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Study on the geological conditions of metallogenesis of the Shazi large-scale anatase deposit in Qinglong County, Guizhou Province

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Abstract The Shazi large-scale anatase deposit in Qinglong County, Guizhou Province, has been discovered recently and now is under exploration. Investigations show that the orebodies mostly occur at the top of the karst unconformity of the Middle Permian Maokou Formation strata and at the bottom of the Emeishan basalt. And the following three prerequisites should be satisfied for the formation of the deposit: 1) there must be the material source of anatase; 2) there must be weekly alkaline media and low-tempeature and low-pressure conditions; 3) there was no high-temperature and high-pressure environment subsequently for the transformation of anatase into rutile. In the Emeishan basalt of western Guizhou, the element Ti mostly entered the silicon-oxygen tetrahedra of picrite in heterovalent isomorphism (Ti^{4+}+Al^{3+}→Mg^{2+}+Si^{4+}). When volcanic ejecta resultant from strong eruption of the Emeishan basalt magma fell into water, picrite was usually dissociated to chlorite. Thus, the element Ti^{4+} in the picrite could be released from the silicon-oxygen tetrahedraa of picrite into water, and conbined with oxygen in the water to form TiO_2. This paper has proved that this deposit, enriched in anatase, discovered recently at Shazi, Qinglong Country, Guizhou Province, is a residual-deluvial-type deposit. Its genesis can be explained as follows. Volcanic clastics formed at the early stage of strong eruption of the Emeishan basalt magma were chemically deposited to form anatase in the low-temperature, low-pressure and weekly alkaline waters in the karst depressions at the top of the Maokou Formation (limestone) strata. The anatase was then dissociated owing to weathering and leaching during the Quaternary and the anatase was further enriched to form the residual-deluvial-type anatase ore deposit.

Key words Shazi anatase deposit; Emeishan basalt; geological condition of metallogenesis; Guizhou Province

1 Introduction

Anatase and rutile are the industrial minerals of critical shortage in China and they are mainly used to produce highly pure titanium dioxide and extract metallic titanium. Its domestric quantity demand is very large (Wu and Zhang, 2006; Cao, 1996). At present, China is almost completely dependent on the imports of high-grade rutile (anatase)-type titanium dioxide that is very expensive. Moreover, anatase is superior to rutile in the field of nano-photocatalysis (Gao and Wang, 2008), and it is one of the 14 kinds of minerals of strategic storage, on which China is highly dependent. Therefore, prospecting and exploration of and research on anatase ore deposits are of great economic significance.

The Shazi anatase ore deposit is a large-scale residual-deluvial-type amatase deposit discovered by Nei, et al. in 2007 in Qinglong County, Guizhou Province. From 2007 to 2011 a reconnaissance and detailed geological exploration had been carried out on this deposit. After being put on records by Guizhou Provincial Office of Land and Resource, it has been already proved that the amount of anatase ore of this deposit is 2306.09 ($\times 10^5$) ton and the amount of TiO_2 resources is 102.48 ($\times 10^5$) ton, with an average grade of 4.39%. In the past only in the Yangtizishan-Moshishan region of Inner Mongonia were the sedimentary metamorphic- and hydrothermal transformation-type anatase ore deposits found (Zhao et al., 2008a, b; 2006). This anatase ore deposit is one discovered for the first time in the residual deluvial soil resultant from weathering of the Emeishan basalt in Guizhou. It is marked that the large-scale residual delluvial-type anatase ore deposit has been discovered for the first time in China, thus ending the history of no titanium ore resource in Guizhou Province. So, the discovery of this anatase ore deposit in Guizhou is of great significance in re-evaluating mineral resources in southwestern Guizhou Province and also has made great contributions to research on the genesis of anatase ore resources throughout the world. It is also of great significance in research on the geological conditions of formation of this anatase ore deposit.

2 Geological background of meallogenesis

2.1 Regionally geological background

The Shazi anatase ore deposit is located in the southwestern part of Guizhou Province, and geotectonically it is situated at the juncture of the southwestern margin of the Yangtze continental block and the western section of the South China fold system. The deposit lies in the eastern part of the Emeishan basalt under the control of the SN-extending East Yunnan deep fault, the NW-extending Yadu-Ziyun deep fault and the EW-extending Nayong-Wengan deep fault, i.e., in the region on the eastern margin of the earliest rift basin induced by the Emeishan mantle plume (Fig. 1).

