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Geochronology of high-temperature rocks and hydrothermal ore deposits in China

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Abstract
Geochronological investigations in China were initiated nearly 50 years ago, mainly since the establishment of university programs teaching isotope geochemistry and the setup of geochronological laboratories. During the late 1970's and early 1990s, the geochronological framework of China's landmass has been established by numerous isotopic studies. Over the past decade, state-of-the-art geochronological laboratories have been established in China, contributing to the country's increasing role in many fields of Geosciences. This article highlights some of the major geochronological achievements of the past decades, with special focus on China's Precambrian geology, the improved understanding of age relationships in the Mesozoic Igneous Province of eastern China, and new developments in the dating of hydrothermal ore deposits.

Keywords: Geochronology, Precambrian continental evolution, Mesozoic Igneous Province, hydrothermal ore deposits, China.

1. History of geochronological research in China

Geochronological investigations in China have been evolved in three major stages: (1) early establishment of geochronological laboratories and initiation of education of isotope geochemistry during late 1950s and 1966; (2) increasing availability of commercial mass spectrometers and increased application of geochronology in geosciences during late 1970s and early 1990s; and (3) establishment of state-of-the-art geochronological laboratories, which represented an important stepping stone for much progress of China's geosciences during the past decade.

The initiation and development of geochronological research in China was a result of the recognition of its fundamental importance to the understanding of the geological evolution of China's landmass and its exploitation for mineral deposits. During the late 1950s and early 1960s, geochronological laboratories were firstly established in two institutions, namely the Chinese Academy of Sciences and the Chinese Academy of Geological Sciences in Beijing. The establishment of the K-Ar and U-Pb dating techniques at these institutions were initiated and led by Profs. Pu Li and Yuqi Chen, respectively. At the time, education of isotope geochronology and geochemistry was spearheaded by the Department of Geochemistry at the University of Science and Technology of China.

The first K-Ar age dates measured by China's isotopic laboratories were published by Li in 1963. A subsequent compilation of new K-Ar and U-Pb dates was given by Chen and Li (1964). These early geochronological investigations significantly promoted geological studies in China and the study of Precambrian geology. However, the early boom of geochronology was interrupted by the ten-year-long Cultural Revolution between 1966 and 1976. The isotopic laboratory at the Chinese Academy of Sciences was moved to Guiyang, the capital city of Guizhou Province in southwestern China. Here, the new Institute of Geochemistry was established. Despite these difficult times, geochronological research continued. The first National Conference on Isotope Geochronology and Geochemistry was held in 1975 at Guiyang and attended by over 200 scientists. The conference continued to be organized as quadrennial meeting. Its ninth meeting returned to Guiyang in 2009.

Isotope geochronology reemerged after the Cultural Revolution, and was booming again during the late 1970s and early 1990s. The increasing availability of commercial mass spectrometers enabled a number of isotopic laboratories to be established. The K-Ar and U-Pb methods were complemented by Rb-Sr, Sm-Nd and Ar/Ar as well as U-series and fission-track dating, ^{14}C and other cosmogenic isotopic systems. Methodology developments made zircon single grain U-Pb dating possible.

Over this period of time, the geochronological framework of China was established through the research efforts by numerous scientists, contributing to the development of the chronological time scale of China, the improved understanding of Precambrian geology, as well as the age dating of igneous rocks, regional tectonic processes, and the formation of ore deposits. A comprehensive review of work conducted during this period was presented by Yu and Li (1997). An English translation was made available by Tu et al. (1998). The majority of geochronological studies during this period was published in Chinese and is, therefore, not easily accessible to the international community.

In the early to middle 1990s, the number of geochronological studies in China decreased due to decreasing funding for basic sciences. This situation only gradually changed since late 1990s as the Chinese Academy of Sciences established new research programs. During the past decade, a number of state-of-the-art geochronological laboratories have been established in China. These are equipped with a series of high-performance mass spectrometers including high-resolution SIMS, AMS, TIMS, and noble gas mass spectrometers. In addition, a large number of MC-ICP-MS and ICP-MS equipped with laser ablation systems are now available for geochronology throughout the country. New geochronological methods established include in-situ zircon U-Pb and sulfide Re-Os. Amongst the different methods, in-situ U-Pb zircon geochronology clearly enjoyed the greatest success, enabling geological events and processes to be accurately placed within a firm time framework. U-Pb zircon geochronology contributed to many regional geological studies in China, in particular in the Eastern North China Craton, the Neoproterozoic Doushantuo Formation, the Early Paleozoic of NW China, the Northern Tibetan Plateau, and the South China Block.

