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A reconnaissance study of potentially important scandium deposits associated with carbonatite and alkaline igneous complexes of the Permian Emeishan Large Igneous Province, SW China

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ABSTRACT

Economically viable Sc deposits in the world are scarce and new and alternative resources are now urgently needed to ensure future sustainable supplies. We report here an essentially unknown, yet potentially important, type of Sc deposit that is associated with carbonatite and alkaline igneous complexes of the Permian Emeishan Large Igneous Province (ELIP), SW China. The ELIP is well known for its variably mineralized intrusions and flood basalts. Associated alkaline igneous complexes are minor in volume but important as possible sources of Sc and other REEs. Several such complexes occur in the N-S-trending Kangdian belt, where they are typically composed of pyroxenite, gabbro, and nepheline syenite. Some complexes also contain jacupirangite, melteigite, ijolite, and urtite. We show that some of these complexes contain carbonatites. The alkaline mafic-ultramafic rocks typically belong to either sodic or potassic magmatic series with high alkali compositions (up to 15.4 wt % $Na_2O + K_2O$). Pyroxenites in these complexes are composed of clinopyroxene with variable amounts of apatite and magnetite and have 39 to 71 ppm Sc. The Sc concentrations of these rocks may be high enough to justify mining under the current prices of Sc, which is nearly 5 times that of gold. Our preliminary study indicates a minimum of ~12,000 to ~36,000 tonnes of Sc metal in three representative complexes. This type of mineralization may ultimately contribute to a reliable and sustainable Sc supply chain in the future. In addition to Sc in the pyroxenites, carbonatites in these complexes will also be potentially important targets for REE exploration.

1. Introduction

Scandium (Sc) is one of the rare earth elements (REEs) and, like others, is in high demand because of its broad application to modern advanced technologies. For example, it can be used as a doping agent to strengthen and lighten Al alloys used in the automobile and aerospace industries, as a material used in solid oxide fuel cells, and lasers for military and medical purposes (Voncken, 2016). However, Sc is highly dispersed in nature and is rarely sufficiently concentrated to form Sc-dominated deposits.

The gap between demand and supply of Sc is recognized and is predicted to increase over the next decade. Currently, tailings of the Bayan Obo REE mine, China, is the main source of Sc in the world (Williams-Jones and Vasyukova, 2018). Other sources are unreliable and unstable due to the difficulties of extracting Sc from such materials as wolframite, pegmatites, mine tailings, red mud, and coal waste (Ercit et al., 2005; Dushyantha et al., 2020). Therefore, the existing Sc supply chains are clearly insufficient to meet future demands and new, alternative sources will be required. Exploration for unconventional Sc resources is essential to maintain a stable Sc supply chain (Verplanck and Hitzman, 2016).

Scandium has a much smaller radius (0.87 Å) than other REEs (1.16–0.97 Å) (Shannon, 1976) and is not typically associated with REE deposits (Williams-Jones and Vasyukova, 2018; Wang et al., 2021). Notably, Sc has a close affinity with Fe, Mg, and high field strength elements (HFSE) such as Nb, Ta, Ti, W, and Sn (e.g., Dill et al., 2006;

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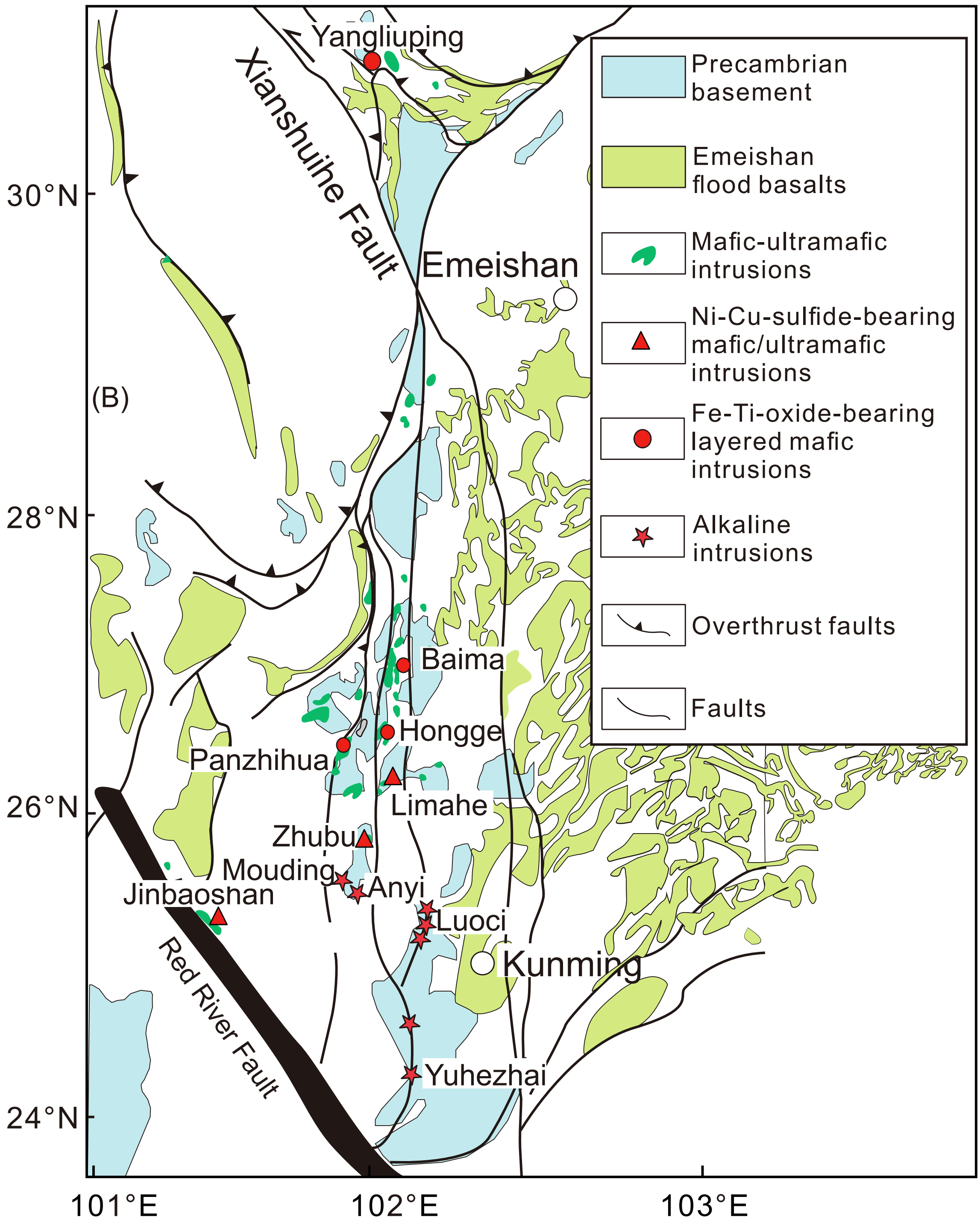

Fig. 1. Simplified geological map showing the distribution of the continental flood basalts, mafic-ultramafic intrusions and associated ore deposits of the ELIP, SW China.

Kempe and Wolf, 2006). Mafic minerals, particularly clinopyroxene and amphibole, and some HFSE minerals such as baddeleyite, zirconolite, columbite, ilmenite, wolframite, and cassiterite, can have high abundances of Sc, which make them tempting exploration targets. Among these minerals, clinopyroxene is the most common and abundant mineral in igneous bodies, thus, pyroxenites can form magmatic Sc deposits, particularly those associated with Alaskan-type mafic-ultramafic intrusions. Here we report that pyroxenites in some alkaline igneous complexes also have high concentration of Sc, which may be due to the much higher partition coefficient of Sc between clinopyroxene and alkaline mafic magmas compared to tholeiitic magmas (Wang, 2022). Scandium-rich pyroxenites are not only exploitable as magmatic sources (Zhu, 2010; Xie et al., 2018), but are also fundamental in the formation of world-class, laterite-hosted Sc deposits (Chassé et al., 2017, 2019).

