2017 年 11 月 地 球 学 报 Nov. 2017
第 38 卷 增刊 1: 21-24 Acta Geoscientica Sinica Vol.38 Supp.1: 21-24
www.cagsbulletin.com

北大巴山平利—镇坪地区碱性火山作用及锌-萤石成矿作用研究

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北大巴山南北两侧分别以城口—房县断裂和安康断裂为界, 是南秦岭构造带的重要组成部分。区内碱性火山作用十分发育, 除局部出露少量碳酸岩之外, 粗面岩、碱性玄武岩及相关火山碎屑岩岩石组合最为发育, 是铜、锌、萤石等矿床(点)的重要赋矿围岩。不同学者对这些碱性火山岩的演化过程、形成时代和形成构造环境仍存在争议, 已有研究缺乏对这些碱性火山岩空间分布变化对比综合研究, 严重影响了对区域演化的认识。同时其内赋存的锌-萤石矿床成矿时代及成矿物质来源缺乏研究, 制约了区域找矿突破。

本文以平利—镇坪一带发育的碱性火山岩为主要研究对象, 对其岩石矿物组合、岩石地球化学、同位素组成特征及形成时代进行了综合研究, 结合区域已发表资料, 对北大巴山地区碱性火山岩岩浆演化过程、形成时代、岩浆源区特征和可能的形成环境进行了探讨; 并对其中赋存的大磨沟—闹阳坪锌-萤石矿床进行了成矿时代及成矿流体进行了研究, 以探讨其矿床成因。

区域地质调查研究表明, 平利—镇坪一带发育以粗面岩为主、碱性玄武岩为辅的火山-沉积岩石组合, 垂向上由底到顶依次为火山熔岩(粗面岩+少量碱性玄武岩)、火山碎屑岩(凝灰质角砾岩、角砾凝灰岩、凝灰岩)和生物碎屑灰岩。其中火山碎屑岩中火山角砾主要为粗面质火山岩, 同时发育大量碱性长石晶屑。玄武岩发育枕状构造, 灰岩透镜体中富含大量火山碎屑物质和生物碎屑, 表明该套火山-沉积作用主要发生在水下环境; 局部发育的柱状节理玄武岩, 表明部分火山岩出露于水面之上。整体上该套岩石具有与典型海山相一致的岩石组合序列。

矿物学和岩石地球化学研究表明, 碱性玄武岩斑晶主要为斜长石及少量磷灰石和榍石; 玄武岩 SiO_2 含量变化较大(44.16~55.92wt%), 全碱含量(Na_2O+K_2O)较高(6.91~8.43wt%), 具有 TiO_2 含量高(2.63~3.10wt%)、Mg#值较低(40~48)以及 Cr(0.97×10^{-6}~10.70×10^{-6})、Co(3.07×10^{-6}~4.40×10^{-6})和 Ni(1.95×10^{-6}~6.11×10^{-6})含量较低的地球化学特征, 暗示北大巴山地区碱性玄武岩岩浆曾经历了较高程度演化; 稀土元素含量较高(ΣREE=226×10^{-6}~399×10^{-6}), 轻、重稀土元素分异强烈(La_N/Yb_N=11~25); 相对于原始地幔, 碱性玄武岩富集 Th、U、Nb、Ta、Zr、Hf 等不相容元素, 显示典型 OIB 型玄武岩地球化学特征。此外, 碱性玄武岩中 Ba 含量高($33\,290\times10^{-6}$~$58\,380\times10^{-6}$), 具有显著正异常特征; 矿物学电子探针分析结果表明 Ba 元素赋存于长石中, 钡长石端元组分(Cn)变化于 4.77~33.81 之间, 属于钡冰长石系列。钡冰长石主要沿钠长石斑晶边部或裂隙发育, 为成岩后受含钾和钡流体交代所致, 其来源可能与区域上寒武系地层中广泛发育的重晶石/毒重石矿床有关。