2.2 Ore-controlling rocks and strata

The ore-controlling rocks and strata are the Upper Permain Emeishan Basalt Formation ($P_3\beta$) and the Middle Permian Maokou Formation limestone (P_2m). The Upper Permian Emeishan Basalt Formation ($P_3\beta$) is divided into two parts:

The upper part ($P_3\beta^2$) consists of basaltic lava, which is grayish-green and dark grey in color, and is a dark brown massive basalt in the weathering front intercalated with basaltic breccias lava, approximately 100–130 m in thickness. The upper part refers to the top of ore-host strata.

The lower part ($P_3\beta^1$) is complicated in petrology, grayish-white, yellowish-white, grayish-black and yellowish-brown in color; compact massive, brecciaed, and laminated in form. It consists of ferritized silicolite, clayey silicolite, clayized silicolite and clayized basaltic sedimentary pyroclastic rocks intercalated with claystone, in unconformable karst contact with the underlying Middle Permian Maokou Formation limestone (P_2m), and its thickness (varying over the range of 0–43 m) is controlled by karst fluctuation. The layer thickness is 0–43 m. This layer is one in which anatase occurs.

The Middle Permian Maokou Formation limestone (P_2m) is a grey, dark grey, mediam-thick layer intercalated with thick-layered micrite-sparite bioclastic limestone and limestone. It is the rock at the bottom of the ore-host strata.

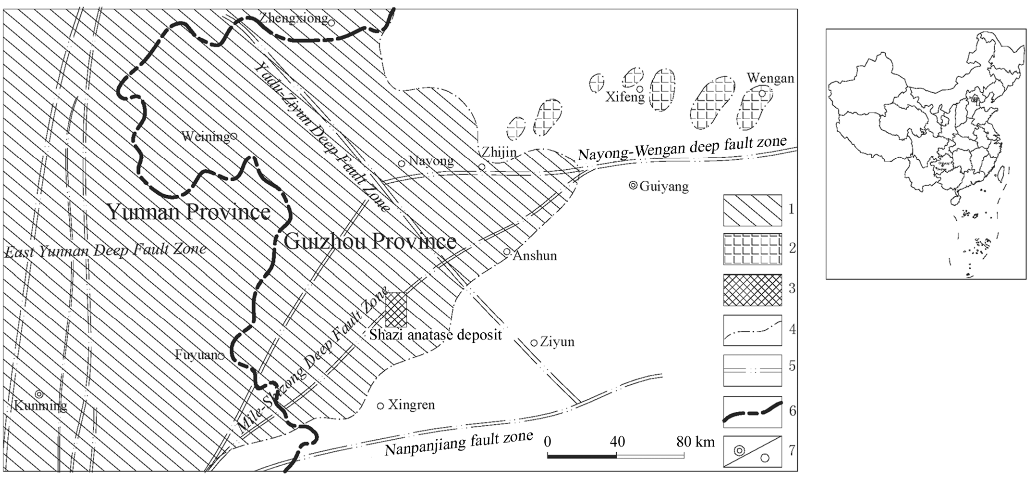

Fig. 1. Geological sketch map showing the distribution of the Emeishan basalt in Guizhou. 1. The region where the Emeishan basalt is widely distributed; 2. the region where the Emeishan basalt is scatteredly distributed; 3. the Shazi anatase ore zone in Qinglong County; 4. the distribution boundary of the Emeishan basalt; 5.deep giant fault zone and fault zone; 6. provincial boundary; 7. provincial capital/county (data source: Gao and Li, 2002; Regional Geology of Guizhou Province, 1987).

2.3 Ore-controlling structure

The mining district is located on the northwestern limb of the Bihenying dome anticline. The Bihenying dome anticline is a northwestward dipping uniclinal structure. From SE to NW there are exposed in succession the Middle Permian Maokou Formation limestone (P_2m), the Upper Permian Emeishan Basalt Formation ($P_3\beta$) and the Upper Permian Longtan Formation coal series (P_3l). The strata strike north-eastwards (25°–45°) and dip north-eastwards with the gentle dip angle varying between 14° and 19°. In the mining district there is a NE-extending fault, and in the hanging wall of the NE-extending fault are developed three karst depressions which are arranged in succession in a NE direction. Vertical fractures are well developed within the mining district, with the NE-SW-extending fractures being dominant. Along the vertical fractures are developed grikes, fluid bowls or sink holes of various sizes. Anatase ore-occurring positions in the lower part of the Emeishan Basalt Formation ($P_3\beta^1$) are distributed in larger karst depressions, which are controlled by the vertical fractures. Clayized basaltic sedimentary pyroclastic rocks are partially weathered to red clay because they are exposed on the Earth's surface and located below the groundwater level.