The well-known Permian Emeishan Large Igneous Province (ELIP) comprises the Emeishan flood basalts and associated mafic-ultramafic intrusions (Fig. 1) (Chung and Jahn, 1995; Zhou et al., 2002b). A number of alkaline igneous intrusions in the N-S- trending Kangdian belt within the ELIP were previously noted (Shi et al., 1985; Huang et al., 1993, 1995a,b; Huang, 1997a,b; Zhao et al., 2010, 2012), but their relationship with the ELIP was not well documented, particularly their origins and natures were not well understood. Based on these previous

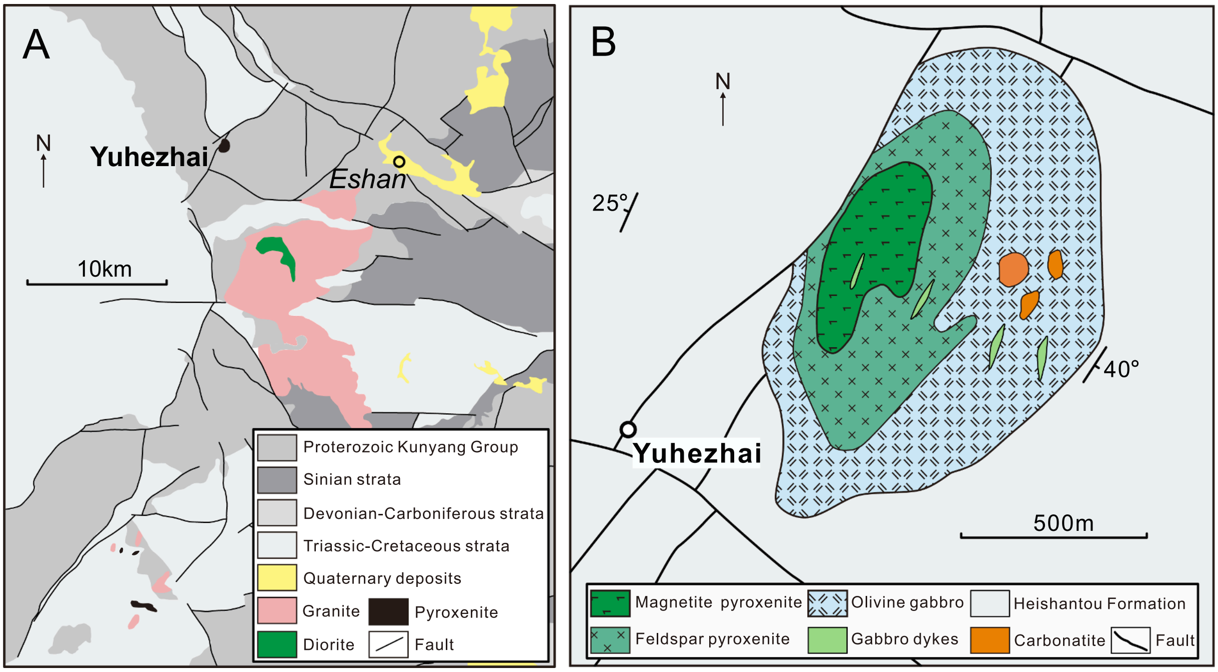

Fig. 2. (A) Geological map of the Eshan region and (B) geological map of the Yuhezhai complex (after Cao et al., 1993).

studies and new analyses, we confirm that they were emplaced at around 260 Ma, and thus, were coeval with other components of the ELIP. These intrusions contain some typical alkaline rocks such as melteigite, ijolite, and urtite. Carbonatites are identified in some of these intrusions. The best-known Mouding complex, is a typical alkaline intrusion containing abundant K-feldspar and biotite in clinopyroxenite, syenogabbro, and monzogabbro, and is currently defined as a Sc-dominated deposit (Zhu, 2010; Wang et al., 2021, 2022).

In this paper, we examine the alkaline complexes in the ELIP and document, for the first time, significant Sc-enrichment of pyroxenites in them. Using new major and trace element data for the different types of rocks in three representative complexes, we assess the possibility of pyroxenites as Sc-dominated ores and conclude that they are potentially important deposits with low-grade ores of large tonnages. Such sources would reduce the dependence of Sc supplies from the limited known deposits and ensure a potentially sustainable and reliable supply.

2. Geological background

In SW China, the Yangtze Block is bounded by the Tibetan Plateau to the west and the Cathaysian Block to the east (Fig. 1). The Yangtze Block has an Archean to Mesoproterozoic basement overlain by a Devonian-Triassic marine sedimentary succession, and a Jurassic to Cenozoic cover sequence that is composed mostly of terrestrial basin deposits. Neoproterozoic mafic-ultramafic intrusions and granitic plutons form the Hannan-Panxi arc along the western and northern margins of the Yangtze Block (Fig. 1, Zhou et al., 2002a).

The late Permian (ca. 260 Ma) Emeishan flood basalts cover an area of $\sim 5 \times 10^5$ km^2 from the Tibetan Plateau in the northwest to north-western Vietnam in the southeast (Chung and Jahn, 1995). They are part of the ELIP and are associated with mafic-ultramafic intrusions. The Emeishan volcanic succession ranges in thickness from several hundred meters in the east to ~5 km in the west (Xu et al., 2004). This large variation is probably due to post-eruption tectonic activity leading to strong uplift and erosion in the Mesozoic and Cenozoic (Ali et al., 2005; P.-P. Liu et al., 2020; J.P. Liu et al., 2020). The volcanic sequence is composed of picrites, basalts, basaltic andesites, and rhyolites (Chung and Jahn, 1995, Xu et al., 2004; Hei et al., 2017), locally accompanied by small quantities of alkaline volcanic rocks, including phonolite and trachyte (Mei et al., 2003). Plutonic rocks of the ELIP have a much smaller volume than the volcanic sequence and are mostly exposed along major faults, particularly in the N-S-trending Kangdian belt. Both magmatic Cu–Ni–sulfide deposits and Fe–Ti–(V) oxide deposits are well known in some major intrusions (Fig. 1).

Sulfide-bearing, mafic-ultramafic intrusions are mostly sill-like bodies hosted in Carboniferous and Devonian sedimentary rocks such as those in the Yangliuping region to the north (Song et al., 2003) and in the Vietnam-China border regions to the south (Wang et al., 2007). These intrusions are considered to be related to low-Ti basalts. Fe–Ti–(V) oxide-bearing, gabbroic layered intrusions, including the well-known giant deposits such as Baima, Hongge, and Panzhihua, are mainly distributed in the Panxi belt where they are related to major N-S-trending faults (Fig. 1) and are spatially and temporally associated with syenitic and granitic intrusions (Zhou et al., 2005; Zhong et al., 2011). The mafic and felsic portions are considered to have formed from separate immiscible mafic and felsic magmas (Zhou et al., 2005, 2008, 2013). Exploration has identified more than 10 billion tonnes of Fe–Ti–V ore in these intrusions, with average ore grades of 25–55 wt% Fe and 4–13 wt% Ti (Ma et al., 2003). In addition, considerable amounts of V and Sc are also present, but these are not fully utilized in the current mining. Ages for Ni-Cu-sulfide and oxide-bearing intrusions are mostly clustered at around 260 Ma (Zhou et al., 2002b; Shellnutt et al., 2008, 2012). It is now accepted that both the volcanic and intrusive rocks were formed by plume-derived magmas within a short period of 1–2 Myr at ca. 260 Ma.

There are also alkaline igneous complexes in the Kangdian belt, including those in the Eshan, Luoci, and Anyi regions from the south to the north (Figs. 2–4). These complexes were originally thought to be Alaskan-type intrusions due to their zonal patterns of lithologies (Cao et al., 1993; Zhu, 2010; Guo et al., 2012). However, we show here that these have quite different geochemistry and contain magnetite with compositions different from those of typical gabbroic layered intrusions in the Panxi belt (Liu et al., 2015; Wang, 2022). Among these complexes, the Anyi intrusion was previously studied by Zhou et al. (2013), Yu et al. (2014) and Liu et al. (2015), but its nature has not been fully confirmed. The intrusion contains zircon grains with SHRIMP U–Pb ages of 247 ± 3 Ma (Yu et al., 2014), and we recently obtained a U-Pb age of 260 Ma for sphene, similar to the sphene U-Pb age for the Mouding intrusion (Wang,