2. Precambrian Geochronology of China's Landmass

Figure 1
(see appendix for larger image)

China's landmass contains three major Archean cratons, namely the North China Craton (NCC), the Tarim Craton (TC), and the Yangtze Craton (YC) (Fig. 1).

The oldest rocks identified in China are three small occurrences of trondhjemite gneiss dated at ca. 3.8 Ga in Anshan, northeastern NCC (Liu et al., 1992, 2008). Anshan is one of the four locations worldwide where ≥3.8 Ga rocks are exposed (Nutman et al., 2001). However, the crystallization ages of these trondhjemite gneisses are controversial because these rocks also contain 3.3-3.1 Ga zircons, suggesting that the ca. 3.8 Ga zircons may represent xenocrysts (Wu et al., 2008). More research is needed to resolve this inconsistency, especially as the undisputedly oldest rocks in the area are 3.3-3.0 Ga old granitoids.

One of the major advances in the understanding of the Precambrian history of the NCC was its division into three tectonic blocks, namely the Eastern and Western Blocks and the intervening belt of the Trans-North China Orogen (Zhao et al., 2007). Mesoarchean rocks are rare in the NCC, with only two localities being well documented. One is located in western Jiaodong, which occurs in the southeastern part of the Eastern Block. Here a biotite enclave and its hosting TTG gneiss are dated at 2.9 Ga (Jahn et al., 2008). The other is at Lushan in the far south of the Trans-North China Orogen where 2.8 Ga tonalite and amphibolite were found (Liu et al., 2009). Late Archean TTG gneisses surrounded by minor supracrustal rocks predominate in the Eastern and Western Blocks. Most of these rocks were formed within a short time interval at ca. 2.5 Ga (Zhao et al., 2005a), with a few ca. 2.7 Ga TTG occurring in Jiaodong (Jahn et al., 2008). Various interpretations for the genesis of these Archean TTG have been proposed including formation during arc-continent collision (Jahn et al., 2008) or underplating of mantle-derived magmas, presumably triggered by a mantle plume (Zhao et al., 1999). A salient feature is that these terminal Archean TTG were metamorphosed soon after their crystallization at 2.50-2.49 Ga, probably reflecting a mantle plume activity that resulted in significant growth of the continental crust (Yang et al., 2008a).

In the Trans-North China Orogen, a long-lived magmatic arc existed during 2.56-1.92 Ga. Collision of the Eastern and Western Blocks and final amalgamation of the NCC caused intense deformation and metamorphism at 1.88-1.82 Ga (Zhao et al., 2005a, 2007). The Trans-North China Orogen is coeval with 2.1-1.8 Ga collisional orogens in most continental blocks worldwide, marking the assembly of the supercontinent Columbia by ca. 1.8 Ga (Zhao et al., 2005b). Following its final assembly, the NCC experienced extensive anorogenic magmatism including 1.78 Ga giant mafic dike swarms and coeval volcanism that was related to rifting (Peng et al., 2008). Emplacement of the 1.75-1.68 Ga anorthosite-mangerite-alkali granitoid-Rapakivi granite suite (Zhang et al., 2007a) most likely manifests the initial phase of the breakup of Columbia (Zhai and Liu, 2003). Large-scale dolerite sills dated at ca. 1.35 Ga might indicate fragmentation of the NCC from other parts of Columbia (Zhang et al., 2009a). The Precambrian geochronological framework of NCC is summarized in Table 1.

Table 1: Precambrian geochronological framework of the North China, Yangtze and Tarim Cratons.

