Provenance and temporal constrain of the Early Cambrian Maotianshan Shale, Yunnan Province, China

Authors: M.H. Hofmann^{1*}, X.H. Li², J. Chen³, L.A. MacKenzie¹, N.W. Hinman¹

¹ Geosciences Department, University of Montana, 32 Campus Drive #1296, Missoula, MT 59812-1296, USA

² State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

³ Nanjing Institute of Geology and Palaeontology, Institute of Evo/Developmental Biology, Nanjing University, China

* corresponding author: michael.hofmann@umontana.edu

Abstract:

The Cambrian Maotianshan Shale in Yunnan Province, China contains the well-preserved soft-body fossils of the Chengjiang Biota. The high quality preservation of the non-mineralizing biota (soft tissues and whole carcasses) shows regional and temporal differences, suggesting that paleogeography and local environmental conditions might have contributed to the taphonomy of these fossils. In this paper we present new results from petrographic, geochemical and detrital zircon analyses, and provide a new interpretation about the provenance of the Maotianshan Shale, as well as add to the understanding of the paleogeography of the South China Block during the Cambrian Stage 3. Results from petrographic analysis indicate that the provenance of the Maotianshan Shale is a recycled orogen overall, bordering the western and southwestern margin on the Yangtze Block. The most likely source of the terrigenous material is an exhumed area extending from the Kangdian paleoland to the southeast, paralleling the Song Ma fault zone. Minor regional differences in geochemical and petrographic proxies between the northwestern Jianshan/Ercai area and the southeastern Maotianshan/Xiaolantian area suggest influence of local sources. Sediments of the southeastern province are less mature and samples include minor elements commonly associated with mafic sources. Sediments from the northwestern province are more mature, largely lack mafic components and are enriched in Zr and Hf. The major population of the Maotianshan Shale detrital zircons group at ~800Ma. This crystallization age matches

well with the age of a widely spread felsic volcanic and intrusive event associated with the Neoproterozoic Kangdian rift, suggesting that these igneous rocks are most likely a major provenance for the Maotianshan sediments. The youngest zircon population yields consistent Concordia ages of ~520 Ma, representing a maximum age constraint on the timing of deposition of the Maotianshan Shale. The zircon crystals of the ~520 Ma populations are euhedral with magmatic zoning, indicative of short-distance transport. Volcanic activity along the Song Ma suture zone is a potential source for the ~520Ma detrital zircon suite.

Keywords

Petrology; Geochemistry; Detrital Zircon U-Pb age; Paleogeography; Chengjiang Biota

1 Introduction

The Early Cambrian Maotianshan Shale deposits in Yunnan Province, China are well known for their exceptional preservation of the soft-bodied fossil fauna known as Chengjiang Fauna or Maotianshan Shale fauna. The high abundance and variety of species displays a diversification of disparate anatomical architectures yielding critical insight into the evolutionary explosion of animal body plans known as the Cambrian Explosion. The fossil preservation of the labile tissues is widely distributed in central Yunnan but its spatial and stratigraphical restrictions within the Maotianshan Shale, and environmental controls remain a mystery.

Provenance analysis traditionally focuses on the compositional analysis of sand sized grains (e.g. Dickinson and Suzek, 1979; Ingersoll et al., 1984), despite the fact that silt sized grains are the most common grain size fraction in many depositional environments (e.g. Hay, 1998, Allison et al., 2003; Curray et al., 2003). Finer sediment components also have the advantage that they are commonly less permeable than their coarser grained counterparts, minimizing the impact of diagenetic alterations in this grain size fraction, and consequently more reliably preserving information about the original depositional setting (Blatt and Sutherland, 1969; Blatt, 1985). Compositional information from silt and smaller sediment components therefore can't be ignored and is essential to conduct an unbiased provenance study (Cullers, 1988; Garzanti et al., 2011).

Here, we present a multi-proxy approach to decipher the provenance of the Maotianshan Shale and add to the understanding of the taphonomic conditions that lead to the preservation of the Chengjiang biota in the Chengjiang, Haikou, and Shankou fossil sites.

2 Geologic Setting

The study area is located near the western edge of the Yangtze Block, in Yunnan Province, South China (Figure 1). The northwestern margin of the Yangtze Block is defined by the Longmenshan fault, separating the Yangtze Block from the Tibetan plateau (Figure 1).

The Precambrian strata of the Yangtze Block is largely composed of Mesoproterozoic lowgrade metamorphic (greenschist facies) clastic sedimentary rocks, and abundant Neoproterozoic granites that intruded in the Mesoproterozoic strata (Guo et al., 1985; Zhou et al., 2002). Mesoproterozoic basement rocks are oldest in the western Yangtze Block (Greentree and Li, 2008), and some of the basement rocks date back as far as the

Archean (Guo et al., 2014). Less common are 822Ma old calc-alkaline volcanic rocks, mainly composed of basalts and rhyolites, with rare andesites (Li et al., 2002, 2008), and 786 Ma granites and granitoids (Shen et al., 2000; Li et al., 2009).

A thick stack of Sinian deposits is largely constrained by the present day Anninghe fault to the west, and the Xiaojiang fault to the east (Figure 1; Liu, H., 1991). In the study area, the Cambrian (Stage 3) deposits of the Maotianshan Shale Member of the Yu'an-shan Formation are well exposed south of the city of Anning and west of the city of Chengjiang (Figures 1 and 2). The Maotianshan Shale is largely composed of mudstones, siltstones, and very fine sandstones (Figure 2; Hu, 2005; Zhao et al., 2012; MacKenzie et al., 2015). The fossil bearing intervals are primarily associated with the middle to upper parts of the Maotianshan Shale (Figure 2; Babcock and Zhang, 2001; MacKenzie et al., 2015).

During the Cambrian, the Kangdian paleoland separated the Yangtze Block from the paleo-tethys (Wang et al., 1985). The history of this paleoland is complex. The Kangdian paleoland initially formed during the Sibao orogeny (Grenville orogeny equivalent), that resulted in granitic intrusions dated to ~ 880 Ma. Rifting, related to the formation of the Kangdian rift basin, resulted in the formation of widespread volcanic rocks and granitic intrusions between ~850-820Ma (e.g., Li et al., 1995, 2002; Greentree et al., 2006; Ye et al., 2007; Li et al., 2008; Li, 1999; Zhao and Cawood, 1999; Zhou et al., 2002; Wang et al., 2006; Zheng et al., 2007; Wang et al., 2007, 2008). Since its formation, the Kangdian paleoland has been exposed for prolonged geologic periods and has been a major source of terrigenous material to the Yangtze Block since the Ediacaran, including the time of the Maotianshan Shale deposition.

Figure 1: Maps showing the major tectonic elements along the western margin of the Yangtze Block and the location of the study area. Major Cenozoic faults outline the margin of the Yangtze Block (faults 2-5) and the inferred margins of a major Neoproterozoic depositional center (Kangdian Rift) (faults 1 and 6) respectively (data from Allen et al., 1984; Wang and Burchfiel, 2000; Zhou et al., 2002; Wang et al., 2012; Li et al., 2014). The position of the Kangdian paleoland marked the western edge of the Yangtze Block during the Cambrian Stage 3 (outline of the paleoland from Wang et al., 1985). The dashed line (0) along the western edge of the Yangtze Block marks an inferred Cambrian suture zone between the Yangtze Block and Indochina (from Cocks and Torsvik, 2013). The study area is located south of Anning (northwestern study area), and east of Chengjiang (southeastern study area). There, Cambrian rocks of the Maotianshan Shale are well exposed in a series of outcrops, including in the five sections that are part of this study.

Early to Middle Cambrian volcanic rocks from the Song Ma zone suggest that it was a tectonically active area during the Cambrian (e.g. Findlay, 1998; Compston et al., 2008; Cocks and Torsvik, 2013). Therefore, in addition to the Kangdian paleoland, the Song Ma zone can be considered a potential source of the Maotianshan Shale deposits.

Despite the uncertainties surrounding the paleogeographic constraints, it is less controversial that the South China Block was established during the early Cambrian, and deposition of early Cambrian strata occurred on a continental shelf. Thrusting and exhumation along the suture zones might have resumed during the early Cambrian (e.g. Xu et al., 2012), contributing to the ongoing discussion about the provenance and depositional

environment of the Maotianshan Shale (e.g. Hou, 1987; Chen and Erdtman, 1991; Pu et al., 1992; Zhu et al., 2001; Hu, 2005; Zhao et al., 2012; MacKenzie et al., 2015).