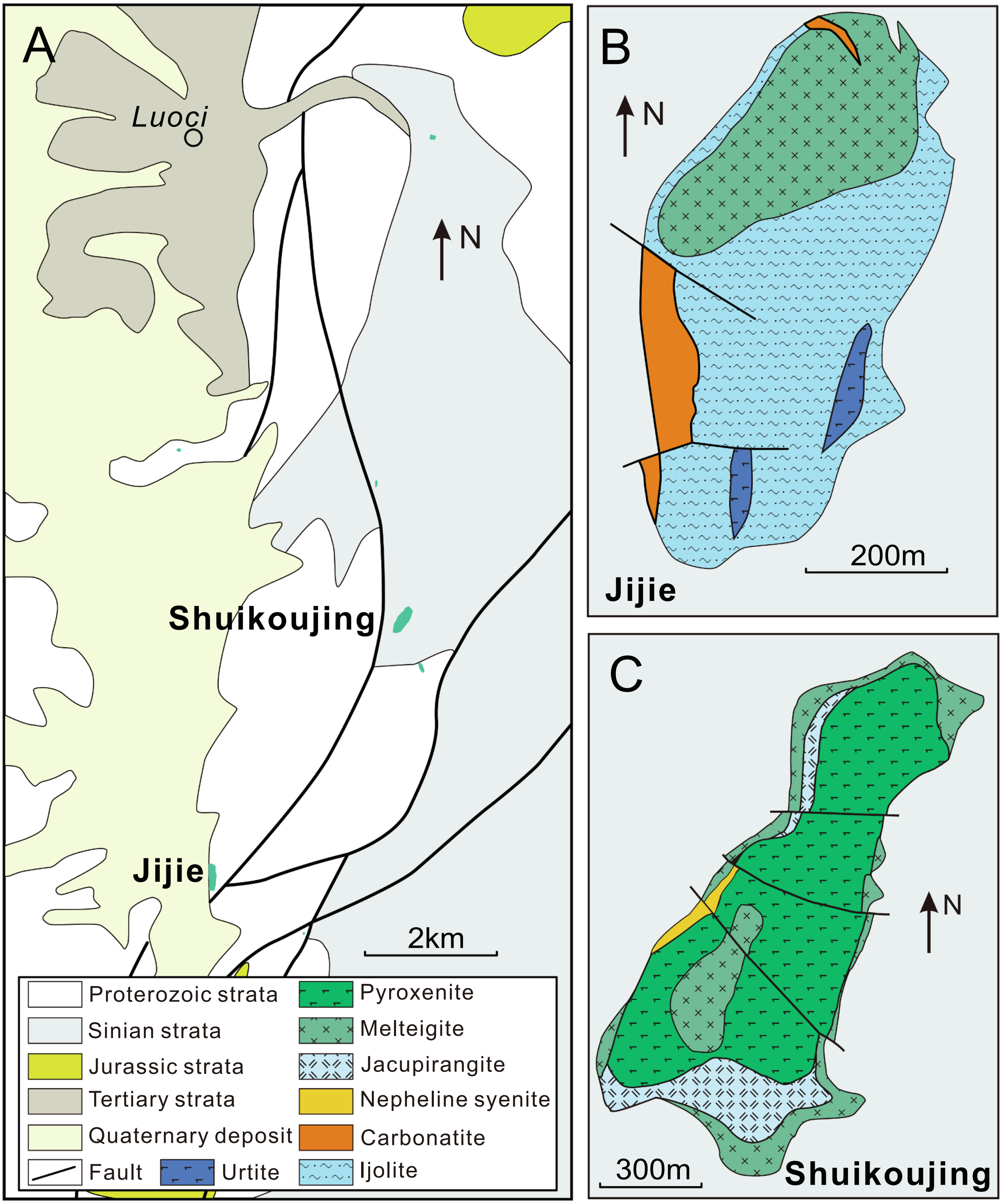

Fig. 3. (A). Geological map of the Luoci region; (B) geological map of the Shuikoujing complex and (C) geological map of the Jijie complex (after Huang et al., 1995a, b; Zhao, 2010).

2022).

3. Carbonatite-alkaline igneous complexes

3.1. Eshan region

Several small intrusions are hosted in Neoproterozoic and Paleozoic sedimentary rocks in the Eshan region of Yunnan Province (Fig. 2A) (Bureau of Geology and Mineral Resources of Yunnan Province, 1990). The northernmost of these is the Yuhezhai complex that intrudes the 1.0-Ga-old Kunyang Group. Some smaller ones farther south intrude an early Paleozoic sequence of shale and sandstone. All these complexes are composed of similar igneous rocks, including magnetite-bearing pyroxenite in the core surrounded by plagioclase pyroxenite and gabbro (Fig. 2B and Fig. 5A). The Yuhezhai complex is also intruded by three bodies of carbonatite, previously identified as marble and skarn (Cao et al., 1993). These rocks show intrusive contacts with the hosting olivine gabbro (Fig. 5B and C).

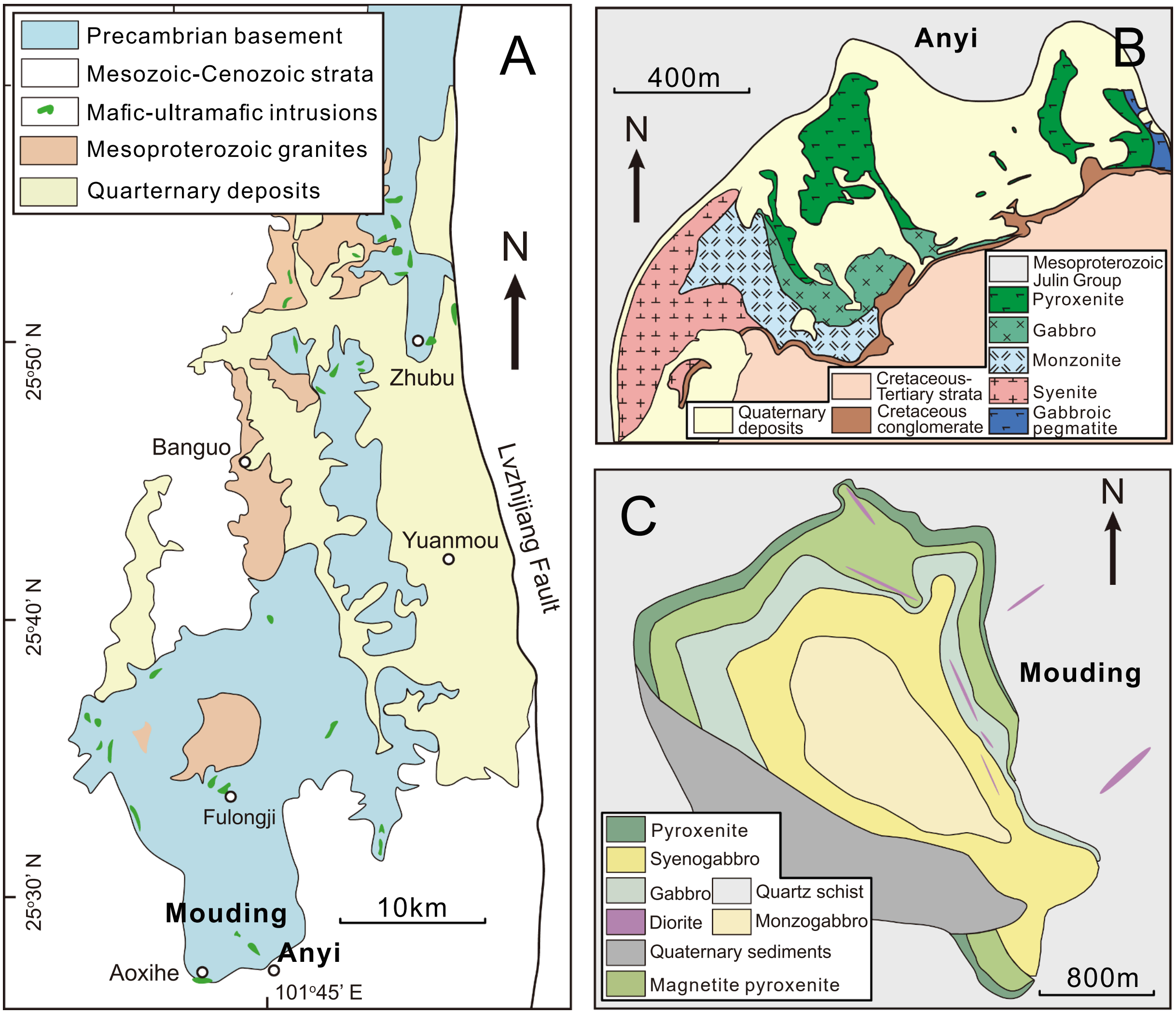

Fig. 4. (A) Geological map of the Anyi region (Zhou et al., 2013); (B) geological map of the Anyi intrusion (Zhou et al., 2013); and (C) geological map of the Mouding intrusion (Wang et al., 2022).

The Yuhezhai complex has an elliptical surface expression about 1400 m long and 800 m wide, with an exposed area of about 1 km^2 (Fig. 2B). The outer rim, which comprises about half of the total area, is composed of olivine gabbro and gabbro, whereas the intermediate and inner parts consist of plagioclase pyroxenite and magnetite pyroxenite, respectively. The plagioclase pyroxenites intrude the gabbros and are intruded by the magnetite pyroxenites which contain minor xenoliths of plagioclase pyroxenite. The core of the intrusion is about 550 m long and up to 250 m wide and consists of clinopyroxene (60–70%), magnetite (20–30%), apatite (5–10%), and olivine (~5%). Apatite crystals are euhedral to subhedral, and range up to 500 μm in length. Large clinopyroxene grains (up to 5 mm long) are subhedral to euhedral and exhibit obvious zoning patterns (Fig. 6A and B). Secondary amphibole is commonly present along the rims of clinopyroxene grains. Three small bodies of carbonatite are composed of calcite and minor amounts of garnet and diopside with granular textures (Fig. 5C). These assemblages are similar to those of skarns but some of these were possibly formed from carbonatitic magmas intruding olivine gabbro.

3.2. Luoci region

Four major intrusions crop out in the Luoci region, which are, from south to north, the Jijie, Zhushimiao, Shuikoujing, Maojie, and Luoci complexes (Fig. 3A). They are mainly composed of pyroxenite, jacupirangite, melteigite, ijolite, urtite, and nepheline syenite. Apart from common mafic minerals such as olivine, diopside, and amphibole, these intrusions also contain a high abundance of alkaline minerals such as aegirine, alkali feldspar and nepheline.