North China Craton	**Yangtze Craton**	**Tarim Craton**
	655-635 Ma Nantuo glaciation	0.74-0.54 Ga glaciation inferred from four layers of diamictites
	0.72-0.66 Ga Jiangkou glaciation	
	0.83-0.75 Ga magmatic flare-up and rift basins related to breakup of Rodinia	0.82-0.74 Ga anorogenic magmatism and rift basins related to breakup of Rodinia
	0.85 Ga dolerite dykes and alkaline intrusions	
	1.1-0.89 Ga orogenic magmatism and metamorphism related to assembly of Rodinia	1.05-0.9 Ga orogenic magmatism and metamorphism related to assembly of Rodinia
1.35 Ga dolerite sills and continental rifting related to fragmentation of Columbia?		
1.78-1.68 Ga intraplate igneous suites and continental rifting related to breakup of Columbia?		
1.88-1.82 Ga metamorphism in Trans-North China Orogen, collision of Eastern and Western Blocks related to assembly of Columbia	1.85 Ga granite	
		2.0-1.9 Ga metamorphism
2.5-1.9 Ga TTG of magmatic arc in Trans-North China Orogen		2.45-2.35 Ga intraplate bimodal magmatism
2.5 Ga TTG and metamorphism of plume-related (?) in Eastern Block		
		2.8-2.6 Ga TTG
2.9-2.7 Ga TTG in Lushan and Jiaodong	3.2-2.9 Ga TTG and amphibolite in Kongling	
3.3-3.0 Ga TTG in Anshan		
3.8 Ga TTG in Anshan?		

Due to a widespread sedimentary cover of middle Neoproterozoic to Cenozoic ages, outcrops of Early Precambrian crystalline basement rocks are scarce in the YC. The oldest rocks belong to the Mesoarchean Kongling Complex near the Yangtze Gorge Dam. These TTG and amphibolites have been dated at 3.2-2.9 Ga (Qiu et al., 2000; Zhang et al., 2006a; Jiao et al., 2009). The Kongling Complex was intruded by 1.85 Ga K-feldspar granites, probably indicating the final cratonization of the YC (Zhang et al., 2006b; Xiong et al., 2008). Metamorphic and calc-alkaline igneous rocks dated at 1.1-0.89 Ga are sporadically distributed around the YC (Ling et al., 2003; Li et al., 2009). They are interpreted to have formed in an active continental margin environment, broadly coeval with the global Grenville-aged orogenesis, marking the amalgamation of the YC with the Cathaysia Block (forming the coherent South China Block) to the south, and probably with the Australian continent to the northwest during the assembly of Rodinia. Neoproterozoic gantitoid and mafic-ultramafic intrusions and their extrusive counterparts dated at 0.83-0.75 Ga are widespread throughout the entire South China Block (Li et al., 2003). While petrogenesis and tectonic implications of these magmatic rocks are still controversial (Li et al., 1999, 2003; Zhou et al., 2002; Wang et al., 2006a; Zheng et al., 2007, 2008; Zhang et al., 2008a), identification of 0.83-0.81 Ga high-temperature komatiitic basalts, continental flood basalts, and 0.78-0.75 Ga mafic dykes (Wang et al., 2007, 2008; Lin et al., 2007), as well as development of continental rift basins (Wang and Li, 2003) and bimodal volcanism (Li et al., 2002), suggest the possibility that these middle Neoproterozoic magmatic rocks were most likely formed by melting above a Neoproterozoic mantle superplume that triggered the breakup of Rodinia.

Neoproterozoic rift basins are well preserved in the YC. U-Pb zircon geochronological investigations provide a firm time scale of the basin evolution since ca. 820 Ma (Wang et al., 2003) and the timing of two intervening glaciations. The older Jiangkou glaciation is dated between 725 Ma and 663 Ma (Zhou et al., 2004; Zhang et al., 2008b), whereas the younger Nantuo glaciation occurred between 655 Ma and 635 Ma (Condon et al., 2005; Zhang et al., 2008c). The Precambrian geochronological framework of YC is presented in Table 1.

The TC in NW China is mostly covered by Cenozoic deserts, with the Precambrian rocks being sporadically exposed along the craton margins. The 2.8-2.6 Ga TTG gneisses are the oldest rocks identified in the TC (Lu et al., 2008), which are locally exposed on the eastern and northern margins of the craton. Early Paleoproterozoic granites and mafic dykes in the same areas are dated at 2.45-2.35 Ga. They are interpreted as bimodal igneous suites formed in a continental rift setting (Zhang et al. 2003; Lu et al., 2008). In the eastern TC, high-grade metamorphism took place at 2.0-1.9 Ga (Lu et al., 2008).

