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ORIGINAL ARTICLE

A preliminary study on ore-forming environments of Xianglushan-type iron deposit and the weathering mineralization of Emeishan basalt in Guizhou Province, China

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Abstract Xianglushan-type iron deposits are one of the new types of iron deposits found in the Weining Area of Western Guizhou. The iron-bearing rock system is a paleo-weathered crustal sedimentary (or accumulating) stratum between the top of the Middle-Late Permian Emeishan basalt formation and the Late Permian Xuanwei formation. Iron ore is hosted in the Lower-Middle part of the rock system. In terms of the genesis of mineral deposit, this type of deposit should be a basalt paleo-weathering crustal redeposit type, very different from marine sedimentary iron deposits or continental weathering crust iron deposits. Based on field work and the analytical results of XRD Powder Diffraction, Electron Probe, Scanner Electron Microscope, etc., the geological setting of the ore-forming processes and the deposit features are illustrated in this paper. The ore-forming environment of the deposit and the Emeishan basalt weathering mineralization are also discussed in order to enhance the knowledge of the universality and diversity of mineralization of the Emeishan Large Igneous Province (ELIP), which may be a considerable reference to further research for ELIP metallogenic theories, and geological research for iron deposits in the paleo-weathering crust areas of the Emeishan basalt, Southwestern, China.

Keywords Emeishan basalt paleo-weathering crust · Xianglushan-type iron deposit · Ore-forming environment · Weathering mineralization · Western Guizhou Province

1 Introduction

In the Pan-Wumengshan region of Western Guizhou, the Middle-Late Permian Emeishan basalts are widely distributed with an area of 30000 km^2 (Guizhou Institute of Geology Survey 2013), belonging to the East margin of the Emeishan Large Igneous Province (ELIP) (Xu and Chong 2001). Recent research results reveal that the ELIP is a result of Emeishan mantle plume activity, rather than a result of ground fracturing (Zengqian et al. 1999; Xu et al. 2013). A great many scholars reckon that the ore forming of lead, zinc, antimony, copper and gold, etc., in the Pan-Wumengshan region of Western Guizhou is associated with Emeishang magma activity (Hu et al. 2005; Nie et al. 2007; Liao 2010; Tang et al. 2013). Study on the contribution of ELIP to ore-forming, in theory, should consist of primary mineralization and secondary mineralization.

However, studies on secondary mineralization for the contribution of ELIP to ore-forming are only a few. Yang Ruidong (Yang et al. 2007), Zhou Lingjie (Zhou et al. 2013) and Zhang Zhengwei (Zhang et al. 2016) have conducted a relatively detailed study on the paleo-weathering crustal type rare earth deposits on top of the Emeishan basalt in recent years, and they realized that the Emeishan basalt had provided rich material sources for the ore-forming of rare earth deposits in the region.

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Xianglushan-type Iron Deposits were found by Team 113 of the Guizhou Provincial Geology and Mineral Bureau for the first time during a geological research study for copper in the Xianglushan district of Weining County in 2012–2013 (Zhang et al. 2013). The Project Management Office (PMO) of the Guizhou Institute of Technology for the Study of Iron Deposit Ore-forming Rule, Ore-controlling Factors and Ore-forming Predication in Western Region of Guizhou Province reckons that this iron deposit stratum is hosted between the top of the Emeishan Basalt Fm and the Xuanwei Fm, and that the iron-bearing rock system is parallel to its upper and lower strata and is in unconformable contact. The ores are of the pisolite structure of pyroclastic rock. The deposit was named Xianglushan-type Iron Deposit by the PMO for the very first time in 2016, representing the paleo-weathering crustal sedimentary (or accumulating) type iron deposits on top of the Emeishan basalt in western Guizhou and the adjacent areas. Based on the illustration of the geological setting of ore-forming processing and the deposit features, the ore-forming environment and the Emeishan basalt weathering mineralization will be systematically discussed in this paper, in order to enhance the knowledge of the universality and diversity of ELIP mineralization. The result of the PMO should play an important practical role in guiding geological research for iron in the distribution area of the Emeishan basalt paleo-weathering crust in Southwest China.

2 Geological setting of ore-forming processing and regional geology

The prospect is located at the southwest border of the Yangtze craton block at the contact part of the Tethys-Himalayas orogenic system and the circum-Pacific tectonic zone, surrounded by the N-S Xiaojiang fault zone, the N-E Mile-Shizong-Guiyang fault zone and the N-W Zhiyun-Shuicheng fault zone. The location of the geotectonics and the regional structure are very special (Fig. 1).

The primarily exposed strata in the prospect are Carboniferous, Permian and Triassic, from top to bottom were divided as Dapu Fm ($C_{1\text{-}2}d$), Weining Fm ($C_{1\text{-}2}w$), Liangshan Fm (P_2l), Xixia Fm (P_2q), Maokou Fm (P_2m), Emeishan basalt Fm ($P_{2\text{-}3}em$), Iron-bearing rock system (TYX), Xuanwei Fm (P_3x), Longtan Fm (P_3l), Feixianguan Fm (T_1f), Jialingjiang Fm (T_1j), Guanling Fm (T_2g)and Erqiao Fm(T_3e).

