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High-precision $^{40}Ar/^{39}Ar$ age constraints on the basal Lanqi Formation and its implications for the origin of angiosperm plants

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ABSTRACT

Abundant Mesozoic terrestrial fossils were discovered in the Haifanggou Formation and the overlying Lanqi Formation in northeastern China. The recent discovery of *Schmeissneria sinensis* from the Haifanggou Formation provides evidence that the origin of angiosperms could be much earlier than previously believed. 92 taxa of plant fossils from the Lanqi Formation provide unique opportunities to understand the floral evolution and its diversification in the Mesozoic. Here we present robust high-precision $^{40}Ar/^{39}Ar$ data of 160.7±0.4 Ma and 158.7±0.6 Ma for two tuffs from the lowest part of the Lanqi Formation near the main outcrop of floral fossils in Beipiao City, Liaoning, China. Our age results indicate the whole Lanqi Formation was deposited in the Late Jurassic; consequently, the underlying Haifanggou Formation and *Schmeissneria sinensis* are at least Middle Jurassic in age. Besides its importance for floral evolution, our high-precision age results for the basal Lanqi Formation indicate the paleoenvironment in the north margin of the North China Craton was dry and hot in the Late Jurassic. Moreover, the new age data for the basal Lanqi Formation suggest that the unearthed fossils from the Haifanggou Formation and Lanqi Formation should be equivalent to the Daohugou Biota in Inner Mongolia, China.

1. Introduction

Well-preserved Mesozoic terrestrial fossils, mainly including plants and insects, were discovered in the Haifanggou Formation and the overlying Lanqi Formation in northeastern China. Since the late 1990s, the fossil-bearing beds have been excavated in Inner Mongolia, Hebei and Liaoning (Figs. 1 and 2). Some previous studies referred to fossils within the Haifanggou Formation in Liaoning (also called the Jiulongshan Formation in Hebei Province) as the Yanliao Biota. Similar fossil components were found from the overlying Lanqi Formation. The name of the Yanliao Biota, however, has not been widely accepted and is not well defined yet. In this study we refer to these assemblages collectively as the Haifanggou and Lanqi fossils (HLF), rather than the Yanliao Biota. The geographic distributions of the less-studied HLF and the well-known Jehol Biota consisting of terrestrial vertebrates including the famous feathered dinosaurs (Chen et al., 1998; Ji et al., 1998; Xu et al., 1999) are similar but the fossils were discovered from distinct formations now believed to be of different ages (Yang and Li, 2008). The lateral extension of the HLF and its correlation with the Daohugou Biota of Inner Mongolia is controversial; however, the unearthed fossils from the HLF have greatly increased our knowledge of Mesozoic terrestrial ecosystems.

The origin and rapid diversification of angiosperms (flowering plants) in the fossil record, referred to by Charles Darwin as the “abominable mystery”, has long been debated (Davies et al., 2004). As more floral fossils have been found since then, evidence suggests that angiosperm characteristics may have been acquired in a series of steps (Soltis and Soltis, 2004; De Bodt et al., 2005). Despite much research on the fossil record and phylogenetic analyses, the origin of the angiosperms and their rise to ecological dominance remain unclear. Recently, most paleobotanists accept an Early Cretaceous origin for angiosperms because fossil pollen provides the oldest evidence of angiosperms at roughly 136 Ma, about 10 Ma ealier than the oldest unknown flower fossil (Friis et al., 2005; Friis et al., 2006; Rydin et al., 2006; Frohlich and Chase, 2007). However, there is some circumstantial evidence that angioperms may have existed much earlier than the current fossil record. Molecular clock data suggested that the crown node of the angiosperms is from the Jurassic (145–208 Ma) (Sanderson et al., 2004).

The recent discovery of *Schmeissneria*, previously identified as a member of Ginkgoales (Kirchner and Van Koniinenbura-Van Cittert, 1994), from the Haifanggou Formation provided evidence that the origin of angiosperms could be earlier than Cretaceous and several theories regarding early seed plants should be reappraised. The well-preserved internal structures of female reproductive organs indicated

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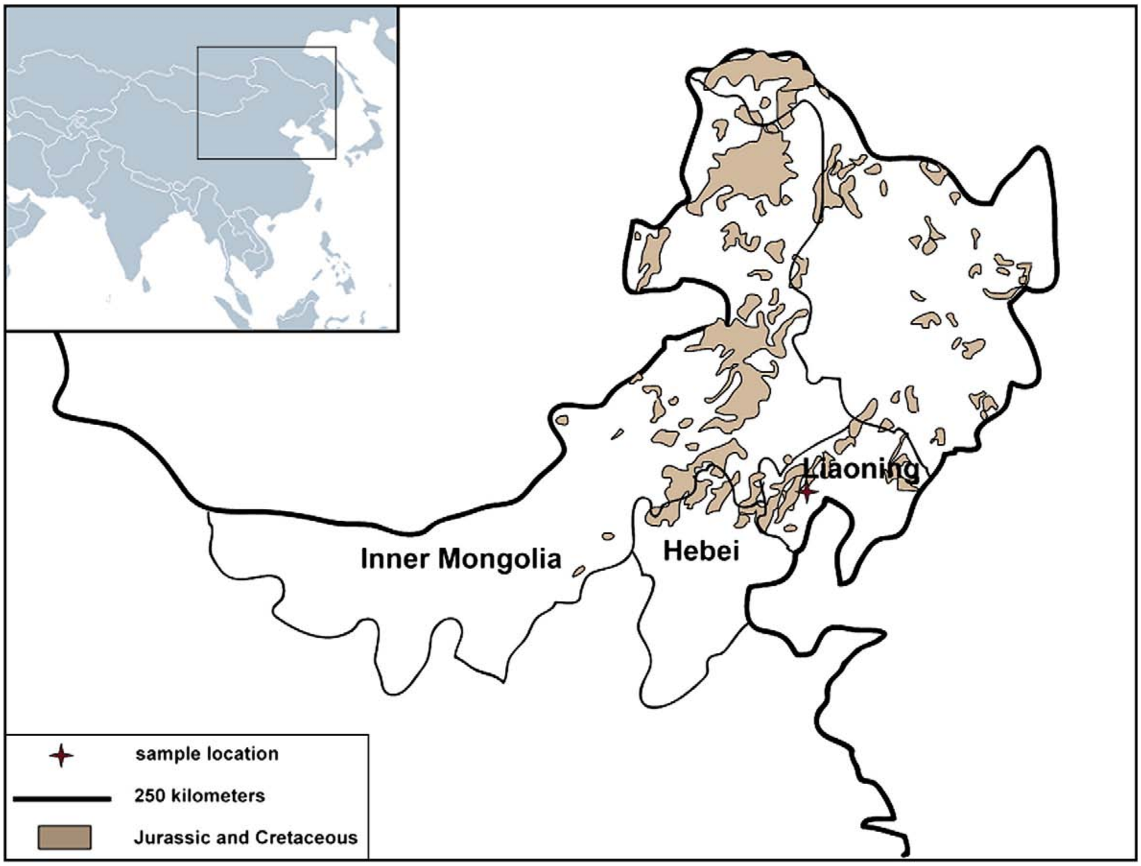

Fig. 1. Overview map of NE China with sample location. The HLF have been mainly excavated in Inner Mongolia, Hebei and Liaoning.

that *Schmeissneria sinensis* could be considered as an angiosperm or a new seed plant group parallel to angiosperms and other known seed plants (Wang et al., 2007). The features of the vertical complete septum and the closed apex of the central unit showed that *Schmeissneria sinensis* was distinct from any known gymnosperms, i.e. definitely not a member of Ginkgoales. Moreover, the appearance of the closed carpel, a character only found in flowering plants, suggested that *Schmeissneria sinensis* should be classified as an angiosperm. On the other hand, *Schmeissneria sinensis*, with some unknown features, does not look like any known angiosperm (Wang et al., 2007). If *Schmeissneria sinensis* is accepted as an angiosperm, the origin of the angiosperms would be pushed back to much earlier than Cretaceous due to *Schmeissneria microstachys from* the Early Jurassic sediments in Germany and Poland (Kirchner and Van Koniinenbura-Van Cittert, 1994). If *Schmeissneria sinensis* is classified as a new seed plant, the finding could challenge our perspective on the plant evolution, diversity and systematics.