Explanations were made by using the ETML and sat-7 remote sensing data and selecting wave bands 7, 4 and 1 and combine them as a remote sensing image structure. In the region linear structures are relatively developed, mainly extending north- eastwards; in the region circular structures are relatively developed as well, in conformity with the linear structures, also extending north-eastwards. In addition they obviously overlap the proven Nos.1, 2 and 3 orebodies (Fig. 2).

3 Geological characteristics of orebodies

3.1 Attitudes of orebodies

There have been proved three anatase orebodies of industrial value, which are arranged in a north-west direction, numbering successively as follows: No. 1 anatase orebody, No. 2 anatase orebody and No. 3 anatase orebody (Nie et al., 2011), as shown in Figs. 2 and 3.

No. 1 anatase orebody: It occurs in the karst depression at the top of the Maokou Formation limestone. The orebody is irregular in form and extends north-westwards on the ground surface. Its cross section is lenticular in shape, covering a surface distribution area of 71655 m^2. The orebody is 498–665 m long, 21–60 m wide and 4.40–22.46 m thick, with a thickness variation coefficient of 43.5%. The variation of its thickness is relatively stable.

No. 2 anatase orebody: It occurs in the karst depression at the top of the Maokou Formation limestone, is irregular in form, and extends in a NNW-SE direction on the ground surface. Its cross section is stratoid in form. The orebody covers a surface-distribution area of 297982 m^2, and it is 580–955 m long, 93–590 m wide and 2.70–42.0 m thick, with a thickness variation coefficient of 42.5%. The variation of its thickness is relatively stable.

No. 3 anatase orebody: It occurs in the karst depression at the top of the Maokou Formation limestone. The orebody, irregular in shape, extends east-westwards. Its cross section is stratoid in form, covering an area of 204135 m^2. The orebody is 320–789 m long, 155–465 m wide and 3.50–24.8 m thick, with a thickness variation coefficient of 41.7%. The variation of its thickness is relatively stable.

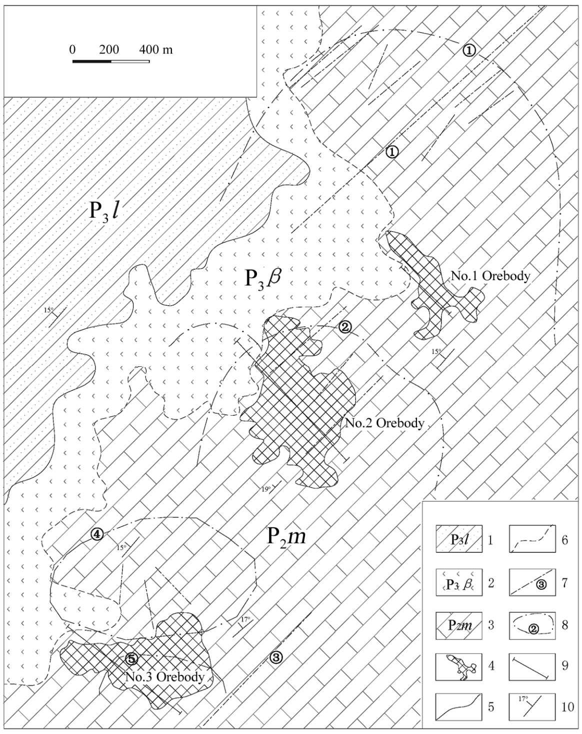

Fig. 2. Geological sketch map of the Shazi anatase ore deposit. 1. Upper Permian Longtan Formation coal series; 2. Emeishan basalt; 3. Middle Permian Maokou Formation limestone; 4. anatase orebody; 5. geological boundary; 6. karst uncomformable boundary; 7. linear structure explained on the basis of remote sensin; 8. circular structure explained on the basis of remote sensing; 9. representative prospecting line profile; 10. attitude of strata.