The Jijie complex is elliptical on the surface being about 800 m long and 400 m wide with an exposed area of about 0.29 km^2. This pluton intrudes the 1.0-Ga Kunyang Group and comprises three zones which are, from the rim to the core, ijolite, fine-grained melteigite, and coarse-grained porphyritic melteigite (Fig. 3B). The ijolite has an intrusive contact with fine-grained melteigite. The inner and medium zones occupy ~20% of the total exposed area, and they contain some lherzolite xenoliths (Huang et al., 1993). The melteigite units are mainly composed of euhedral and subhedral aegirine (60–75%) which mostly forms green, columnar crystals, and subhedral nepheline (15–30%) with minor apatite, olivine, magnetite, and biotite (~10% in total) (Fig. 6C and D). Zoning is ubiquitous in the aegirine grains with higher MgO in the cores and FeO in the rims. The complex is also intruded by urtite and nepheline syenite dykes. Carbonate rocks were reported in the map, but their origin was unknown. In our field investigation, we tentatively interpret these as carbonatites, particularly the carbonatite dyke in the northwestern part of the complex (Fig. 3B).

The Shuikoujing complex has a typically elliptical surface expression, being about 1470 m long and up to 830 m wide, resulting in an exposed area of about 0.69 km^2. The intrusion is funnel-shaped in three

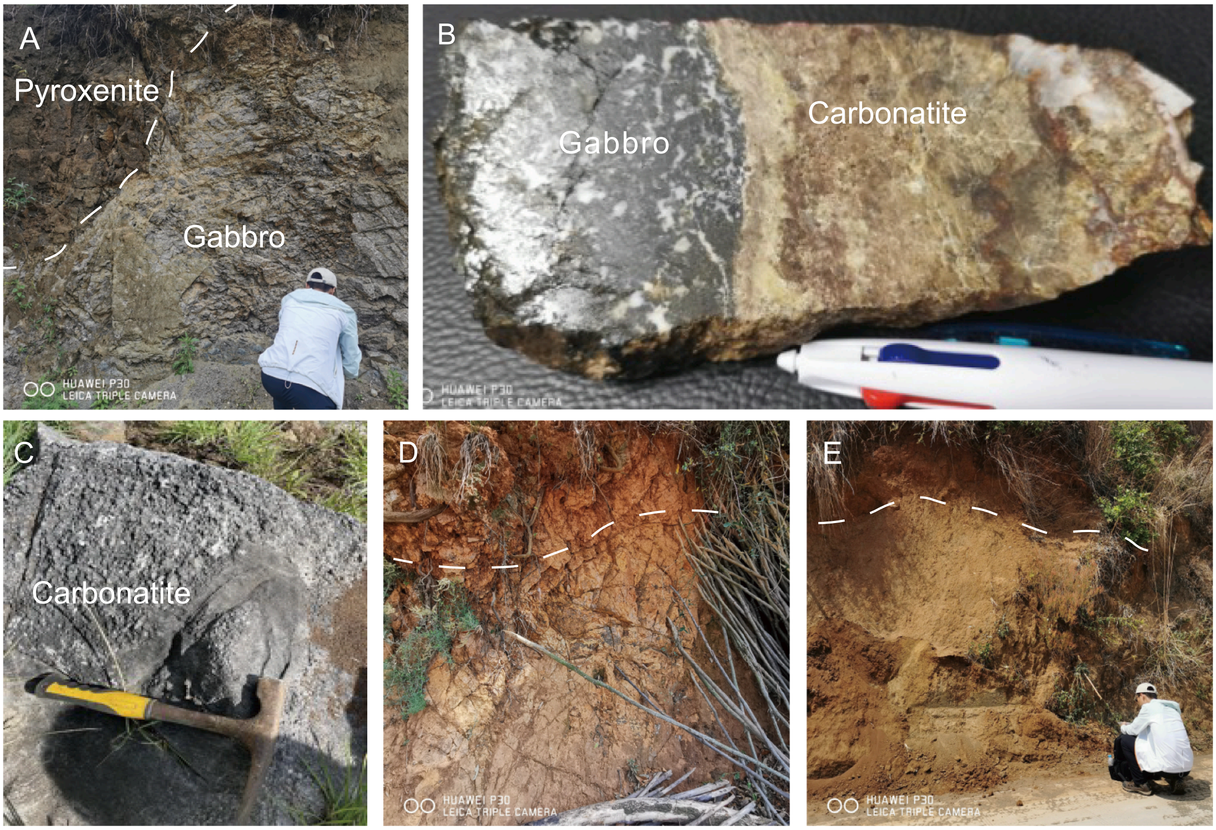

Fig. 5. Field photos of the alkaline complexes: (A) boundary between gabbro and pyroxenite in Yuhezhai; (B) boundary between carbonatite and gabbro in Yuhezhai; (C) Carbonatite in Yuhezhai; (D) weathered crust in Shuikoujing and (E) weathered crust in Jijie,

dimensions as revealed by drilling. It also intrudes the Kunyang Group and is composed of three zones, from the rim to the core: melteigite, jacupirangite, and pyroxenite (Fig. 3C). The pyroxenite has an exposed area of ~0.35 km^2 and is a coarse-grained rock with euhedral clinopyroxene crystals that make up 70–90 modal% (Fig. 6E and F), accompanied by accessory olivine, magnetite, and biotite. The Jijie and Shuikoujing alkaline complexes have variably weathered profiles (Fig. 5D and E).

3.3. Anyi region

In the Anyi region, two major intrusions are notable, the Anyi and Mouding complexes (Fig. 4). The Anyi complex is ~1.2 km long and 300 to 620 m wide and has an exposed area of ~0.65 km^2. It intrudes schist and marble of the Julin Group to the north and is unconformably overlain by Cretaceous conglomerate and mudstone to the south (Fig. 4B) (Zhou et al., 2013; Yu et al., 2014). This complex is composed of monzonite, syenite, monzogabbro, Fe–Ti oxide-bearing pyroxenite, pyroxenite and olivine pyroxenite. The pyroxenite is composed of euhedral and subhedral clinopyroxene (50–70%), disseminated Fe–Ti oxides (10–25%), K-feldspar (5–10%), biotite (~5%), and minor olivine.

The Mouding complex in the same region is lithologically similar to the Anyi complex. It is oval-shaped at the surface, being ~360 m long and 100–300 m wide with an exposed area of about 0.15 km^2 (Fig. 4C). The intrusion is composed of an inner core of monzogabbro, syenogabbro, and gabbro, and a rim of magnetite-bearing pyroxenite and pyroxenite (Wang et al., 2022). Both types of pyroxenite consist of euhedral to subhedral clinopyroxene (60–75%), K-feldspar (<10%), magnetite (<25%), and biotite (3–5%).

4. Major and trace element compositions

4.1. Sample collection and analytical methods

Three representative complexes, the Yuhezhai, Jijie, and Shuikoujing (Figs. 2 and 3) were selected for this study. Both the alkaline intrusions and their weathered products were systematically sampled at 20 m intervals along several profiles across each complex, in order to investigate compositional variations and to identify Sc-rich units. In total we collected more than 200 soil and rock samples, all of which were analyzed and compared with literature data.

All the samples were pulverized using a laboratory TEMA mill and powdered using a tungsten mortar. Major and trace element concentrations were measured using X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS), respectively, at both the Australian Laboratory Service (ALS) P/L and the State Key Laboratory of Ore Deposit Geochemistry, IGCAS (Qi et al., 2000). Analytical precisions for both ALS and IGCAS are <1 % for major oxides and <5 % for trace elements.

4.2. Major element oxides and REEs

Major elemental oxides of alkaline rocks from three representative complexes are summarized in Table 1. Overall, these three complexes have low SiO_2 and high Na_2O + K_2O, implying an alkaline affinity (Table 1 and Fig. 7).