粗面岩斑晶由钾长石、黑云母和角闪石共同组成; 粗面岩 SiO_2 含量变化于 60.46 ~ 71.44wt%, TiO_2 含量相对偏低为 0.79~1.09wt%, 全碱含量(Na_2O+K_2O)较高为 8.08~12.75wt%, 岩石 Mg#值较低为 19~32; 稀土元素含量极高(ΣREE=443×10^{-6}~$1\,111\times10^{-6}$), 轻、重稀土元素分异强烈(La_N/Yb_N=14~25), 相对于碱性玄武岩亏损中稀土元素(Gd_N/Yb_N=1.4~2.4), 同时具有显著 Eu 负异常(δEu=0.48 ~ 0.90)。原始地幔标准化微量元素蛛网图显示, 粗面岩富集 Th、U、Nb、Ta、Zr、Hf 等不相容元素, 亏损 Ba、Sr、P 和 Ti 元素。

碱性玄武岩 Nb/Yb 比值较高(22~28), 与典型 OIB 玄武岩比值一致, 在 Th/Yb-Nb/Yb 图解上落于

本文由国家自然科学基金项目(编号: 41172178)、中国地质科学院地质研究所基本科研业务费项目(编号: J1002)和中国地质调查局地质调查研究项目(编号: 1212011121091)联合资助。
收稿日期: 2016-07-27; 改回日期: 2016-08-07。责任编辑: 闫立娟。
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MORB-OIB 地幔演化线范围内，表明其岩浆未经历明显地壳混染作用。全岩 Sm-Nd 同位素分析结果表明碱性玄武岩和粗面岩具有一致的同位素组成特征，对应初始 $^{143}Nd/^{144}Nd$ 比值分别为 0.512 301~0.512 340 和 0.512 252~0.512 328，$\varepsilon_{Nd}(t)$值分别为+2.55~+3.32 和+1.60~+3.07，进一步说明碱性玄武岩和粗面岩具有相同的岩浆源区且主要为 HIMU 地幔源区。此外，Rb-Sr 同位素分析结果显示碱性玄武岩和粗面岩具有异常初始 $^{87}Sr/^{86}Sr$ 比值(0.701 418~0.714 437)，可能为受后期流体交代作用影响的结果。

区域对比研究表明，不同于平利—镇坪地区碱性火山岩具有以粗面岩为主碱性玄武岩为辅的特征，紫阳—岚皋地区滔河口组和竹山地区竹溪组火山岩以碱性玄武岩为主粗面岩为辅；同时两者在碱性玄武岩斑晶矿物组成上也有明显差别，其中平利—镇坪地区主要发育长石斑晶碱性玄武岩，而紫阳—岚皋和竹山地区碱性玄武岩斑晶为辉石和少量的金云母，并在局部地段可见地幔捕掳体。总体上，平利—镇坪地区碱性玄武岩和粗面岩与紫阳—岚皋和竹山地区的碱性玄武岩和粗面岩分别具有相似的稀土元素配分模式和微量元素蛛网图模式，同时其 Sr-Nd 同位素组成具有可对比性，表明这些火山岩的岩浆成分非常相似，但紫阳—岚皋地区滔河口组和竹山一带的碱性火山岩更为接近原始岩浆成分。

系统的矿物学和岩石地球化学综合研究表明，北大巴山地区碱性玄武岩与粗面岩在成分上呈现规律性变化，暗示分离结晶作用在岩浆演化过程中起重要作用，表现为岩浆演化早期主要发生以单斜辉石和钛铁矿(榍石)为主的矿物分离结晶作用，晚期则以斜长石和磷灰石矿物分离结晶作用为主。伴随岩浆演化，稀土元素等不相容元素在粗面岩中更为富集，从而导致粗面岩中稀土元素含量普遍较高。岩浆演化晚期发生的磷灰石分离结晶作用，可能是粗面岩中稀土元素(MREE)相对亏损的原因，而斜长石分离结晶造成了粗面岩中 Eu 和 Sr 负异常。