In addition to the Haifanggou Formation, the overlying Lanqi Formation yielded a rich and varied terrestrial flora which includes 92 taxa of bryophytes, ferns, cycads, ginkgos and conifers (Jiang et al., 2008). The high diversity and abundance of the paleoflora provides a unique window to understand the floral evolution and its diversification in Mesozoic. Discovery of the wood fossil *Sahnioxylon rajmahalense,* the first ever in China, indicated that during the Mesozoic *Sahnioxylon* had a much wider distribution than expected. Furthermore, examination of *Sahnioxylon* demonstrated it could be an ancestral type of angiospermous wood devoid of vessels which represented a transition between gymnosperm and angiosperm (Zheng et al., 2005). The anatomical study of *Millerocaulis sinica*, a new species of fern from the Lanqi Formation, provided phylogenetic evidence that *Millerocaulis sinica* was an intermediate link between living fern *Osmunda* and its ancestor (Cheng and Li, 2007). In addition to its importance for floral evolution, the fossil assemblage of silicified woods and compressed plants from the Lanqi Formation indicated a subtropical, humid and seasonal climate (Jiang et al., 2008).

Determining the age of the HLF is critical to establishing its role in floral evolution, particularly of the angiosperms. However, reliable radioisotopic age determinations for these fossil-bearing formations are lacking. Previous age studies of the Haifanggou Formation and the overlaying Lanqi Formation were mainly focused on the tectonic evolution of the North China Craton. Previously reported ages are scattered and the uncertainties of these ages were fairly large. Here, we present new ^{40}Ar/^{39}Ar data for two tuffs from the lowest part of the Lanqi Formation near the main outcrop of floral fossils in Beipiao City, Liaoning, China. These data serve to precisely define the age of the HLF, and may provide the oldest constraint yet reported for the origin of the angiosperm plants.

2. Geological setting and previous geochronology

During the middle-late Mesozoic period, the sampling location and the surrounding area were located near the northern margin of the North China Craton, in a terrestrial environment at a paleolatitude of approximately 45°N (Smith et al., 1994). Geochemical and isotopic studies provide evidence for lithospheric thinning beneath the North China Craton during that period (Xu, 2002; Zhang et al., 2005a; Yang and Li, 2008). Interbedded tuffs from recurrent volcanism were responsible for the exceptional preservation of abundant fossils (Fursich et al., 2007).

The Haifanggou Formation, containing fauna including conchostracans *Euestheria ziliujingensis*, bivalves *Ferganoconcha* spp., insects *Mesoneta beipiaoensis* Wang, *Mesoblattina* sp., *Sinoplecia protansa* Wang, *Platyperla plotypoda* B. R. et G., and *Lycoriomimodes ruida* Wang, and abundant plants (Chen, 2003), is mainly composed of sandstone,

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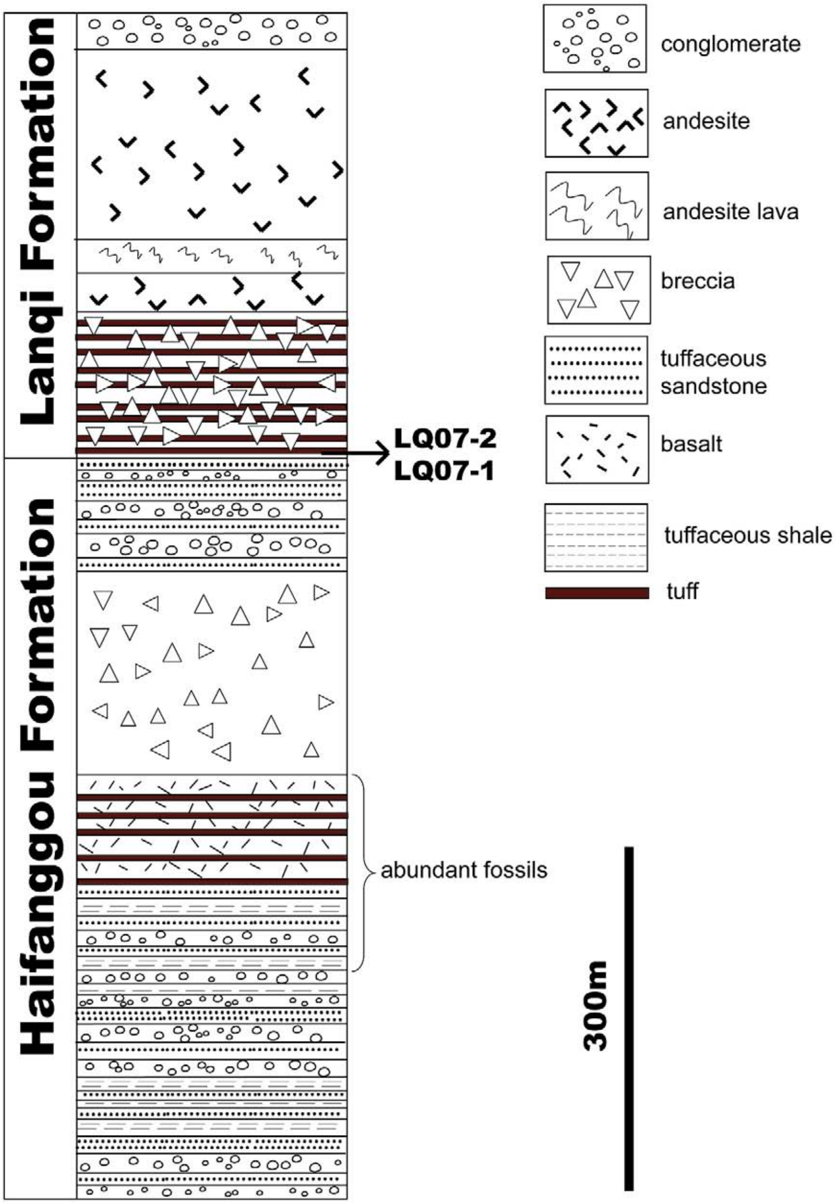

Fig. 2. Stratigraphic column for the Haifanggou Formation and the Lanqi Formation in Beipiao City, Liaoning, China.

conglomerate, shale and interbedded pyroclastic rocks. The lower Haifanggou Formation has more conglomerate and the proportion of pyroclastic rocks increases upward. Limited radioisotopic studies for the Haifanggou Formation have been reported. K/Ar whole rock analyses from a drilled core from the Haifanggou Formation yielded ages of 146.3 ± 8.5 Ma for a volcanic rock at 900 m depth, 161.6 ± 1.6 Ma for one at 1,300 m depth and 177.8 ± 7.7 Ma for one at the base (Chen et al., 1997). Wu et al. (2004) reported Rb/Sr isochron ages of 177.2 ± 28.0 Ma from three samples and 188.3 ± 43.7 Ma from four samples. The large uncertainties of most of these data and the incomplete stratigraphic descriptions of the samples limit their value for high-resolution chronostratigraphy.

