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RESEARCH ARTICLE

Elemental and Sm-Nd isotopic geochemistry on detrital sedimentary rocks in the Ganzi–Songpan block and Longmen Mountains

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Abstract Systematic results of major and trace element geochemistry and Sm-Nd isotopic geochemistry on detrital sedimentary rocks of Precambrian to Triassic in the Ganzi–Songpan block and Longmen Mountains are presented. The rocks are classified into greywackes or feldspar sandstones, grains of which are the mixtures of mafic rocks, felsic rocks, and quartz + calcite. Total rare earth elements (REE) contents of the rocks increase gradually and negative Eu anomalies become more obvious from Precambrian to Triassic, which may indicate intensifying crustal anatexis. Tectonic setting was stable during the Late Paleozoic, therefore there are obvious negative Ce anomalies. Nd model ages are between 1.6 Ga and 2.4 Ga, which are very similar to those of the Yangtze craton, South Qinling and North Qinling belts and quite different from those of the North China craton. Therefore, provenance of the sedimentary rocks in the Ganzi–Songpan block and Longmen Mountains was the Yangtze craton and/or the Qinling orogen, which evolved on the basis of the Yangtze craton. The correlation between provenances and tectonostratigraphic strata of the western Yangtze craton shows that the source materials should be primarily from Neoproterozoic. Secondary sources were Archean and Paleoproterozoic strata. Triassic clastic sedimentary rocks contain Late Paleozoic mantle-derived materials, represented by the Emeishan Permian flood basalts. Spatial distribution of initial Nd isotopic compositions indicates that denudating areas were in the east and the north and depositing areas of deep water were in the west and the south for the Ganzi–Songpan basin during Triassic.

Keywords clastic sedimentary rocks, Ganzi–Songpan block, Nd model age, provenance, geotectonics

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The Ganzi–Songpan block is a primary tectonic unit in China. Several blocks converged and joined together there. It is the convergent area between the Central Orogen that stretches across mainland China from east to west and the north-south trending Sichuan–Yunnan–Helanshan tectonic belt. It is mainly a Triassic deep sea sedimentation series (Bureau of Geology and Mineral Resources of Qinghai Province, 1991; Bureau of Geology and Mineral Resources of Sichuan Province, 1991). Some researchers consider that this block records the continuously orogenic events from paleo-Tethys to Tethys and was a mountain chain that slipped away from the Yangtze craton with regard to its tectonic study (Xu et al., 1992; Wang et al., 1997). However, Yang (2002) held that the main body of the Ganzi–Songpan block should be a sedimentary wedge and accretionary complex of basement in the Late Carboniferous–Late Triassic foreland basin of paleo-Tethys. The study of sedimentary tectonics and paleogeography suggested that there are obvious distinctions from the eastern, western, to the northern parts (Bureau of Geology and Mineral Resources of Qinghai Province, 1991; Bureau of Geology and Mineral Resources of Sichuan Province, 1991). Shen et al. (1998) concluded Nd depleted mantle model ages (2.28–1.98 Ma) of metamorphic rocks in the Danba area from the block and suggested they are mixtures of Neoarchean crust in the Yangtze craton and Meso/Neoproterozoic plate edge materials. Bruguier et al. (1997) studied the zircon U-Pb ages in sedimentary rocks from Middle/Lower Triassic strata in the block and maintained that the major provenances are the Mesoproterozoic rocks (1.8–2.0 Ga). And they also suggested that some Neoarchean materials (2.5–2.6 Ga) are mainly from the southern margin of the North China–Korea craton, and some may also come from the Yangtze craton or Kunlun arc, north of the basin. Sinian (ca. 760 Ma) detrital zircons dominate the age spectrum of Upper Triassic sandstones, which should mainly originate from the Yangtze craton (Bruguier et al., 1997). As a result of the limitation of methodology (single grain evaporation) and the dated grains as well as the incomplete Chinese geological information, some conclusions are not very convincing.

The compositions of sandstones in a depositional basin are mainly controlled by their source areas. Therefore, chemical compositions of sandstones may indicate the tectonic settings and the characters of their source area. The distribution of zircon U-Pb ages in clastic sedimentary rocks can reflect the magmatic/metamorphic events of their source areas and thereby the structure of tectonostratigraphic strata in their source areas. In the perspective of sedimentary geochemistry, the study of material transportation in a basin and coupled relationship between provenances and the denudation of blocks surrounding the basin are not only critical to understanding uplift history and movement for the blocks, but also are of continental dynamic significance on the coupling effect between lithospheric deep process and sedimentation response. This paper presents the major and trace elements, and Sm-Nd isotopic geochemistry results of clastic sedimentary rocks with different periods in the Ganzi–Songpan block and the Longmen Mountain. Their provenances and tectonic affinity are discussed.

1 Geological setting

The Ganzi–Songpan block (belts) lies in the southwest of China, in the eastern margin of the Tethys–Himalaya orogen. It is an orogen with a long evolution history since the Mesozoic. Its main body constitutes the West Sichuan plateau and Baryan Har. The Amnyemaqen suture abuts on the Laurasia in the north. In the west, it conjoins the Qiangtang–Changdu block, which is the outer margin of the Gondwanaland by the Jinshajiang suture. In the southeast, the block connects the Yangtze craton through the Longmen Mountains–Jinpingshan. To the northwest of the orogen, the Baryan Har strenches from east to west; whereas to east, the West Sichuan plateau converges sharply southwards appearing as an up-side-down triangular bag. In the northeast, the Motianling of the Ganzi–Songpan block connects the Qinling orogen (Xu et al., 1992).

The Ganzi–Songpan block is mainly composed of five arcuate thrust nappes, which stretch from east to west (Motianling, Ma’erkang, Danba, Yajiang and Muli). The Ma’erkang and Yajiang nappes mainly consist of the Triassic Xikang Group. They belong to a flysch wedge that is comprised of hemi-deep sea flysch, slope flysh, marginal sea flysch, and carbonate mesa flysch. The bottom of the flysch wedge is Late Triassic ductile decollement. The Motianling, Danba and Muli nappes, mainly composed of Paleozoic and Presinian metamorphic basement, are characterized by the multiple hiberarchy deep decollements and thrusts from north to south. The Ganzi–Songpan block is separated into two parts by the NW trending Xianshui River fault.

The Longmen Mountain–Jinpingshan constitute the foreland thrust wedge of the Ganzi–Songpan block, which developed synchronously with the interior fold system in the Ganzi–Songpan block, i.e. Triassic (two principal tectonic episodes: the end of Carnian, and the end of Norian) (Liu, 1998; Liu et al., 2001). Then it underwent multiple tectonic events during the Yanshanian and Himalayan periods (Liu et al., 2001). Xu et al. (1996) suggested that the block formed in the Jinning period based on the studied results of granitoids, which were partial melting products of middle to late Middle Proterozoic meta-volcanic and meta-sedimentary basement. They concluded that the Longmen Mountain–Jinpingshan, the Ganzi–Songpan, and Neoproterozoic orogenic belt in the western margin of the Yangtze craton are significant parts of the paleo-Yangtze block.