The late Mesoproterozoic and Neoproterzoic geology of the TC is characterized by 1.05-0.9 Ga orogenic magmatism and metamorphism and 0.82-0.74 Ga anorogenic magmatism and basin rifting (Xu et al., 2005; Zhang et al., 2007b; Lu et al., 2008), which is broadly contemporaneous to the YC. Together with the South China Block, the TC was, therefore, involved in the assembly and breakup of the supercontinent Rodinia. The Neoproterozoic basin at

Quruqtagh in the northwestern TC preserves four layers of diamictites in the Bayisi, Altungol, Tereeken, and Hankalchough Formations that have ages between 740 Ma and the end of the Precambrian (Xu et al., 2009), providing an unique natural laboratory for studying the global complexity of Neoproterozoic glaciation. A Precambrian geochronological framework of TC is presented in Table 1. There is a striking similarity in geochronology between the YC and TC during the latest Meosoproterozoic and Neoproterozoic time.

3. Geochronology of the Mesozoic Igneous Province of eastern China

Eastern China comprises three major tectonic blocks, from north to south, the Xing-Mong Orogenic Belt in NE China, the Eastern Block of the NCC, and the eastern South China Block (SCB). These blocks amalgamated to form most of the Southeast-Asian landmass during the late Paleozoic to early Mesozoic (Li et al., 1993; Zhang et al., 2009b). Mesozoic igneous rocks are widespread throughout eastern China, consisting predominantly of granitoid intrusions and their extrusive counterparts along with subordinate mafic and alkaline rocks. Over the past decade, numerous investigations helped establishing a firm geochronological framework for the igneous activity in this part of China.

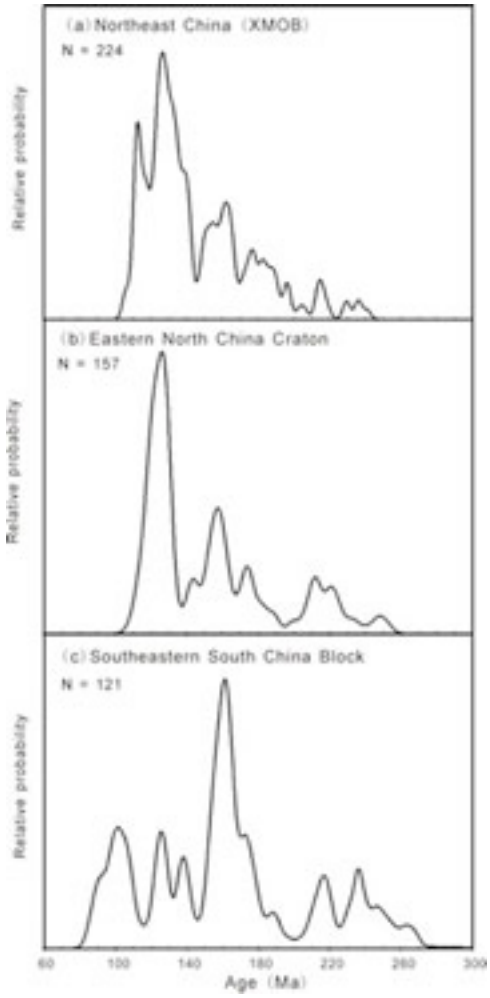

Figure 2
(see appendix for larger image)

Mesozoic igneous rocks in the XMOB of NE China occurred mainly in the Lesser Xing'an-Zhangguangcai Ranges to the east and northeast, and the Great Xing'an Range to the west, which are separated by the Cenozoic Songliao Basin in the middle (Fig. 1). The total exposed area of the Mesozoic igneous rocks is almost 400,000 km^2. Igneous activity occurred largely during the Cretaceous (140-110 Ma) and to a lesser degree during the Jurassic (190-150 Ma) and Triassic (Fig. 2a) (Wu et al., 2002, 2003; Zhang et al., 2008d). There is a younging trend landwards from the continental margin for Jurassic rocks, whereas Cretaceous rocks show the opposite trend (Wang et al., 2006b). In combination with petrological and geochemical data, the Jurassic igneous rocks are thought to have formed in an active continental margin environment that was related to the westward subduction of an oceanic slab. Cretaceous igneous rocks formed in response to asthenosphere upwelling and crustal melting in an extensional setting due to large-scale lithospheric delamination (Wu et al., 2005a).