The 130–970 meter thick Lanqi Formation of Western Liaoning, called the Tiaojishan Formation in Hebei and Inner Mongolia, mainly consists of basalt, andesite, rhyolite, tuff, tuffaceous sandstone and conglomerate. Besides the abundant plant fossils, a fauna including conchostracans *Triglypta pingquanensis* and *T. yangshulingensis* were found from the Tiaojishan Formation over Hebei as well (Deng et al., 2003). Estimates of the Lanqi/Tiaojishan Formation have ranged from the Early Jurassic (Toarcian) to the latest Jurassic (Tithonian). Based on floral fossils, paleobotanists suggested that the Lanqi Formation is Middle Jurassic in age (Zhang and Zheng, 1991; Cheng and Li, 2007). However, the radioisotopic ages for the Lanqi Formation obtained by different methods presented various results (Table 1). Six

Table 1
Summary of the previous radioisotopic ages for the Lanqi Formation

Age (Ma)	Method	Location/ stratigraphy	Reference
188 ± 19	Sm-Nd/ whole rock	Western Hills near Beijing/ TJS	Wang and Li, 2001
174.4 ± 1.4	^{40}Ar/^{39}Ar; andesite whole rock	TJS	Zhang et al., 2004
175–147	^{40}Ar/^{39}Ar	TJS and LQ	Davis, 2005
162.8 ± 3.2	LA-ICP-MS U/Pb; zircon	Hebei/ the uppermost of TJS	Zhang et al., 2005b
166–153	SHRIMP U/Pb and ^{40}Ar/^{39}Ar	Liaoning and Inner Mongolia	Yang and Li 2008
156.3 ± 8.5	K/Ar	LQ	Diao and Li, 1983
148.9 ± 3.0	^{40}Ar/^{39}Ar; plagioclase	TJS	Li et al., 2001;

*TJS: the Tiaojishan Formation; LQ: the Lanqi Formation.

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Table 2
Ar data corrected for decay, blank and mass discrimination (2 σ errors)