The Ganzi–Litang suture is a boundary between the eastern and western Ganzi–Songpan. The principal constituents in the east are composed of the Xikang Group (extending to Baryan Har westwards). The Triassic volcanic, clastic, and carbonate rocks comprise the Yidun Group in the west. The Xikang Group developed from a passive continental margin of the Yangtze craton, which was an association seashore and shallow sea facies in Early–Middle Triassic, i.e. sand-mud and carbonate formation. The Upper Triassic flysch association can be divided into Zhuwo, Xinduqiao, and Lianghekou formations from lower to upper parts (Zou, 1995). The formation in the Lower Triassic association can be divided into Runiange (grey-green slate, crystalline limestone, and silt), and Bocigou (deep grey slate and silt) formations from upper to lower parts (Bureau of Geology and Mineral Resources of Sichuan Province, 1991).

The meta-clastic sedimentary rocks concerned in this paper are distributed in the Longmen Mountain and the Ganzi–Songpan block, east of the Ganzi–Litang suture (Fig. 1). The samples span the periods from Cambrian, Silurian, Devonian to Triassic. Detailed information of each sample concerning lithology, period, and locality is listed in Table 1.

2 Analytical method

The thin sections of clastic sedimentary rocks were observed for their structure, components, and alteration under an optical microscope to select unaltered and unweathered ones for further study. The whole-rock samples were crushed to 1–2 cm and 100 g fresh grains were collected. Then, they were crushed into powder of less than 200 meshes by an uncontaminated corundum crusher. A powder sample was reduced to three aliquots, 5 g per aliquot. Then, the petrochemistry, trace element analyses and Sm-Nd isotope analysis were done at the Institute of Geology and Geophysics, Chinese Academy of Sciences. About 100 mg whole-rock powder was used in Sm-Nd isotope analyses. We added quantitatively ^{149}Sm-^{150}Nd spikes and purified HF-$HClO_4$ to a sample in a Teflon bomb with steel-jacketed. Then the sample was heated over 72 h under 250°C until it was fully decomposed. Rare earth elements and other elements were

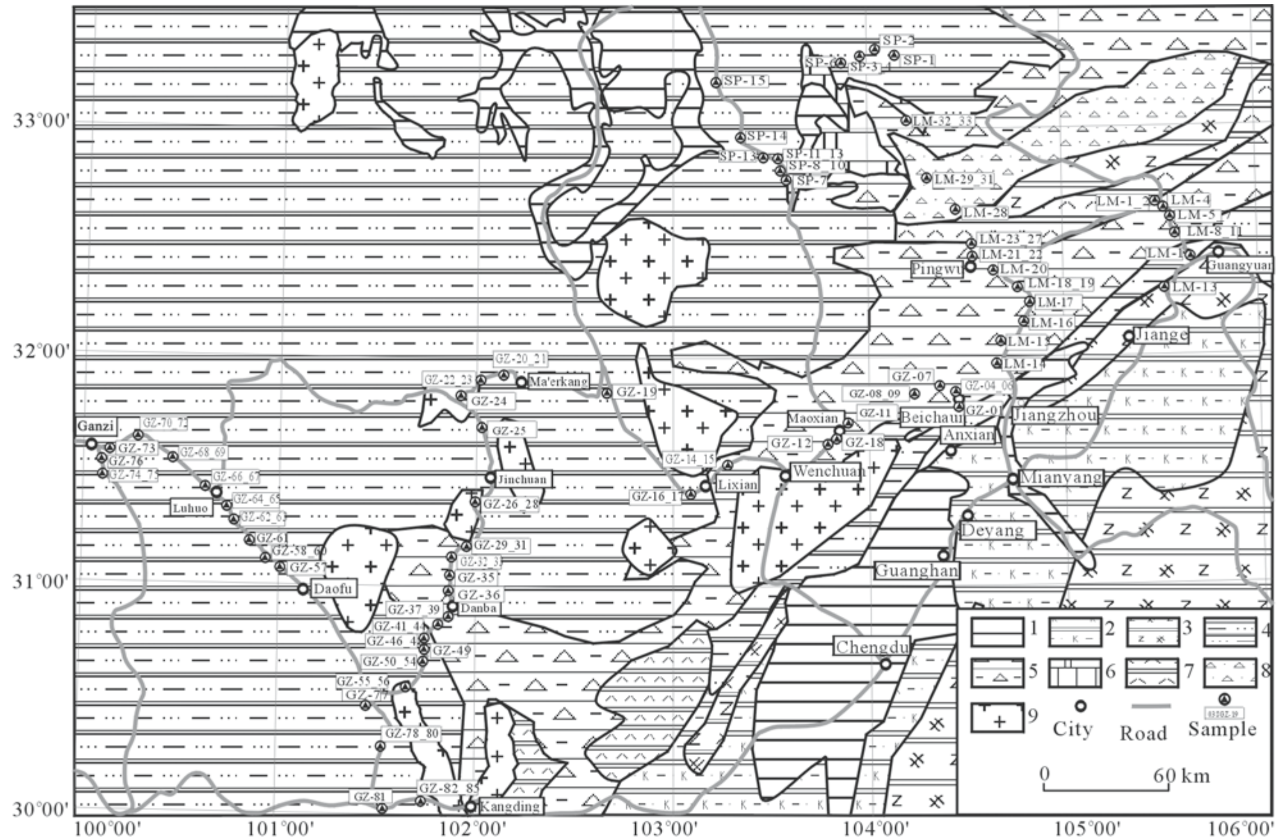

Fig. 1 Geological sketch map of the Ganzi–Songpan block and Longmen Mountain and distribution of samples (revised after Digital Geological Map of CGS at a scale of 1:500 000). 1. Quaternary fluvial sediment; 2. Cretaceous mudstone, sandstone; 3. Jurassic sandstone, mudstone; 4. Triassic sandstone, slate; 5. Paleozoic clastic rocks, mudstone; 6. Carboniferous dolomite, limestone; 7. Precambrian meta-intermediate-mafic volcanic rocks; 8. abyssal-sub-abyssal turbidite; 9. granitoids

Table 1 The (meta)-sedimentary rocks in the Longmen Mountain and Ganzi–Songpan block, Sichuan Province