3 Deposit features

3.1 The iron-bearing rock system

The iron bearing rock system is distributed at Zhejue, Heshitou (Black Stone), Zhejiatian, Xianglushan, Jieli, Xijie and Majikuai in Weining County, and is exposed along the wings and transition end of the syncline. The system has a

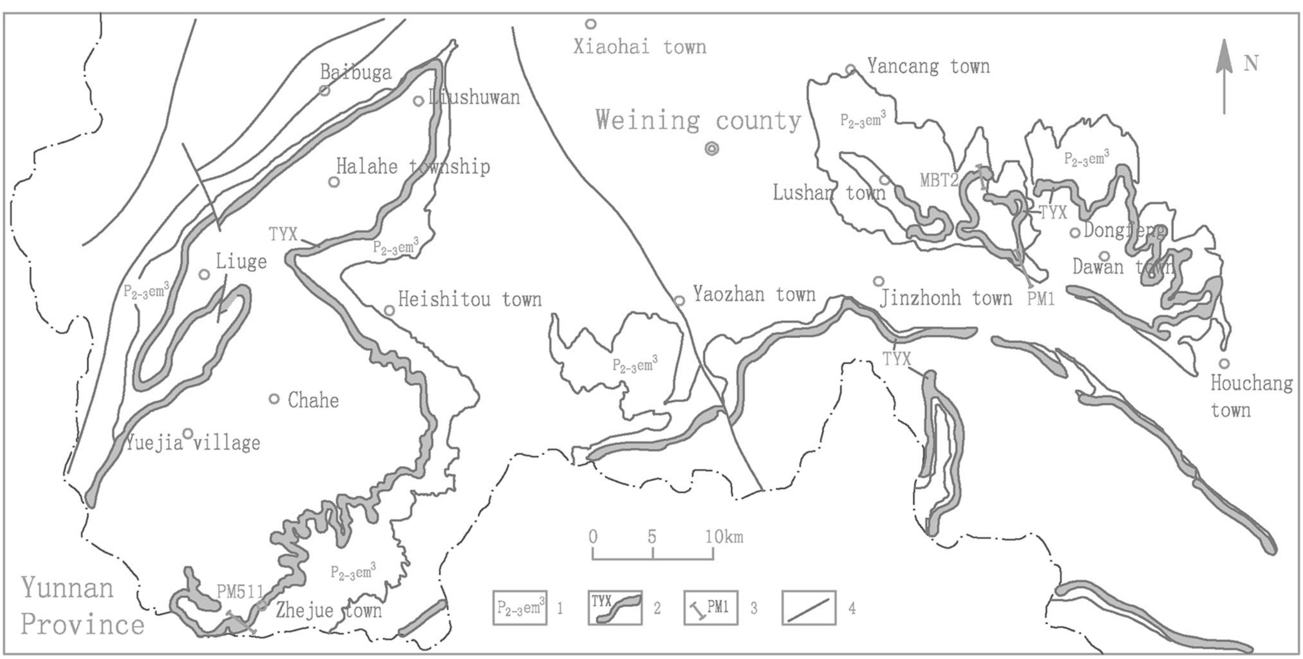


Fig. 1 Geological Sketch of Weining Area. *1* Emeiashan Basalt Fm, *2* Iron-bearing Rock System, *3* Location of Profile, *4* Fault