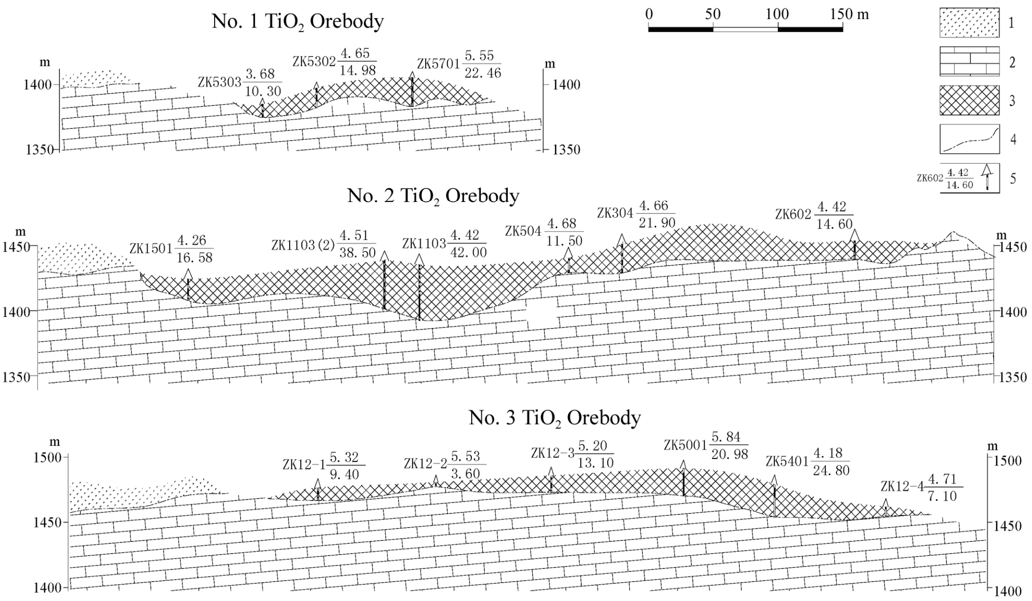

Fig. 3. Cross section of orebodies in the Shazi anatase deposit. 1. Emeishan basalt; 2. Middle Permian Maokou Formation limestone; 3. anatase orebody; 4. karst uncomformity; 5. completed drilling hole, drilling hole No, the average TiO_2 value (%) of a single drilling hole/the real thickness (m) of ore bed in a single drilling hole.

3.2 Characteristics of ores

3.2.1 Chemical composition of ores

No. 1 anatase orebody: TiO_2 2.09%–6.16%, averaging 4.15%; grade variation coefficient is 11.7%. The variation of ore grade is stable.

No. 2 anatase orebody: TiO_2 1.87%–5.91%, averaging 4.29%; the grade variation coefficient is 17.9%; the variation of ore grade is stable.

No. 3 anatase orebody: TiO_2 1.89%–6.11%, averaging 4.29%; the grade variation coefficient is 15.7%; the variation of ore grade is stable.

Results of analysis for oxides of macroelements in the three orebodies (n=10) are presented below. Mean values are: SiO_2 37.15%, TiO_2 4.34%, Al_2O_3 20.51%, CaO 0.42%, MgO 0.58%, K_2O 0.74%, Na_2O 0.17%, MnO_2 0.22%, P_2O_5 0.40%, and TFe_2O_3 21.39%, with LOSS=12.11%.

Results of REE analysis (n=73) for the three orebodies are shown as follows: the contents of La, Ce. Pr. Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y are very low, even lower than the REE contents of normal basalts, generally falling within the range of clark values.

Results of trace element analysis for the three orebodies (n=68) are presented as follows: the contents of such trace elements as Ag, Sb, Hg, As, Ba, Be, Bi, Cd, Cs, Co, Cr, Cu, Ga, In, Hf, Mo, Nb, Ta, Ni, Rb, Sr, Th, Tl, U, V, Zn and Li are not high, mostly falling within the range of clark values. The content of Sc is relatively high. This needs to be further studied.

3.2.2 Mineral composition of ores

The ores of the three orebodies are mainly composed of red, yellow anatase-bearing clay and mild clay. Gravels are commonly seen in the clay and they are compositionally dominated by basaltic pyroclastic rock, clayey siliceous rock, ferromanganic claystone, tuff, etc. The gravels are variable in size, ranging from 2 milimeters to several tens of centimeters. Ore minerals are mainly anatase and limonite. Gangue minerals are mainly sericite, chlorite, kaolinite and quartz and subordinately mica, plagioclase, ferruginous and argillaceous materials, etc. The ores are complicated in composition and have preserved ferritized siliceous rock, clayey siliceous rock, clayized basaltic sedimentary pyroclastic rock intercalated with claystone in the original rocks.