Run ID	Laser (W)	^{40}Ar	^{40}Ar error	^{39}Ar	^{39}Ar error	^{38}Ar	^{38}Ar error	^{37}Ar	^{37}Ar error	^{36}Ar	^{36}Ar error	%^{40}Ar*	age (Ma)	±w/o J
LQ07-1	*D* = 1.00704 ± 0.00150													
16842-04A	0.5	0.5842	0.0016	0.0166	0.00009	0.00020	0.000011	0.00010	0.00026	0.000031	0.000025	98.4	161.3	2.2
16842-04B	1.0	4.3412	0.0039	0.1250	0.00025	0.00154	0.000014	0.00085	0.00027	0.000056	0.000029	99.6	160.8	0.5
16842-04C	2.0	3.0242	0.0032	0.0871	0.00024	0.00107	0.000013	0.00070	0.00027	0.000047	0.000028	99.5	160.6	0.7
16842-04D	3.5	0.5653	0.0013	0.0161	0.00008	0.00019	0.000011	−0.00009	0.00027	0.000013	0.000025	99.3	162.0	2.3
16842-04E	5.0	0.2540	0.0014	0.0070	0.00009	0.00008	0.000011	−0.00011	0.00027	0.000013	0.000024	98.5	165.8	5.0
16842-04F	6.5	0.0398	0.0012	0.0011	0.00007	0.00001	0.000011	−0.00060	0.00027	−0.000024	0.000023	118.0	200.0	31.0
16842-04G	8.0	0.0010	0.0012	0.0001	0.00005	−0.00003	0.000011	−0.00043	0.00027	−0.000010	0.000023	390.0	330.0	570.0
16842-05A	0.5	0.0722	0.0012	0.0021	0.00005	0.00002	0.000011	0.00012	0.00028	−0.000022	0.000024	109.0	176.0	16.0
16842-05B	0.8	8.0942	0.0048	0.2333	0.00040	0.00287	0.000017	0.00149	0.00029	0.000053	0.000032	99.8	160.9	0.4
16842-05C	1.2	5.3848	0.0044	0.1547	0.00031	0.00190	0.000015	0.00099	0.00028	0.000027	0.000028	99.9	161.4	0.5
16842-05D	1.8	1.7933	0.0015	0.0515	0.00015	0.00062	0.000012	0.00051	0.00027	0.000038	0.000026	99.4	160.8	0.9
16842-05E	2.5	0.2920	0.0013	0.0082	0.00006	0.00010	0.000011	0.00011	0.00028	0.000003	0.000024	99.7	165.4	4.1
16842-05F	5.0	0.0753	0.0013	0.0020	0.00007	0.00002	0.000011	−0.00024	0.00027	−0.000017	0.000023	106.7	181.0	16.0
16842-05G	8.0	0.0043	0.0012	0.0000	0.00005	0.00000	0.000011	−0.00011	0.00028	−0.000016	0.000022	210.0	10000.0	580000.0
16842-06A	0.5	4.2894	0.0036	0.1232	0.00027	0.00150	0.000013	0.00091	0.00028	0.000029	0.000028	99.8	161.4	0.5
16842-06B	0.7	5.2651	0.0044	0.1511	0.00027	0.00187	0.000015	0.00136	0.00028	0.000073	0.000030	99.6	161.2	0.5
16842-06C	1.0	0.1454	0.0013	0.0041	0.00006	0.00005	0.000011	0.00004	0.00028	0.000001	0.000024	99.8	163.1	8.1
16842-06D	1.5	0.0039	0.0012	0.0001	0.00005	−0.00001	0.000011	−0.00028	0.00028	−0.000023	0.000022	270.0	470.0	340.0
16842-06E	2.5	−0.0010	0.0012	0.0000	0.00005	0.00000	0.000011	−0.00020	0.00028	−0.000012	0.000022	−250.0	1000.0	4500.0
16842-06F	5.0	−0.0001	0.0012	0.0000	0.00005	−0.00001	0.000011	−0.00003	0.00027	−0.000039	0.000022	−20000.0	NAN	−12000.0
16842-06G	8.0	0.0023	0.0012	−0.0001	0.00006	−0.00001	0.000011	−0.00010	0.00027	0.000013	0.000021	−80.0	110.0	410.0
16842-07A	0.3	0.0253	0.0012	0.0006	0.00006	−0.00001	0.000011	−0.00030	0.00028	−0.000009	0.000019	110.0	217.0	48.0
16842-07B	0.5	3.4874	0.0028	0.1000	0.00019	0.00125	0.000014	0.00088	0.00029	0.000113	0.000021	99.1	160.5	0.5
16842-07C	0.8	1.7244	0.0017	0.0502	0.00017	0.00063	0.000012	0.00053	0.00028	0.000020	0.000026	99.7	159.2	0.9
16842-07D	1.2	2.7267	0.0043	0.0789	0.00021	0.00096	0.000013	0.00072	0.00029	−0.000019	0.000026	100.2	160.9	0.7
16842-07E	1.8	0.8106	0.0024	0.0231	0.00020	0.00027	0.000012	0.00031	0.00027	0.000021	0.000023	99.2	162.0	2.0
16842-07F	4.0	0.0882	0.0013	0.0025	0.00006	0.00003	0.000011	0.00002	0.00028	0.000002	0.000020	99.2	162.0	11.0
16842-07G	8.0	0.0037	0.0012	0.0000	0.00005	−0.00001	0.000011	−0.00009	0.00028	−0.000016	0.000019	230.0	900.0	1200.0
16842-08A	0.3	0.0000	0.0012	0.0000	0.00005	−0.00001	0.000011	0.00014	0.00029	−0.000003	0.000019	−2000.0	200.0	1500.0
16842-08B	0.5	0.1460	0.0013	0.0039	0.00006	0.00005	0.000011	0.00018	0.00029	0.000039	0.000020	92.0	159.2	7.1
16842-08C	0.8	13.5061	0.0059	0.3897	0.00064	0.00479	0.000020	0.00258	0.00030	0.000049	0.000037	99.9	160.9	0.4
16842-08D	1.2	4.1502	0.0038	0.1195	0.00025	0.00150	0.000014	0.00118	0.00029	0.000053	0.000028	99.6	160.8	0.5
16842-08E	1.8	16.9516	0.0075	0.4852	0.00073	0.00594	0.000021	0.00323	0.00031	0.000379	0.000028	99.3	161.2	0.4
16842-08F	4.0	3.2614	0.0034	0.0932	0.00024	0.00118	0.000014	0.00088	0.00029	0.000125	0.000021	98.9	160.8	0.6
16842-08G	8.0	0.2919	0.0014	0.0077	0.00009	0.00012	0.000012	0.00038	0.00029	0.000070	0.000020	92.9	163.0	3.9
16842-09A	0.3	0.0007	0.0008	0.0000	0.00004	0.00000	0.000010	−0.00001	0.00023	0.000000	0.000016	110.0	200.0	1400.0
16842-09B	0.5	3.3783	0.0043	0.0973	0.00023	0.00122	0.000012	0.00082	0.00023	0.000086	0.000018	99.3	160.2	0.5
16842-09C	0.8	14.8761	0.0065	0.4309	0.00057	0.00533	0.000019	0.00285	0.00025	0.000100	0.000035	99.8	160.1	0.3
16842-09D	1.2	3.5751	0.0031	0.1021	0.00016	0.00127	0.000013	0.00098	0.00023	0.000196	0.000018	98.4	160.0	0.4
16842-09E	1.8	2.5422	0.0028	0.0730	0.00019	0.00089	0.000012	0.00077	0.00024	0.000096	0.000018	98.9	160.1	0.6
16842-09F	4.0	0.4492	0.0009	0.0129	0.00009	0.00018	0.000012	0.00022	0.00024	0.000014	0.000022	99.1	160.5	2.5
16842-09G	8.0	0.1303	0.0009	0.0035	0.00004	0.00003	0.000012	−0.00025	0.00023	0.000003	0.000021	99.2	172.8	8.3
16842-10A	0.2	−0.0002	0.0007	0.0000	0.00003	−0.00001	0.000011	0.00010	0.00023	−0.000005	0.000016	−900.0	−200.0	750.0
16842-10B	0.4	0.0046	0.0007	0.0001	0.00003	−0.00001	0.000011	−0.00004	0.00024	−0.000016	0.000018	200.0	600.0	390.0
16842-10C	0.7	2.3932	0.0028	0.0692	0.00022	0.00084	0.000018	0.00042	0.00023	0.000065	0.000023	99.2	159.5	0.7
16842-10D	1.0	6.7065	0.0045	0.1937	0.00031	0.00229	0.000028	0.00113	0.00023	0.000035	0.000027	99.9	160.6	0.4
16842-10E	1.5	11.6135	0.0051	0.3353	0.00063	0.00406	0.000034	0.00198	0.00025	0.000088	0.000032	99.8	160.6	0.4
16842-10F	4.0	2.5508	0.0028	0.0726	0.00022	0.00089	0.000020	0.00052	0.00025	0.000103	0.000017	98.8	161.2	0.7
16842-10G	8.0	0.2197	0.0011	0.0066	0.00006	0.00008	0.000012	0.00050	0.00024	0.000040	0.000016	94.6	146.5	3.6
LQ07-2	*D* = 1.00786 ± 0.00154													
16845-03	8.0	0.1965	0.0008	0.0056	0.00006	0.00008	0.000012	0.00876	0.00028	0.000023	0.000017	96.9	159.1	4.3
16845-04	8.0	0.1463	0.0013	0.0042	0.00004	0.00003	0.000013	0.00501	0.00028	0.000012	0.000020	97.9	158.8	6.7
16845-05	8.0	0.3121	0.0013	0.0092	0.00005	0.00011	0.000013	0.01424	0.00026	0.000007	0.000020	99.7	159.1	3.1
16845-07	8.0	0.6496	0.0019	0.0191	0.00013	0.00025	0.000014	0.02602	0.00038	0.000022	0.000021	99.3	158.6	1.9
16845-08	8.0	0.1203	0.0010	0.0034	0.00005	0.00004	0.000011	0.00477	0.00027	0.000022	0.000020	95.0	157.2	8.1
16845-10	8.0	0.1352	0.0011	0.0040	0.00005	0.00007	0.000012	0.02910	0.00044	0.000017	0.000020	98.0	154.7	7.1
16845-13	8.0	0.2156	0.0015	0.0063	0.00005	0.00008	0.000012	0.00760	0.00026	0.000018	0.000020	97.8	156.7	4.6
16845-14	8.0	0.4177	0.0014	0.0123	0.00009	0.00014	0.000013	0.01860	0.00032	0.000005	0.000020	100.0	159.2	2.5
16845-15	8.0	0.2649	0.0015	0.0078	0.00006	0.00011	0.000013	0.00938	0.00029	0.000003	0.000016	99.9	159.1	3.2
16845-16	8.0	0.2763	0.0015	0.0078	0.00005	0.00010	0.000013	0.07686	0.00050	0.000049	0.000017	97.0	162.2	3.2
16845-19	8.0	0.5810	0.0016	0.0167	0.00012	0.00026	0.000013	0.08799	0.00059	0.000065	0.000020	97.9	160.1	2.1
16845-20	8.0	0.0792	0.0008	0.0024	0.00004	0.00004	0.000012	0.02327	0.00035	0.000012	0.000019	97.8	155.7	11.0
16845-21A	0.3	0.0987	0.0008	0.0019	0.00004	0.00005	0.000011	0.00363	0.00041	0.000163	0.000020	51.4	129.0	15.0
16845-21B	0.5	2.5447	0.0041	0.0734	0.00015	0.00094	0.000018	0.18464	0.00097	0.000291	0.000022	97.2	158.3	0.6
16845-21C	0.7	5.4566	0.0069	0.1601	0.00029	0.00196	0.000025	0.33160	0.00130	0.000314	0.000018	98.8	158.1	0.5
16845-21D	0.9	4.5640	0.0055	0.1333	0.00035	0.00163	0.000022	0.27350	0.00120	0.000215	0.000018	99.1	159.3	0.6
16845-21E	1.1	2.3921	0.0039	0.0696	0.00021	0.00091	0.000015	0.24500	0.00120	0.000159	0.000022	98.8	159.5	0.7
16845-21F	1.4	1.9796	0.0028	0.0580	0.00018	0.00072	0.000018	0.13103	0.00074	0.000120	0.000022	98.7	158.2	0.8
16845-21G	1.8	0.6308	0.0020	0.0186	0.00012	0.00025	0.000013	0.04948	0.00067	0.000055	0.000021	98.0	156.7	1.9
16845-21H	2.3	0.1997	0.0008	0.0057	0.00005	0.00005	0.000010	0.01204	0.00045	-0.000002	0.000019	100.8	166.5	4.7
16845-21I	2.8	0.1515	0.0008	0.0042	0.00004	0.00007	0.000010	0.01188	0.00046	0.000019	0.000019	96.9	164.2	6.3
16845-21J	3.3	0.1731	0.0013	0.0050	0.00004	0.00005	0.000011	0.04208	0.00056	0.000023	0.000020	97.9	160.6	5.7
16845-21K	5.0	0.0574	0.0007	0.0015	0.00005	0.00002	0.000010	0.00755	0.00043	0.000009	0.000016	96.5	169.0	15.0

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Table 2 (*continued*)