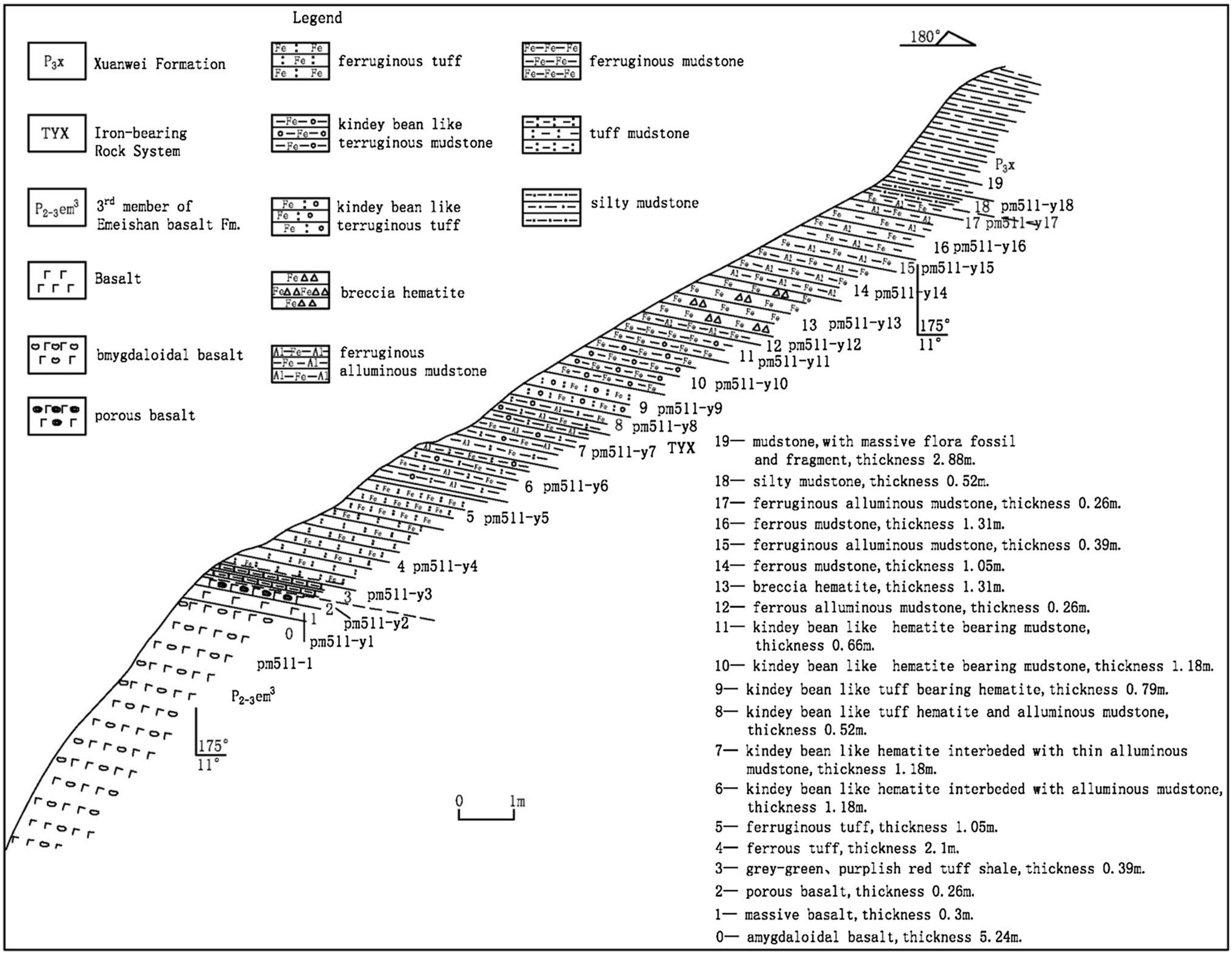


Fig. 2 Profile of ore-bearing rock system at Zhejue, Weining (PM511)

thickness of 3–15 m and the iron-bearing layer is at the Middle-Lower part of the system with a thickness of 0.6–2 m. The iron-bearing layer becomes thicker so long as the system is thick, and the same to the grade. From Zhejue to Xianglushan, the system becomes thicker and thicker, and to the adjacent area of Ertang, the system wedges out and then the iron bearing layer disappears.

The floor rock and the roof of the Zhejue profile (PM511) are exposed very well, and the profile could be divided into 20 lithological layers (Fig. 2), of which, the 0–2 layers are porous basalt at the top of the 3rd Member of the Emeishan basalt Fm; 18–19 layers are clay rock interbedded with siltstone of the Xuanwei Fm. The iron-bearing rock system (3–17 layers in Fig. 2) is 11.4 m thick, and consists of tuff clay rock, ferruginous sedimentary volcanic breccias, ferruginous weathering crusts, etc. There are 2 iron-bearing layers, from bottom up, the first layer (5–9 layers) is 3.54 m thick and the second layer (13 layer) is 1.31 m thick.

3.2 Deposit features

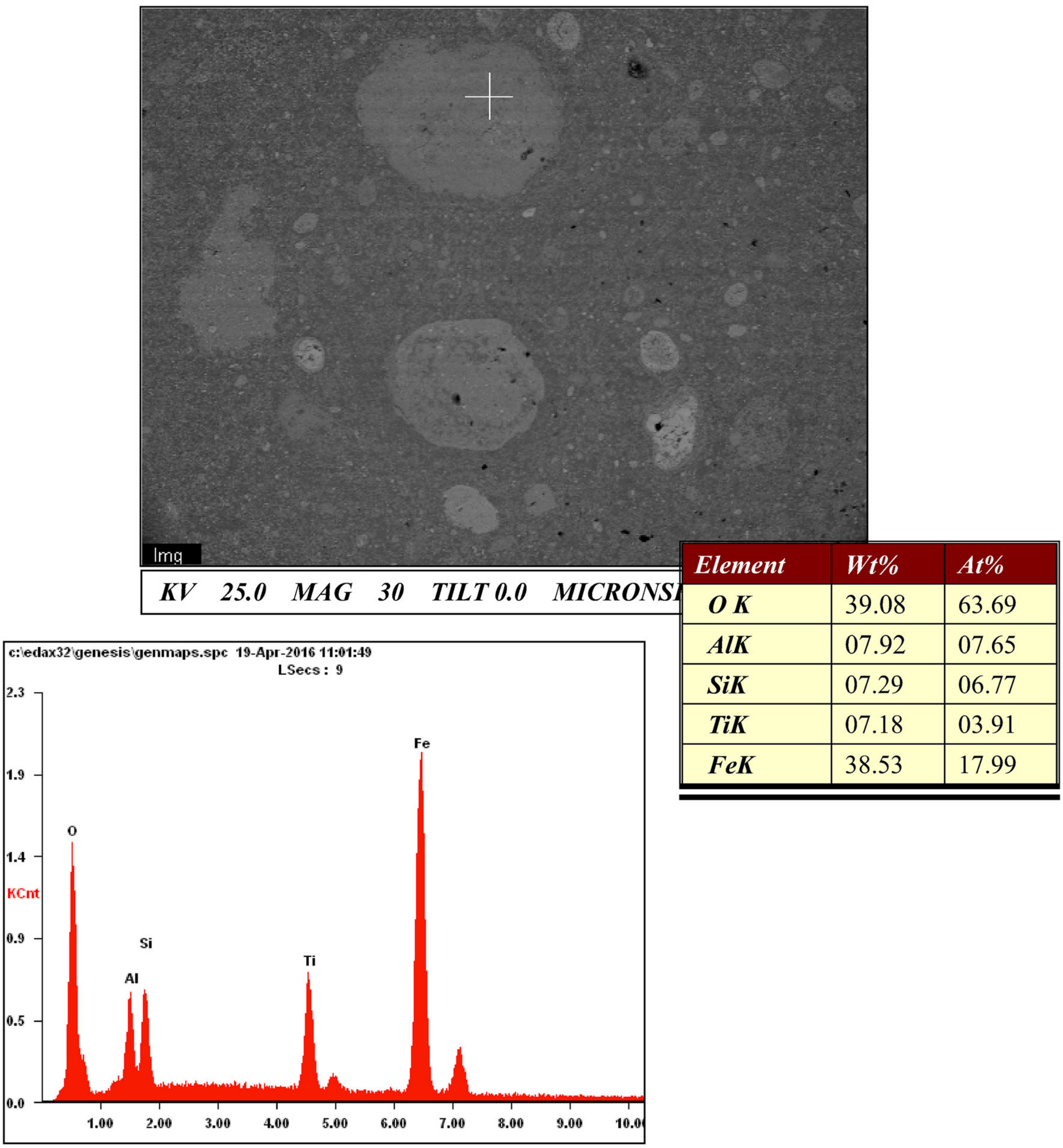
There are 2 iron-bearing layers hosted in the iron-bearing rock system, Mineralization I and Mineralization II, from top to bottom respectively (The 113 team 2015).