Figure2: Cambrian stratigraphy in the study area. The Maotianshan Member of the Yu'an-shan Formation contains fossils of the *Eoredlichia-Wutingaspis* biozone, part of the Cambrian Stage 3 (Zhao et al., 2012). The Maotianshan Shale is composed of mudstones and siltstones with minor sandstone interbeds. Silt and sandstones beds become more abundant towards the top of the interval. A general type log of the Maotianshan Shale for the Xiaolantian area is presented to the right in this figure. The main fossil intervals are associated with the middle and upper part of the Maotianshan Shale and highlighted by the black bars. Numbers 1-4 mark the inferred stratigraphic position of the zircon samples presented in this study, based on stratigraphic correlations by MacKenzie et al. (2015). 1 – sample JS4/4 (Jianshan section); 2 – sample HO-20130512JS (Jianshan section); 3 - sample LM-24 (Shankou section); 4 – sample LM-23-12 (Xiaolantian section).

3 Methods

Samples were selected from outcrops at five different locations near the city of Kunming (Figure 1). All locations are known for abundant fossils, and some locations are located in designated geoparks and world heritage sites. The samples vary in color, reflecting the variable degree of weathering in the area. The least weathered sample stems from a deep core from the Maotianshan area. Other unweathered samples were taken

from fresh exposures in the Kunyang Phosphate Mine (Jianshan locality). All other samples were taken from surface locations.

3.1 Petrographic Analysis

Petrographic analyses were conducted on a small sub-set of samples that were identified as silty sandstones and contained countable amounts of sand-sized grains. Framework mineral composition (modal analysis) was determined by point counting largely following the Gazzi-Dickinson method (Dickinson et al., 1983; Ingersoll et al., 1984). In this method, single sand-sized components of rock fragments are counted in the mineral category of the component, rather than in that of the rock fragment. This approach has the advantage over traditional point counting techniques in that samples with the same provenance but different grain size are classified more homogeneously (e.g., Ingersoll, et al., 1984 ; Zuffa, 1985). However, hydraulic sorting of minerals is not addressed with this method, and detrital modes may still be markedly size-dependent (Garzanti et al., 2003, 2006). To counter this size dependency and to develop a more accurate interpretation of the provenance, we systematically included silt- and sand- sized grains in our petrographic analysis.

Petrographic slides were also analyzed using electron microscopy. This analytical step has been proven essential, given the small grain size of even the coarsest rocks in the Maotianshan Shale. All samples were first imaged using backscatter electrons (BSE) on a Tescan Vega-3 LMU VP-SEM with LaB6 electron gun at the University of Montana SEM laboratory, to analyze grain contacts, grain alteration, and sample composition. Subsequently samples were analyzed for their elemental composition using an Oxford X-Max 80mm² EDS (energy dispersive X-ray spectroscopy) detector.

3.2 Chemical analysis

Major and trace element concentrations on bulk samples were measured by ICP-AES at SGS Laboratory (Ontario, Canada). Provenance based on chemical analyses are discussed for a variety of elements and were compared to the element concentration in the upper crust and standard shale (e.g. Taylor and McLennan, 1985).

We included the Weathering Index of Parker (WIP; Parker, 1970) and the Chemical Index of Alteration (CIA; Nesbitt and Young, 1982) in our analysis to assess the post-depositional alteration of the Maotianshan

Shale samples and to determine the provenance of samples more accurately. The WIP is calculated using molecular proportions of mobile alkali and alkaline earth metals to capture the transformation from feldspar to clay minerals, one of the major processes of chemical weathering (Bahlberg and Dobrzinski, 2011). The WIP does not include any relatively immobile reference phase (e.g. Al_2O_3) in the calculation, lacking the ability to monitor relative changes of relevant mineral groups, but it is considered a good weathering index for heterogeneous sources including metamorphic rocks (e.g. Borges and Huh, 2007; Price and Velbel, 2003; Bahlberg and Dobrzinski, 2011). The CIA is the most commonly used weathering index in clastic sedimentary rocks of all ages. It uses whole-rock geochemical data of major element ratios relative to the predominantly immobile reference phase, Al_2O_3 (Nesbitt and Young, 1982). These ratios are commonly interpreted to most accurately measure the conversion from less stable minerals, like feldspars, into stable minerals, like clays.

Major elements in all samples were largely disregarded for provenance analysis. These elements are most commonly used to categorize the provenance and tectonic setting of coarse-grained sediments. However, the Maotianshan samples are best described as siltstones and mudstones and therefore major element analyses outside the weathering indices would be an inaccurate tool to determine the source of those rocks.

The most reliable chemical information included in this study comes from the analysis of trace elements that are commonly immobile and therefore preserve the original depositional conditions most accurately. We systematically separated the different lithofacies identified in the Maotianshan Shale (MacKenzie et al., 2015), to compare the reliability of provenance information preserved in these different rock types.

3.3 Detrital Zircon U-Pb Analysis

Zircon crystals were separated from approximately 2 kg of crushed sample, using conventional density and magnetic separation techniques. Zircon grains, together with zircon standards TEMORA-2 and 91500 were mounted in epoxy resin. The mounts were then ground and polished to section the crystals in half for analysis. All zircons were documented with transmitted and reflected light photomicrographs and cathodoluminescence (CL) images. Measurements of U and Pb isotopes were conducted using a Cameca 1280 SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG-CAS) in Beijing, using the operating and data processing procedures similar to those described by Li XH et al. (2009). Because the detrital zircons are mostly

20–40 μm in size, a small analytical spot in size of ca. $10 \times 15 \mu\text{m}$ was used. A long-term uncertainty of 1.5% (1 RSD) for $^{206}\text{Pb}/^{238}\text{U}$ measurements of the standard zircons was propagated to the unknowns (Li QL et al., 2010), even though the measured $^{206}\text{Pb}/^{238}\text{U}$ error during the course of this study is around 1% (1 RSD) or less. U–Pb ratios were determined relative to the TEMORA-2 standard zircon (Black et al., 2004), and the absolute abundances were calibrated to the standard zircon 91500 (Wiedenbeck et al., 1995). Measured compositions were corrected for common Pb using the ^{204}Pb -method; an average of present-day crustal composition (Stacey and Kramers, 1975) is used for the common Pb. Data reduction was carried out using the Isoplot/Ex v. 2.49 program (Ludwig, 2001). All U–Pb data are listed in the electronic supplement. For statistical purposes, zircon ages with discordance $< 5\%$ were considered as usable.

4 Provenance of the Maotianshan Shale

4.1 Detrital components

Sediments of the Maotianshan Shale were predominantly siltstones and mudstones (Figure 2), and only a small number of samples exhibited grain sizes in the coarse silt and very fine sand range that were suitable for petrographic modal analysis. The majority of detrital components of the very fine (vf) sandy siltstones were quartz (Q), feldspar (F), lithic fragments (L), and minor accessory and heavy minerals. Grain sizes of QFL were most commonly reduced to coarse siltstone (31 – 62.5 μm) and vf sandstone grains (62.5 – 125 μm) (Figure 3). Quartz grains are the coarsest on average with approximately one third of the grains in the very fine sandstone fraction, but regional differences exist (Figure 3). The vf sandy siltstones were poorly sorted and detrital grains were commonly angular to subangular (Figure 4).

Quartz was the most abundant detrital mineral in any of sandy siltstone samples, ranging from 55 to 60 %. The majority of the quartz grains were sub-angular to angular monocrystalline quartz (Figure 4). Monocrystalline quartz is most commonly derived from granitic and volcanic sources (Dickinson, 1985); conversely, the deficiency of polycrystalline quartz in the analyzed samples may result from the absence of source rocks containing polycrystalline quartz, such as metamorphic rocks. The lack of polycrystalline quartz in the Maotianshan samples, however, might also be the result of disaggregation of the original polycrystalline quartz during long distance or high-energy transport from the source area (Dabbagh and Rogers, 1983). The

small grain sizes in all of the Maotianshan samples, including the coarsest Maotianshan facies, are the result of extensive physical abrasion during transport, suggesting that transport might affect the interpretation of provenance based on quartz grain types.

Figure 3: Grain size distribution of the major detrital components (QFL) from the coarse grained Maotianshan Shale samples. (A) On average only 1/4 of the feldspar and lithic grains are part of the sand fraction, but 1/3 of the quartz grains are part of this coarser grain size suite. Figures B-D show the regional variability in grain size distribution for the main mineral components (QFL). Sample B is from the southeastern part of the study area (Xiaolantian section), samples C and D are from the northwestern part of the study area (Shankou and Jianshan samples). For detailed explanation see text.