Sample	Lithology	Strata	Location	Latitude/(°)	Longitude/(°)
GZ-03	Sandstone	Late Carboniferous	East to Leigu, Beichuan	31.779 6	104.443 1
GZ-04	Sandstone	Cambrian	North to Beichuan, Wanyuan-Aba Highway	31.840 5	104.457 1
GZ-07	Sandstone	Silurian	East to Shenkengzi, Wanyuan-Aba Highway	31.867 1	104.359 7
GZ-14	Sandstone	Devonian	North to Daqilianshanzhai, Chengdu–Naqu Highway	31.538 1	103.285 9
GZ-15	Sandstone	Upper Triassic Zhuwo Group	West to Xindianzi, Chengdu–Naqu Highway	31.524 4	103.245 0
GZ-16	Sandstone	Upper Triassic Zagunao Group	North to Putoudong, Chengdu-Naqu Highway	31.404 8	103.102 2
GZ-20	Graywacke	Upper Triassic Xinduqiao Group	East to Zhangdang, Chengdu–Naqu Highway	31.928 9	102.178 6
GZ-21	Sandstone	Upper Triassic Zhuwo Group	Mo'erxia, Chengdu–Naqu Highway	31.914 7	102.100 4
GZ-47	Sandstone	Upper Triassic Zhuwo Group	Southwest to Badandonggu Bridge	30.771 9	101.722 0
GZ-51	Sandstone	Carboniferous	North to boiler house, Yingxiu–Luhuo Highway	30.712 0	101.743 3
GZ-53	Silt	Devonian	North to boiler house, Yingxiu–Luhuo Highway	30.699 0	101.748 9
GZ-72	Sandstone	Upper Triassic Yajiang Group	Southwest to Kasha, Chengdu–Naqu Highway	31.642 6	100.264 8
GZ-76	Sandstone	Upper Triassic Lianghekou Group	South to Esa, Shiqu–Xiangcheng Highway	31.539 3	100.092 7
GZ-82	Sandstone	Upper Triassic Xinduqiao Group	East to Diru, Shanghai–Zhangmu Highway	30.057 8	101.734 5
GZ-83	Sandstone	Upper Triassic Zagunao Goup	Zheduoding Hill, Shanghai–Zhangmu Highway	30.074 3	101.804 2
SP-1	Silt	Triassic	Southwest to the factory, Nanping–Hongyuan Highway	33.311 7	104.155 2
SP-6	Sandstone	Triassic	Jiuzhaigou, Nanping–Hongyuan Highway	33.294 0	103.864 8
SP-13	Sandstone	Upper Triassic Zhagashan Group	Zhuchisi–Nuo'ergai Highway	32.882 8	103.457 0

separated by AG50W-X12 cation exchange resin column (200–400 mesh), while Sm and Nd were separated and purified by Teflon powder column with P507. The mass spectrum analyses of Sm and Nd isotopes ratios were done by double rhenium belts. The background in the whole process of Sm-Nd analyses was under 50 pg. We used MAT262 (Finnigan Co., Germany) solid-source mass-spectrometry. The uncertainties of Nd and Sm contents are less than 0.5%.

Nd isotopic fractionation is normalized to 0.721 9 of $^{146}Nd/^{144}Nd$ ratio. During the analyses, average $^{143}Nd/^{144}Nd$ ratio of JMC standard is 0.511 937 ± 10 (2σ); while the $^{143}Nd/^{144}Nd$ ratio of BCR-1 standard is 0.512 594 ± 10 (2σ).

3 Petrology and trace element geochemistry

We observed structures and constituents of the clastic sedimentary rocks under an optical microscope. The rocks are composed of quartz (18%–78%), plagioclase (0–30%), K-feldspar (0–8%) and some clays, such as illite (0–27%) and smectite (0–18%); and carbonate cements. The content of carbonate cement is up to 80% in GZ-51, while others are between 4% and 55%. Apatite, sphene, zircon are main accessory minerals. The petrochemistry and trace elements of the 13 representative samples are listed in Table 2.

Table 2 shows that SiO_2 contents of Triassic sandstones are between 48.64% and 87.31%. The other sandstones with SiO_2 contents of less than 65% contain CaO of over 10%. The samples of Devonian and Carboniferous are characterized by the lowest SiO_2 content (19.19%–34.67%) and the highest CaO content (27.56%–43.29%), and loss of ignition (LOI)

Table 2 The petrochemistry and contents of trace elements of clastic sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province