Mineralization I is hosted in the mid-upper part of the iron-bearing rock system, and in a stratiform-like or large lenticular form. The size of the ore body is small and lacks continuity, as the thickness is various and strikes several tens and hundreds meters, dips several tens meters to 100 m, with thicknesses of 0.2–1.2 m. The grade (content of Fe) is generally 15%–20%.

Mineralization II is hosted in the mid-lower part of the iron-bearing rock system, and is hosted in the lower part of the system in a stratiform or stratiform-like form. Ores are mainly brown, dark red ferrous clay rock, kidney bean like ferrous clay rock, ferrous tuff clay rock, and ferrous breccia clay rocks. The mineralization layers are relatively continuous with an average thickness of 1.89 m, strikes 910–7700 m long, and dips deepening generally 285–3020 m. The grade is generally 25.05%–35.96%, with the highest at 45% and an average of 28.23%, and is relatively stable along the strikes and dips.

3.3 Mineral composition of ore-bearing rocks

Observation under a polarizing microscope shows that the rock is composed of volcanic debris (60%–96%), clay mineral (3%–12%), quarts (4%–7%), limonite, hematite, pyrite and ilmenite, etc. (Guizhou Institute of Technology 2016). Analysis of XRD powder crystal diffraction indicates that



Element	Wt%	At%
O K	39.08	63.69
AlK	07.92	07.65
SiK	07.29	06.77
TiK	07.18	03.91
FeK	38.53	17.99

Fig. 3 Energy spectrum analysis of scanner electron microscope (MBT2-7B-1) for Xianglushan deposit, Weining (after School of Natural Resource and Environmental Engineering 2016)