Run ID	Laser (W)	^{40}Ar	^{40}Ar error	^{39}Ar	^{39}Ar error	^{38}Ar	^{38}Ar error	^{37}Ar	^{37}Ar error	^{36}Ar	^{36}Ar error	%^{40}Ar*	age (Ma)	±w/o J
LQ07-2	*D = 1.00786 ± 0.00154*													
16845-21L	8.0	1.7694	0.0018	0.0013	0.00004	0.00111	0.000017	0.00901	0.00044	0.005893	0.000025	1.6	105.0	46.0
16845-22A	0.3	0.0797	0.0008	0.0013	0.00004	0.00004	0.000011	0.00130	0.00042	0.000173	0.000020	35.9	102.0	21.0
16845-22B	0.4	0.6649	0.0019	0.0191	0.00015	0.00028	0.000012	0.03504	0.00062	0.000168	0.000021	93.0	152.4	2.0
16845-22C	0.6	2.3046	0.0046	0.0674	0.00018	0.00084	0.000020	0.12385	0.00093	0.000141	0.000023	98.6	158.4	0.7
16845-22D	0.7	3.7179	0.0049	0.1080	0.00030	0.00134	0.000023	0.21730	0.00120	0.000278	0.000018	98.3	158.7	0.6
16845-22E	0.9	1.6729	0.0013	0.0488	0.00017	0.00059	0.000014	0.09598	0.00075	0.000099	0.000017	98.7	158.9	0.8
16845-22F	1.1	2.5811	0.0026	0.0750	0.00020	0.00094	0.000018	0.24570	0.00120	0.000178	0.000018	98.7	159.5	0.6
16845-22G	1.3	0.7090	0.0021	0.0206	0.00017	0.00027	0.000013	0.04683	0.00061	0.000079	0.000017	97.2	157.3	1.8
16845-22H	1.8	0.2002	0.0007	0.0054	0.00005	0.00008	0.000011	0.01291	0.00048	0.000062	0.000016	91.4	159.7	4.3
16845-22I	2.5	0.0853	0.0007	0.0024	0.00005	0.00002	0.000010	0.00407	0.00043	0.000011	0.000016	96.6	162.8	9.7
16845-22J	3.5	0.0737	0.0007	0.0020	0.00004	0.00002	0.000010	0.00382	0.00043	0.000003	0.000016	99.2	172.0	11.0
16845-22K	5.5	0.3899	0.0014	0.0039	0.00006	0.00019	0.000013	0.00678	0.00043	0.000839	0.000018	36.5	169.3	7.0
16845-22L	8.0	0.8657	0.0026	0.0004	0.00004	0.00052	0.000015	0.00090	0.00041	0.002849	0.000020	2.8	300.0	100.0

samples from the Tiaojishan Formation at the Western Hills near Beijing yielded a Sm/Nd isochron age of 188 ± 19 Ma (Wang and Li, 2001). Davis (2005) suggested the Lanqi/Tiaojishan Formation ranged from 175–147 Ma by combining several ^{40}Ar/^{39}Ar ages. An andesite from the Tiaojishan Formation yielded a whole rock ^{40}Ar/^{39}Ar isochron age of 174.4 ± 1.4 Ma (Zhang et al., 2004). Zircon LA-ICP-MS U/Pb dates on volcanic breccia samples from the uppermost of the Tiaojishan Formation at Luanping area, Hebei provided an age of 162.8 ± 3.2 Ma (Zhang et al., 2005b). Yang and Li (2008) proposed the age of Lanqi Formation is 166–153 Ma combining SHRIMP U/Pb and ^{40}Ar/^{39}Ar data. K/Ar isotopic dating indicated that some of the volcanic rocks of the Lanqi Formation are around 156.3 ± 8.5 Ma (Diao and Li, 1983). Plagioclase grains from a Tiaojishan trachyandesite gave plateau and isochron ^{40}Ar/^{39}Ar ages of 148.9 ± 3.0 and 146.6 ± 2.9 Ma (Li et al., 2001).

3. Methodology

We collected two tuff samples from the Lanqi Formation near Yujiagou village of Beipiao City, Liaoning, China (N 41°50.568', E 120°46.592'). Tuff LQ07-1 is from the lowermost Lanqi Formation and Tuff LQ07-2 is about 10 m higher than LQ07-1. Examination of petrographic thin sections reveals that both tuff samples contain phenocrysts of sanidine, plagioclase, biotite and quartz. All minerals from LQ07-1 are more coarse-grained and fresher than those from LQ07-2. Biotite and sanidine from LQ07-2 show slight alteration, but plagioclase is fresh. Thus, sanidine from LQ07-1 and plagioclase from LQ07-2 are suitable for ^{40}Ar/^{39}Ar dating. Both hand samples were crushed and separated into sieved size fractions. 250–420 μm size fractions of sanidine from LQ07-1 and 180–250 μm size fractions of plagioclase from LQ07-2 were separated using a Frantz magnetic separator and heavy-liquids. Only transparent minerals were hand-picked under a binocular microscope. The minerals were cleaned in diluted HF for 1 minute and then thoroughly rinsed in distilled water in an ultrasonic cleanser.

Following selection, sanidine and plagioclase were loaded into two pits of a 1.9 cm diameter and 0.3 cm depth Al disk (as described by Renne et al., 1998). Fish Canyon sanidine with an age of 28.02 Ma (Renne et al., 1998) was used as neutron fluence monitor and was loaded into five pits bracketing the samples (shown in the electronic supplement). Samples and standards were irradiated (IR#370SCC) for 10 h duration using the cadmium-lined in-core irradiation tube (CLICIT) facility of the Oregon State University TRIGA reactor, USA.

After irradiation, all standards and samples were degassed using an automated CO_2 laser-based extraction system and analyzed with a MAP 215–50 mass spectrometer at the Berkeley Geochronology Center. Identical J values of 0.0027169 ± 0.0000384, 0.0026969 ± 0.0000391, 0.0026998 ± 0.0000393, 0.0027257 ± 0.0000406, 0.0027015 ± 0.0000384 (2 σ errors are presented here, and throughout this paper) were determined from the weighted mean of data from 11 FCs crystals from each irradiation position. Total variance of the neutron fluence as calculated for the whole disk is 1.2% varying regularly as shown in the electronic supplement. J values for the samples were calculated using multivariate interpolation, yielding values of 0.0026936 ± 0.0000331 for LQ07-1 sanidine and 0.0027164 ± 0.0000336 for LQ07-2 plagioclase. Incremental heating is the preferred mode of analysis because of the ability of the age spectrum to reveal and mitigate the effects of alteration and/or partial Ar loss (McDougall and Harrison 1999). Because both samples are tuffs, there is a potential for xenocrystic contamination to bias the results. Fortunately, the LQ07-1 sanidine crystals were sufficiently large to enable step heating of single crystals, thereby allowing detection of anomalously old ages from xenocrysts. LQ07-2 plagioclase, because of its lower K content and small grain size, could not be analyzed by step heating of single crystals. Thus, this sample was analyzed first by total fusion of twenty individual grains in order to evaluate the possibility of xenocrysts. Seven single LQ07-1 sanidine grains were degassed in seven steps each by incrementally increasing the laser power. Two individual multigrain step-heating analyses of LQ07-2 plagioclase were degassed in twelve steps. Blanks and air aliquots from an automated pipette were measured between every three and twelve sample runs, respectively. Mass discrimination determined as a power law relationship from the air pipette data was 1.00704 ± 0.00150 Da^{-1} (Dalton; atomic mass unit) for the standard (FCs) and LQ07-1 sanidine, and 1.00786 ± 0.00154 Da^{-1} for LQ07-2 plagioclase. Ar isotopic data corrected for blanks, mass discrimination and radioactive decay are given in Table 2. Plateau ages were defined as three or more contiguous steps corresponding to a minimum of 50% of the ^{39}Ar released and showing no statistically significant slope. The ages were calculated based on the decay constants $\lambda_{\bar{\beta}}=4.962\times10^{-10}$ and $\lambda^{40}{}_{Ar}=0.581\times10^{-10}$ (Steiger and Jager, 1977) and the age for FCs of 28.02 Ma (Renne et al., 2005). Systematic errors arising from the decay constants and standards age are not included in the age errors. The values of these quantities are known to be superseded by more accurate determinations (e.g., Kuiper et al., 2008; Jourdan and Renne, 2007), but the ages presented herein are based on the conventional values for consistency with other data. The correction factors for interfering isotopes at the TRIGA facility are $(^{39}Ar/^{37}Ar)_{Ca}=(6.95\pm0.09)\times10^{-4}$, $(^{36}Ar/^{37}Ar)_{Ca}=(2.65\pm0.02)\times10^{-4}$ and $(^{40}Ar/^{39}Ar)_{K}=(7.30\pm0.92)\times10^{-4}$ (Renne et al., 2005).