Specifically, in the Shuikoujing complex, the average SiO_2 contents of the pyroxenite (42 wt%) are comparable to those of jacupirangite (44 wt%) and melteigite (43 wt%) and lower than nepheline syenite (54 wt %), whereas their Na_2O + K_2O contents are 2.1, 4.1, 5.4 and 12.9 wt%, respectively. Similarly, melteigite in the Jijie complex has an average SiO_2 (41.2 wt%) comparable to ijolite (41.2 wt%) and urtite 43.6 wt%,

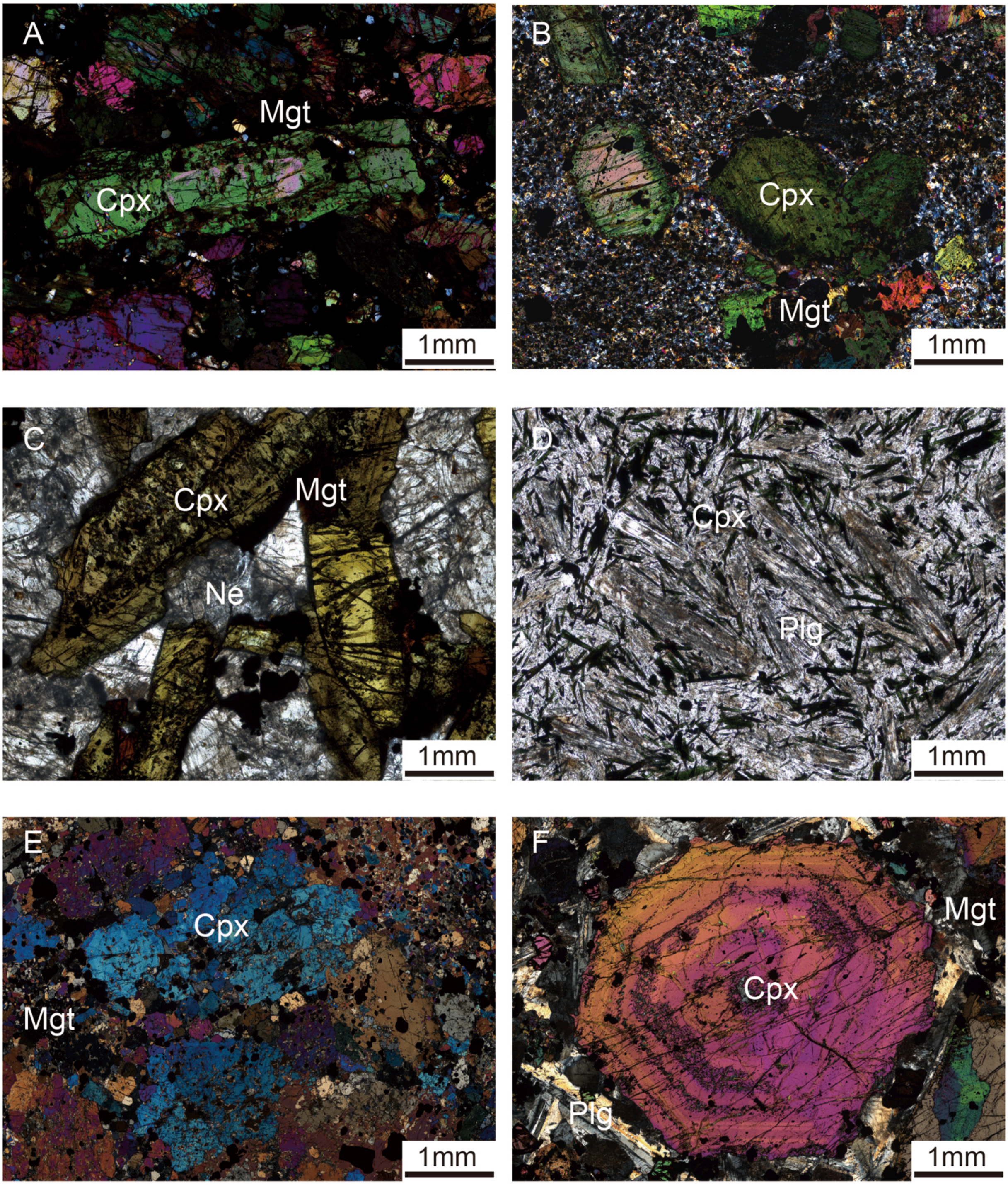

Fig. 6. (A) Magnetite pyroxenite and (B) gabbro in the Yuhezhai complex under the crossed polarized light. Core-rim variations are clearly shown in euhedral clinopyroxene grains. (C) Melteigite and (D) mariupolite in the Jijie complex under the plane polarized light. Clinopyroxene grains are all aegirine with green color and high length-width ratios. (E) pyroxenite and (F) melteigite in the Shuikoujing complex under the crossed polarized light. Clinopyroxene crystals are subhedral in pyroxenite but euhedral in melteigite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

much lower than mariupolite (56.1 wt%). The $Na_2O + K_2O$ contents of melteigite (4.8 wt%) and ijolite (7.4 wt%) are lower than those of urtite (13.7 wt%) and mariupolite (14.7 wt%). In the Yuhezhai complex, magnetite pyroxenite has 25.9–46.7 wt% SiO_2, 7.1–10.0 wt% MgO, and 1.4–3.0 wt% $Na_2O + K_2O$, lower than the gabbros with 42.1–51.5 wt% SiO_2, 2.6–8.1 wt% MgO, and 3.4–7.8 wt% $Na_2O + K_2O$.

All the rocks in these complexes have similar, strongly LREE-enriched, chondrite-normalized REE patterns, and all the samples have both negative and positive Eu anomalies (Fig. 8). The total REE concentrations of rocks from the Shuikoujing (44.0 ppm on average) are comparable to those in the Jijie complex (44.0 ppm) but much lower than those in the Yuhezhai complex (131 ppm).

The total REE concentrations of weathered crusts on the Shuikoujing complex are 39.3 ppm on average, much lower than those in the Jijie complex (137 ppm), and the Yuhezhai complex (157 ppm), which are similar to, or slightly higher than, the fresh rocks. The weathered products all display similar chondrite-normalized REE patterns with strong enrichment in LREE (Fig. 8).

Table 1
Summary of major elemental oxides (wt.%) of the Yuhezhai, Shuikoujing and Jijie complexes in the Kangdian belt, SW China.

			SiO_2	TiO_2	Al_2O_3	$^TFe_2O_3$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Yuhezhai	magnetite	Ave.	32.1	4.7	3.0	28.2	0.4	9.2	16.4	1.6	0.1	3.8	0.2	99.8
	pyroxenite	Max.	46.7	7.6	3.3	34.7	0.4	10.0	23.2	2.7	0.3	4.4	2.0	100.0
	(n = 16)	Min.	25.9	0.7	2.6	9.5	0.2	7.1	15.0	1.3	0.1	3.5	–	99.6
	gabbro	Ave.	45.6	2.2	12.8	16.4	0.2	5.2	9.8	4.9	0.7	1.3	0.2	99.5
	(n = 23)	Max.	51.5	2.5	16.6	19.8	0.3	8.1	12.7	6.7	1.1	1.7	0.5	100.3
		Min.	42.1	1.5	10.3	11.1	0.2	2.6	6.4	3.2	0.2	0.8	–	98.4
Shuikoujing	pyroxenite	Ave.	42.1	2.2	8.2	15.0	0.2	11.0	18.2	1.8	0.3	0.1	0.9	100.1
	(n = 35)	Max.	44.6	3.5	13.0	25.9	0.2	13.4	19.8	4.4	1.1	0.3	1.7	100.7
		Min.	35.3	1.4	6.7	9.1	0.1	10.3	15.5	0.7	0.1	0.0	0.1	99.7
	melteigite	Ave.	43.1	1.8	13.2	13.3	0.2	8.2	13.4	4.3	1.1	0.4	0.8	99.8
	(n = 23)	Max.	45.5	2.3	16.1	16.6	0.2	10.2	15.6	6.5	1.6	0.6	1.6	100.5
		Min.	41.0	1.3	10.6	10.9	0.1	6.2	10.1	3.2	0.7	0.2	0.1	98.8
	jacupirangite	Ave.	43.7	1.5	11.3	13.1	0.2	9.8	15.0	3.3	0.8	0.3	0.8	99.7
	(n = 16)	Max.	45.4	2.2	15.8	19.1	0.2	11.6	16.5	5.4	1.7	0.6	1.5	100.0
		Min.	39.8	1.1	9.7	11.5	0.2	6.1	9.9	2.2	0.5	0.1	0.6	99.3
	nepheline	Ave.	53.7	0.5	20.9	4.7	0.1	0.8	3.6	11.2	1.7	0.1	2.1	99.5
	syenite	Max.	58.1	1.2	23.1	8.6	0.2	2.2	7.9	13.0	2.1	0.4	3.0	100.2
	(n = 16)	Min.	48.6	0.2	18.5	2.4	0.1	0.1	1.0	8.5	1.4	0.0	1.2	99.1
Jijie	melteigite	Ave.	41.2	2.3	11.5	14.5	0.2	8.7	14.0	4.5	1.3	0.8	1.2	100.1
	(n = 44)	Max.	43.6	2.8	17.5	18.1	0.3	11.1	16.3	6.8	2.1	1.4	2.9	101.1
		Min.	38.9	1.8	9.1	11.7	0.1	6.2	10.1	3.3	0.8	0.4	0.4	99.0
	ijolite	Ave.	41.2	2.3	13.2	13.5	0.2	7.3	12.8	5.6	1.8	1.0	1.2	100.0
	(n = 24)	Max.	42.8	2.7	17.3	14.9	0.3	9.1	14.2	6.8	2.4	1.9	2.2	100.6
		Min.	39.7	1.9	11.4	10.8	0.2	5.9	10.7	4.9	1.5	0.7	0.4	99.0
	mariupolite	Ave.	56.1	0.4	21.3	3.9	0.1	0.6	1.4	11.9	2.8	0.1	1.4	100.0
	(n = 3)	Max.	57.3	0.5	22.8	4.5	0.1	0.7	1.6	12.6	3.0	0.1	2.9	100.1
		Min.	53.8	0.2	20.6	3.4	0.1	0.6	1.1	11.0	2.7	0.1	0.6	100.0
	urtite	Ave.	43.6	1.1	23.1	7.4	0.1	2.5	6.1	11.3	2.4	0.7	1.5	99.9
	(n = 20)	Max.	44.6	1.5	26.0	8.7	0.2	3.6	8.0	12.8	2.8	1.0	2.2	100.6
		Min.	42.0	0.8	20.0	6.2	0.1	1.9	5.0	9.8	2.1	0.5	1.0	99.3