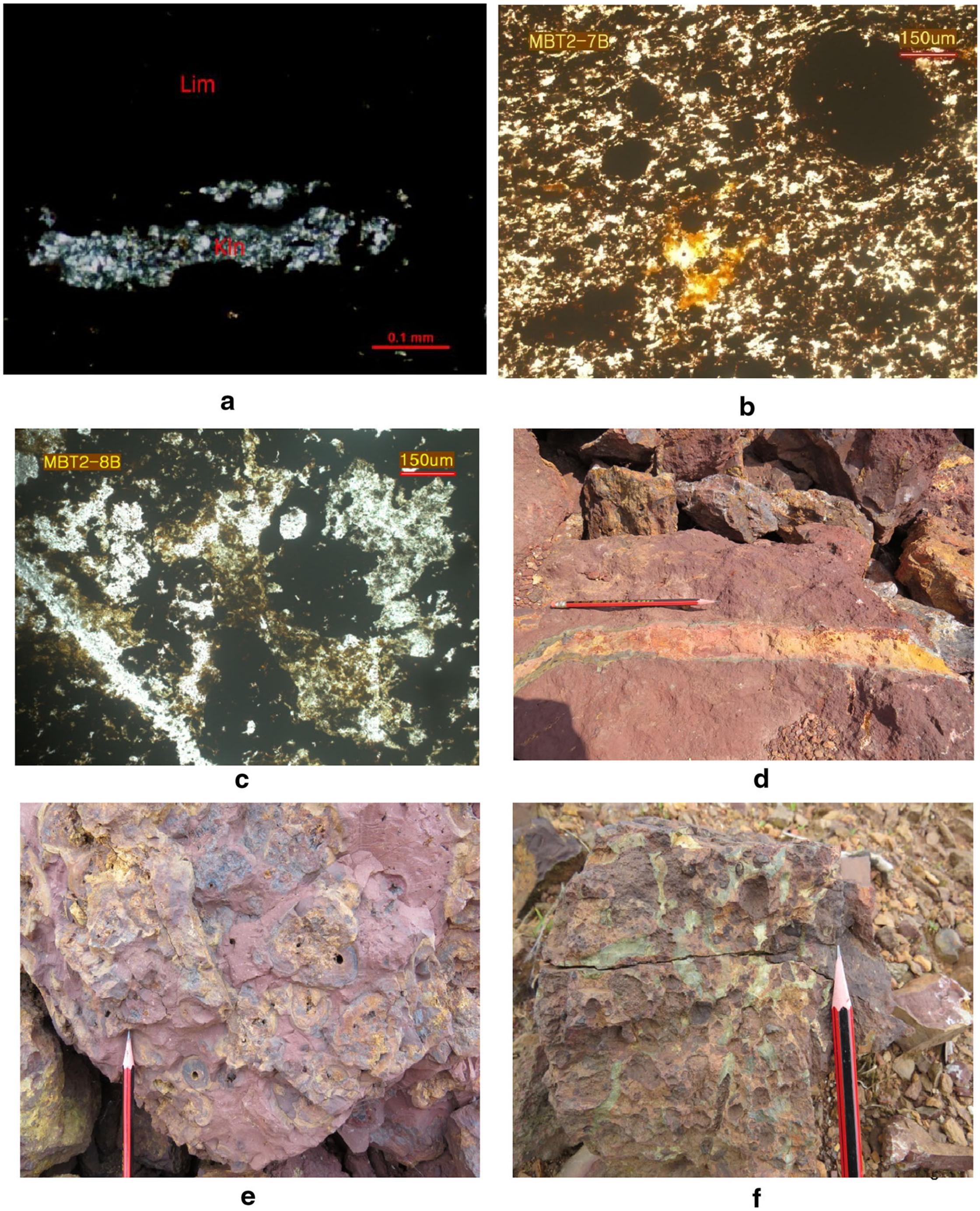


Fig. 4 Features of Ore Texture/Structure. **a** Kaolinite filled in limonite crack, **b** texture of breccia tuff (MBT2-7B), **c** texture of tuff breccia, **d** penetration pipe in ore-bearing rock (profile MBT2), **e** penetration holes in ore-bearing rock, **f** dry crack structure (profile MBT2)

the rock is mainly composed of hematite, kaolinite, plagioclase, anatase, quarts, calcite and amorphous minerals.

Analysis with a scanner electron microscope indicates that the rock is mainly composed of limonite, quarts, aluminiferous minerals (kaolinite?) and titaniferous minerals (anatase?). O and Fe content is about 82%, Si, Al and Ti content is about 18% (Fig. 3). The content of Si, Al and Ti is in a negative proportion to Fe, that is to say, the higher the content of Si, Al and Ti, and the lower the content of Fe in the rock. The composition of

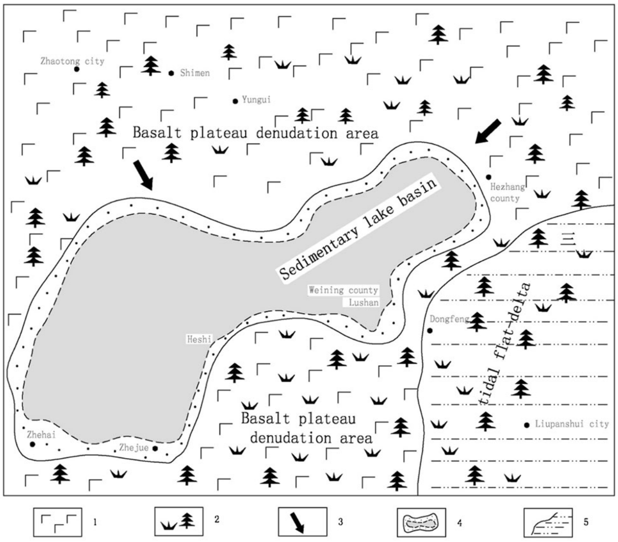


Fig. 5 Paleogeography sketch of iron-bearing rock system. *1*. Basalt plateau denudation area, *2*. Cathaysia flora, *3*. Transportation direction of material sources, *4*. Lake basin and margin, *5*. Tidal flay to delta

the rock is relatively complicated, but priority has been given to Fe, and other minerals could exist either independently or in isomorphism (Liu et al. 2016).

3.4 Rock texture/structure

Rock texture mainly consists of filled crack texture (Fig. 4a), breccias tuffaceous texture (Fig. 4b) and tuffaceous breccias texture (Fig. 4c). In addition, weathering leaching structures like penetration holes (Fig. 4d), penetration pipe (Fig. 4e) and dry crack (Fig. 4f) are also seen in rocks.

4 Ore-forming environment analysis

The ore-bearing rock system is only exposed in the Late Permian Xuanwei Fm region on the 3rd Member of the Emeishan basalt Fm, or the basalt plateau area. After the Longtan region of the marine-continental interfacies, the system becomes thinner and then disappears. The iron mineralization layer also wedges out, indicating that the spatial distribution of the system is strictly controlled by the paleogeography of the Late Permian lithofaces (Fig. 5).

The features of Lith！ligy, sedimentary structure, spatial distribution and rock texture and structure of the system comprehensively indicate that the characteristics of the sedimentary (or accumulating) basin iron-bearing rock system could be near the shore of large shallow lakes of the continental faces (Fig. 5). Water depth of the basin is within 5 m and the floor is relatively flat. The basin marginal area, with quick changing hydrodynamic forces, rich material sources for mineralization and strong elutriation, and is located in an oxidation–reduction interface zone, should be the most favorable part for mineralization. At home and abroad, examples for continental facing large shallow lakes in Earth's history are not rare (Alert and Cline 2000), and the Taihu Lake in east China is an example (Qin and Fan 2002).

5 Weathering and mineralization process

In ELIP, secondary deposits associated with Emeishan basalt weathering are widely distributed. Recently, Meng Changzhong (Men et al. 2015) suggested that the forming of Fe-polymetallic deposits in the Weining-Liupanshui area is associated with the uplifting and unroofing of ELIP and that the unroofing of ELIP has provided direct material sources for the forming of the Fe-polymetallic deposits (England and Houseman 1988).