Alkali feldspars with extensive alteration rinds were the only feldspars recognized in the samples of the Maotianshan Shale. Feldspar grains were often slightly elongated and were less rounded than associated quartz grains. In most samples feldspars accounted for <10% of the total grain counts, but extensive alteration of feldspars to clay (sericite and illite) might result in underestimating the original feldspar percentage.

Lithic fragments were the third common components in the Maotianshan sandy siltstone samples. Fragments were usually heavily altered, limiting the reliability of recognizing their original composition, but metamorphic lithic grains were not observed in any of the samples. Dolomite was common in the fresh samples from the core and the Jianshan section, but absent in the weathered rocks from all other sections. Most of the

dolomite was authigenic as a late stage replacement of quartz (Figure 4), but a few detrital dolomite grains were observed in the samples.. The source of the detrital grains was likely the underlying Dahai Member of the Zhujiqing Formation (Figure 2).

Figure 4: Example of the composition of the coarse Maotianshan Shale facies (Sample JS-4/4/2013_2-1) from the northwestern part of the study area. The image at the top right is a SEM-BSE image with EDS point spectra data (a-f) shown to the left. The image at the bottom right is a cross polarized light thin section photo of the same sample. The black box outlines the area shown in the SEM image; points a-f are the same mineral grains and crystals as highlighted in the SEM-BSE image and shown in the EDS spectral data. This sample is largely composed of sub-angular to sub-rounded, silt- and vf sand-sized detrital quartz grains (d). Other detrital components include phosphate grains (f), feldspar grains (e), dolomite (c), and biotite (b) and mica flakes; authigenic minerals include Fe-oxide (a), clay, and dolomite.

Accessory and heavy minerals in the vf sandy siltstone samples include phosphates, biotite, muscovite, Ti-oxides, zircon, and Fe-oxides (Figure 4). Although the exact source of the phosphatic grains is unknown, a potential source is the underlying Zhujiqing Formation. Large detrital mica flakes, both muscovite and biotite, are abundant in most of the samples (Figure 4).

In general, all of the vf sandy siltstone samples of the Maotianshan Shale contain 70% to 90% quartz, ~10% lithic grains and the remainder feldspar when normalized to the main components QFL. These QFL detrital modes are common for sandstones sourced by recycled orogenic belts (Figure 5; Crook, 1974; Dickinson and Suczek, 1979; Dickinson et al., 1983; Ingersoll et al., 1984). In the vicinity of the study area, the Kangdian paleoland was largely an inactive orogenic belt during the Cambrian Stage 3 (Figure 1), and might have contributed significant amounts of sediment to the Maotianshan Basin.

Figure 5: QFL diagram and inferred provenances (based on Dickinson and Suczek, 1979). The coarse grained sample from the southeastern outcrop (Xiaolantian) contains a higher percentage of quartz (Q), firmly placing it in the field of a typical recycled orogen province; the samples from the northwestern province (Shankou and Jianshan) contain larger amounts of feldspar grains, moving it closer to a composition typical for continental blocks.

4.2 Limitations of detrital modal analysis of the Maotianshan Shale

Although a detailed analysis of post-depositional alterations of the vf sandy siltstone samples is outside the scope of the study, it is important to develop some understanding of the alteration process after deposition to confirm the accuracy of the provenance determination based on the coarsest grain fraction. In the case of the Maotianshan Shale, these post-depositional alterations include the partial replacement of quartz by carbonate, partial replacement of feldspar by clay minerals, and replacement of lithic fragments by phyllosilicates.

The most widespread of these modifications is the alteration of K-spar and of potential lithic fragments to clay minerals. Ghost structures of the original grains are visible at times, enabling the separation of pseudomatrix from real matrix, but this separation is often uncertain, skewing results from point counting.

Quartz corrosion, usually by dolomite, is present but less common. This secondary replacement of quartz by dolomite can lead to underestimating the quartz content in the samples. Extensive mechanical compaction is evident by the abundance of pressure solution contacts between quartz grains and can also result in underestimating the original quartz content (Figure 4).

The latest stage diagenetic processes are related to the dissolution of dolomite in samples at or near the present day surface. Samples affected by carbonate dissolution or partial dissolution of feldspar and rock fragments have extensive secondary porosity. Porosity is variable; less weathered samples from the Jianshan area contain the least porosity while samples of the weathered Shankou, Xiaolantian and Maotianshan sections are highly porous. Iron oxide cements and replacement minerals are also most common in samples from weathered outcrops, similarly suggesting iron oxides formed during a very late stage, near surface alteration process.

In general, the alteration of the three main mineral components is not insignificant and might insert some uncertainty when using petrographic data to determine the provenance of the Maotianshan Shale.

4.3 Geochemistry

4.3.1 Major elements and their alteration

Major element chemistry is a well established method to determine the tectonic settings of sandstones and siltstones, by comparing ratios of different geochemical proxies (Schwab, 1975; Bhatia, 1983; Bhatia and Crook, 1986; Roser and Korsch, 1986; Cullers, 1988; Kroonenberg 1994; Zimmermann and Bahlburg 2003; Armstrong-Altrin et al., 2004). The determination of the correct provenance requires nearly unaltered samples, because factors governing the concentration of the different elements in the bulk composition are strongly affected by diagenesis and other alteration processes (e.g. McLennan et al., 1993; McLennan, 2001).

To determine the effect of post depositional alteration on the Maotianshan Shale samples, we compared the composition of our sample suite to the mean composition of the continental crust using the Weathering Index of Parker (WIP; Parker, 1970) and the Chemical Index of Alteration (CIA; Nesbitt and Young, 1982). In the case of the Maotianshan Shale, all samples exert high CIA values (>70) suggesting intermediate to high alteration rates independent of grain size (Figure 6). In addition to the CIA, the CN-A-K ternary system is useful to

examine the alteration of fresh samples, because the depletion of Ca and Na and enrichment of Al and K reflects the transformation of some of the most common minerals in the upper continental crust during alteration (Nesbitt and Young, 1984, 1989; Fedo et al., 1995). Samples of the Maotianshan Shale are typically enriched in K and Al, independent of grain size, reflecting the transformation of feldspars into clay minerals. Only two samples, the core sample and one sample from the Jianshan section have higher Ca and Na values resulting from the incomplete transformation of those minerals (Figure 6). The same ternary system can also be used to reconstruct the original composition of the source rock based on the linear depletion trends of Ca and Na sub-parallel to the A-CN axis (Fedo et al., 1995). Based on this relationship, all Maotianshan Shale samples, including the two samples with higher Ca and Na concentrations, fall on the same weathering trend line originating from a granitic source rock close to the average upper continental crust composition (Figure 6).

We did not include any of the widely used discrimination diagrams for major elements into our provenance analysis because of the intermediate to high alteration of the original composition.

Figure 6: (A) Relationship between the two weathering proxies WIP (Parker, 1970) and CIA (Nesbitt and Young, 1982) for the Maotianshan samples. (B) CN-A-K ternary diagram for the Maotianshan Shale samples; note that the lower part of the diagram with A < 40 is not shown. The diagram includes the typical magmatic source rock types (1, gabbro; 2, tonalite; 3, granodiorite; 4, granite; 5, A-type granite; 6, charnokite; 7, potassic granite; Fedo et al. 1995) and average compositions of different continental crusts (LCC, BCC, UCC; McLennan, 2001; Bahlburg and Dobrzhinski, 2011). All Maotianshan Shale samples conform to the predicted weathering trend (gray area) of UCC type source lithologies (Nesbitt and Young, 1984). The effects of grain sorting on the weathering trend are highlighted by the dotted arrow (Nesbitt et al., 1997).

4.3.2 Trace Elements

In difference to the major elements that can be affected by alteration processes, many trace elements,

including Th, V, Ni, La, Sc, Zr, and Hf, in clastic sedimentary rocks are considered immobile and therefore can serve as more reliable provenance indicators of the original source area composition (Cullers et al., 1979; Taylor and McLennan, 1985; Bhatia and Crook 1986; McLennan et al. 1993; Bahlburg, 1998; McLennan, 2001).

All Maotianshan Shale samples showed enrichment of Th and V compared to Ni, typical for a more felsic composition of source area rocks (Figure 7). This suggests that granites and/or other felsic rocks were exposed in the hinterland that sourced the Maotianshan Shale sediments.

