceous strata from western North America that were correlated biostratigraphically with ammonites from type sections in Europe. It was proposed at 98.5–98.9 Ma by Gradstein and Ogg (1996) and others (e.g., Skelton, 2003). The most recent definition of the boundary is 99.6 ± 0.9 Ma (Gradstein et al., 2004). Burmite is only the second Cretaceous deposit of fossiliferous amber with a close radiometric age constraint, the other being amber from the Foremost Formation of Alberta, Canada. A maximum age for this formation is 79.14 ± 0.15 Ma and a minimum of 78.2 ± 0.2 Ma, using Ar–Ar (Goodwin and Deino, 1989; Eberth and Deino, 1992). Cretaceous amber from the Kuk and Kaolak Rivers of northern Alaska has also been dated radiometrically to 95.4 ± 0.3 Ma using Ar–Ar in zircons extracted from bentonitic clays (D. Grimaldi, and D. Triplehorne, unpublished analyses done at the University of Alaska, Fairbanks). Amber from northern Alaska is abundant but rarely has inclusions of organisms; its similar age should make comparisons of such inclusions (when found) with those in Burmese amber interesting.

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