Weathering is a key element for weathering crust development and the forming of weathering crust deposits. The strength of weathering and the associated influence of the Prospect has been well recorded in the profile of the ore-bearing rock system. In this paper, major elements of the samples from the ore-bearing rock system in the Zhejue Profile were adopted for the calculation of currently commonly used indexes like the Chemical Index for Alteration (CIA), Chemical Index for Weathering (CIW), Plagioclase Index for Alteration (PIA) and Coefficient for Weathering and Leaching (Table 1), etc. Projection point A–CN–K is a result of the CIA value and the end member component value (Table 1).

From Table 1 and Fig. 6, it could be seen that from the 19 samples of the Zhejue profile, except for the new basalt one (CIA 30), the remainders could be divided into 2 groups as per rate of weathering: Group 1 is moderately weathered with CIA 73–83, group 2 is strongly weathered with CIA 98–99. The A–CN–K Triangle Diagram reveals that the data points of the 19 samples from the Zhejue profile have been distributed along the line A-K and are concentrated near point A, indicating that the plagioclase in the samples has been almost completely weathered, and that elements Ca and Na in the plagioclase are losing and that Al is strongly enriched. Weathering products are mainly kaolinite and gibbsite with the level of weathering being strong, and part of the products are montmorillonite and illite with the level of weathering being moderate. Preliminary comparison shows that the level of weathering in the weathering crust of the basalt top in the Weining area

Table 1 Analytical result of major element and parameter of weathering index for the profile (PM511) of the Zhejue iron-bearing rock system, Weining

Sample ID	Content of major element(%)											Parameter of weathering index						
	SiO_2	TiO_2	Al_2O_3	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5	LOI	Fe_2O_3	CIA	BA	A	CN	K	CIW	PIA
pm511-1	56.63	4.36	16.96	0.69	0.24	1.38	0.67	1.66	0.67	5.45	10.42	75.82	42.18	75.82	16.15	8.03	82.44	80.76
pm511-Y1	38.29	3.56	14.06	0.74	0.93	15.10	2.69	0.40	0.50	12.81	10.33	30.32	243.1	30.32	68.75	0.93	30.6	29.94
pm511-Y2	59.97	4.12	15.78	0.58	0.15	1.31	0.48	1.68	0.60	4.84	9.42	75.97	40.92	75.97	15.27	8.76	83.27	81.49
pm511-Y3	46.16	4.18	17.36	0.90	0.03	1.48	0.08	3.12	0.60	5.40	20.49	73.68	48.83	73.68	11.98	14.33	86.01	83.2
pm511-Y4	37.68	5.59	21.52	0.62	0.02	0.98	0.14	2.13	0.47	6.67	23.52	83.29	27.35	83.29	7.79	8.92	91.45	90.52
pm511-Y5	28.08	4.03	22.25	0.10	0.03	0.14	0.04	0.07	0.42	8.41	35.13	98.25	2.92	98.25	1.42	0.34	98.58	98.57
pm511-Y6	28.37	5.49	22.79	0.09	0.02	0.16	0.04	0.04	0.22	8.59	33.69	98.28	2.75	98.28	1.54	0.19	98.46	98.46
pm511-Y7	26.43	5.05	21.51	0.09	0.07	0.08	0.03	0.03	0.12	8.21	37.32	98.95	2.12	98.95	0.9	0.15	99.1	99.1
pm511-Y8	28.66	6.22	23.01	0.10	0.01	0.09	0.04	0.03	0.13	8.70	32.62	98.87	2.24	98.87	0.99	0.14	99.01	99.01
pm511-Y9	21.95	5.57	17.36	0.06	0.06	0.06	0.03	0.03	0.14	6.82	46.71	98.91	1.97	98.91	0.9	0.19	99.1	99.09
pm511-Y10	33.31	3.38	27.31	0.08	0.02	0.04	0.03	0.03	0.03	11.38	22.82	99.44	1.31	99.44	0.45	0.12	99.55	99.55
pm511-Y11	38.41	2.22	32.11	0.09	0.01	0.05	0.05	0.03	0.04	11.63	14.45	99.36	1.35	99.36	0.54	0.1	99.46	99.46
pm511-Y12	31.92	6.38	23.12	0.10	0.13	0.05	0.04	0.03	0.27	10.09	27.15	99.19	1.91	99.19	0.67	0.14	99.33	99.33
pm511-Y13	22.72	2.88	17.48	1.44	0.16	0.03	0.01	0.01	0.17	9.19	45.24	99.53	21.31	99.53	0.4	0.06	99.6	99.6
pm511-Y14	42.22	7.58	34.41	0.19	0.01	0.11	0.07	0.08	0.14	12.76	2.13	98.85	2.56	99.85	0.91	0.25	99.1	99.09
pm511-Y15	35.35	5.49	29.03	0.12	0.81	0.07	0.04	0.09	0.29	13.22	14.03	99.01	2.05	99.01	0.66	0.33	99.34	99.34
pm511-Y16	42.95	5.73	34.76	0.18	0.01	0.07	0.08	0.13	0.08	12.70	2.98	98.86	2.46	98.86	0.74	0.4	99.26	99.26
pm511-Y17	42.94	3.23	24.04	0.12	0.05	0.04	0.05	0.21	0.30	11.66	16.52	98.43	2.85	98.43	0.64	0.93	99.36	99.35
pm511-Y18	45.83	3.34	25.44	0.14	0.05	0.06	0.06	0.26	0.31	11.46	12.81	98.11	3.32	98.11	0.8	1.09	99.19	99.18