镇坪牛头店火山-沉积序列中发育的灰岩透镜体中富含生物化石，这些化石分布不规律，以生物碎屑形式存在，其中赋存的古生代海百合茎碎屑暗示其同期的碱性火山作用可能发生于古生代。同时本文对粗面岩中钾长石斑晶进行了 Ar-Ar 年代学分析，获得 Ar-Ar 坪年龄(363±3) Ma，表明北大巴山平利—镇坪一带碱性火山作用形成于晚泥盆世。综合前人于紫阳—岚皋地区煌斑岩中所获得的金云母 Ar-Ar 时代 432 Ma 等资料，本文认为北大巴山地区碱性火山岩可能是多期岩浆活动的产物，早期岩浆活动始于中志留世早期，最晚可到晚泥盆世。

早古生代时期北大巴山地区处于扬子北缘被动大陆边缘，大量侵入的辉长辉绿岩脉表明早古生代晚期发生裂陷，而北大巴山古生代碱性火山岩总体上为扬子板块北缘被动大陆边缘裂陷作用下火山活动的产物。岩浆供给速率及演化程度可能是控制本区不同岩性碱性火山岩分布的主要原因：中志留世—早泥盆世(？)期间(432~407 Ma?)，扬子板块北缘发生初始裂陷，岩浆供给速率较快，形成了紫阳—岚皋和竹山等地以碱性玄武岩为主的火山岩组合；晚泥盆世时期(363 Ma)，岩浆供给速率减慢，岩浆经历了显著分离结晶作用，从而形成平利—镇坪地区以粗面岩为主碱性玄武岩为辅的火山岩组合。

大磨沟—闹阳坪锌-萤石矿床与古生代粗面岩关系密切，矿体(化)严格受断裂控制，主要发育于志留系竹溪群和粗面岩接触部位靠近粗面岩一侧，赋矿围岩为粗面质角砾岩。按照矿化类型可分为大磨沟矿区和闹阳坪矿区，其中大磨沟矿区主要发育闪锌矿化和萤石矿化，及少量黄铁矿化、黄铜矿化和方铅矿化。其中锌矿体主要以团块状或细脉状产出，萤石多呈透镜状或层状产出，根据矿(脉)石间的穿插关系，成矿期次可划分为早期的脉状萤石矿化和晚期的石英-闪锌矿脉矿化。闹阳坪矿区主要发育萤石矿化，萤石矿化呈团块状、细脉状产出，发育梳状结构和晶洞结构，表明萤石矿化过程中有气液成矿作用的参与。总体上，该矿床为受构造控制的气水-热液型矿床。

流体包裹体测温结果显示萤石中原生流体包裹体均一温度为 243~383℃，为中温成矿，而与闪锌矿脉伴生的石英中所记录流体包裹体均一温度较低为 140~273℃。萤石 Sr-Nd 同位素组成和伴生细脉状黄铁矿硫同位素特征显示其成矿物质来源于壳源物质，流体包裹体中 CH_4 等有机质的存在暗示了成矿流体可能来自于矿区内富含生物碎屑的竹溪群灰岩。本文通过萤石矿物 Sm-Nd 等时线，获得了闹阳坪矿区紫色萤石成矿时代为(215.3±3.6) Ma，表明成矿作用发生于晚三叠世。

关键词： 碱性火山岩；OIB；大磨沟—闹阳坪；被动大陆边缘；北大巴山

中图分类号： P511.3; P536 **文献标志码：** A **doi:** 10.3975/cagsb.2017.s1.07

Alkali Volcanism and Zinc-fluorite Mineralization of Pingli–Zhenping Area, North Daba Mountains

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North Daba Mountains, which is an important part of the South Qinling belt, was confined by An'kang Fault in the north and Chengkou–Fangxian Fault in the south. Besides minor lamprophyre and carbonatite, alkali volcanic rocks, characterized by trachyte, alkali basalt and related volcanoclastic rocks, are widespread in North Daba Mountains. These alkali volcanic rocks are the main hosting rocks of copper, Zinc and Fluorite mineralization. Debates on the magmatic evolution, formation age and tectonic setting about the alkali volcanic rocks still exist due to lack of comparison and systematical research of distribution of alkali volcanic rocks, which blocks the perspective of regional evolution. The lack of study on mineralization age and ore-forming material of zinc-fluorite deposit constrains the breakthrough of mineral deposit exploration.