3.2.3 Texture and structure of ores

(1) Ore structure

The ores are yellow, light brown and grey in color and loosely earthy in form, mainly exhibiting earthy structure, followed by massive, cellular and brecciaed structures.

(2) Ore texture

Pelitic texture: the ores exibit mainly politic texture and are composed predominantly of ferruginous and argillaceous materials, with the grain size <0.004 mm in most cases. Either crystalloblasts or matrixes are mostly composed of argillaceous material.

Micro-scaly texture: sericite, kaolinite, chlorite and other minerals in the ores mostly exhibit micro-scaly textures, and are distributed randomly, with grain size <0.03 mm in common cases.

Blastoporphyritic texture: The matrix exhibits blastopelitic texture. The protolith of ores is igneous effusive rock. The composition of phenocrysts in the prolith can not be distinguished, and they are composed mainly of ferruginous and argillaceous (kaolinite, sericite, etc.) materials. Their aggregates are usually platy, columnar and perfectly round in shape. The phenomena of corrosion, fragmentation and polymerization can be commonly observed, and the edges are relatively distinct. The matrix is composed mainly of ferruginous material (<0.004 mm in grain size), with a minor amount of detritus particles that consist of quartz, mica, feldspar and other minerals. The detritus particles are angular and xenomorphically granular in form and are distributed randomly.

Coming next are microcrystalline texture, pseudomorphic texture, alteration intergranular inersertal texture, etc.

3.2.4 Ore types

The ores are of oxide ore type. The oxide ores can roughly divided into five types: clayey oxide ore, siliceous clayey oxide ore, siliceous tuffaceous oxide ore, ferromanganic oxide siliceous clayey oxide ore and kaolinite siliceous oxide ore.

3.3 Occurring forms of anatase

Titanium in the orebodies occurs mainly as micro-fine-grained anatase embraced in the aggregates of clay minerals, clay with feldspar pseudomorphism, limonite and secondary quartz. Anatase is very fine in grain size. Phase analysis, X-ray diffraction analysis and laboratory ore-dressing experiment indicated that anatase is present as a grey, black and colorless aggregate or mono-mineral. It is 8–20 μm, mostly 10–16 μm in grain diameter. This part of titanium accounts for 77.38% of the total, so it is called the titanium which is hard to pick out. The rest titanium is present in the isomorphic form in limonite, accounting for 18.97% of the total, which is referred to as the titanium which is impossible to pick out. Please see Fig. 4 (photos 1, 2, 3, and 4).

4 Analysis of the geological conditions of metallogenesis

4.1 Forming conditions of anatase minerals

It is well known that anatase as a secondary minerals is widespread in crystalline rocks, or as such alteration minerals as sphene, ilmenite and titanomanganetite (Geology Dictionary Office, 1981). Anatase is not so stable and common as rutile, so it is far more rarely seen than rutile. Anatase is a Ti-bearing independent mineral which is rarely seen in nature. The commonly seen Ti-bearing minerals in nature are mainly ilmentite and rutile (Qiu, 1980).

The chemical composition of anatase is TiO_2 and the contents of TiO_2 in anatase are mostly within the range of 98%–99% and the contents of FeO are low (mostly lower than 0.4%). It occurs as uniaxial negative crystals (Li, 2008). Anatase, rutile and brookite are the three heteromorphic forms of crystallization. The forming conditions of the three minerals are different. Anatase is formed under low-temperature and low-pressure conditions (Vincheel and Vincheel, 1953; Doucet and Synthese, 1967), whereas rutile is produced under high-temerature and high-pressure conditions (Goldsmith and Force, 1978; Force, 1991). Anatase can be formed in weakly alkaline media and brookite can be formed in the alkaline media in which sodium oxide is high (Jackson et a1., 2006; Chen and Ji, 1985). The above data indicate that the forming condition scope of anatase is relatively narrow. Only under such conditions that sufficient oxygen gas is supplied, the temperature and pressure are low and the forming environment is weakly alkaline can anatase be formed.