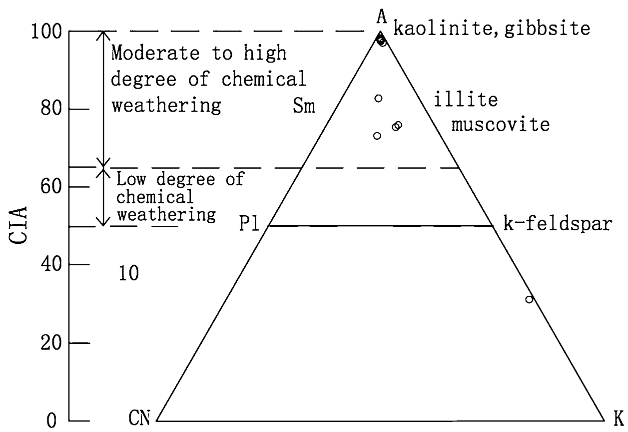


Fig. 6 A–CN–K Ternary diagram [A = n(Al_2O_3), K = n(K_2O) ,CN = n(CaO* + Na_2O)] (modified after Guo and Su 2014)

is much stronger and that the paleoweathering occurred at the warm and wet climatic condition.

Through comparisons of the major element, trace element, rare earth element in the iron-bearing rock system and the crust (Fig. 7), the following has been indicated:

(1) In the paleoweathering crust of the Zhejue ore-bearing rock system, major elements Al, Fe and Ti are extremely enriched, however Si, K, Na, Ca and Mg are severely losing.
(2) Trace elements V, Co, Cu, Zn, Rb, Ga, Zr, Nb, Mo, In, Hf, Ta, Bi, Th and U are enriched, Rb, Nb, Zr, Ga, In and Hf are super enriched, and Sr, Cr, Cd, Cs, W and Tl are losing elements. These might been caused by the difference of activity of elements in the supergene weathering condition (Jiang et al. 2006).
(3) By weathering, almost all rare earth elements have been enriched, especially the light rare earth element appears to be unusually enriched.

5.1 Discussion on weathering process

Xianglushan-type iron deposit is a result of a series of mineralizations in the Emeishan basalt, i.e. weathering denudation, sedimentary (or accumulating) transportation and secondary leaching enrichment, etc. The author suggests that the mineralization material of Xianglushan-type iron deposits mainly comes from the underlying 3rd Member of the Emeishan basalt Fm, and that the ferruginous materials come from the resolution of ferruginous silicate minerals (pyroxene, etc.) of the parent rocks and the auxiliary minerals of pyrite and magnetite, etc. under certain favorite conditions in the supergene oxidized zone (Yao et al. 2006).

There might be 3 ways for the transportation of ferruginous materials, by true solution, colloidal solution and suspended fragment.

The geochemical characteristic of iron indicates that iron is a typical variation element, existing in the form of Fe^{2+} and Fe^{3} in the nature. Under warm and wet climate conditions, the hydrolysis and acidolysis in the parent rock of the denudation area could mainly be a chemical mechanism or biochemical mechanism. After hydrolysis, iron-bearing mineral produces second order iron particles, which, by an easy reaction with H_2O and CO_2, can produce bicarbonate into the solution and be transported in the form of true solution. The chemical formula (Lei et al. 2006) (1) for the hydrolysis reaction is as bellow:

$$Fe^{2+} + 2CO_2 + H_2O \rightarrow Fe(HCO_3)_2 \quad (1)$$

However, previous research reveals that second order iron can quickly be oxidized to insoluble $Fe(OH)_3$ colloid (Formula 2) in the condition under which vast free oxygen exists in surface. This kind of colloid, with a positive charge, could produces relatively stable humate complex by easy combination with humic acid, $Fe(HCO_3)_2$, when aqueous solution contains appropriate humic acid. Therefore, the humic acid, as a protective agent, could transport the $Fe(HCO_3)_2$ colloid a certain distance in waters.

$$Fe^{2+} + O_2 + H_2O \rightarrow Fe(OH)_3 \quad (2)$$

After the ferruginous materials in the solution were transported for a certain distance to the sedimentary basin, due to the changes caused by the aqueous medium condition and the oxidation-reducing condition, Fe $(OH)_3$ is dehydrated, then produces hematite ($F_{e2}O_3$). The chemical reaction formula (3) is as bellow:

$$2Fe(OH)_3 \rightarrow TFe_2O_3 + 3H_2O \quad (3)$$

However, dehydration and hydration always appears and happens alternately. Hematite under a wet climate condition could easily be hydrated and then produce pyrite, in which goethite ($\alpha \sim Fe(OH) \cdot n\ H_2O$) or aqueous goethite ($Fe_2O_3 \cdot nH_2O$) is the main component. The chemical reaction formula (4) is as bellow:

$$TFe_2O_3\ (hematite) + nH_2O \rightarrow TFe_2O_3 \cdot nH_2O(aqueous\ goethite) \quad (4)$$

In the weathering crust eluvial area, ordinary pyroxene, by action of oxygen and water, could directly produce hematite. The oxidizing reaction (5) of ordinary pyroxene, Ca(Mg,Fe,Ti,Al)[$(Si,Al)_2O_6$], is as bellow:

$$2Ca(Mg,Fe,Ti,Al)\left[(Si,Al)_2O_6\right] + 5O_2 + 8H_2O \rightarrow TFe_2O_3 + (Ca,Mg)O + 2TiO_2 + 2Al_2O_3 + 4H_2SiO_4 \quad (5)$$