Figure 7: Trace elements ternary diagrams; (A) Ni-V-Th diagram (after Bracciali et al., 2007); all Maotianshan Shale samples cluster close to the field of expected felsic composition; not the overall higher Ni concentration in the samples from the Xiaolantian and Maotianshan sections (triangles) ; Th-La-Sc (B) and Sc-Th-Zr/10 (C) diagrams after Bathia and Crook (1986); samples from all loactions have a composition that resample the composition of rocks from continental island arcs (CIA); ACM = Active Continental Margin; PCM = Passive Continental Margin; OIA = Oceanic Island Arc

A similar source rock composition can be implied when comparing the concentrations of Th and La in discrimination plots, and Th, La, and Sc in a ternary diagram (Figure 7,8). In both cases the Maotianshan Shales are enriched in La, and the overall composition is comparable to samples derived from a Continental Island Arc setting. It is important to note that the Th and La ratios are very similar across grain sizes, but the coarser grained fraction appears to be slightly depleted in both elements.

Similarly, the ratios of Th, Sc, and Zr suggest that the Maotianshan Shale samples were deposited in a Continental Island Arc setting with mainly continental crust (Figure 7). The increase in Zr in some of the samples is attributed to the enrichment of Zr in the coarser grained samples, as result of heavy mineral fractionation. Zr and Hf show a strong positive correlation ($r = 0.81$) amongst all samples. The Zr/Hf ratio for Maotianshan samples ranges between 30 and 45, close to the ratio of pure zircon crystals (Murali et al., 1983), suggesting that these minerals contributed most of Zr and Hf. Therefore it is expected that the La/Th ratio to Hf

discriminant plot indicate a felsic (continental) island arc source similar to ternary plots including Zr (Floyd and Leveridge, 1987; Floyd et al., 1991) (Figure 8).

Figure 8: Relationship between La/Th and Hf (left) and La vs. Th (right) for the Maotianshan Shale samples. All Maotianshan Shale samples are compositional similar to samples typical of a continental island arc source (CIA). The increase in recycled sediment components and a shift to a passive continental margin source (PCM) is associated with the coarsest sediments in the sample suite and interpreted to be an effect of grain sorting rather than a different source area. It is important to note that samples from the Jianshan area, on average, plot closer to the PCM field than samples from the Xiaolantian and Shankou, respectively. Diagrams modified from Bathia and Crook (1986), and Floyd et al. (1987). UCC composition from McLennan (2001).

4.4 Detrital Zircon Analysis

A total of 376 zircon grains from four siltstone samples were dated using the SIMS U-Pb technique, including 113, 89, 64 and 110 analyses from samples HO-20130512JS, JS-4-4, LM-24 and LM-23, respectively (data table in online supplemental information; inferred stratigraphic position in Figure 2). The U-Pb results are presented in the Concordia plot (Figure 9). All but a few are concordant analyses (<5% discordance) within uncertainties. The concordant analyses of the four samples display similar age distribution patterns, with a dominant mid-Neoproterozoic age peak at ~800 Ma and a subordinate peak at ~520-525 Ma (Figure 10). 11, 13, and 8 analyses of the youngest groups from sample HO-20130512JS, JS-4-4 and LM23-12 yield Concordia ages of 521.7 ± 4.5 Ma, 521.7 ± 6.1 Ma, and 519.6 ± 5.3 Ma, respectively providing a maximum age constraint on the timing of deposition of the Maotianshan Shale sediments. It is noteworthy that most of these ~520 Ma zircons are euhedral crystals with magmatic zoning under cathodoluminescence (Figure 11) indicative of short-distance transportation from their provenance(s). The predominant mid-Neoproterozoic detrital zircons in these siltstones are mostly subhedral in shape (Figure 11); their crystallization ages of ~0.8 Ga are broadly consistent with the widespread mid-Neoproterozoic felsic volcanic and intrusive rocks along the Kangdian Rift (Figure 1; e.g., Li et al., 2003, 2003; Zhou et al., 2002). Thus, the regional preexisting mid-Neoproterozoic magmatic rocks

are most likely the major provenance for the Maotianshan sediments.

Mesoproterozoic and older detrital zircons are rare, apart from sample JS-4-4 showing a small age peak at ~2540 Ma.

Figure 9: Concordia plots for the 4 zircon samples included in this study. Samples HO-20130512JS and JS-4-4 are from the Jianshan area, sample LM-24 is from the Shankou area and sample LM-23-12 is from the Xiaolantian area. See text for explanation.

Figure 10: Zircon distribution plots; All samples exhibit a dominant age peak at around 800Ma and a subordinate peak at ~520-525Ma; in this latter zircon group note the inferred time transgressive relationship from the Shankou section (sample LM-24, 525Ma), to the Jianshan samples (522 and 523 Ma), to the southeastern Xiaolantian sample (sample LM-23-12, 520Ma). The two Jianshan samples are also the only samples that contain a higher amount of older Proterozoic zircons (~2540 Ma). Note each graph has a different Y-axis scale.

Figure 11: Cathodoluminescence images of zircon shapes from sample HO-0130512JS; the majority of zircons of the youngest group (sample 47 and sample 117) are euhehal with well developed magmatic zoning, indicative of short-distance transport; older zircons exhibit a subhedral shape and often lack magmatic zoning (sample 17 and 27). Circles mark sample locations, numbers next to sample numbers age of sample in Ma. All scale bars (white bars) are 20 μ m.

4.5 Provenance Summary

Provenance analysis often provides non-unique solutions when focusing on one data set. The integration of several different provenance proxies mitigates uncertainty and provides a good representation of the source area in a particular study area. In the case of the Maotianshan Shale, the provenance proxies largely point towards a source area with felsic composition associated with a recycled orogen. Table 1 provides a summary of all proxies included in this study.

			Tectonic Regime			Source Area Composition	
			ACM	PCM	CIA	Felsic	Mafic
Method	Figure	Components	Mag. Arc	Cont. Block	Rec. Or.	UCC	LCC
Petrography	3&4	QFL					
		Quartz type					
Major Elements, WI	5	CN, A, K					
Trace Elements	6	Th, V, Ni					
		Th, La, Sc					
		Th, Sc, Zr					
	7	Th, La					
		La, Th, Hf					
Detrital Zircon	9&10	0.8Ga suite					
		younger suite					

Table1: Results of provenance analysis. Fields highlighted in green are the most likely tectonic regime and source area composition for the samples included in the study. Fields in yellow highlight other potential interpretations or areas of minor contribution. The vast majority of proxies included in this study indicate a felsic (upper continental crust, UCC) provenance related to a Recycled Orogen (Rec. Or.) or Continental Island Arc (CIA) (black box). Minor contributions are of mafic origin or from a passive continental margin (PCM). This table incorporates results from all samples from all regions.

The ratios of the major rock constituents quartz, feldspar, and lithic fragments found in the coarse grained fractions of the Maotianshan Shale deposits are typical for sediments derived from a recycled orogen or continental island arc (Figure 5). The relative abundance of stable heavy minerals such as zircon and titanium oxides in the Maotianshan Shale samples indicates prolonged chemical weathering in the source area and the recycling of earlier detrital material. During the Cambrian, the study area was located in a low latitude setting (~30°S) in the southern hemisphere (Figure 1), with high evaporation rates and limited precipitation, as shown by an abundance of Cambrian age evaporite deposits on the Yangtze Block (Peng et al., 2009; McKenzie et al., 2011; Cocks and Torsvik, 2013; Li et al., 2014). The weathering indices of coarse and fine grained samples as shown in the CN-A-K ternary diagram and CIA plot (Figure 6) suggest that all samples included in this study

have been depleted of many of the mobile major elements. Although our data does not allow distinction between different alteration stages, the depletion of mobile major and minor elements might have resulted from intense chemical weathering in a low latitude paleogeographic setting during the time of deposition. Despite the heavy diagenetic overprint, the concentrations of major elements in a CN-A-K ternary system suggest that the original source of these constituents is granite of almost UCC composition (Figure 6).

The enrichment of the high field strength elements Zr, Hf, and Th in many of the Maotianshan Shale samples is also indicative of a granitic source (Figure 7,8) as these elements are generally unaffected by alteration processes and are preferentially enriched in felsic rocks (Feng and Kerrich, 1990). These petrographic and geochemical results are consistent with the results from detrital zircon analysis (Figures 9-11). The predominant mid-Neoproterozoic detrital zircons in these siltstones are mostly subhedral in shape; their crystallization ages of ~ 0.8 Ga are broadly consistent with the widespread mid-Neoproterozoic felsic volcanic and intrusive rocks along the Kangdian Rift (e.g., Zhou et al., 2002; Li et al., 2003). Thus, the regional preexisting mid-Neoproterozoic magmatic rocks are most likely the major provenance for the Maotianshan sediments. It is noteworthy that the younger suite of detrital zircons (~ 520 Ma zircons) are euhedral crystals with magmatic zoning under cathodoluminescence images (Fig. 11), indicative of short-distance transportation from their provenance(s). Mesoproterozoic and older detrital zircons are rare, apart from sample JS-4-4 showing a small age peak at ~ 2540 Ma.