Results of rock assemblage, geochemistry, isotopic composition and formation age of volcanic rocks from Pingli–Zhenping area are presented in this study. The magmatic evolution, formation age, magma sources and formation setting were concluded from our new results and previous data. In addition, the ore genesis of Damogou–Naoyangping zinc-flourite deposit was deduced based on our new results of mineralization age and ore-forming fluid.

A suit of alkali volcano-sedimentary rocks composed of trachyte, alkali volcanic rocks and volcanoclastic rocks develops at Niutoudian area, Pingli–Zhenping County. From bottom to top, the sequence is composed of alkali lava (trachyte and minor basalt), volcanoclastic (tuffaceous breccia, breccia tuff and tuff) and bioclastic limestone, which is typical of seamount assemblage. The volcanic breccias in volcanoclastic rocks are mainly composed of trachyte, and subordinate alkali feldspar. Pillow basalt and limestone enriched with abundant volcanic breccias and bioclasts imply under-water setting. However, the occurrence of columnar basalt indicates parts of the volcanic edifice exposed above the water.

Alkali basalt with phenocrysts composed of plagioclase with minor apatite and titanite, is characterized by various SiO_2 content (44.16~55.92wt%), relatively high Na_2O+K_2O (6.91~8.43wt%) and TiO_2(2.63~3.10wt%) contents, low Mg# values (40~48), Cr (0.97×10^{-6}~10.70×10^{-6}), Co (3.07×10^{-6}~4.40×10^{-6}) and Ni (1.95×10^{-6}~6.11×10^{-6}) contents, representing highly evolved magma. Enriched incompatible elements of Th, U, Nb, Ta, Zr, Hf and REEs (ΣREE=226×10^{-6}~399×10^{-6}), with strongly differentiated REE (La_N/Yb_N=11~25), displaying OIB geochemical attributes. Ba in alkali basalt has an extremely high content of $33\ 290\times10^{-6}$~$58\ 380\times10^{-6}$ and displays positive anomaly. Electron microprobe analysis results for minerals in alkali basalt indicate that Ba is hosted in hyalophane (Cn=4.77~33.81) which occurs along the rim and cracks in feldspar as the product of post-diagenesis fluid metasomatism. The upper Cambrian strata with abundant barite are the potential sources for Ba.

The phenocrysts in trachyte include K-feldspar, biotite and amphibole. Trachyte has various SiO_2 content of 60.46~71.44wt%, relatively low TiO_2 content of 0.79~1.09wt% and Mg# value of 19~32, high Na_2O+K_2O content of 8.08~12.75wt%. The rare earth element content of trachyte is extremely high (ΣREE=444×10^{-6}~$1\ 111\times10^{-6}$) with intense differentiated REE (La_N/Yb_N=14~25), negative Eu anomaly (δEu=0.48~0.90) and more depleted MREE (Gd_N/Yb_N=1.4~2.4) compared with alkali basalt. The Primitive Mantle normalized spider diagram of trachyte is characterized by enriched incompatible elements of Th, U, Nb, Ta, Zr and Hf and delpeted Ba, Sr, P and Ti.

The high Nb/Yb ratios (22~28) of alkali basalt are consistent with OIB-type geochemistry. Alignment along MORB-OIB array on the Th/Yb-Nb/Yb diagram excludes apparent crustal contamination. Alkali basalt and trachyte share common isotopic composition, which is characterized by identical initial $^{143}Nd/^{144}Nd$ ratios (0.512 301~0.512 340 in alkali basalt and 0.512 252~0.512 328 in trachyte) and $\varepsilon_{Nd}(t)$ values (+2.55 ~ +3.32 in alkali basalt and +1.60 ~ +3.07 in trachyte). The HIMU mantle is considered as the potential source for alkali basalt and trachyte. Affected by later stage fluid metasomatism, variable initial $^{87}Sr/^{86}Sr$ ratios of 0.701 418~0.714 437 were obtained.