Element	GZ-03	GZ-04	GZ-14	GZ-15	GZ-21	GZ-47	GZ-51	GZ-53	GZ-72	GZ-83	SP-1	SP-6	SP-13
SiO_2	31.01	64.24	87.31	57.69	71.77	48.64	19.91	34.67	69.45	63.57	50.86	61.63	69.93
TiO_2	0.07	0.53	0.36	0.41	0.58	0.69	0.05	0.15	0.39	0.41	0.58	0.48	0.57
Al_2O_3	1.29	12.49	4.49	7.37	13.45	15.29	0.87	3.68	6.93	6.86	9.62	6.35	13.30
Fe_2O_3	0.00	1.32	1.07	1.46	1.39	0.45	0.00	0.47	1.07	0.16	1.00	0.78	1.22
FeO	2.94	2.67	2.19	1.60	2.52	6.04	0.62	0.44	1.48	2.10	2.70	1.66	2.52
MnO	1.10	0.07	0.04	0.08	0.05	0.09	0.11	0.18	0.10	0.06	0.09	0.05	0.04
MgO	1.73	2.43	1.14	3.08	1.72	3.65	1.05	0.84	1.82	2.23	2.53	2.44	1.60
CaO	32.25	4.46	0.06	13.22	1.22	10.18	43.29	27.56	7.42	11.18	14.36	11.45	1.63
Na_2O	0.00	3.54	0.22	1.12	2.18	1.09	0.00	0.00	1.52	1.09	0.87	1.03	2.69
K_2O	0.14	2.17	0.51	0.86	2.54	3.04	0.10	1.23	1.04	1.19	1.79	0.98	2.19
P_2O_5	4.47	0.18	0.04	0.11	0.15	0.15	0.02	1.41	0.11	0.11	0.14	0.12	0.13
LOI	24.01	5.10	1.67	12.63	1.78	8.92	34.51	28.72	7.97	10.34	14.78	12.37	3.43
Li	6.69	28.10	32.70	40.20	36.01	45.20	1.30	12.30	23.20	30.90	40.60	25.06	25.87
Be	1.48	1.10	0.38	1.21	1.68	3.20	0.21	1.17	0.93	1.11	1.40	0.93	1.82
Sc	8.19	9.44	5.93	6.93	9.63	10.70	1.87	5.26	6.39	6.57	10.10	6.67	9.93
V	16.80	83.20	33.80	52.10	60.00	116	5.20	317	30.10	44.40	71.10	53.16	43.33
Co	4.16	57.40	26.90	27.70	50.00	85.60	4.59	51.10	45.50	30.80	46.60	47.73	52.78
Ga	12.00	89.90	19.80	16.90	34.00	50.90	12.30	66.80	40.20	36.90	44.00	31.25	30.85
Rb	7.90	61.80	23.00	41.90	101	153	3.74	58.70	41.70	53.70	81.30	42.30	87.51
Sr	514	133	18.90	175	264	223	241	407	235	187	853	201	193
Y	108	23.0	14.70	19.20	14.20	23.40	20.20	22.10	25.00	18.50	20.40	20.66	19.84
Zr	32.5	152	354	155	203	136	10.80	46.50	216	235	157	372	207
Nb	1.47	9.51	7.37	9.51	12.30	16.20	0.84	3.46	9.37	8.76	14.70	9.78	10.90
Cs	0.38	2.78	1.26	1.81	5.54	8.87	0.09	0.64	1.88	8.61	4.61	3.45	4.54
La	36.70	17.60	22.30	22.30	27.00	40.00	11.70	17.80	31.30	29.20	33.20	37.31	33.22
Ce	74.50	39.50	47.00	43.10	52.60	76.80	14.40	23.00	60.20	56.10	66.20	72.49	67.31
Pr	8.77	5.20	5.61	5.17	6.29	8.82	2.37	3.58	6.99	6.50	7.75	8.37	7.57
Nd	38.10	20.40	21.80	19.50	22.10	30.70	9.45	14.00	24.60	22.80	27.20	29.48	26.66
Sm	11.00	4.15	4.58	4.06	4.25	6.02	1.99	2.74	4.94	4.48	5.62	5.91	5.07
Eu	3.37	1.13	0.84	0.82	0.93	1.20	0.49	0.61	0.93	0.88	1.03	0.98	1.13
Gd	14.80	4.36	3.81	3.87	3.41	5.21	2.44	2.89	4.64	3.98	5.08	5.34	4.59
Tb	2.38	0.66	0.56	0.61	0.47	0.77	0.41	0.42	0.72	0.58	0.78	0.79	0.65
Dy	14.50	3.80	2.99	3.56	2.67	4.48	2.77	2.67	4.26	3.34	4.52	4.55	3.71
Ho	3.07	0.79	0.57	0.75	0.54	0.90	0.61	0.61	0.86	0.67	0.96	0.92	0.74
Er	7.92	2.27	1.63	2.13	1.60	2.72	1.81	1.89	2.48	1.95	2.81	2.71	2.23
Tm	1.11	0.33	0.25	0.32	0.25	0.40	0.24	0.29	0.35	0.29	0.42	0.41	0.32
Yb	6.77	2.08	1.67	2.13	1.64	2.56	1.55	2.01	2.31	1.87	2.72	2.69	2.14
Lu	0.97	0.31	0.26	0.32	0.26	0.40	0.22	0.35	0.33	0.27	0.42	0.42	0.31
Hf	0.91	4.44	10.20	4.34	5.66	4.11	0.32	1.01	5.96	6.57	4.63	10.84	5.91
Ta	0.17	0.69	0.54	0.62	2.67	1.47	0.09	0.08	0.64	0.57	0.96	0.76	0.85
Tl	0.14	0.33	0.10	0.19	0.51	0.81	0.02	0.36	0.19	0.30	0.52	0.25	0.42
Pb	2 491	6.23	6.82	14.60	11.30	22.90	8.05	8.70	9.44	10.7	3.66	10.43	17.52
Bi	0.28	0.13	0.13	0.16	0.17	0.61	0.03	0.24	0.07	0.10	0.18	0.11	0.15
Th	6.08	5.71	6.86	7.84	8.52	14.40	1.19	4.23	8.72	8.81	13.60	13.56	9.37
U	16.10	1.90	2.07	1.86	1.80	3.43	0.32	5.68	1.76	2.16	3.19	3.47	2.11

Major elements in %, trace elements in 10^{-6}.

(24.01%–34.51%). On the diagram of SiO_2/Al_2O_3 vs. Na_2O/K_2O (Pettijohn et al., 1973) (Fig. 2), the sandstones belong to greywacke and arkose. As for the samples with CaO content over 10%, their chemical compositions are normalized to 100% by CaO content of 5% (average CaO content of general sandstones). All samples, including other unlisted ones, are plotted on SiO_2 vs. K_2O/Na_2O diagram (Roser and Korsch, 1986) (Fig. 3) with some unlisted. Figure 3 suggests that clastic sedimentary rocks of Precambrian (principal Sinian)–Cambrian–Ordovician–Silurian are dominantly projected in the range of active continental margin, and only a few are in the range of oceanic island arc, which is consistent with the Neoproterozoic island-arc setting and intensive Early Paleozoic tectonism in the western Yangtze craton suggested by Sun (1994), Xu et al. (1996), and Chen et al. (2005).

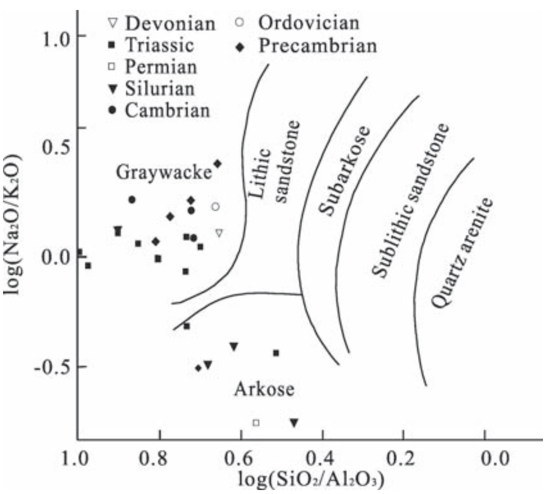

Fig. 2 Classification diagram of Na_2O/K_2O vs. SiO_2/Al_2O_3 for detrital sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province

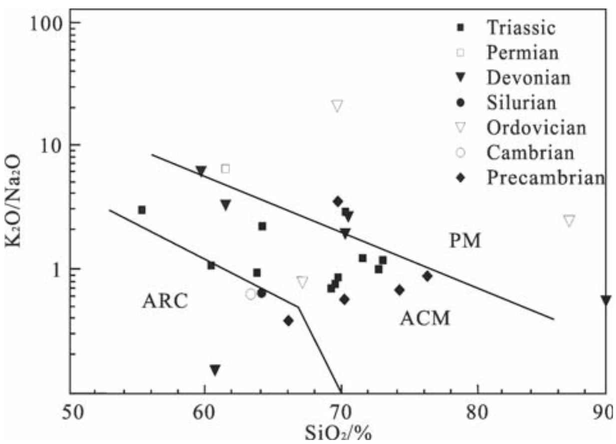

Fig. 3 Discrimination diagram of tectonic settings by plot of K_2O/Na_2O vs. SiO_2 for clastic sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province. ACM: active continental margin; ARC: area of ocean island arc; PM: passive continental margin

However, Devonian and Permian clastic sedimentary rocks are mainly plotted in the range of passive continental margin. Except for two samples in the passive continental margin, and oceanic island arc respectively, other samples are plotted in the area of active continental margin, which indicates that an amount of juvenile crustal component provided material to the sedimentary rocks.