Mesozoic igneous rocks in the eastern NCC crop out in four discrete areas that are separated by extensive areas of Cenozoic sedimentary cover (i.e., the Jiaodong, Yan-Liao, Taihang and Jiaodong-Luxi areas). Age patterns (Fig. 2b) of these rocks are broadly similar to those in NE China, with most of the igneous activity being of Cretaceous age (130-120 Ma). Rocks of Jurassic (180-150 Ma) and Triassic (250-200 Ma) age occur in subordinate amounts (Wu et al., 2005a, b; Yang et al., 2005, 2008b). The minor Triassic rocks formed by post-orogenic magmatism along the northern and eastern margin of the NCC, which collided with the XMOB of NE China and YC in late Permian and in early Triassic, respectively. The intensive Jurassic-Cretaceous magmatism is likely associated with the progressive reactivation, replacement, and final 'decratonization' of the Precambrian lithosphere beneath the eastern NCC (Yang et al., 2008b).

The southeastern SCB is characterized by widespread of igneous rocks in age between 270 and 80 Ma (Fig. 2c) (Li and Li, 2007), with a total exposed area of ca. 280,000 km^2. The 270-210 Ma magmatism is associated with the northeasterly trending, ~1300-km-wide South China Fold Belt (SCFB). There is a northwesterly younging trend from the continental margin for these syn-orogenic magmatic rocks as well as coeval deformation and metamorphism in the broad SCFB, which is best explained by a flat-slab subduction model (Li and Li, 2007). Jurassic igneous rocks are distributed in the inland, consisting of an early phase of minor amount of bimodal magmatic rocks (basalts and A-type felsic volcanic rocks and their intrusive counterparts) dated at ca. 190-170 Ma and a later phase of flare-up of fractionated I- and A-type granites dated at 165-155 Ma (Li et al., 2007). These Jurassic rocks are thought to be anorogenic products formed in response to the upwelling of asthenosphere mantle caused by the break-up and foundering of an early Mesozoic subducted flat-slab beneath southeastern China. Cretaceous igneous rocks occur mostly along the coastal region, consisting of ca. 95% felsic volcanic and intrusive rocks and ca. 5% mafic rocks dated at 140-80 Ma. A coastward migration of both extensional and arc-related magmatism is likely formed in a retreating arc system (Li and Li, 2007).

4. Dating of hydrothermal ore deposits

Precise and accurate isotopic geochronology is crucial for constraining the timing and genesis of mineral deposits. However, direct age determination of hydrothermal ore deposits is often difficult due to the lack of minerals suitable for conventional radiometric age dating. Over the past decades, several new methods have been developed and are now widely applied in ore deposit research in China.

Pyrite, one of the most common sulfides in many hydrothermal deposits, contains variable concentrations of Rb and Sr with diverging Rb/Sr ratios, thus permitting direct dating of deposits. Yang and Zhou (2001) presented a method of direct Rb-Sr age determination of pyrite from a lode gold deposit in the Jiaodong area, demonstrating that this method is a promising geochronological technique. Li et al. (2008) further improved this method, which can now be used to date single grains of pyrite.

The Re-Os isotopic system proved to be an ideal geochronometer for molybdenite-bearing ores. In China, Du et al. (1993) developed the first molybdenite Re-Os dating method. This isotopic system has subsequently been applied to the dating of other sulfide minerals such as pyrite (Liu et al., 2004) and arsenopyrite (Yu et al., 2005). In China, the sulfide Re-Os isotopic system has become one of the most widely used geochronometers for the dating of hydrothermal ore deposits.

Direct dating of fluid inclusions can also provide robust constrains on the timing of hydrothermal ore deposits. Early attempts of Rb-Sr isochron age determination were conducted on quartz (Li et al., 1992, 2000), but were not always successful due to the complexity of inclusion assemblages and the presence of K-bearing phases as impurities in the dated quartz. The Ar/Ar age dating of quartz following the crushing of quartz under vacuum, combined with a step heating process (Qiu 1996; Qiu et al., 2002), proved to be advantageous for the dating of fluid inclusions. Gases released by the crushing are mainly derived from the fluid inclusions whereas those emitted from the sample during heating are largely sourced by inclusions of K-bearing minerals. The combined use of progressive crushing and heating has also been successfully applied in the Ar/Ar dating of sphalerite from the world-class Fankou Pb-Zn deposit in South China (Qiu and Jiang, 2007). One of the major advantages of this technique is that primary and secondary fluid inclusions within sphalerite can be clearly distinguished.