4. Result

Seven single grains of LQ07-1 sanidine yielded plateau ages of 160.8 ± 0.9 Ma, 161.1 ± 0.7 Ma, 161.3 ± 0.8 Ma, 160.5 ± 0.8 Ma, 161.0 ± 0.8 Ma, 160.1 ± 0.6 Ma and 160.6 ± 0.6 Ma (2 σ errors are presented here and throughout this paper) (Fig. 3). The weighted mean age of all plateau ages is 160.7 ± 0.4 Ma with an MSWD of 0.91, indicating

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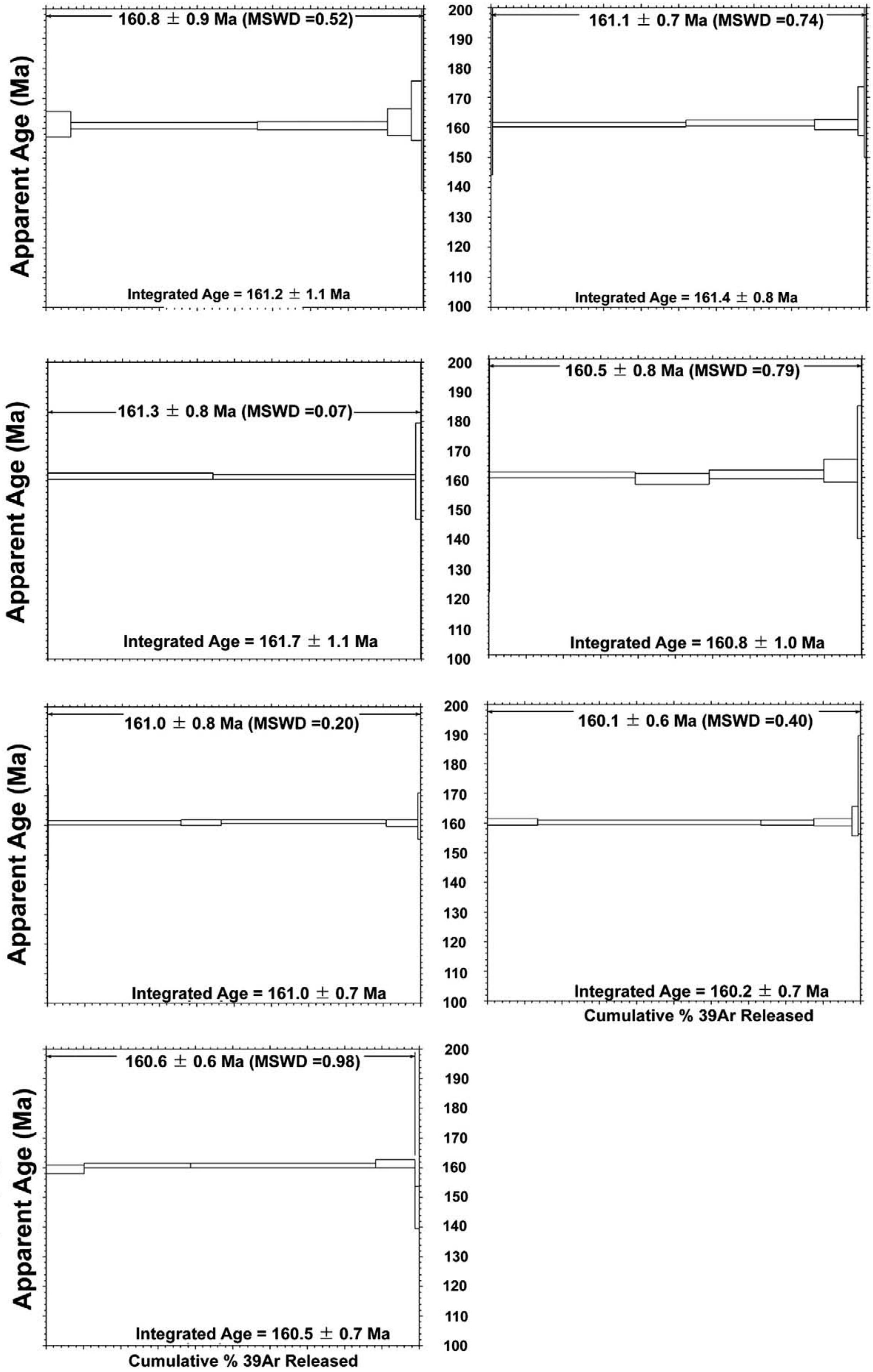

Fig. 3. ^{40}Ar/^{39}Ar apparent age spectra from seven single-grain step-heating analyses for LQ07-1 sanidine.

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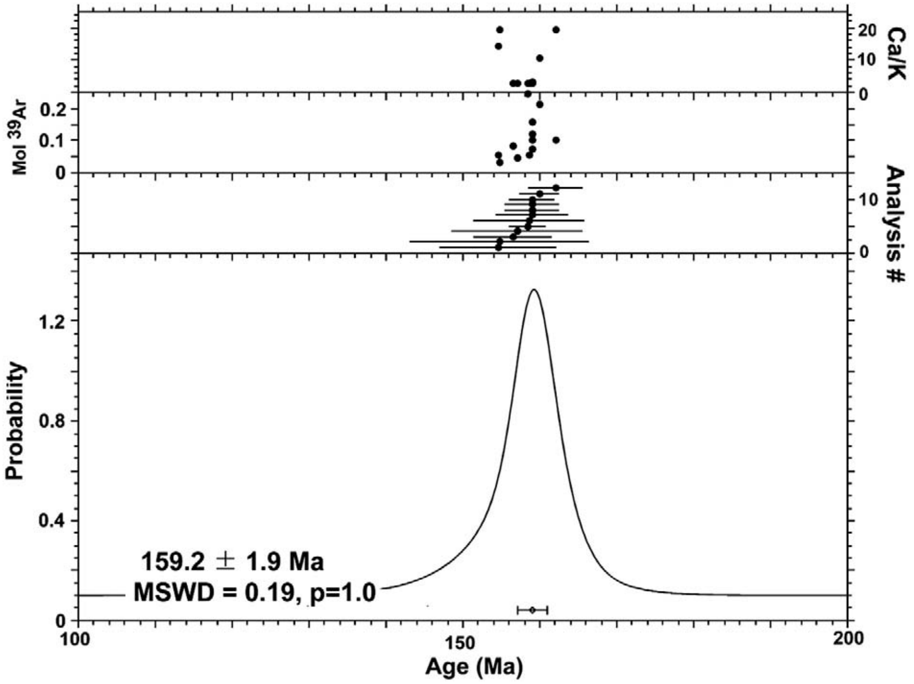

Fig. 4. ^{40}Ar/^{39}Ar age probability plot for LQ07-2 plagioclase from single crystal total fusion. (Error calculation method: SEM, but if MSWD>95% prob. Use SEM *sqrt (MSWD)*).