The wide array of felsic deposits associated with Neoproterozoic volcanic activity and intrusions are present in the Kangdian paleoland and in proximity to the Song Ma tectonic zone (Figure 1). Both areas were potentially exhumed areas during the Cambrian Stage 3 and are located approximately 100km to the west and southwest of the study area, making them a likely source of the Maotianshan Shale sediments (Figure 1).. Lithic fragments and some of the younger zircons that have been transported over shorter distances might also have been derived from the Song Ma tectonic zone.

5 Local source area variations, hydraulic sorting, and implications on the taphonomy

The fate of the Changjiang organisms after death depends on physical and biologic factors that influence taphonomy. Provenance is a physical factor that controls, in part, sediment composition in a basin and

ultimately might influence the chemical and physical conditions at or near the sediment water interface or during early burial.

The interpretation of the general provenance of the Maotianshan Shale from detrital zircon, whole rock geochemistry, and petrography places the source area for the Maotianshan sediments close to an established continental island arc (recycled orogen, felsic source), with minor influx from volcanic sources. However, a closer look at the data reveals systematic changes of most proxies across the study area, and provides a more detailed picture of potential changes in local provenance, changes in hydrologic conditions, and their effect on taphonomy.

5.1 Local Provinces

The sample locations presented in this study can be separated in a northwestern area that includes the Ercai, Jianshan and Shankou sites, and a southeastern area that includes the Xiaolantian and Maotianshan sections (Figure 1). Samples from the northwestern areas yield a higher percentage of feldspar and a lower percentage of quartz than the samples from the southeastern region (Figure 5). Similarly some of the trace element concentrations reveal changes between the southeastern and the northwestern sections. Samples from the northwestern region have higher concentrations of Zr and Hf (Figure 12), suggesting a higher contribution of zircon-bearing sources in the northwestern province. Conversely, samples from the southeastern region are enriched in Ni (Figures 7, 12), potentially revealing the presence of mafic components in this source area.

These minor changes in the main mineral constituents and trace element concentrations were interpreted as the result of local changes in provenance in an overall recycled orogen (continental island arc) setting. The inferred drainage divide was located parallel to the southern splay of the Cenozoic Anninghe fault during the Cambrian Stage 3 (Figure 13). A swath of pre-900 Ma basement rocks are exhumed in the inferred northwestern source area (Li et al., 2014), and were the likely source of Maotianshan Shale sediments for the Jianshan, Ercai, and Shankou sections (Figure 13). The more pronounced signal of a stable craton source composition for the Maotianshan Shale in the northwestern study area (Figure 5), as well as a higher abundance of an older zircon suite in samples from this area (Figure 10), is a direct result of these more mature, older source rocks. The inferred southeastern drainage roughly follows the axis of the Neoproterozoic Kangdian Rift basin (Li et al.,

2009). As a result, major source rocks for the Maotianshan Shale in the southeastern region are Neoproterozoic rift basin deposits (Figure 13). This Neoproterozoic rift fill sequence contains an abundance of clasts and sediments derived from Neoproterozoic granites and calc alkaline volcanic rocks, including basalt (Li et al., 2002 ; Zhou et al., 2002). The higher concentration of mafic components found in the Maotianshan Shale sediments of the southeastern region is interpreted to be a direct result of this less mature source area composition. Alternatively, mafic rocks of various ages are well known from the Song Ma tectonic zone, and this area might also be the source of the mafic components in the southeastern study area (Figure 1 and 13).

Figure 12: Source area variation of Ni and Zr. Zr concentrations are higher in the northern sample suite (green and orange boxes) and are depleted in the southeastern region (blue box). The higher concentration of Zr, on average, in the northwestern region is attributed to a more felsic (mature) source resulting from the higher abundance of older (pre-900Ma) basement rocks in this northwestern area. The enrichment of Ni in the samples from the southeast as well as the Shankou samples is interpreted as result of the mafic detrital grains being incorporated in the respective sample suites.

Minor variations in trace element concentrations amongst some of the northwestern sites, namely the Ercai/Jianshan and Shankou sites, might also be the result of variations in source area but are not well understood at this time.

Results from zircon analysis are not unique but rather, extensively overlap. However, the sample from the southeastern Maotianshan section (sample LM 231212) contains a slightly younger age of 519 Ma for the youngest Concordia ages than the samples from the northwest (samples JS), which were calculated at 521 Ma. Recent detailed sedimentologic studies have demonstrated a time transgressive relationship between the different fossil locations in the Maotianshan Shale (MacKenzie et al., 2015). Our data, although rattled by some uncertainty, supports these findings from this previous study, suggesting a slightly older depositional age to the

northwest and younger depositional age to the southeast. This time transgressive relationship could also explain the minor changes in provenance that are implied from the geochemical and petrographic analysis presented in this manuscript.

Figure 13: Paleogeographic map of the study area and the inferred different source areas for the Maotianshan Shale. The inferred shoreline for the Maotianshan Shale (dashed line) was located parallel to the Song Ma fault (2) and the outline of the Kangdian paleoland (dotted pattern; outline from Wang et al., 1985), respectively (shoreline position modified from MacKenzie et al., 2015). Local variations in composition are explained by the presence of an inferred drainage divide that paralleled the southern splay of the present day Anninghe fault (1). The southeastern catchment (Maotianshan, Xiaolantian) was a near-axial drainage following the Neoproterozoic Kangdian rift basin and mainly reworking volcanic and igneous rocks and rift fill sequences (gray area with diamond pattern; outline from Li et al., 2009). The northwestern region (Shankou, Ercai, Jianshan) was sourced from an area northwest of the inferred drainage divide with a larger area of exhumed pre-900Ma basement rocks (medium gray area; outline from Li et al., 2014). The youngest suite of euhedral zircons indicates little to no recycling and short distance transport and reflect active volcanism in the hinterland, likely along the paleo suture zones between the Yangtze Block and Indochina (0 and 2) For details see text.

5.2 Hydraulic mineral fractionation

The differences in provenance as indicated by the Maotianshan sample suite can be controlled by compositional variations in the source area, but might also be the result of mineral fractionation by hydraulic sorting during sediment transport. The coarser grained sediments are generally enriched in Zr and Hf compared

to the finer grained sediments, independent of the sample area. This enrichment of elements associated with fast settling, coarser, and denser tectosilicates and ultradense minerals suggests hydraulic fractionation during sediment transport. This process is also reflected in the progressive enrichment of elements associated with phyllosilicates (micas and clays), that are concentrated in the finer grained sediments usually transported in the suspended load. Although this process is relevant when evaluating provenance, in the case of the Maotianshan Shale, samples with similar grain sizes and sedimentary characteristics show stark variations of Zr and Hf concentrations. This enrichment of Zr in the northwestern samples can best be explained by compositional variations in the source area rather than hydraulic sorting.

Other elements, such as Th and La are highly concentrated in the finer grain-size fraction (Figure 7,8). Th and La are common constituents of monazite, a very labile phase that likely was associated with the suspended load fraction during transport. The concentration of those elements in the finer fraction might therefore be the result of the hydraulic sorting. However, in the case of the trace elements, potential hydraulic mineral fractionation does not have any effect on the interpretation of provenance as concentrations of both elements seem to increase equally, thus not changing the ratio of these two phases.

5.3 Taphonomic implications

Minor variations in the geochemical and petrographic composition also imply that samples from the Maotianshan Shale are compositionally distinct for different parts of the study area and potentially sourced from different drainage areas separated by a drainage divide (Figure 13). Sediment supply to the Maotianshan Basin was through two or more feeder systems resulting in the compositional variations observed between the northwestern and southeastern areas. Paleoflow measurements of Maotianshan samples also indicate that sediments were supplied to the study area through a series of feeder systems (MacKenzie et al., 2015).

The time transgressive sediment supply to the Maotianshan Basin from a variety of provenances as suggested by our data, might have affected the development or preservation of different fossil assemblages in the Anning (Shankou), Haikou (Jianshan and Ercai), and Chengjiang (Xiaolantian and Maotianshan) (Zhao et al., 2012), but further studies are needed to confirm this interpretation.