The CHUR-normalized REE patterns (Boynton, 1984) are shown in Fig. 4. They demonstrate that from Precambrian to Triassic total contents of REE increase gradually, and the negative δEu anomalies become more obvious. The LREE/HREE ratios increase, which indicates more intensive fractionation of the provenance crusts throughout the geologic history from Precambrian to Triassic. The relation between Na_2O/K_2O ratios of the rocks and total contents of REE (ΣREE) is shown in Fig. 5. This diagram shows that all samples are in the triangular area that comprises high Na_2O/K_2O ratio and low ΣREE end-member (MF), low Na_2O/K_2O ratio and low ΣREE end-member (QC), and low Na_2O/K_2O ratio and high ΣREE end-member (FS). The mafic rocks derived from the mantle are characterized by low REE concentration and high Na_2O/K_2O ratio, thus MF end-member represents mafic rocks. As quartz and carbonate are characteristic of low Na_2O/K_2O ratio and low REE concentration, QC end-member should represent quartz and carbonate cements. The felsic rocks, represented by granites, are typical of high REE concentration and low Na_2O/K_2O ratio, thus FS should represent the felsic rock end-member. Most Triassic sandstones were characterized by a large amount of felsic components in them. The origin of Precambrian sandstone is more complicated. Most Precambrian clastic sedimentary rocks have high contents of mafic components. The clastic sedimentary sandstones of Late Paleozoic were mainly composed of quartz, felsic materials or carbonate, which may reflect a relatively stable passive continental margin setting in the western margin of the Yangtze craton.

4 Sm-Nd isotopic geochemistry

Table 3 shows the Sm-Nd analytical results of clastic sedimentary rocks from the Longmen Mountains and Ganzi–Songpan block. The samples, GZ-03, GZ-51, GZ-53, with the minimum contents of SiO_2 content and maximum CaO contents, have model ages of 1.70 Ga, 1.73 Ga, and 1.77 Ga, respectively. Nd model ages of two samples with $^{147}Sm/^{144}Nd$ ratios of >0.13 are calculated by a two-stage model (Li and McCulloch, 1996), which shows no obvious differences from those of Triassic clastic sedimentary rocks with SiO_2 contents up to 71.77%. Therefore, Nd model age has not been affected by higher contents of carbonate cements. The $\sum$REEs of samples GZ-51 and GZ-53 are only 50.45×10^{-6} and 72.86×10^{-6}, which are the lowest in all the clastic sedimentary rocks. Thus, it is better not to use samples with higher contents of carbonate cement to discuss the petrogenesis related to total contents of REE.

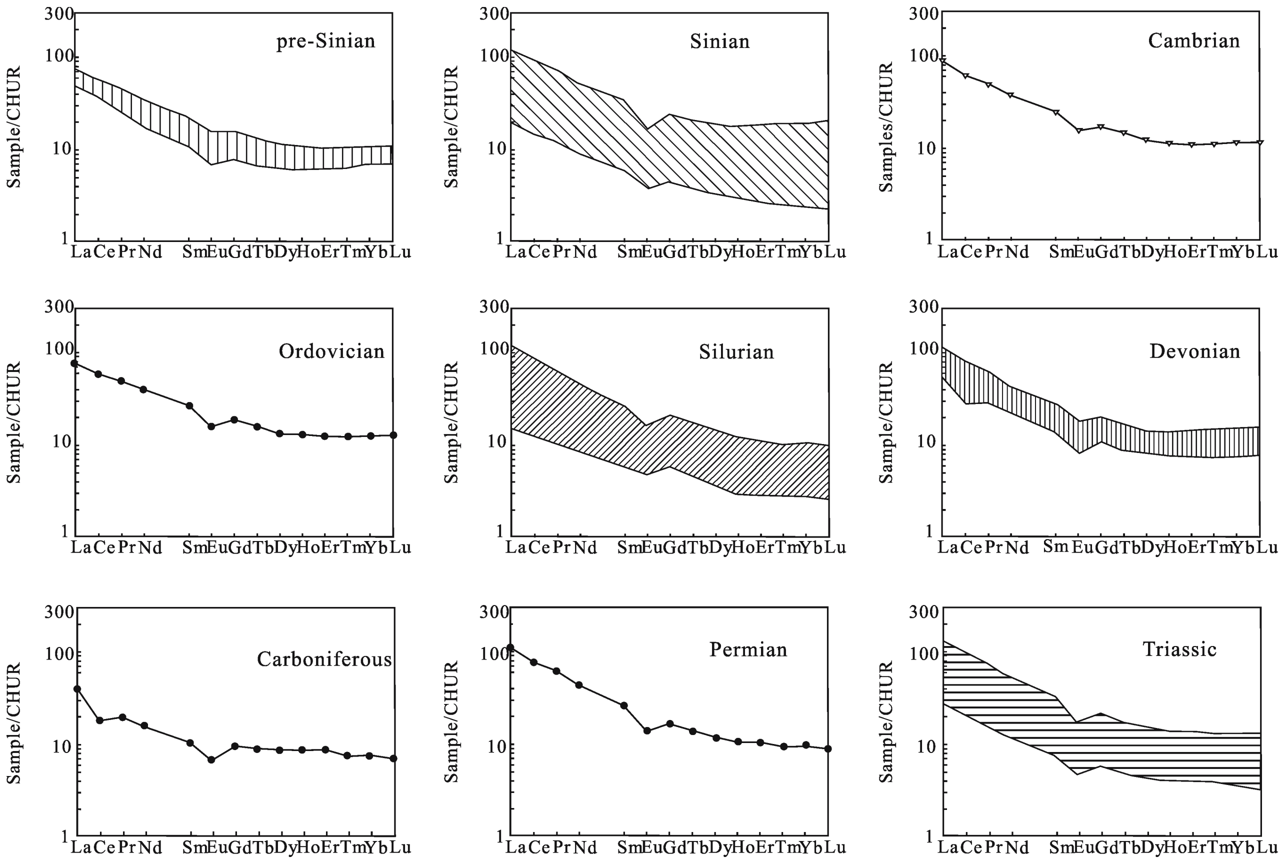

Fig. 4 Chondrite-normalized REE patterns of detrital sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province

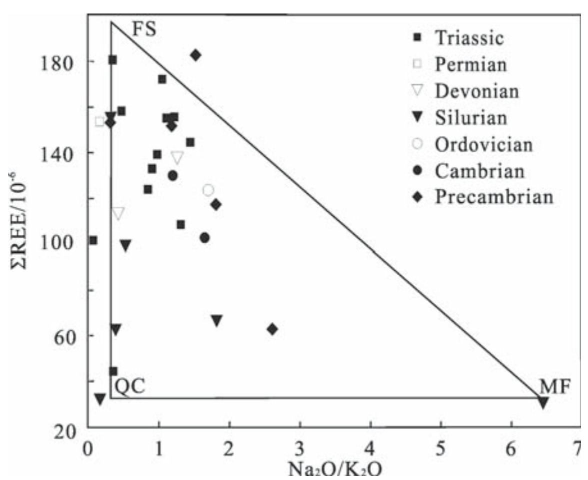

Fig. 5 Plot of the total REE content vs. Na_2O/K_2O for clastic sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province