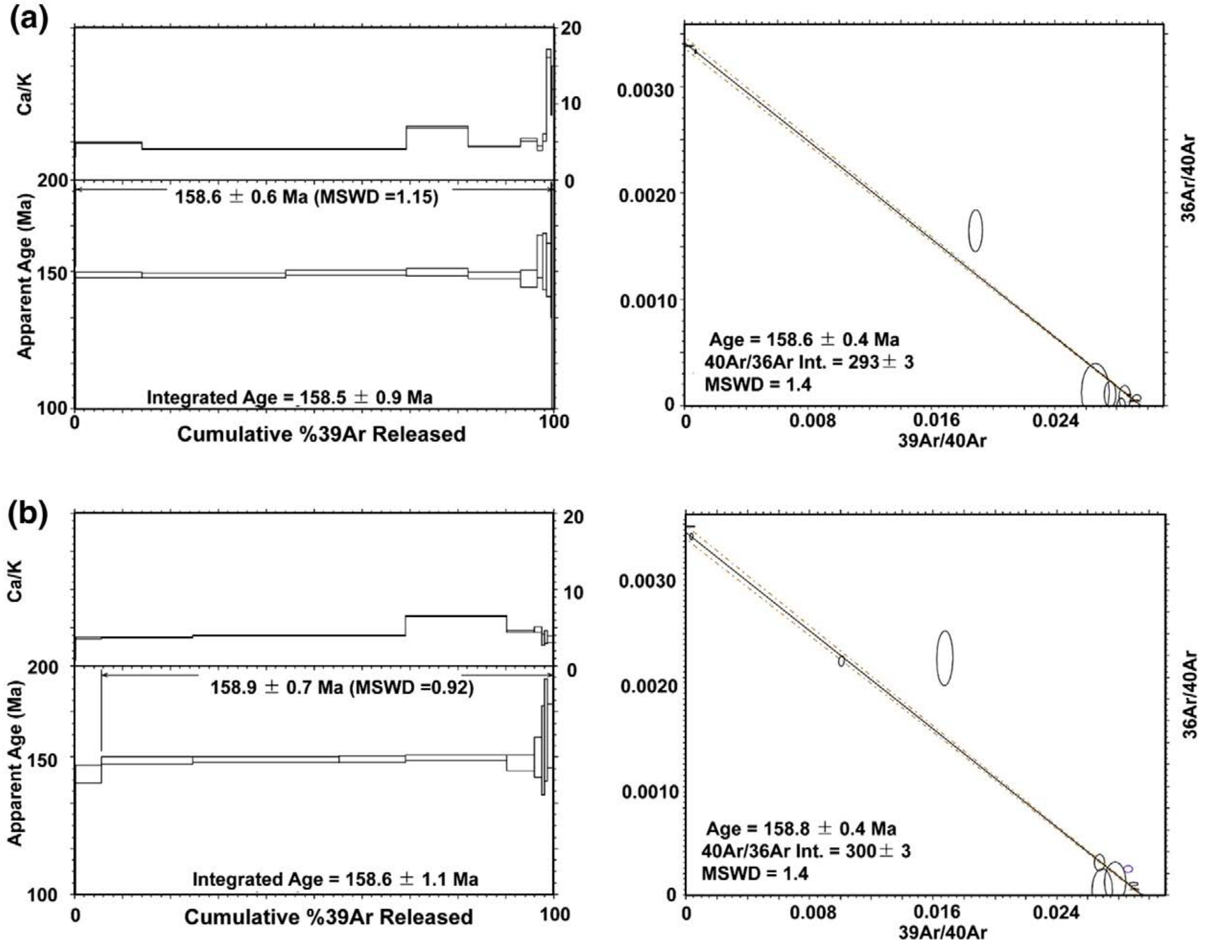

Fig. 5. (Left) ^{40}Ar/^{39}Ar apparent age and related Ca/K ratio spectra of multi-grain step-heating analyses for LQ07-2 plagioclase; (right) inverse isochron plots for individual two analyses.

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that data are not significantly scattered in excess of analytic errors (MSWD > 1) and that analytic errors are not overestimated (MSWD < 1). The spectra are mostly flat and show negligible difference between the plateau ages and the integrated ages. MSWD from six of seven plateau ages are much smaller than 1, suggesting overestimation of analytic errors. All plateau ages are indistinguishable at the 2 σ level which suggests no reworking or xenocrystic contamination of sanidine in this tuff.

The weighted mean age of single crystal total fusion results for LQ07-2 plagioclase is 159.2 ± 1.9 Ma with an MSWD of 0.19, indicating that correlated error might exist between the constituent results. Eight of twenty plagioclase grains were omitted from the age probability plot (Fig. 4) due to small gas yields and huge errors which indicate either the laser missed the grains or the grains were quartz. The age probability plot, showing a narrow Gaussian distribution, suggests no xenocrystic contamination in this tuff. Two step-heating analyses of LQ07-2 plagioclase yield distinguishable plateau ages of 158.6 ± 0.6 Ma and 158.9 ± 0.7 Ma, respectively, with MSWD of 1.15 and 0.92 (Fig. 5). The weighted mean age of two plateau ages is 158.7 ± 0.6 Ma with MSWD of 1.01, indicating good correspondence between scatter and estimated errors from all plateau steps. The concordant age spectra for the multi-grain step-heating provide evidence of no obvious argon loss and/or trapped argon and no apparent xenocrystic contamination of LQ07-2 plagioclase. The Ca/K (derived from the $^{37}Ar_{Ca}/^{39}Ar_{K}$) spectra from two analyses are roughly flat and identical. The Ca/K ratios are slightly increased at the high temperature steps, likely resulting from normal compositional zoning of plagioclase. Two isochron ages of 158.6 ± 0.4 Ma and 158.8 ± 0.4 Ma for LQ07-2 plagioclase are in excellent agreement with the plateau ages, both with MSWD of 1.4. The $^{40}Ar/^{36}Ar$ intercepts of 293 ± 3.0 and 300 ± 3.0 from two inverse isochron diagrams are close to the air ratio (i.e. 295.5, Nier, 1950 or 298.56, Lee et al., 2006).

5. Discussion

5.1. Previous geochronology

Previous radioisotopic results for the Lanqi Formation obtained by different methods were discordant. Most recently, Yang and Li (2008) reported a $^{40}Ar/^{39}Ar$ plateau age of 166.14 ± 0.89 Ma, including 92.2% of ^{39}Ar released, for a basalt sample from the lower part of the Lanqi Formation near our sampling site. However, the standard used as neutron fluence monitor, the criteria for the determination of this plateau and MSWD for this so-called plateau age are unknown. The age spectrum showed significantly older apparent ages in several low temperature steps which may cause the plateau age to be spuriously old due to recoil artifacts or excess ^{40}Ar. An age of 162.8 ± 3.2 Ma for the uppermost Tiaojishan Formation at Luanping area, Hebei was obtained by LA-ICP-MS U/Pb dating (Zhang et al., 2005b). Although eight of eighteen results were excluded as outliers, ten zircons from this sample yielded scattered ages and the concordia diagram showed the zircons were affected by xenocrystic contamination and Pb loss. Thus, the accuracy of this reported age is open to some discussion. The Sm/Nd study showed an older but imprecise age of 188 ± 19 Ma for six samples from the Western Hills near Beijing (Wang and Li, 2001), suggesting the voluminous volcanic rocks of the Tiaojishan Formation formed before the early Middle Jurassic (in the Bajocian age).

5.2. Interpretation of the new data

We obtained $^{40}Ar/^{39}Ar$ ages of 160.7 ± 0.4 Ma for LQ07-1 and 158.7 ± 0.6 Ma for LQ07-2, ten meters above LQ07-1 from the same section. Results from seven analyses of single-grain step-heating for LQ07-1 sanidine are consistent, and preclude significant alteration or xenocrystic contamination in this tuff. Two identical age spectra for the multi-grain step-heating analyses of LQ07-2 plagioclase provide no evidence of argon loss and/or non-atmospheric trapped argon, and single crystal total fusion analyses reveal no apparent xenocrystic contamination of this tuff. Based on the accuracy and the precision of our results, we propose the age of the basal Lanqi Formation is 160.7 ± 0.4 Ma.

Our precise new $^{40}Ar/^{39}Ar$ data for the basal Lanqi Formation raise questions about the accuracy of previous radioisotopic results and the correlations of the Lanqi/Tiaojishan Formation in the different sampling locations over Liaoning, Inner Mongolia and Hebei. In this study, two tuff samples were collected from the lowest part of the classic Lanqi Formation in Beipiao, western Liaoning, China. Besides the well-studied stratigraphy, important fossils of the HLF were excavated from nearby, thus minimizing ambiguities about long distance correlations. We note that the $^{40}Ar/^{39}Ar$ age of 166.14 ± 0.89 Ma (Yang and Li, 2008) obtained from the lowest Lanqi Formation near our sampling location will be close to our results, if the higher apparent age at the low temperature steps is discarded from its calculation for the plateau age. Thus, our reported age for the basal Lanqi Formation should be accepted as the model for the further stratigraphic correlation and geochronological studies.