6 Temporal constraint of the Maotianshan Shale deposition

Results from our detrital zircon analysis indicates that the youngest zircon populations of three of our four dated siltstone samples yield consistent Concordia ages of 521.7 ± 4.5 Ma, 521.7 ± 6.1 Ma, and 519.6 ± 5.3 Ma, respectively (Figure. 10), providing a maximum age constraint on the timing of deposition of the Maotianshan sediments of ~ 520 Ma. These new detrital zircon dates for the Maotianshan Shale confirm a Cambrian Stage 3 depositional age for the Maotianshan Shale in Yunnan Province (Figure 1), consistent with results from biostratigraphy and other detrital zircon geochronological studies. In the study area, the lower Black Shale Member of the Yu'an-shan Formation is characterized by the *Parabadiella* biozone, late Atdabanian (530-524 Ma), and the Maotianshan Shale and the Upper Siltstone Member are characterized by the *Eoredlichia* and *Wutangaspis* biozones (~ 520 Ma) (Figure1; Zhu et al., 2003; Rozanov et al., 2008). The Zhongyicun Member of the Zhujiqing Formation has been dated to 539.4 ± 2.9 and the base of the Shiyantou Formation to 526.5 ± 1.1 Ma, both providing maximum depositional ages for the Yu'an-shan Formation (Compston et al., 2008). These dates are consistent with the results of SIMS Pb/U dating of a volcanic tuff within the Zhongyicun phosphorite that has been dated to 535.2 ± 1.7 Ma (Zhu et al., 2009) and a U-Pb SHRIMP date of 538.2 ± 1.5 for the same tuff (Jenkins et al., 2002; Zhou et al., 2008). Most recently a volcanic tuff at the base of the Dahai Member has been dated to 523.9 ± 6.7 Ma (Okada et al., 2013), meeting the overall maximum temporal framework of the Cambrian strata in the study area. Time equivalent strata to the Maotianshan Shale in Zunyi, South China, was dated at 534 ± 60 Ma and 518 ± 5 Ma (Chang et al., 2007; Zhou et al., 2008), corresponding to the overall age range of the Maotianshan Shale.

7 Conclusion/Summary

The analysis of petrographic, geochemical, and detrital zircon data from the Maotianshan Shale in Yunnan Province, China revealed the following sediment provenance and temporal constraint of Maotianshan deposition:

- The Kangdian paleoland and an uplifted area paralleling the present day Song Ma fault were bordering the western and southwestern margin of Yangtze Block during the Cambrian Stage 3 and were the terrigenous source of the Maotianshan Shale deposits, but local differences in sandstone composition,

trace element ratios and detrital zircon assemblage indicate a more complex sourcing of the Maotianshan Shale, spatially and through time.

- The detrital components of the coarsest grained rocks (silty vf sandstones) of the Maotianshan Shale comprise quartz, feldspar, accessory and heavy minerals, and lithic fragments. Compositional QFL variations reflect local changes of an overall recycled orogen provenance.
- Minor changes in geochemical and petrographic proxies between the northwestern Jianshan/Ercai area and the southeastern Maotianshan/Xiaolantian area suggest the presence of local sources for these two areas. Sediments of the southeastern province are less mature and samples include minor elements commonly associated with mafic sources. Sediments from the northwestern province are more mature, largely lack mafic components and are enriched in Zr and Hf.
- The youngest zircon population of our detrital zircon suite yields consistent Concordia ages of ~520 Ma, representing a maximum age constraint on the timing of deposition of the Maotianshan Shale. The zircon crystals of the ~520 Ma populations are euhedral with magmatic zoning under cathodoluminescence, indicative of short-distance transport.
- Detrital zircons of ~0.8 Ga are the major populations of the Maotianshan Shale detrital zircons. Their crystallization age matches well with the age of the widely spread, Neoproterozoic felsic volcanic and intrusive rocks in the Kangdian paleoland and rift province. This interpretation suggests that the preexisting mid-Neoproterozoic magmatic rocks in Kangdian paleoland are the most likely provenance for the Maotianshan sediments.
- Volcanic activity along the Song Ma suture zone is a potential source for the ~520Ma detrital zircon suite.

8 Acknowledgements

We gratefully acknowledge the support of this research by a grant from the National Science Foundation to MHH (NSF-RAPID, EAR-1338442), a grant by the Chinese Ministry of Science and Technology to XHL (grant no. 2013CB835005), grants from the National Science Foundation of China to CJ (grant no: 41023008 and

41272008), and a graduate student grant from the National Science Foundation to LAM (NSF-EAPSI 0914034). Other funding was provided by the University of Montana, the Geological Society of America's Graduate Student Research Grant and the Sigma Xi Grants In Aid Award. We greatly appreciate the assistance that Huai Zhi Wu provided in the field and with logistics. Two unknown reviewers are thanked for helpful and encouraging reviews.

9 References

- Allen, C.R., Gillespie, A.R., Yuan, H., Sieh, K.E., Zhang, B., Zhu, C., 1984. Red River and associated faults, Yunnan province, China: Quaternary geology, slip rates, and seismic hazard. *Geological Society of America Bulletin* 95, 686-700.
- Allison, M.A., Khan, S.R., Goodbred, S.L., Kuehl, S.A., 2003. Stratigraphic evolution of the late Holocene Ganges–Brahmaputra lower delta plain. *Sedimentary Geology* 155, 317–342.
- Armstrong-Altrin, J.S., Lee, Y., Verma, S., Ramasamy, S., 2004. Geochemistry of sandstones from the Upper Miocene Kudanul Formation, southern India: implications for provenance, weathering and tectonic setting. *Journal of Sedimentary Research* 74, 167–179.
- Babcock, L.E., Zhang, W.T., 2001. Stratigraphy, paleontology and depositional setting of the Chengjiang Lagerstätte (lower Cambrian), Yunnan, China. *Palaeoworld* 13, 66-86.
- Bahlburg, H., 1998. The geochemistry and provenance of Ordovician turbidites in the Argentine Puna. *Geological Society of London Special Publications* 142, 127–142.
- Bahlburg, H., Dobrzinski, N., 2011. A review of the Chemical Index of Alteration (CIA) and its application to the study of Neoproterozoic glacial deposits and climate transitions. *Geological Society of London Memoirs* 36, 81–92.
- Bhatia, M.R., 1983. Plate tectonics and geochemical composition of sandstones. *Journal of Geology* 91, 611–627.
- Bhatia, M.R., Crook, K.A.W., 1986. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. *Contributions to Mineralogy and Petrology* 92, 181–193.
- Black, L. P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil, R., Campbell, I.H., Korsch, R.J., Williams, I.S., Foudoulis, C., 2004. Improved $^{206}\text{Pb}/^{238}\text{U}$ microprobe geochronology by the monitoring of a trace-element-related matrix effect; SHRIMP, ID–TIMS, ELA–ICP–MS and oxygen isotope documentation for a series of zircon standards. *Chemical Geology* 205, 115-140.
- Blatt, H., 1985. Provenance studies and mudrocks. *Journal of Sedimentary Research* 55, 69–75.
- Blatt, H., Sutherland, B., 1969. Intrastratal solution and non-opaque heavy minerals in mudrocks. *Journal of Sedimentary Petrology* 39, 591–600.
- Borges, J., Huh, Y., 2007. Petrography and chemistry of the bed sediments of the Red River in China and Vietnam: provenance and chemical weathering. *Sedimentary Geology* 194, 155–168.
- Bracciali, L., Marroni, M., Luca, P., Sergio, R., 2007. Geochemistry and petrography of Western Tethys Cretaceous sedimentary covers (Corsica and Northern Apennines): From source areas to configuration of margins. *Geological Society of America Special Papers* 420, 73-93.
- Chang, X., Chen, L., Hu, S., Wang, J., Zhu, B., 2007. Isotopic dating of the Chengjiang Fauna-bearing horizon in central Yunnan Province, China. *Chinese Journal of Geochemistry* 26, 345-349.