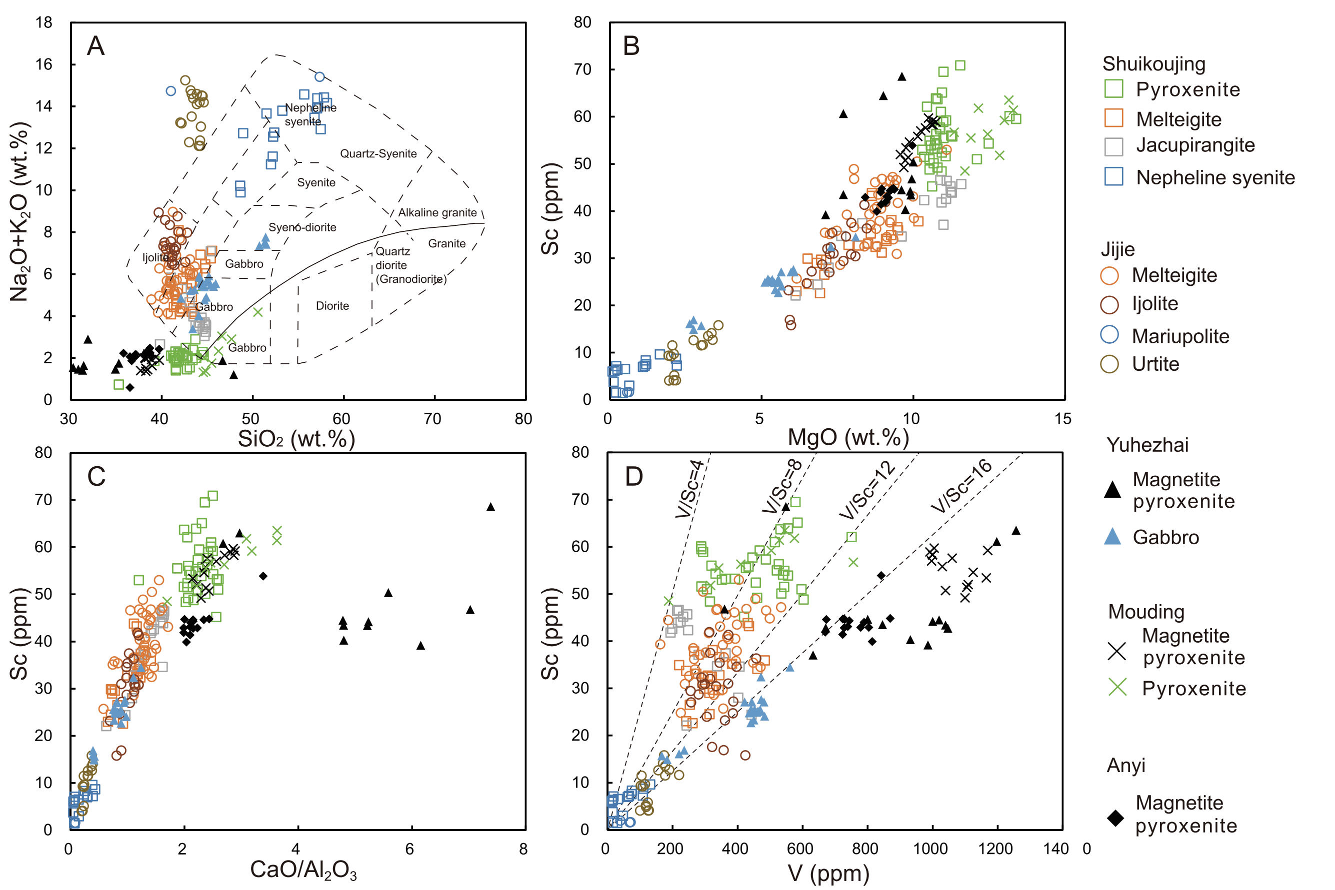

Fig. 7. (A) TAS diagram, (B) Sc versus MgO, (C) Sc versus CaO/Al_2O_3 ratios and (D) Sc versus V contents of various rocks of the alkaline complexes.

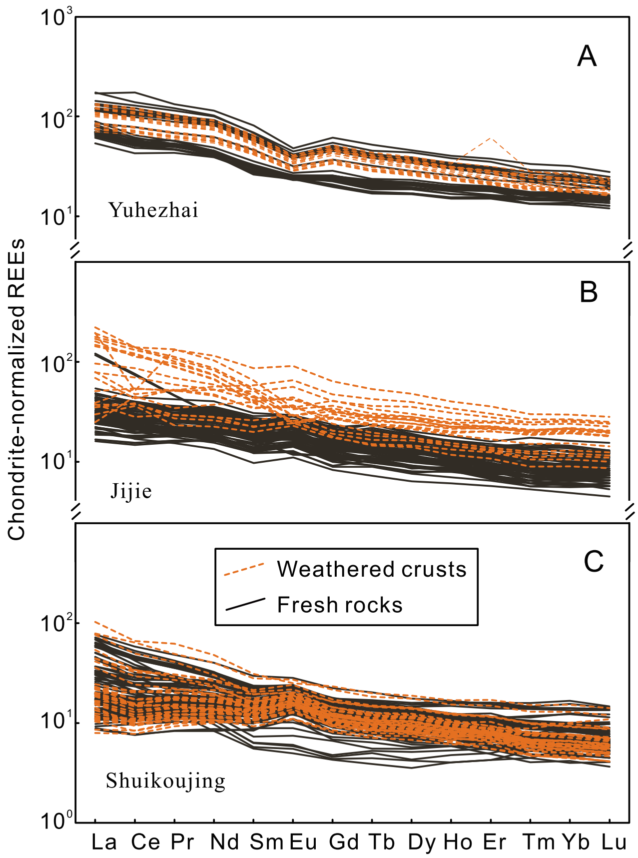

Fig. 8. Chondrite-normalized patterns of fresh rocks and weathered crust of the alkaline complexes: A -Yuhezhai, B-Jijie and C-Shuikoujing.

4.3. Sc concentrations

Scandium concentrations of the three representative complexes are summarized in Table 2. In the Yuhezhai complex, magnetite-bearing pyroxenite has an average Sc content of 48.9 ppm, higher than the gabbro (24.4 ppm). Pyroxenite and jacupirangite in the Shuikoujing complex have Sc concentrations of 56 and 43 ppm on average, respectively, both of which are higher than melteigite (33 ppm) and nepheline syenite (6.1 ppm). In Jijie, melteigite has an average Sc concentration of 40 ppm, obviously higher than iolite (30 ppm), mariupolite (1.7 ppm), and urtite (9.4 ppm). The weathered crusts of the Shoukoujing, Jijie and, Yuhezhai complexes have average Sc contents of 51, 37, and 44 ppm, respectively, all showing slight enrichment compared to the parental rocks.

Scandium contents of the Shuikoujing and Jijie complexes correlate positively with MgO and CaO/Al_2O_3, both of which reflect the abundance of clinopyroxene in various rock types (Fig. 9). Ultramafic rocks of both complexes have higher Sc contents than the mafic to intermediate rocks. In addition, Sc and V contents of each phase in the Shuikoujing, Jijie, and Yuhezhai complexes show positive correlations, implying simultaneous enrichment of the two elements in these alkaline complexes. Magnetite-bearing pyroxenite has relatively high V contents, up to ~2000 ppm, indicating a major role for magnetite in controlling V partitioning.

5. The role of clinopyroxene in the concentration of Sc

Scandium rarely occurs as separate minerals in igneous rocks but is commonly incorporated into the structure of other minerals because it has an ionic radius of about 0.87 Å (Shannon 1976), much smaller than the other lanthanides, but similar to Mg^{2+} and Fe^{2+}, which allows ready substitution into these sites in mafic minerals. Scandium has high partitioning coefficients between many minerals (e.g., garnet, clinopyroxene, amphibole, fluorapatite, and titanomagnetite) and various melts, thus, cumulates of these minerals from magmas may comprise Sc orebodies. Favorable bodies for this type of deposit are mafic-ultramafic intrusions derived from hydrous mafic magmas formed by partial melting of fertile mantle sources (Wang et al., 2021, 2022). Involvement of water during fractional crystallization is essential to suppress the crystallization of orthopyroxene and thereby to enrich the melt in Sc that can then be incorporated into clinopyroxene and amphibole. In subduction-related environments, hydrous mafic–ultramafic intrusions may be rich in Sc with the potential to form magmatic deposits. Here we emphasis that alkaline mafic-ultramafic intrusions also have high potential for the formation of this type of deposit. Although alkaline mafic magmas may not be extremely rich in Sc, the element has a high partition coefficient between clinopyroxene and such melts.