Figure 6 shows the histogram of Nd depleted mantle model ages. Table 3 and Fig. 6 demonstrate that the population of Nd model ages is between 1.6 Ga and 2.4 Ga, peaking at 2.0 Ga, which is consistent with that of clastic sedimentary rocks from the Yangtze craton, South Qinling and North Qinling (Zhang et al., 2002) and the meta-sedimentary rocks of Silurian, Devonian, Triassic in the Danba region (Shen et al., 1998) in contrast to the population of Paleoproterozoic and Archean Nd model ages of those from the North China craton (Zhang et al., 2002). Therefore, provenance materials of the Songpan–Ganzi block and the Longmen Mountains are supposed to principally originate from the western margin of the Yangtze craton other than the North China craton proposed by Bruguier et al. (1997) only based on comparison of zircon U-Pb dating.

5 Discussion and conclusion

According to the data in Table 3, we calculated the $\varepsilon_{Nd}(t)$ values and plotted them on the relation diagram of $\varepsilon_{Nd}(t)$ value vs. stratum age (Fig. 7). Figure 7 indicates that the samples of Sinian and Cambrian have the highest $\varepsilon_{Nd}(t)$ values. Samples of Silurian and Devonian have larger variation range of $\varepsilon_{Nd}(t)$ values. The Carboniferous samples vary at the narrowest range of $\varepsilon_{Nd}(t)$ values. The $\varepsilon_{Nd}(t)$ values of the Triassic samples scatter widely, some of which are even greater than those of Paleozoic and the youngest Nd model ages are even lower than those of Sinian–Cambrian. The Triassic variation implies that some juvenile mantle materials may have been involved in provenance in this stage. Other samples have a

Table 3 Sm-Nd isotopic compositions of clastic sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province

Sample	Time/Ma[a)]	$Sm/10^{-6}$	$Nd/10^{-6}$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd\pm2\sigma$[b)]	t_{DM}/Ga[c)]	t_{2DM}/Ga[d)]
GZ-03	Carboniferous/318	10.92	37.06	0.178 4	0.512 132, 12		1.70
GZ-04	Cambrian/510	4.44	20.77	0.129 5	0.512 170, 10	1.77	
GZ-07	Silurian/426	4.51	15.90	0.171 5	0.511 947, 8		2.01
GZ-9	Silurian /426	2.44	8.55	0.172 7	0.511 942, 10		2.03
GZ-12	Silurian /426	4.09	18.51	0.133 6	0.511 973, 13		1.82
GZ-14	Devonian/398	4.92	22.12	0.134 6	0.511 873, 11		1.96
GZ-15	Late Triassic/210	4.01	18.94	0.128 0	0.511 880, 9	2.25	
GZ-16	Late Triassic /210	4.03	21.29	0.114 7	0.511 834, 11	2.02	
GZ-20	Late Triassic /210	6.30	45.62	0.119 1	0.512 124, 12	1.65	
GZ-21	Late Triassic /210	4.41	23.93	0.111 4	0.512 021, 12	1.68	
GZ-47	Triassic/237	6.13	32.48	0.114 2	0.511 876, 8	1.95	
GZ-51	Carboniferous/318	1.75	7.44	0.142 0	0.512 034, 11		1.73
GZ-53	Devonian/398	2.62	13.63	0.116 5	0.512 018, 11	1.77	
GZ-72	Late Triassic /210	5.05	25.85	0.118 2	0.511 838, 13	2.09	
GZ-76	Late Triassic /210	5.56	30.10	0.111 9	0.511 835, 8	1.96	
GZ-82	Late Triassic /210	7.18	37.20	0.116 8	0.511 957, 11	1.87	
GZ-83	Late Triassic /210	4.46	23.59	0.114 4	0.511 847, 13	1.99	
SP-1	Triassic/237	4.44	23.32	0.114 1	0.511 874, 10	1.95	
SP-13	Middle Triassic/237	4.98	26.38	0.114 3	0.512 083, 11	1.63	
SP-6	Triassic/237	5.30	28.62	0.112 0	0.511 809, 10	2.00	
LM-11	Triassic/237	3.57	18.77	0.115 1	0.512 009, 11	1.76	
LM-26	Sinian/600	5.21	26.39	0.119 5	0.512 100, 10	1.69	

a) The ages used are the strata ages, using geologic time scale in the 32nd Geological Conference (Gradstein et al., 2004); b) the data in $^{143}Nd/^{144}Nd$ ratio column after the comma were 2σ error, that is equal to 0.000 0 ××; c) the calculation of the depleted mantle model age from the reference Chen and Yang (2000); d) two-stage model age (i.e. the sample with $^{143}Sm/^{144}Nd > 0.13$) presumed the differentiation within the crust caused the high $^{147}Sm/^{144}Nd$ ratio (Li and McCulloch, 1996).

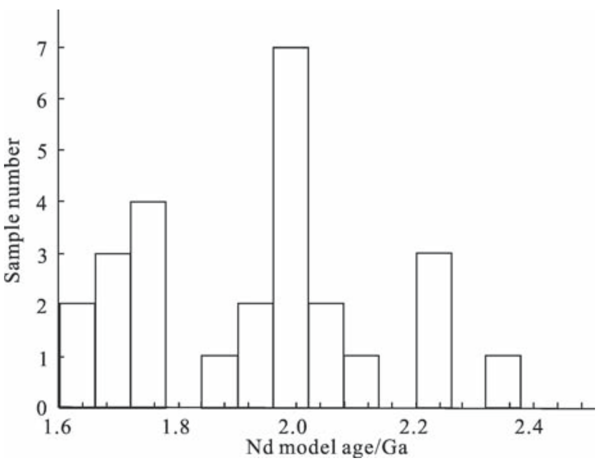

Fig. 6 Histogram of Nd model ages for clastic sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province

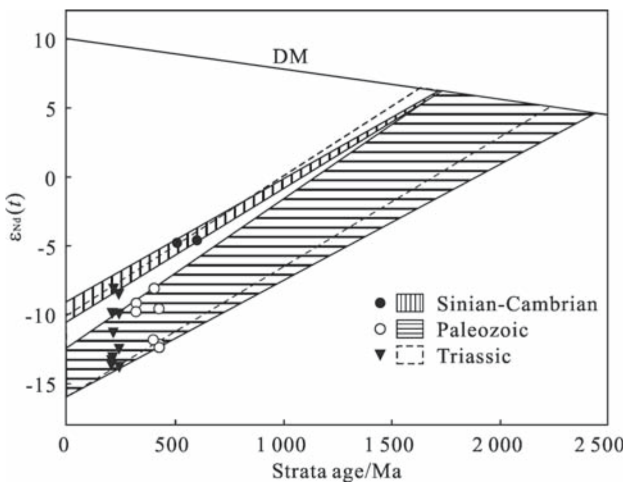

Fig. 7 Plot of $\varepsilon_{Nd}(t)$ value vs. stratum age for detrital sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province. DM: evolution line of depleted mantle; intersects with the evolution line of depleted mantle for clastic sedimentary rocks of different periods indicate their Nd depleted mantle model ages

generally equal value with those of Paleozoic, which suggests consistent provenances.