Regionally, the volcano-sedimentary sequence in Pingli–Zhenping area consists of primary trachyte and minor alkali basalt, while the volcano-sedimentary sequences of Taohekou Group in Ziyang–Langao and Zhuxi Group in Zhuashan area are composed of alkali basalt (with mantle xenolith encircled) and minor trachyte. The phenocrysts of theses alkali basalt include clinoproxene and subordinate phlogopite. Geochemistry and Sr-Nd isotopic compositions of these alkali volcanic rocks are similar with those in Pingli–Zhenping area, but displaying a more primitive magma component.

The change discipline of geochemical component between alkali basalt and trachyte indicates fractional crystallization plays an important role in magma evolution process. Removal of Clinopyroxene and ilmenite (titanite) was dominant during the early stage. Fractional crystallization of plagioclase and apatite took over in the subsequent stage. As the consequence of fractional crystallization, REEs became more enriched in trachyte. Removal of apatite in trachytecaused depletion of MREE and fractional crystallization of plagioclase induced Eu and Sr negative anomalies.

Paleozoic crinoid had been discovered in limestone lenticle in Niutoudian volcano-sedimentary rocks indicating the alkali volcanism erupted at Paleozoic. The age of (363±3) Ma obtained from Ar-Ar dating of K-feldspar phenocryst constrains the alkali volcanism in Pinglin–Zhenping area occurred at Late Devonian. The alkali volcanism in North Daba Mountains was probably the product of multi-stages volcanism commenced at the early stage of Middle Silurian (432 Ma) based on previous research.

The Paleozoic North Daba Mountains was part of the passive margin of Yangtze plate. Rifting occurred at late stage of Paleozoic triggered intrusion of extensive gabbro-diabase. Paleozoic alkali volcanic rocks from North Daba Mountains formed under extensional setting on passive continental margin of Yangtze plate. Magma supply rate and evolution degree were considered to be the main factor controlling the distribution of alkali volcanic rocks. During Middle Silurian to Early Devonian (?), high magma supply rate gave rise to extensive alkali basalts in Ziyang–Langao and Zhushan area. With a low magma supply rate in Late Devonian (363 Ma), magma experienced sufficient fractional crystallization, generating massive trachyte in Pingli-Zhenping area.

Damogou-Naoyangping zinc-fluorite deposit is spatially associated with Paleozoic trachyte. The orebody is strictly bounded by faults, developing along the contact zone of trachyte and Zhuxi group with brecciaed trachyte as the hosting rocks. Two mining districts: Damogou and Naoyangping, are divided based on mineralization type. The Damogou district is predominated by zinc and fluorite mineralization with ore minerals of sphalerite and fluorite, and minor pyrite, chalcopyrite and galena. The zinc orebody exhibit crumby or veinlet structure, which is posterior to fluorite lens and vein. However, fluorite is the primary mineralization type in Naoyangping district, with crumby or veinlet structure. The occurrence of comb and miarolitic texture of fluorite suggested hydrothermal mineralization. The Damogou–Naoyangping deposit is considered as the fault-controlled hydrothermal deposit.

The homogenization temperature of primary inclusion in fluorite is 243~383℃, whereas those inclusions in quartz from sphalerite veinlet have lower homogenization temperature of 140~273 ℃. The Sr-Nd isotopic composition of fluorite and sulfur isotopes indicate a crustal source for ore forming material, which is probably from the Zhuxi group limestone. Fluorite Sm-Nd isochron age of (215.3±3.6) Ma indicate the mineralization took place in the Late-Triassic.

Key words: alkali volcanic rocks; OIB; Damogou–Naoyangping; passive continental margin; north Daba Mountains

Acknowledgements:

This study was supported by National Natural Science Foundation of China (No. 41172178), Central Public-interest Scientific Institution Basal Research Fund (No. J1002) and China Geological Survey (No. 1212011121091).