Alaskan-type ultramafic-mafic intrusions are typically composed of dunite, wehrlite, olivine clinopyroxenite, clinopyroxenite, and hornblendite and occur in subduction-related settings, such as Duke Island in Alaska and the Ural Mountains. Rocks from these intrusions contain Sc ranging from 21 to >100 ppm; some even have Sc well above the current ore grades of 35 ppm (Xie et al., 2018; Wang et al., 2021). Clinopyroxenites in the Duke Island Complex and the Urals contain 54–110 ppm and 78–135 ppm Sc, respectively (Krause et al., 2007; Li et al., 2013). Scandium-rich ultramafic-mafic intrusions in Australia and New Caledonia are generally rich in clinopyroxenite and amphibolite and have average Sc concentrations of ~80 ppm to over 100 ppm, respectively (Chassé et al., 2017; Teitler et al., 2019). These mafic-ultramafic intrusions are also regarded as potential exploration targets for Sc resources.

Major magmatic Sc deposits hosted in alkaline complexes are typically associated with REE deposits. The Bayan Obo REE mine has Sc as a by-product. In this deposit the Sc is related to aegirine, which is abundant in many REE ores. However, details regarding Sc mineralization at Bayan Obo are not available. The Tomtor Massif in Russia, one of the largest carbonatite complexes in the world, has a carbonatite core enclosed by nepheline syenite and nepheline-pyroxenite. The carbonatite is mostly rich in Nb, REE, Y and Sc and contains 0.057 wt% Sc on average (Panina et al., 2018), which is typically hosted in monazite, florencite, and xenotime (Lapin et al., 2016; Kuzmin et al., 2019). In the Kovdor deposit phoscorite and carbonatite are both rich in Sc, which is mostly in baddeleyite (Ivanyuk et al., 2016).

In the ELIP, oxide-bearing intrusions in the Panxi belt were previously noted to contain considerable amounts of Sc, mostly related to augite, amphibole, and ilmenite, but studies of Sc occurrences and

Table 2
Summary of Sc concentrations (ppm) of different rocks from the Yuhezhai, Shuikoujing and Jijie complexes in the Kangdian belt, SW China.

		Yuhezhai		Shuikoujing				Jijie			
		magnetite pyroxenite (n = 16)	gabbro (n = 23)	pyroxenite (n = 35)	melteigite (n = 23)	jacupirangite (n = 16)	nepheline syenite (n = 16)	melteigite (n = 44)	ijolite (n = 24)	mariupolite (n = 3)	urtite (n = 20)
Sc	Ave.	48.9	24.4	56.1	32.6	42.8	6.08	40.2	29.5	1.71	9.39
	Max.	69.3	34.5	70.9	43.8	46.6	9.60	53.0	41.9	1.94	15.8
	Min.	39.2	14.9	45.2	22.6	22.1	1.45	24.8	15.8	1.56	4.06

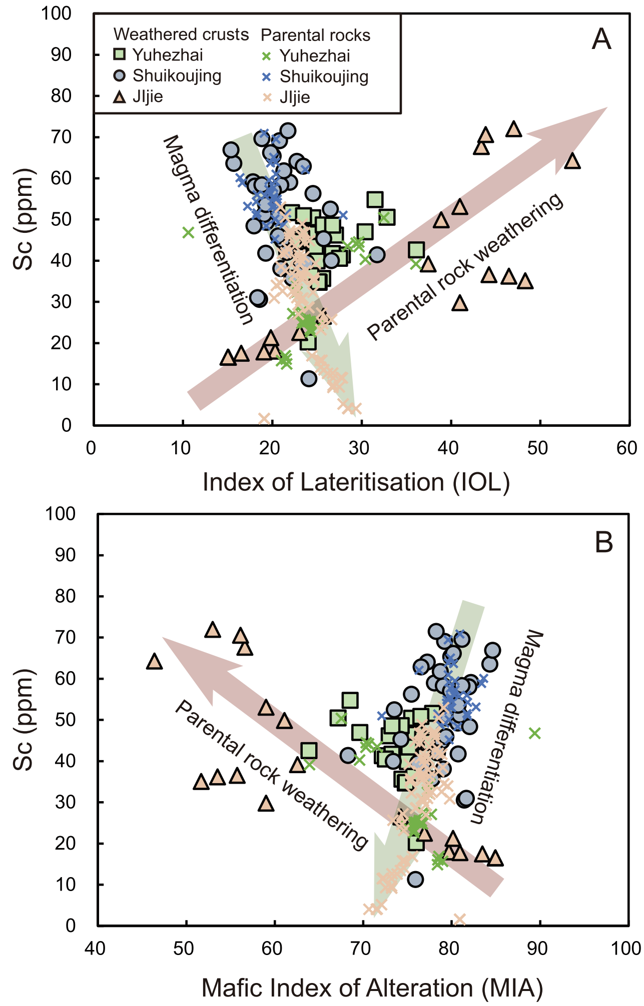

Fig. 9. Scandium concentration versus (A) index of lateritisation (IOL) and (B) mafic index of alteration (MIA) of the weathered crusts and parental rocks of the Yuhezhai, Shuikoujing, and Jijie complexes. The Sc contents of weathered crust from the Jijie complex follow the weathering trend, whereas those in the Yuhezhai and Shuikoujing complexes are more coherent with the magma differentiation trend.

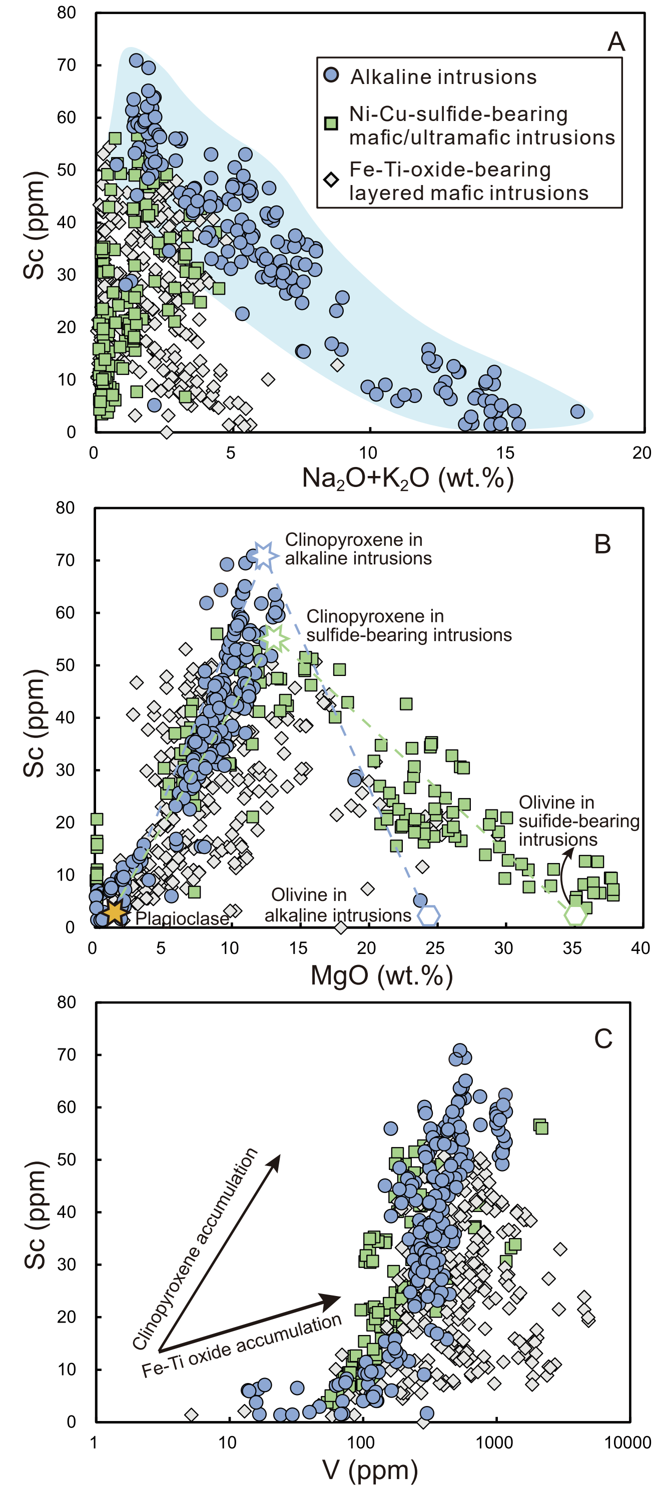

Fig. 10. Plots of Sc contents versus (A) Na_2O + K_2O; (B) MgO; and (C) V contents of three types of plutonic rocks: alkaline intrusions, Ni-Cu sulfide-bearing intrusions, and Fe-Ti oxide ore-bearing intrusions in the ELIP.