- Chen, J.Y., Erdtmann, B.D., 1991. Lower Cambrian fossil Lagerstätte from Chengjiang, Yunnan, China: insights for reconstructing early metazoan life. In: Simonetta, A., Conway Morris, S. (Eds.), *The Early Evolution of Metazoa and the Significance of Problematic Taxa*. Cambridge University Press, Cambridge, pp. 57 – 76.
- Cocks, L.R.M., Torsvik, T.H., 2013. The dynamic evolution of the Palaeozoic geography of eastern Asia. *Earth-Science Reviews* 117, 40-79.
- Compston, W., Zhang, Z., Cooper, J.A., Ma, G.G., Jenkins, R.J.F., 2008. Further SHRIMP geochronology on the early Cambrian of south China. *American Journal of Science* 308, 399–420.
- Crook, K.A.W., 1974. Lithogenesis and geotectonics: the significance of compositional variations in flysch arenites (graywackes). *SEPM Special Publications* 19, 304–310.
- Cullers, R.L., 1988. Mineralogical and chemical changes of soil and stream sediment formed by intense weathering of the Danberg granite, Georgia, USA. *Lithos* 21, 301–314.
- Cullers, R.L., Chaudhure, S., Kilbane, N., Koch, R. 1979. Rare earths elements in size fractions and sedimentary rocks of Pennsylvania-Permian age from the mid-continent of the USA. *Geochimica Cosmochimica Acta*, 43, 1285–1302.
- Curry, J.R., Emmel, F.J., Moore, D.G., 2003. The Bengal Fan: morphology, geometry, stratigraphy, history and processes. *Marine and Petroleum Geology* 19, 1191–1223.
- Dabbagh, M.E., Rogers, J.J., 1983. Depositional environments and tectonic significance of the Wajid Sandstone of southern Saudi Arabia. *Journal of African Earth Sciences* 1, 47–57.
- Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, G.G. (Ed.), *Provenance of Arenites*. D Reidel Publishing Company, pp. 333 – 361.
- Dickinson, W.R., Suczek, C., 1979. Plate tectonics and sandstone composition. *American Association of Petroleum Geologists Bulletin* 63, 2164–2182.
- Dickinson, W. R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin* 94, 222-235.
- Fedo, C.M., Nesbitt, H.W., Young, G.Y., 1995. Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. *Geology* 23, 921-924.
- Feng, R., Kerrich, R., 1990. Geochemistry of fine-grained clastic sediments in the Archean Abitibi greenstone belt, Canada: implications for provenance and tectonic setting. *Geochimica et Cosmochimica Acta* 54, 1061-1081.
- Findlay, R.H., 1998. The Song Ma Anticlinorium, northern Vietnam: the structure of an allochthonous terrane containing an early Palaeozoic island arc sequence. *Journal of Asian Earth Sciences* 15, 453-464.
- Floyd, P. A., Leveridge, B.E., 1987. Tectonic environment of the Devonian Gramscatho basin, south Cornwall: framework mode and geochemical evidence from turbiditic sandstones. *Journal of the Geological Society* 144, 531-542.
- Floyd, P. A., Shail, R., Leveridge, B. E., Franke, W., 1991. Geochemistry and provenance of Rhenohercynian synorogenic sandstones: implications for tectonic environment discrimination. *Geological Society of London, Special Publications* 57, 173-188.
- Garzanti, E., Andò, S., Vezzoli, G., Dell'Era, D., 2003. From rifted margins to foreland basins: investigating provenance and sediment dispersal across desert Arabia (Oman, UAE). *Journal of Sedimentary Research* 73, 572–588.
- Garzanti, E., Ando, S., Vezzoli, G., Ali Abdel Megid, A., El Kammar, A., 2006. Petrology of Nile River sands (Ethiopia and Sudan): sediment budgets and erosion patterns. *Earth and Planetary Science Letters* 252, 327–341.

- Garzanti, E., Ando, S., France-Lanord, C., Censi, P., Vignola, P., Galy, V., Lupker, M., 2011. Mineralogical and chemical variability of fluvial sediments 2. Suspended-load silt (Ganga–Brahmaputra, Bangladesh). *Earth and Planetary Science Letters* 302, 107–120.
- Greentree, M. R., Li, Z.X., 2008. The oldest known rocks in south–western China: SHRIMP U–Pb magmatic crystallisation age and detrital provenance analysis of the Paleoproterozoic Dahongshan Group. *Journal of Asian Earth Sciences* 33, 289–302.
- Greentree, M.R., Li, Z.X., Li, X.H., Wu, H., 2006. Late Mesoproterozoic to earliest Neoproterozoic basin record of the Sibao orogenesis in western South China and relationship to the assembly of Rodinia. *Precambrian Research* 151, 79–100.
- Guo, J.L., Gao, S., Wu, Y.B., Li, M., Chen, K., Hu, Z.C., Liang, Z.H., Liu, Y.S., Zhou, L., Zong, K.Q., Zhang, W., Chen, H.H., 2014. 3.45 Ga granitic gneisses from the Yangtze Craton, South China: Implications for Early Archean crustal growth. *Precambrian Research* 242, 82–95.
- Guo, L.Z., Shi, Y.S., Ma, R.S., Lu, H.F., Ye, S.F., 1985. Plate movement and crustal evolution of the Jiangnan Proterozoic mobile belt, SE China. *Earth Sci. J. Geol. Soc. Jpn.* 2. 156–166.
- Hay, W.W., 1998. Detrital sediment fluxes from continents to oceans. *Chemical Geology* 145, 287–323.
- Hou, X.-G., 1987. Two new arthropods from the Lower Cambrian Chengjiang, eastern Yunnan. *Acta Geologica Sinica* 26, 236–256.
- Hu, S.X., 2005. Taphonomy and palaeoecology of the Early Cambrian Chengjiang biota from Eastern Yunnan, China. *Berliner Paläobiologische Abhandlungen* 7, 1–197.
- Ingersoll, R.V., Bullard, T., Ford, R., Grimm, J., Pickle, J., Sares, S., 1984. The effect of grain size on detrital modes: a test of the Gazzi Dickinson point-counting method. *Journal of Sedimentary Petrology* 54, 103–116.
- Jenkins, R.J.F., Cooper, J.A., Compston, W., 2002. Age and biostratigraphy of Early Cambrian tuffs from SE Australia and southern China. *Journal of the Geological Society London* 159, 645–658.
- Kroonenberg, S.B., 1994. Effects of provenance, sorting and weathering on the geochemistry of fluvial sands from different tectonic and climatic environments. *Proceedings of the 29th International Geological Congress, Part A*, 69–81.
- Li, Z.X., Zhang, L., Powell, C., 1995. South China in Rodinia: part of the missing link between Australia–East Antarctica and Laurentia? *Geology* 23, 4077–4410.
- Li, X.H., 1999. U–Pb zircon ages of granites from the southern margin of the Yangtze Block: timing of Neoproterozoic Jinning Orogeny in SE China and implications for Rodinia assembly. *Precambrian Research* 97, 43–57.
- Li, X.H., Li, Z.X., Zhou, H., Liu, Y., Kinny, P.D., 2002. U–Pb zircon geochronology, geochemistry and Nd isotopic study of Neoproterozoic bimodal volcanic rocks in the Kangdian Rift of South China: implications for the initial rifting of Rodinia. *Precambrian Research* 113, 135–154.
- Li, X.H., Li, W.X., Li, Z.X., Liu, Y., 2008. 850–790 Ma bimodal volcanic and intrusive rocks in northern Zhejiang, South China: a major episode of continental rift magmatism during the breakup of Rodinia. *Lithos* 102, 341–357.
- Li, X.H., Li, W.X., Li, Z.X., Lo, C.H., Wang, J., Ye, M.F., Yang, Y.H., 2009. Amalgamation between the Yangtze and Cathaysia Blocks in South China: constraints from SHRIMP U–Pb zircon ages, geochemistry and Nd–Hf isotopes of the Shuangxiwu volcanic rocks. *Precambrian Research* 174, 117–128.
- Li, X.H., Li, Z.X., Li, W.X., 2014. Detrital zircon U–Pb age and Hf isotope constrains on the generation and reworking of Precambrian continental crust in the Cathaysia Block, South China: A synthesis. *Gondwana Research* 25, 1202–1215.
- Li, Z.X., Li, X.H., Zhou, H.W., Kinny, P.D., 2002. Grenvillian continental collision in south China: new SHRIMP U–Pb zircon results and implications for the configuration of Rodinia. *Geology* 30, 163–166.