Therefore, the following three prerequisites must be satisfied for the formation of anatase deposits: (1) there must exist material sources for the formation of titanium ores; (2) there must be low-temperature and low-pressure, weakly alkaline media for the formation of anatase; and (3) there is no later high-temperature and high-pressure environment which will make anatase convert to rutile.

4.2 Analysis of the geological conditions of metallogenesis of anatase ore deposits

4.2.1 Material sources for the formation of anatase ore deposits in the region

In the region titanium involved in the formation of anatase ore deposits was derived mainly from the Emeishan basalt. The mining district is located in the eastern part of the Emeishan basalt sheet that is thick in the west and thin in the east. It is the eastern marginal zone of the earliest rift basin induced by the Emei mantle plume (Song et al., 2002). According to previous studies and regional data, western Guizhou includes the Shazi region of Qinglong County, where the basalts are chemically high in Ti but low in Mg, belonging to the high-Ti tholeiites (Mao et al., 1992). The chemical compositions of basalts in the mining district are SiO_2 46.44%,$Ti0_2$ 3.64%, Al_2O_3 14.35%, Fe_2O_3 6.67% and FeO 7.70%. Mineralogical studies of the basalts indicated that such secondary minerals as titanomagnetite and ilmenite are rarely observed in the basalts, the contents of titanium in the major metanocritic mineral—picrite are relatively high, and Ti in the basalts finds its way into the silicon-oxygen tetrahedra of picrite mostly in heterovalent isomorphic form (Ti^{4+}+Al^{3+}→Mg^{2+}+Si^{4+}), and titanium mono-minerals are seldom formed.

The Qinglong region of Guizhou was just located in the shore tidal flat facies belt during the Late Maokou stage (Early-Middle Permian) (Nie, 2008; Chen et al., 2003; Cao, 1991). At the same time when the crust was uplifted along with the Dongwu movement, the strong eruption of the Emeishan basalt magma occurred (Feng, 1991). The volcanic ejecta resultant from the eruption of the Emeishan basalt magma fell into water, therefore, they must have been eroded and disintegrated. As a result, the melanocritic mineral—picrite would necessarily decomposed and disintegrated to chlorite, and Ti in the picrite would be completely released from the host mineral into water, thus providing an abundant source of Ti for the formation of anatase ores in the region.

4.2.2 Typical geochemical barriers in the karst depressions with weekly alkaline water

In the Qinglong region of Guizhou the top of the Middle Permian Maokou Formation limestone was exposed on the ground surface due to the influence of crust uplifting caused by the Dongwu movement, followed by karstification. As a result, there were formed such paleomorphological features as karst highland and karst depression. Because of near-shore tidal flats there was waterlogging in the karst depressions (Wang, 1994).