The main tectonostratigraphic strata include: (1) Archean high-grade metamorphic terranes represented by the Kongling complex (Ling et al., 1997; Gao et al., 2001); (2) Paleoproterozoic metamorphic complex represented by the Houhe Group (Li X H et al., 2002a); (3) Neoproterozoic plutonic and volcanic complexes, such as the Kangding complex and Suxiong volcanic rocks (Li X H et al., 2002b; Li Z X et al., 2003, Zhang and Wang, 2003; Chen et al., 2005); (4) Late Paleozoic Emeishan basaltic volcanic rocks (Chung and Jahn, 1995) in the western margin of the Yangtze craton. These representative tectonostratigraphic rocks and the clastic sedimentary rocks in each stage are plotted in $^{143}Nd/^{144}Nd$ vs. 1/Nd diagram (Fig. 8). This diagram indicates that all of the clastic sedimentary rocks from Longmen Mountains and the Ganzi–Songpan block can be represented by the mixing among the end-member with high $^{143}Nd/^{144}Nd$ ratio and high

Nd concentration of the intermediate to mafic rocks in the Kangding complex (the Triassic clastic sedimentary rocks may have originated from the Emeishan basalts), the old crustal end-member with low $^{143}Nd/^{144}Nd$ ratio and high Nd concentration of felsic rocks in the Kongling and Houhe groups, and the younger curstal felsic end-member with low Nd concentration and intermediate $^{143}Nd/^{144}Nd$ ratio. Some Paleozoic samples approach the felsic end-member, which may reflect long distance transportation of source materials to the basin, whereas the mafic materials have limited contribution to the clastic sedimentary rocks after long distance transportation because of the breakdown of mafic minerals.

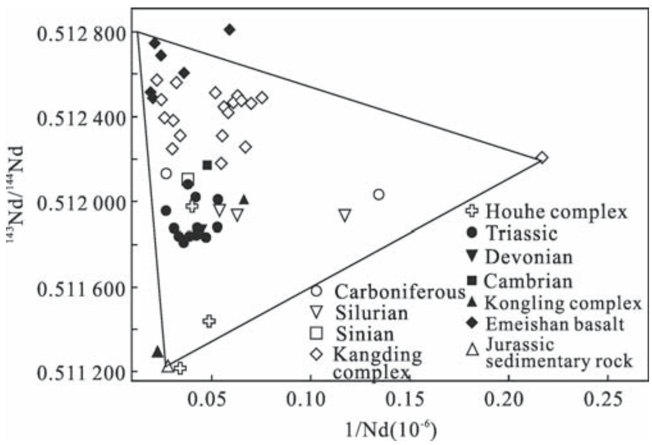

Fig. 8 Plot of Nd isotopic ratio vs. reciprocal Nd content for clastic sedimentary rocks in the Longmen Mountains and Ganzi–Songpan block, Sichuan Province and main tectonostratigraphic strata in the Yangtze craton

We draw a diagram of isolines of $\varepsilon_{Nd}(t)$ value of the Triassic clastic sedimentary rocks by Suffer 8 with Kriging interpolation (Fig. 9). The diagram indicates that the higher $\varepsilon_{Nd}(t)$ values of Triassic sedimentary rocks are concentrated in the northern and eastern parts, while the lowest $\varepsilon_{Nd}(t)$ values distribute in the southern and western areas, which may suggest the denudation centres in the northern and eastern parts. Weathered mafic rocks provided materials to nearby deposition. As it flew toward the west and south, the water became deeper. Therefore, mafic materials were decomposed completely after long distance transportation and sorting. Finally, the clay or quartz remained and deposited into the deep water. Tectonically, the Middle–Late Triassic was a key stage to the closure of the Mianlue paleo-oceanic basin between the Yangtze craton and Qinling micro-plate and the collision between the Yangtze and North China blocks.[1] A large amount of mafic magma erupted during the intensive tectonic movement and fed the depositional basin during Triassic period. Thus, not only the materials from the Yangtze craton, but also the mafic rocks formed during the collision and up-lifting.

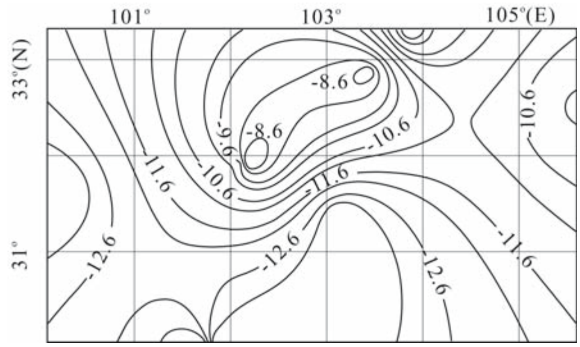

Fig. 9 The contours of $\varepsilon_{Nd}(t)$ values for Triassic clastic sedimentary rocks in the Ganzi–Songpan block, Sichuan Province

Through the study of petrology, trace element geochemistry and Sm-Nd isotopic geochemistry, we draw the conclusions as follows.

(1) The main types of the clastic sedimentary rocks in the Ganzi–Songpan block and Longmen Mountains from Precambrian to Triassic belong to greywacke and arkose. The SiO_2 vs. Na_2O/K_2O diagram indicates the principal active continental margin setting during most periods, which suggests main contribution of mafic protoliths to the clastic sedimentary rocks. Some Late Paleozoic samples are plotted in the area of passive continental margin, which indicates stable state of their provenance crust. With the closure of the Mianlue Ocean in the Triassic, juvenile mafic rocks derived from the mantle were exposed to the surface. The juvenile mafic rocks may have also provided materials to the Ganzi–Songpan depositional basin.

(2) The Nd depleted mantle model ages are similar to those of the Yangtze craton, South Qinling and North Qinling. They are between 1.6 Ga and 2.4 Ga, peaking at 2.0 Ga in contrast to Paleoproterozoic and Archean Nd depleted model ages of the North China craton. The Nd model ages suggest that the material mainly originated from the Yangtze craton and/or the Qinling orogen, and there is little contribution from the North China craton.

(3) In terms of provenances, the clastic sedimentary rocks in the Ganzi–Songpan block and Longmen Mountains are the mixture of mafic, felsic, and quartz + carbonate cements, which reflects the tectonostratigraphic strata of Neoproterozoic (Kangding complex and Suxiong volcanic rocks), Archean and Paleoproterozoic basement of the Yangtze craton (i.e. Kongling Group and Houhe Group), in addition to some Late Paleozoic juvenile mafic rocks in Triassic clastic sedimentary rocks.