grades are rare. In these intrusions, giant V-Ti-Fe oxide deposits have been mined for ages, and Sc as a by-product has tonnages of >40,000 Sc oxide (Guo et al., 2012), although the average Sc concentration of the bulk ores and tailings from which Fe and Ti have been extracted is only about ~15–35 ppm. Rocks in these intrusions have Sc contents, lower than pyroxenites of the alkaline complexes (Fig. 10). Pyroxenites from Fe-Ti-oxide-bearing intrusions are only minor but the importance of these rocks needs to be evaluated. On the other hand, both the Anyi and Mouding complexes have low-grade magnetite ores that were explored by the local geological survey. It is known that pyroxenites of the Mouding complex are sufficiently rich in Sc to form a deposit (Guo et al., 2012). In this study, we confirm that pyroxenites from the three alkaline igneous complexes in the Eshan and Luoci regions have Sc concentrations similar to, or even higher, than those in the Mouding complex (Table 3). It is possible that these complexes were derived from mantle domains that were different from those that generated most intrusions in the Panxi belt and the majority of the Emeishan volcanic sequence. We suspect that trachytes and phonolites reported within the volcanic sequence by Mei et al. (2003) are the eruptive equivalents of these alkaline complexes. In the past, these complexes were not investigated for their mineral potential. Like other alkaline complexes in the world, they may have great potential to host both Sc and REE deposits.

Supergene processes under tropical and sub-tropical climates can further concentrate Sc through weathering of protoliths to form regolith-hosted deposits. Laterites underlain by ultramafic-mafic rocks in Australia and New Caledonia are rich in Sc and comprise a major exploration target. The Sc grades in these laterites are extremely high (200–500 ppm) (Platina Resources Ltd., 2017; Huleatt, 2019). Scandium in these laterites was released from ultramafic-mafic parent rocks and incorporated in secondary smectite and was further concentrated when

Table 3
Exploration target range estimation for Sc in three representative alkaline igneous complexes in the Kangdian belt, SW China.

		Exploration Target: Estimated Sc Grade[1] (ppm)		Exploration Target: Estimated Volume[2] (km^3)		Exploration Target: Estimated Tonnage[3] (million tonnes)		Exploration Target: Estimated Sc Mineralization Potential[4] (tonnes)	
		from	to	from	to	from	to	from	to
Yuhezhai	magnetite pyroxenite	39.1	58.7	0.050	0.100	68	135	2,641	7,922
Shuikoujing	pyroxenite	44.9	67.3	0.071	0.142	96	192	4,302	12,905
	jacupirangite	34.2	51.4	0.017	0.034	23	46	795	2,385
Jijie	melteigite	32.2	48.2	0.096	0.191	129	258	4,151	12,452
Total Exploration Target								**11,888**	**35,664**

Note:
1 The Sc grade estimates for all Exploration Target was based on the average grade (+/-20%) of available geochemical analyses of published literature and this study.
2 The surface area of Exploration Target is quantitatively measured on geological map. Down-dip Exploration Target range is qualitatively estimated to be 200–400 m based on previous geological models for such intrusion.
3 The estimated potentially mineralized Exploration Target is assumed to have similar density of 2.7 g/cm^3. It was assumed that a 50% discount has been applied to the Exploration Target tonnage to reflect the inherent discovery risk.
4 It is important to note that the Exploration Target statement contains quantity and grade estimations that are conceptual in nature. To date there has been insufficient exploration to estimate a Mineral Resource, and it is uncertain if further exploration will result in the estimation of a Mineral Resource.

the smectite dissolved and the Sc was re-absorbed in goethite (Chassé et al., 2019). Consequently, the limonitic laterite layer may contain Sc up to 500 ppm (Chassé et al., 2017). These deposits are also rich in Ni, Co and Pt (Huleatt, 2019).

In our preliminary studies, weathered profiles are well developed on top of the pyroxenites in the alkaline complexes in the Kangdian belt (Fig. 5D and E). Soils over the mafic-ultramafic intrusions in the Eshan and Luoci regions have slightly higher concentrations of Sc but systematic sampling through a complete profile is lacking.

6. Economic potential of Sc mineralization

6.1. Exploration Target range estimates

Pyroxenites from the three representative complexes in the Kangdian belt have moderate concentrations (Sc = 39–71 ppm) (Fig. 9). The current required Sc ore grades for development in China are set at 35 ppm and thus, these pyroxenites can be regarded as low-grade ores. Although these alkaline complexes are relatively small, the tonnage of pyroxenite in the region is huge.

In our estimates of target ranges, we use the average Sc contents of the main lithologies such as magnetite pyroxenite of the Yuhezhai complex, melteigite of the Jijie complex and pyroxenite and jacupirangite of the Shuikoujing complex. The weathered crusts of those intrusions are not included in the Exploration Target estimates at this stage. The Exploration Target estimates for these complexes are reported in compliance with the JORC Code 2012 Edition. The purpose of these estimates is to highlight potential resources for further exploration and exploitation.

Scandium grades for three Exploration Targets are based on average grades (+/-20%) of available geochemical analyses from the literature (Huang et al., 1993; Zhao, 2010; Guo, 2019) and this study. Down-dip Exploration Targets are qualitatively estimated to be 200 to 400 m down-dip extensions from surface exposures based on previous geological models for such intrusions. The surface areas of the Exploration Targets have been quantitatively measured from available geological maps, and the estimated potentially mineralized Exploration Targets are assumed to have a density of 2.7 g/cm^3. We also applied a 50% discount to the tonnage to reflect the inherent discovery risk. The results are listed in Table 3. Our estimates reveal a Sc mineralization potential of ~12,000 to ~36,000 tonnes for Exploration Targets of the Yuhezhai, Shuikoujing, and Jijie complexes. It is important to note that the Exploration Target statement contains quantity and grade estimations that are conceptual in nature. To date there has been insufficient exploration to allow accurate estimates for a Sc Mineral Resource, and it is uncertain if further exploration will produce results that are consistent with our estimates.

6.2. The impact of unconventional Sc deposits to the world supply chains

Due to high demand, prices for metallic Sc are currently very high. Sc oxide was about $3800 /kg in 2020, over 6 to 1900 times that of other rare earth metal oxides (REO) (Statista, 2021, USGS, 2021). Clearly Sc has the highest market prices among the REEs. Because of economic growth and a possible shortage of Sc, it has been predicted that there will be a 27% compounded annual growth rate (CAGR) to 2026 in the Sc market (Scandium International Mining Corp., 2016). Much of the Sc currently on the market is from pre-existing tailings or waste residues, such as those in the uranium districts in Kazakhstan and Russia. Therefore, the discovery of new and alternative supply chains of Sc is urgently required.

In this context, higher abundances of Sc in pyroxenites compared to other types of rocks highlight the economic importance of these lithologies. For example, the estimated Sc grades of ~30 to ~70 ppm in such deposits and the potential exploration target capacity of ~12,000 to ~36,000 tonnes of Sc metal for the investigated complexes, together with the already determined resource of 750 tonnes of Sc metal in the Mouding complex, demonstrate that this region should be an important exploration target.

Because of the high demand, low-grade Sc sources like other REEs, are very likely to become economically viable in the near future (Batapola et al., 2020). We consider that pyroxenites from alkaline igneous complexes can be significant alternative sources for Sc. In addition, weathered products of these pyroxenites may have higher Sc concentrations than the protolith and may become another potentially important, unconventional source of the metal.

7. Conclusions

Pyroxenite, jacupirangite, and melteigite of the alkaline igneous complexes of the ELIP have Sc grades ranging from ~30 to ~70 ppm with an estimated mineralization potential of ~12,000 to ~36,000 tonnes of Sc. Compared to other Sc deposits in the world, these have low grades but high tonnages. However, such deposits may become important Sc sources in the future, because of the rapidly growing demand for this scarce metal. The extraction of Sc from low-grade ores could contribute significantly to the world supply chain as a sustainable, unconventional source of Sc. Additionally, the weathered products of these Sc-rich pyroxenites could also become a potentially important and unconventional source of the metal. Our study demonstrates that the Kangdian belt in SW China is potentially an important Sc metallogenic province.

CRediT authorship contribution statement

Mei-Fu Zhou: Supervision, Conceptualization, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Zhen-Chao Wang:** Investigation, Visualization, Writing - original draft, Writing - review & editing. **Wen Winston Zhao:** Investigation, Visualization, Writing - original draft, Writing - review & editing. **Liang Qi:** Data curation, Methodology. **Zheng Zhao:** Resources, Writing – review & editing. **Jiaxi Zhou:** Resources, Writing – review & editing. **Zhilong Huang:** Resources, Writing – review & editing. **Wei Terry Chen:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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