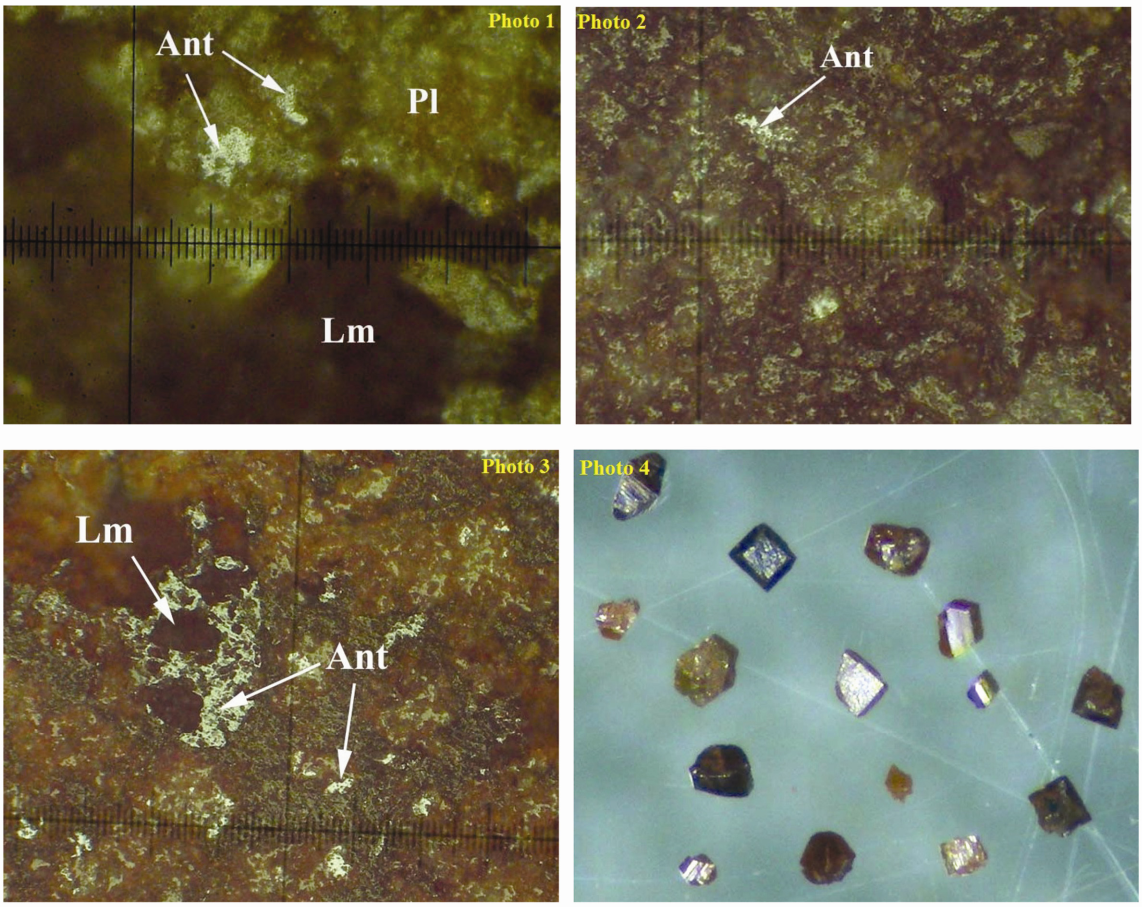

Fig. 4. The micrograph of anatase. Photo 1. Anatase (Ant) embraced in clay with plagioclase (Pl) pseudomorphism. Reflective single polarized light, each metre on the scaleplate is 0.006 mm. Photo 2. Anatase (Ant) in argillaceous material. Reflective single polarized light, each metre on the scaleplate is 0.006 mm. Photo 3. Anatase (Ant) in intergrowth with limonite (Lm). Reflective single polarized light, each metre on the scaleplate is 0.006 mm. Photo 4. Anatase (Ant) in artificial heavy concentrate (stereoscopic microscope photo).

According to our studies, basalts in western Guizhou including the Shazi region, Qinglong County, are enriched in Na but depleted in K (Na_2O 5.33%, K_2O 0.17%). The Na-rich feldspars were eroded and decomposed in the water body of the karst depression. Under this circumstance K^+ found its way into clay minerals while Na^+ was dissolved in water, thus forming a typical geochemical barrier in the karst depression with weekly alkaline water. As the karst depression with weekly alkaline water is situated on the earth's surface oxidation zone, there will be sufficient O_2, thus creating sufficient conditions for the formation of TiO_2. Such the karst depression water body was separated by karst highland to become a relatively isolated weekly alkaline water regime, i.e., a special geochemical barrier, thus providing the necessary environmental conditions for the formation of anatase.

4.2.3 Low-temperature and low-pressure conditions for the formation of anatase during the stage of metallogenesis in the region

By using ETML and sat-7 remote sensing data and selecting wave bands 7, 4 and 1 and combining them as the remote sensing image, it is indicated that the ring-like structures and linear structures in the region consistently extend north-eastwards, obviously overlapping the proven Nos.1, 2 and 3 orebodies in space. According to the analysis of regional data, the mining district is just located in the Mile-Shizong fault zone. It is deduced that there would exist a local heat source during the eruption of basalt magma. Additionally, high-temperature volcanic ejecta fell into the water body of the karst depression, forming earth's surface hot water. It is deduced from the thickness of accumulated pyroclastic deposits that the water body at that time was as deep as more than ten meters and had a certain static pressure, creating a low-temperature and low-pressure environment, thus satisfying the conditions for the formation of anatase.

4.3 The mechanism of formation of the Shazi anatase ore deposit

Due to the outer electron configuration of the element Ti ($3d^24s^2$), four electrons are easy to lose to form a Ti^{4+} cation. Titanium in the Emeishan basalt in the western part of Guizhou usually finds its way into the silicon-oxygen tetrahedra of picrite in hetrovalent isomorphic form ($Ti^{4+}+Al^{3+}\rightarrow Mg^{2+}+Si^{4+}$). Along with the process that volcanic ejecta resultant from strong eruption of the Emeishan basalt magma fell into water and the eroded and dissociated. As a result, picrite was disaggregated to chlorite, and Ti in the picrite would be released from silicon-oxygen tetrahedra into water and combine with oxygen in the water to produce TiO_2.