(4) The spatial distribution of Nd isotope compositions for the Triassic clastic sedimentary rocks is characterized by higher $\varepsilon_{Nd}(t)$ values in the east and north, and lower $\varepsilon_{Nd}(t)$ values in the west and south, which may reflect the deep water environment in the south and west. After long distance transportation, the contents of mafic components in clastic sedimentary rocks decrease obviously. As the northern

[1] Zhang G W (2004). The Key Project of National Natural Science Foundation of China "the Formation and Evolution of South Qinling–Songpan Tectonic Knot". Middle stage report (in Chinese)

and eastern parts approach their provenance, the clastic sedimentary rocks contain higher mafic components and show obvious immaturity.

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References

Boynton W V (1984). Geochemistry of the rare earth elements: Meteorite studies. In: Henderson P, ed. Rare Earth Element Geochemistry. New York: Elsevier, 63–114

Bruguier O, Lancelot J R, Malavieille J (1997). U-Pb dating on single detrital zircon grains from the Triassic Songpan–Ganze flysch (Central China): Provenance and tectonic correlations. Earth Planet Sci Lett, 152(1–4): 217–231

Bureau of Geology and Mineral Resources of Qinghai Province (1991). Regional Geology of Qinghai Province. Beijing: Geological Publishing House, 1–662 (in Chinese with English abstract)

Bureau of Geology and Mineral Resources of Sichuan Province (1991). Regional Geology of Sichuan Province. Beijing: Geological Publishing House, 1–830 (in Chinese with English abstract)

Chen Y L, Luo Z H, Zhao J X, et al (2005). Petrogenesis and dating of the Kangding complexes, Sichuan Province. Sci in China (Series D), 48(5): 622–634

Chen Y L, Yang Z F (2000). Nd model ages of sedimentary profile from the northwest Yangtze craton, Guangyuan, Sichuan Province, China and their geological implication. Geochem Journal, 34(4): 263–270

Chung S L, Jahn B M (1955). Plume-lithosphere interaction in generation of the Emeishan flood basalts at the Permian–Triassic boundary. Geology, 23: 889–892

Gao S, Qiu Y M, Ling W L, et al (2001). SHRIMP single zircon U-Pb dating of the Kongling high-grade metamorphic terrain: Evidence for >3.2 Ga old continental crust in the Yangtze craton. Sci in China (Series D), 44(4): 326–335 (in Chinese)

Gradstein F M, Ogg J G, Smith A G (2004). A new geologic time scale with special reference to Precambrian and Neogene. Episodes, 27(2): 83–100

Li X H, Li Z X, Zhou H W, et al (2002a). U-Pb zircon geochronological, geochemical and Nd isotopic study of Neoproterozoic basaltic magmatism in western Sichuan: Petrogenesis and geodynamic implications. Earth Sci Frontiers, 9(4): 329–338 (in Chinese with English abstract)

Li X H, Zhou H W, Li Z X, et al (2002b). Petrogenesis of Neoproterozoic bimodal volcanics in western Sichuan and its tectonic implications: Geochemical and Sm-Nd isotopic constraints. Chinese Journal of Geol, 37(3): 264–276 (in Chinese with English abstract)

Li X H, McCulloch M T (1996). Nd isotopic evolution of sediments from the southern margin of the Yangtze block and its tectonic significance. Acta Petrologica Sinica, 12(3): 359–369 (in Chinese with English abstract)

Li Z X, Li X H, Kinny P D, et al (2003). Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze craton, South China and correlation with other continents: Evidence for a mantle super-plume that broke up Rodinina. Precambrian Res, 122: 85–109

Ling W L, Gao S, Zhang B R, et al (1997). Early Precambrian continental crust evolution at the northern margin of Yangtze craton: Constrain from the elemental and isotopic geochemical study of Houhe complex. Journal of Mineralogy and Petrology, 17(4): 26–32 (in Chinese with English abstract)

Ling W L, Gao S, Zhang B R, et al (2000). Late Paleoproterozoic tectonic-thermal events of the Yangtze continental nucleus and the Yangtze craton's evolution. Chinese Sci Bull, 45(21): 2343–2348 (in Chinese)

Liu S (1998). On properties of tectonic movement in east margin of middle and northern Longmen Mountains at the end of Triassic period. Journal of Chengdu University of Technology, 25(4): 524–528 (in Chinese with English abstract)

Liu S G, Zhao X K, Luo Z L, et al (2001). Study on the tectonic events in the system of the Longmen Mountain–West Sichuan foreland basin, China. Journal of Chengdu University of Technology, 28(3): 221–230 (in Chinese with English abstract)

Pettijohn F J, Potter P E, Siever R (1973). Sand and sandstone. New York: Springer-Verlag, 1–618

Roser B P, Korsch R J (1986). Determination of tectonic setting of sandstone mudstone suites using SiO_2 content and K_2O/Na_2O ratio. J Geol, 94: 635–650

Shen W Z, Lu H P, Xu S J, et al (1998). Sm-Nd isotopic study on metasediments in the area of Danba, China. Scientia Geologica Sinica, 33(3): 367–373 (in Chinese with English abstract)

Sun C M (1994). Proterozoic ophiolites in West Sichuan and orogenic belt along the western margin of the Yangtze craton. Journal of Chengdu University of Technology, 21(3): 11–16 (in Chinese with English abstract)

Wang Z X, Xu Z Q, Yang T N (1997). A model for deformation structure evolution of Songpan–Garze orogene. Scientia Geologica Sinica, 32: 327–336 (in Chinese with English abstract)

Xu S J, Wang R C, Shen W Z, et al (1996). U-Pb, Rb-Sr isotopic chronology of Jinning granites in Songpan–Ganze orogenic belt and its tectonic significances. Sci in China (Series D), 39(6): 576–586

Xu Z Q, Hou L W, Wang, Z X, et al (1992). Building process of the Ganze–Songpan orogenic belt. Beijing: Geological Publishing House, 1–190 (in Chinese with English abstract)

Yang Z R (2002). The formation and evolution of the Songpan–Garze fore-arc basin, western Sichuan. Sedimentary Geology and Tethyan Geology, 22(3): 53–59

Zhang B R, Gao S, Zhang H F, et al (2002). Geochemistry of the Qinling Orogenic Belt. Beijing: Science Press, 1–187 (in Chinese)

Zhang Z C, Wang F S (2003). Sr, Nd and Pb isotopic characteristics of Emeishan basalt province and discussion on their source region. Earth Sci—Journal of China Univ of Geosci, 28(4): 431–439 (in Chinese with English abstract)

Zou G F (1995). Advance of the research on the Garze–Litang plate junction. Acta Geologica Sichuan, 15(4): 257–263 (in Chinese with English abstract)