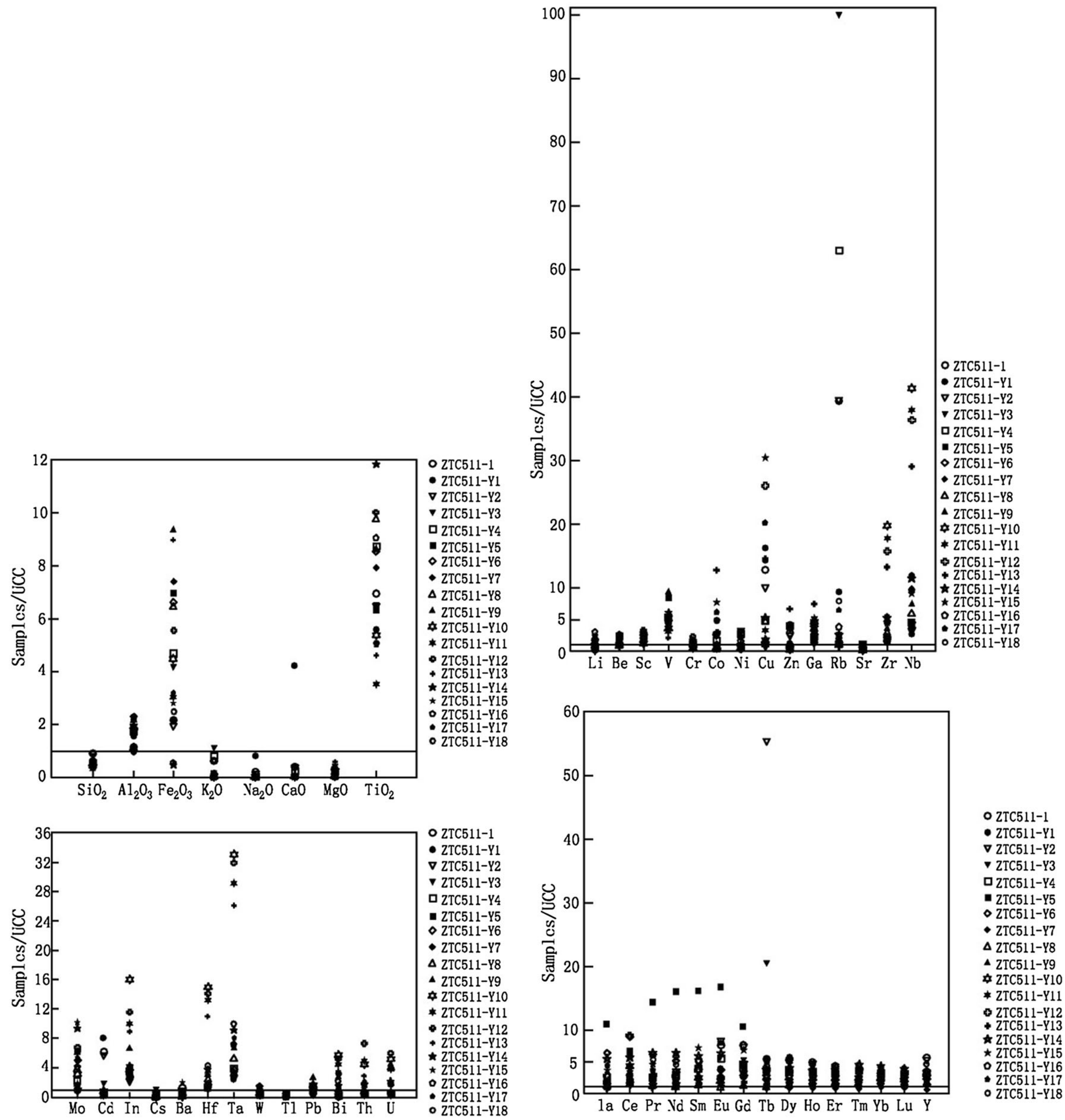


Fig. 7 Comparison of major element, trace element, rare earth element in the iron-bearing rock system and upper continental crust (base map after Guo and Su 2014)

Therefore, hematite, in the form of debris, could be produced in the weathering crust eluvial area and this type of hematite could be removed and re-transported to the sedimentary basin.

When the hydrolysis reaction happens to ferruginous silicate minerals, the non- ferruginous feldspathic minerals would also be in a hydrolysis reaction concurrently and then produces kaolinic minerals, i.e. the hydrolysis reaction of albite (6) is as bellow:

$$4Na[AlSi_3O_8]\,(albite) + 6H_2O \rightarrow Al_4[Si_4O_{10}](OH)_8(kaolinite) + 8SiO_2 + 4NaOH \quad (6)$$

6 Conclusions

(1) In terms of the genesis of mineral deposit, the Guizhou Xianglushan-type iron deposit is of the Emeishan basalt top paleo-weathering crustal re-sedimentary (or accumulating) type. The iron-bearing rock system is widely distributed in the eastern border of ELIP in western China and has great potential for ore-forming.

(2) For the Xianglushan-type iron deposits, material sources are provided by Emeishan basalt weathering. The product of weathering is deposited (or accumulated) in the large shallow lake basin of the near

shore continental faces of the Late Permian Guizhou basalt plateau. Thereafter, the processes produced an initial iron-bearing rock system which is influenced by the secondary leaching which overlaps the late stage of diagenesis. The deposit is a typical example of ELIP weathering mineralization.

(3) Parameters of the geochemical characteristics and weathering index of the iron-bearing rock system indicate that the deposit occurred in warm and wet climate conditions and that weathering has reached an advanced level.

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