Although most Tiaojishan samples for the previous radioisotopic works were collected from Hebei and Inner Mongolia, at least 200 km apart from our sampling location, the correlations of the Mesozoic formations between Hebei and Liaoning are clear. It is, therefore, possible that the discrepant ages in this study and previous reports are artifacts of diachronous chronostratigraphies as well as interlaboratory errors.

5.3. The correlation with Daohugou beds

Recently, a wide range of well-preserved Mesozoic fossils were unearthed from Daohugou village of Ningcheng county, Inner Mongolia, China. The Daohugou Biota, including insects, conchostracans, salamanders, pterosaurs, dinosaurs, mammals and plants, has provided a rare opportunity to understand the evolutionary history of several groups and to reconstruct the Mesozoic ecosystem in terrestrial environment. However, the stratigraphy of Daohugou section is highly debatable. Controversy remains over whether or not these Mesozoic formations have been overturned (Ren and Gao, 2002; He et al., 2004; Wang et al., 2005). Despite the argument about the stratigraphy, most radioisotopic ages for the Daohugou beds, a series fossil-bearing rock deposits, obtained by different methods presented similar results. He et al. (2004) reported a $^{40}Ar/^{39}Ar$ plateau age of 159.8 ± 0.8 Ma for the ignimbrite, right below the fossil-bearing deposits. SHRIMP U/Pb zircon ages for lavas overlying and underlying the salamander-bearing bed suggested that the Daohugou Biota occurred at an interval from 168 to 152 Ma (Liu et al., 2006). Chen and Zhang (2004) reported an age of 165-159 Ma for the Daohugou beds by combining SHRIMP U/Pb and $^{40}Ar/^{39}Ar$ data although the known ~1% bias between U/Pb and $^{40}Ar/^{39}Ar$ methods (Min et al., 2000) was not accounted for. Nowadays, the Daohugou beds of Inner Mongolia are generally correlated with the Haifanggou Formation in Liaoning (Ren and Gao, 2002; Gao and Ren, 2006; Jiang, 2006). Our new age data for the basal Lanqi Formation suggest that the Daohugou beds might be equivalent to the Lanqi Formation as well. Here we propose that the HLF might be related to the Daohugou Biota although further geological, radioisotopic and paleontological studies are needed.

5.4. Implication for floral evolution and paleoenvironment

Although the floral fossil record has greatly increased since the time of Darwin, the origin of the angiosperms and their rise to ecological dominance remain unknown. Recently, *Schmeissneria* has been proposed as an angiosperm or a new seed plant (Wang et al., 2007). Regardless of how it is classified, the discovery improves our

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understanding of floral evolution in the Mesozoic. In this study, we conclude that the basal Lanqi Formation is 160.7±0.4 Ma and the whole Lanqi Formation was deposited in the Late Jurassic. Consequently, the underlying Haifanggou Formation and *Schmeissneria sinensis* are at least Middle Jurassic in age. Two species of *Schmeissneria, S. sinensis* from the Haifanggou Formation in NE China and *S. microstachys* from the Liassic (Early Jurassic) of Germany and Poland, were reported (Wang et al., 2007; Kirchner and Van Koniinenbura-Van Cittert, 1994). If *Schmeissneria* is accepted as an angiosperm, the origin of angiosperms should be pushed back to the Early Jurassic based on *S. microstachys* from Europe. However, no basis for the Early Jurassic (Liassic) age ascribed by Kirchner and Van Koniinenbura-Van Cittert (1994) to the *Schmeissneria*-bearing formations in Europe was provided, and this age remains to be substantiated by biostratigraphic or other means. In any case, results presented here provide the first absolute age for *Schmeissneria* and support the theory of pre-Cretaceous angiosperm origin if *Schmeissneria* is accepted as an angiosperm. Accordingly, several hypotheses related to insect-plant and herbivore-plant coevolution should be reappraised.

Besides the finding of *Schmeissneria* from the Haifanggou Formation, the high diversity and abundance of terrestrial flora from the overlying Lanqi Formation affected several hypotheses regarding floral evolution as well. The fossil record demonstrates that bryophytes, ferns, cycads, ginkgos and conifers thrived during the deposition of the whole Lanqi Formation. Our age for the basal Lanqi Formation indicates that *Sahnioxylon*, a transition form between gymnosperms and angiosperms (Zheng et al., 2005), was widely distributed in the Late Jurassic. Based on the anatomical study of *Millerocaulis sinica* from the Lanqi Formation (Cheng and Li, 2007), *Millerocaulis sinica* was a sister taxon to the living fern Osmunda. Combined the phylogenetic study of *Millerocaulis sinica* and our new Late Jurassic age result for the Lanqi Formation, the evolutionary rate of living fern *Osmunda* could be recalculated.

Besides its importance for floral evolution, our high-precision age results for the basal Lanqi Formation affect the interpretation of the Mesozoic climatic patterns. Generally, much of the world was warm and moist in the Early and Middle Jurassic but became hot and dry in the Late Jurassic (Hallam, 1975, 1984, 1985; Vakhrameev, 1991). According to the fossil assemblage of coniferous woods from the Lanqi Formation, Jiang et al. (2008) proposed that the paleoclimate was hot and dry during its deposition. However, the authors cited a Middle Jurassic age for the Lanqi Formation and suggested that the hot and dry climatic pattern was initiated as early as the late Middle Jurassic. Here, our ^{40}Ar/^{39}Ar data indicate the whole Lanqi Formation should be the Late Jurassic in age. The paleoenvironment in the north margin of the North China Craton, accordingly, was dry and hot in the Late Jurassic and no evidence indicates this climatic pattern initiated in the late Middle Jurassic.

6. Conclusions

Two tuff samples collected from the basal Lanqi Formation near Yujiagou village of NE China yield robust high-precision ^{40}Ar/^{39}Ar ages of 160.7±0.4 Ma and 158.7±0.6 Ma, providing accurate age calibration for the Lanqi Formation and the underlying Haifanggou Formation. Although further paleontological and stratigraphic studies are needed, our age result indicates the Daohugou beds of Inner Mongolia might be correlated to the Haifanggou Formation as well as the overlying Lanqi Formation. In other words, the HLF and the Daohugou Biota were probably contemporaneous. Well-preserved fossils of the Daohugou Biota, including insects, conchostracans, salamanders, pterosaurs, dinosaurs, mammals and plants, have greatly improved our understanding of the evolutionary history of these diverse taxa. Establishing the correlation between the Daohugou Biota and the HLF improves our knowledge of Mesozoic terrestrial ecosystems that existed in North China.

Abundant floral fossils within the Lanqi Formation and the underlying Haifanggou Formation indicate that the north margin of the North China Craton was a Jurassic botanic garden which provides a wealth of detailed information to understand the fundamental questions of floral evolution, such as: how did the Jurassic seed plants evolve? When did the angiosperms originate? In particular, several hypotheses regarding the Mesozoic flora and paleoclimate should be reappraised. Regardless of how *Schmeissneria* is classified, the discovery challenges our perspective on the floral evolution, diversity and systematics. Because no basis for the Early Jurassic (Liassic) age ascribed by Kirchner and Van Koniinenbura-Van Cittert (1994) to the *Schmeissneria*-bearing formations in Europe was provided, results presented here provide the first absolute age for *Schmeissneria*. Accepting *Schmeissneria* as an angiosperm pushes the origin of this group back in time by at least 40 Ma and supports the theory of pre-Cretaceous angiosperm origins. The evolution of specialized insect pollinators and the evolution of larger energy-rich animals to disperse fruits had a dynamic effect on early angiosperm evolution. Although how insect pollinators played the role in early angiosperm evolution is debated (Stebbins, 1981; Hu et al., 2008), the insect-plant coevolution is certainly an influential process. Thus, if *Schmeissneria* is accepted as an angiosperm, the pre-Cretaceous origin of the angiosperms would impact our understanding of insect systematics and evolution. Moreover, the well-constrained age for the origin of angiosperms will improve our understanding of Jurassic ecosystems in general, including the nature of dinosaur-angiosperm interactions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.12.045.

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