- Li, Z.X., Li, X.H., Kinny, P.D., Wang, J., Zhang, S., Zhou, H., 2003. Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze Craton, South China and correlations with other continents: evidence for a mantle superplume that broke up Rodinia. *Precambrian Research* 122, 85–109.
- Li, Z.X., Li, X.H., Li, W.X., Ding, S.J., 2008. Was Cathaysia part of Proterozoic Laurentia? New data from Hainan Island, south China. *Terra Nova* 20, 154–164.
- Liu, H., 1991. The Sinian System in China (in Chinese). Science Press, Beijing, 388p.
- Ludwig, K. R., 2001. Eliminating mass-fractionation effects on U-Pb isochron ages without double spiking. *Geochimica et Cosmochimica Acta* 65, 3139–3145.
- MacKenzie, L.A., Hofmann, M.H., Chen, J., Hinman, N.W., 2015. Stratigraphic controls of soft-bodied fossil occurrences in the Cambrian Chengjiang Biota Lagerstätte, Maotianshan Shale, Yunnan Province, China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 420, 96–115.
- McKenzie, P.M., Hughes, N.C., Myrow, P.M., Choi, D.K., Part, T.Y., 2011. Trilobites and zircons link north China with the eastern Himalaya during the Cambrian. *Geology* 39, 591–594.
- McLennan, S. M., 1993. Weathering and global denudation. *Journal of Geology* 101, 295–303.
- McLennan, S.M., 2001. Relationships between the trace element composition of sedimentary rocks and upper continental crust. *Geochemistry, Geophysics, Geosystems* 2, 1021.
- Murali, A. V., Parthasarathy, R., Mahadevan, T. M., Das, M. S., 1983. Trace element characteristics, REE patterns and partition coefficients of zircons from different geological environments—a case study on Indian zircons. *Geochimica et Cosmochimica Acta* 47, 2047–2052.
- Nesbitt, H. W., Young, G. M., 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. *Nature* 299 715–717.
- Nesbitt, H. W., Young, G. M., 1984. Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. *Geochimica et Cosmochimica Acta* 48, 1523–1534.
- Nesbitt, H. W., and Young, G. M., 1989. Formation and diagenesis of weathering profiles. *Journal of Geology* 97, 129–147.
- Okada, Y., Sawaki, Y., Komiya, T., Hirata, T., Takahata, N., Sano, Y., Han, J., Maruyama, S., 2014. New chronological constraints for Cryogenian to Cambrian rocks in the Three Gorges, Weng'an and Chengjiang areas, South China. *Gondwana Research* 25, 1027–1044.
- Parker, A., 1970. An index of weathering for silicate rocks. *Geological Magazine* 107, 501–504.
- Peng, S., Hughes, N.C., Helm, N.A., Sell, B.K., Xhu, X., Myrow, P.M., Parcha, S.K., 2009. Cambrian trilobites from the Parahio and Zanskar Valleys, Indian Himalaya. *Paleontological Society Memoirs* 71, 1–95.
- Price, J.R., Velbel, M.A., 2003. Chemical weathering indices applied to weathering profiles developed on heterogeneous felsic metamorphic parent rocks. *Chemical Geology* 202, 397–416.
- Pu, X.C., Zhou, H.D., Wang, X.L., Luo, A.P., Li, S.J., Wang, J., Ye, H.Z., Pan, X.G., Zeng, R.L., Huang, Z.Y., Lin, M., 1992. Cambrian Lithofacies, Paleogeography and Mineralization in South China. Geological Publishing House, Beijing. 191 pp.
- Roser, B.P., Korsch, R.J., 1986. Determination of tectonic setting of sandstone–mudstone suites using SiO₂ and K₂O/Na₂O ratio. *Journal of Geology* 94, 635–650.
- Rozanov, A.Y., Zhu, M., Pak, K.L., Parkhaev, P.Y., 2008. The 2nd Sino-Russian symposium on the Lower Cambrian subdivision. *Paleontology Journal* 42, 441 – 446.

- Schwab, F.L., 1975. Framework mineralogy and chemical composition of continental margin-type sandstone. *Geology* 3, 487–490.
- Shen, W., Li, H., Xu, S., Wang, R., 2000. U-Pb chronological study of zircons from the Huangcaoshan and Xiasuozi granites in the western margin of Yangtze Plate. *Geol. J. China Univ.* 6, 412–416.
- Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters* 26, 207–221.
- Taylor, S.R., McLennan, S.M., 1985. *The Continental Crust: its composition and evolution*. Blackwell Scientific, Oxford, 312 pp.
- Wang, E., Burchfiel, B.C., 2000. Late Cenozoic to Holocene deformation in southwestern Sichuan and adjacent Yunnan, China, and its role in formation of the southeastern part of the Tibetan Plateau. *Geological Society of America Bulletin* 112, 413–423.
- Wang, H., Chu, X., Liu, B., Hou, H., Ma, L., 1985. *Atlas of Paleogeography of China*. Cartographic Publishing House, Beijing, China.
- Wang, X., Shi, X., Jiang, G., Zhang, W., 2012. New U-Pb age from the basal Niutitang Formation in South China: Implications for diachronous development and condensation of stratigraphic units across the Yangtze platform at the Ediacaran-Cambrian transition. *Journal of Asian Sciences* 48, 1–8.
- Wang, X.L., Zhou, J.C., Qiu, J.S., Zhang, W., Liu, X., Zhang, G., 2006. LA-ICP-MS U–Pb zircon geochronology of the Neoproterozoic igneous rocks from Northern Guangxi, South China: implications for tectonic evolution. *Precambrian Research* 145, 111–130.
- Wang, X.C., Li, X.H., Li, W.X., Li, Z.X., 2007. Ca. 825 Ma komatiitic basalts in South China: first evidence for N1500 °C mantle melts by a Rodinian mantle plume. *Geology* 35, 1103–1106.
- Wang, Y., Wang, X.L., Huang, Y.M., 2008. Megascopic symmetrical metazoans from the Ediacaran Doushantuo Formation in the northeastern Guizhou, South China. *Journal of China University of Geosciences* 19, 200–206.
- Wiedenbeck, M. A. P. C., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., von Quadt, A., Roddick, J.C., Spiegel, W., 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards Newsletter* 19, 1–23.
- Xu, Y., Du, Y., Cawood, P.A., Zhu, Y., Li, W., Yu, W., 2012. Detrital zircon provenance of Upper Ordovician and Silurian strata in the northeastern Yangtze Block: Response to orogenesis in South China. *Sedimentary Geology* 267/268, 63–72.
- Ye, M.F., Li, X.H., Li, W.X., Liu, Y., Li, Z.X., 2007. SHRIMP U–Pb zircon geochronological and geochemical evidence for early Neoproterozoic Sibaoan magmatic arc along the southeastern margin of Yangtze Block. *Gondwana Research* 12, 144–156.
- Zhao, F., Hu, S., Caron, J.-B., Zhu, M., Yin, Z., Lu, M., 2012. Spatial variation in the diversity and composition of the Lower Cambrian (Series 2, Stage 3) Chengjiang Biota, Southwest China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 346/347, 54–65.
- Zhao, G., Cawood, P. A., 1999. Tectonothermal evolution of the Mayuan Assemblage in the Cathaysia Block; implications for Neoproterozoic collision-related assembly of the South China Craton. *American Journal of Science* 299, 309–339.
- Zheng, Y.F., Zhang, S.B., Zhao, Z.F., Wu, Y.B., Li, X.H., Li, Z.X., Wu, F.Y., 2007. Contrasting zircon Hf and O isotopes in the two episodes of Neoproterozoic granitoids in South China: implications for growth and reworking of continental crust. *Lithos* 96, 127–150.
- Zhou, M.F., Yan, D.P., Kennedy, A.K., Li, Y.Q., Ding, J., 2002. SHRIMP U–Pb zircon geochronological and geochemical evidence for Neoproterozoic arc magmatism along the western margin of the Yangtze block, South China. *Earth and Planetary Science Letters* 196, 51–67.

Zhou, M.F., Luo, T., Li, Z., Zhao, H., Long, H., Yang, Y., 2008. SHRIMP U-Pb zircon age of tuff at the bottom of the Lower Cambrian Niutitang Formation, Zunyi, South China. *Chinese Science Bulletin* 53, 576-583.

Zhu, M.Y., Zhang, J.M., Li, G.X., 2001. Sedimentary environments of the Early Cambrian Chengjiang biota: Sedimentology of the Yu'an Shan Formation in Chengjiang County, Eastern Yunnan. *Acta Geologica Sinica* 40, 80-105.

Zhu, M.Y., Zhang, J.M., Steiner, M., Yang, A.H., Li, G.X., Erdtmann, B.D., 2003. Sinian– Cambrian stratigraphic framework for-shallow- to deep-water environments of the Yangtze Platform: an integrated approach. *Progress in Natural Science* 13, 951–960.

Zhu, R., Li, X., Hou, X.G., Pan, Y., Wang, F., Deng, C., He, H., 2009. SIMS U-Pb zircon age of a tuff layer in the Meishucun section, Yunnan, southwest China: Constraint on the age of the Precambrian-Cambrian boundary. *Science in China Series D: Earth Sciences* 52, 1385-1392.

Zimmermann, U., Bahlburg, H., 2003. Provenance analysis and tectonic setting of the Ordovician clastic deposits in the southern Puna Basin, NW Argentina. *Sedimentology* 50, 1079–1104.

Zuffa, G.G. 1985. Provenance of arenites. Reidel, Dordrecht, NATO-ASI Series, 148, 408pp.