The Sm-Nd isotopic system represents another useful geochronometer permitting direct dating of hydrothermal ore deposits. Jiang et al. (2000) demonstrated that the Sm-Nd method can be used for the age determination of hydrothermal tourmaline- and sulfide-bearing ores. At the Shizhuyuan polymetallic skarn and greisen deposit in southeast China, hydrothermal minerals include garnet, fluorite, and wolframite proved to be suitable for Sm-Nd isochron dating as these cogenetic phases display a wide range of Sm and Nd concentrations at variable Sm/Nd ratios (Li et al., 2004).

5. Conclusions

Geochronological research has achieved great success in many areas of geosciences research in China. Examples of past and current trends for the dating of high-temperature rocks and hydrothermal minerals are highlighted in the present contribution. However, much work is still needed in both geochronological method developments and their application in the real world. For instance, despite great success of in-situ U-Pb zircon dating by SIMS and LA-ICP-MS, the high-precision TIMS U-Pb techniques is still not available in China due to the lack of appropriate isotopic spikes. These shortcomings will likely be overcome in the next couple years through international collaboration and the involvement of Chinese scientists in the EARTHTIME project.

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Appendix – Figure 1

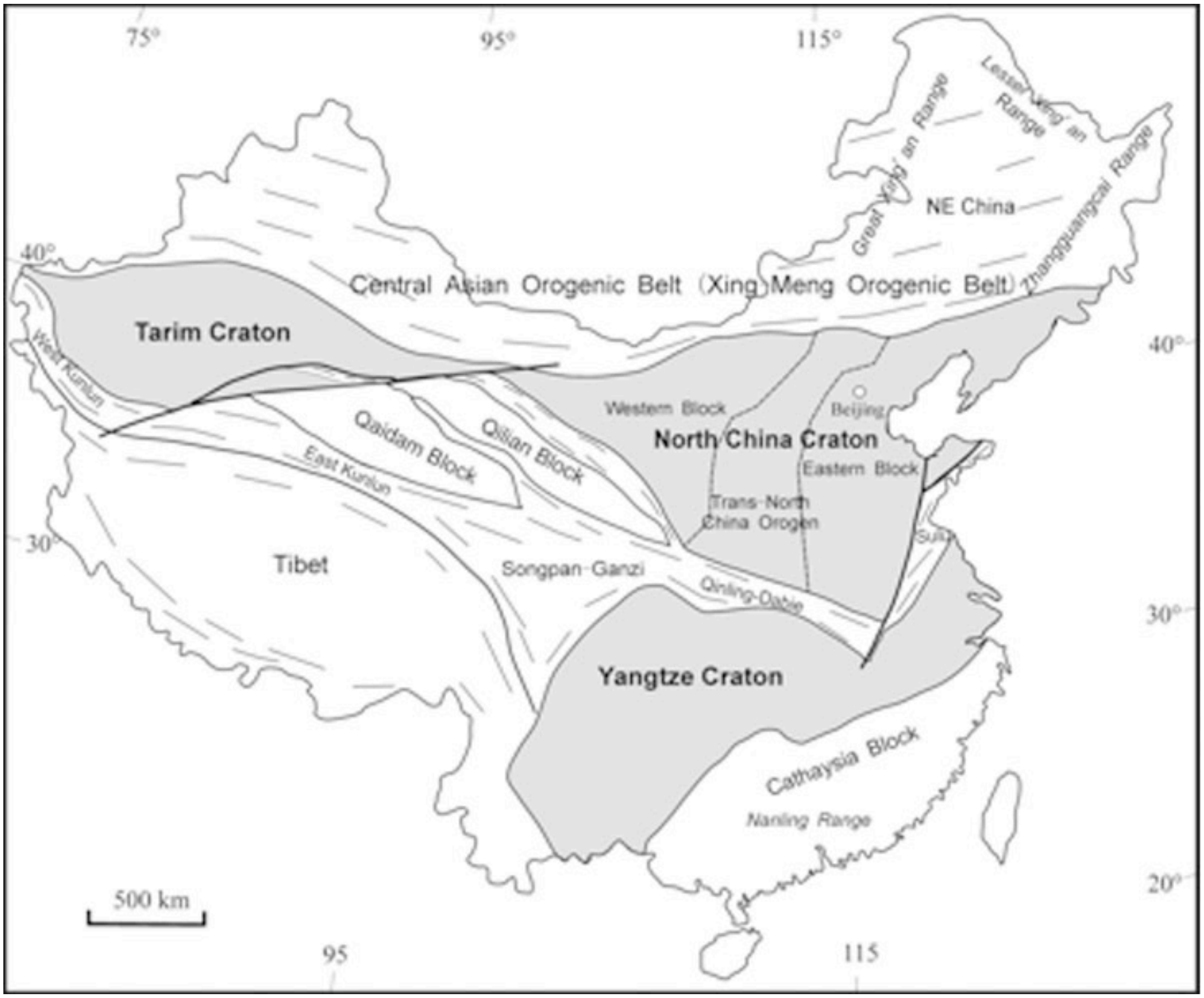

Figure 1. Sketched tectonic map of China showing the major Precambrian cratons and younger orogens.

Appendix – Figure 2

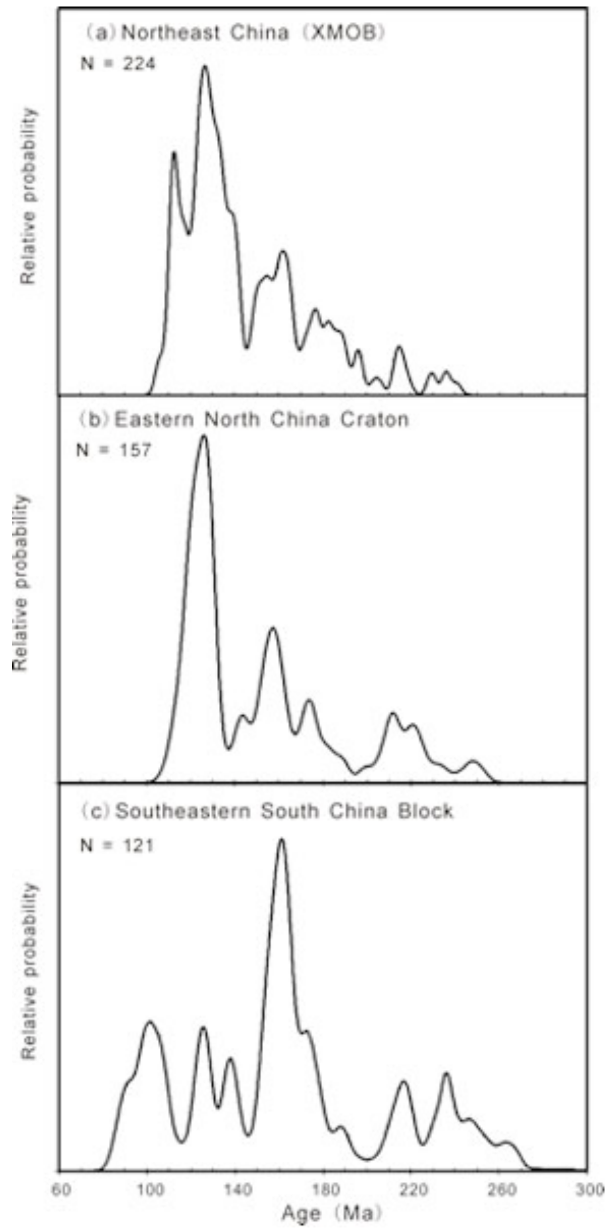

Figure 2. Histogram of isotopic ages for Mesozoic igneous rocks form eastern China: (a) the XMOB in NE China, (b) the eastern NCC, and (c) the southeastern SCB.

About the Author

Xian-hua Li is a professor and the director of the SIMS laboratory at the Institute of Geology and Geophysics, Chinese Academy of Sciences. He received his PhD in 1989 from the Institute of Geochemistry in Chinese Academy of Sciences. Between 1989 and 2005, he worked in the laboratory of isotope geochemistry at the Guangzhou Institute of Geochemistry and subsequently moved to the Institute of Geology and Geophysics in Beijing. His research interests are geochronology, isotope geochemistry, igneous petrogenesis and chemical geodynamics. He was elected as a Fellow of the Geological Society of America in 2006.