There are a number of paleo-geomorphological karst highlands and karst depressions at the top of the Middle Permian Maokou Formation limestone around the Shazi region, Qinglong County. Owing to the near-shore tital flats, some of the karst depressions are waterlogged. As the basalts in the Shazi region, Qinglong County, are enriched in Na but depleted in K, the Na-rich feldspars experienced diabrochomorphism and dissociation, accompanied with the dissolution of Na^+ in water, making the water accumulated in the karst depressions become weekly alkaline, thus providing the necessary environmental conditions for the formation of anatase in the region. In addition, there was developed an low-temperature and low-pressure environment in such a confined water regime, leading to the production of relatively pure anatase (TiO_2). Due to the limitation of the water regime in a single karst depression, there is only a little difference in water temperature and pressure, as well as in pH value. As there is only a small difference in concentrations between Ti^{4+} and O_2, Ti mineralization in a single karst depression is very uniform, and the variation coefficient of TiO_2 in ore is smaller than 20%. Again, due to longer-time sedimentary hiatus at the late Maokou stage, karstification at the tope of the Maokou Formation limestone is not strong, the karst depressions do not fluctuate greatly, and the thickness of ore beds varies relatively steadily, with the thickness variation coefficient <50%.

After the formation of each anatase orebody, the study region underwent Late Permian and later sedimentation and Yanshanian tectonism, but all those geological processes did not come up to such an extent as to create an environment where regional metamorphism was so strong and the temperature and pressure were so high to make anatase convert to rutile. So, the anatase orebodies which were already formed, have been preserved stably. The Hercynian and neotectonic movements made the anatase orebodies exposed on the ground surface, and such carbonate rocks as anatase-enriched basalts were further weathered, leached and decomposed to soil. Then, anatase was therefore enriched in the soil layers to a certain extent.

The genesis of the Shazi anatase ore deposit is expounded as follows. At the early stage of intense eruption of the Emeishan basalt magma the chemical deposition of pyroclastics occurred in the low-temperature and low-pressure, weekly alkaline water media in the karst depressions at the top the Maokou Formation limestone, thus leading to the formation of anatase. After Quaternary weathering and decomposition, anatase was further enriched to form the residual delluvial-type anatase ore deposits like the Shazi anatase ore deposit.

5 Conclusions

(1) It is confirmed that there are three anatase orebodies of industrial value in the Shaxi region, Qinglong County, Guizhou Province and it has been already proven that the amount of ore in this anatase ore deposit is 2306.09×10^5 ton, the resource amount of TiO_2 is 102.48×10^5 ton and the average grade of TiO_2 is 4.39%. The orebody thickness and ore grade are both relatively constant.

(2) There are three prerequisites for the formation of anatase ore deposits: (1) there must exist material sources for the formation of titanium ores; (2) there must be low-temperature and low-pressure, weakly alkaline media for the formation of anatase; and (3) there is no later high-temperature and high-pressure environment which will make anatase convert to rutile.

(3) There do exist the material sources, geochemical barriers in karst depressions with special weakly alkaline water, and low-temperature and low-pressure conditions during the period of mineralization for the formation of anatase in the Shazi region, Qinglong County.

(4) In the Emeishan basalt in western Guizhou titanium is in most cases finds its way into silicon-oxygen tetrahedra of picrite in heterovalent isomorphic form ($Ti^{4+}+Al^{3+}\rightarrow Mg^{2+}+Si^{4+}$). Volcanic ejecta from the strong eruption of the Emeishan basalt magma fell into water, and then eroded and disintegrated. As a result, the picrite was decomposed and disintegrated to chlorite, etc. Ti^{4+} in the pyroxene was released from the silicon-oxygen tetrahedra into water and combined with oxygen in the water to produce anatase (TiO_2).

(5) The genesis of the Shazi anatase ore deposit can be expounded as follows. In the early period of strong eruption of the Emeishan basalt magma the pyroclastics in the low-temperature and low-pressure, weakly alkaline water media in the karst depressions at the top of the Maokou Formation limestone were chemically deposited to form anatase. This anatase was further enriched to form the residual delluvial-type anatase ore deposit.

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