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敦煌地块中酸性火山岩锆石 U-Pb 年代学、岩石成因 及对古亚洲洋俯冲的指示

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摘要:【研究目的】敦煌地块地处塔里木板块、中亚造山带和祁连造山带的结合部位, 其形成时代、构造属性等一直存在争议, 本文以出露于敦煌地块东北缘的中酸性火山岩为研究对象, 尝试对解决以上问题提供证据。【研究方法】通过对 3 件英安岩样品进行 LA-ICP-MS 锆石 U-Pb 测年、对中酸性火山岩进行岩石地球化学分析, 探讨该套火山岩的形成时代、岩石成因及构造属性等。【研究结果】锆石 U-Pb 年代学表明 3 件英安岩样品的成岩年龄为(533.2±6.1)Ma、(527.7±6.1)Ma、(514.9±3.4)Ma, 时代为早寒武世。研究区出露的安山岩具有典型高镁安山岩特征, 如 SiO₂ 含量 51.4%~55.98%, 具有高 MgO(5.81%~12.31%) 和 Mg[#](59~72)、高 Cr(166×10⁻⁶~1020×10⁻⁶) 和 Ni(41.4×10⁻⁶~169×10⁻⁶) 以及低 FeO^T/MgO(0.79~1.56) 比值的特征, 此外安山岩也具有高的 Ti/Zr、Ti/Y 比值和低的 Rb/Sr 比值, 具有高的 La/Nb、Ba/Nb 和 Ba/La 比值。中酸性火山岩富集大离子亲石元素(Rb、Ba、U、K) 及 LREE, 亏损高场强元素(Nb、Ta、Zr、Ti) 及 HREE, 具有近平坦的右倾稀土配分模式, 以及较低的 Nb/La(0.36~0.46) 和 Hf/Th(1.02~1.34) 比值和较高的 Hf/Ta(5.71~8.60)、La/Ta(21.72~29.50) 比值, 显示了岛弧火山岩的地球化学属性。【结论】该套中酸性火山岩为敦煌群之上早寒武世火山岩盖层, 形成于岛弧环境, 可能由俯冲的早寒武世古亚洲洋洋壳熔体(流体)交代地幔楔部分熔融作用形成, 且在上升过程中受到地壳物质的混染, 根据火山岩形成时代及岩石地球化学特征认为古亚洲洋的俯冲作用最早可追溯至早寒武世。

关键词: 敦煌地块; 锆石 U-Pb 测年; 火山岩盖层; 高镁安山岩; 古亚洲洋; 地质调查工程

创新点: 对出露于敦煌地块东北缘火山岩的时代与归属进行了重新厘定; 对古亚洲洋的俯冲时限进行了探讨。

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Zircon U-Pb geochronology, petrogenesis of intermediate-acid volcanic rocks in Dunhuang block and its indication of subduction of Paleo-Asian Ocean

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Abstract: This paper is the result of geological survey engineering.

[Objective] Dunhuang block is located at the junction of Tarim Plate, Central Asian Orogenic Belt and Qilianshan Orogenic Belt. Its formation age and tectonic attributes have always been controversial. This paper takes the intermediate-acid volcanic rocks exposed in the northeastern margin of Dunhuang block as the research object, and attempts to provide evidence for solving the above problems. **[Methods]** In this paper, LA-ICP-MS zircon U-Pb dating of three dacite samples and geochemical analysis of intermediate-acid volcanic rocks were carried out to explore the formation age, petrogenesis and tectonic attributes of the volcanic rocks. **[Results]** LA-ICP-MS zircon U-Pb geochronology indicates that three dacite samples form at (533.2±6.1) Ma, (527.7±6.1) Ma and (514.9±3.4) Ma, belonging to Early Cambrian. The andesite exposed in the area has typical characteristics of high-Mg andesite, e.g., SiO₂ contents (51.4%–55.98%), high MgO contents (5.81%–12.31%) and Mg[#] values (59–72), high Cr (166×10⁻⁶–1020×10⁻⁶) and Ni (41.4×10⁻⁶–169×10⁻⁶) contents, and low FeO^T/MgO (0.79–1.56) ratios. Otherwise, the andesites have high Ti/Zr, Ti/Y ratios and low Rb/Sr ratios, high La/Nb and Ba/Nb and Ba/La ratios. The intermediate-acid volcanic rocks are enriched in large ionic lithophile elements (Rb, Ba, U, K) and light rare earth elements, depleted in high field strength elements (Nb, Ta, Zr, Ti) and heavy rare earth elements, with characteristics of near-flat right-leaning rare earth distribution pattern, low Nb/La (0.36–0.46) and Hf/Th (1.02–1.34) ratios, high Hf/Ta (5.71–8.60) and La/Ta (21.72–29.50) ratios, indicative of the geochemical properties of island arc volcanic rocks. **[Conclusions]** It is considered that the volcanic rocks should be the Early Cambrian volcanic caprock above Dunhuang Group. The volcanic rocks in the area should be formed in the island arc environment, which may be formed by partial melting of metasomatic mantle wedge in the subduction of the Early Cambrian Paleo-Asian Ocean crust melt (fluid), and contaminated by crustal materials during the ascending process. According to the formation age of volcanic rocks and the characteristics of petrogeochemistry, the subduction of the Paleo-Asian Ocean can be traced back to the Early Cambrian.

Key words: Dunhuang block; zircon U-Pb dating; volcanic cap rocks; high-Mg andesite; Paleo-Asian Ocean; geological survey engineering

Highlights: The age and attribution of volcanic rocks exposed in the northeastern margin of Dunhuang block were re-determined. The subduction time limit of the Paleo-Asian Ocean is discussed.

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1 引言

中亚造山带是世界上最大的增生型造山带之一 (Jahn et al., 2000; Windley et al., 2001, 2007; Kovalenko et al., 2004; Kröner et al., 2008; Xiao et al., 2010, 2013; Xiao and Santosh, 2014), 北接西伯利亚克拉通, 南部与塔里木地块—华北地块相接 (图 1a), 其形成与古亚洲洋的长期俯冲增生作用密不可分 (Khain et al., 2003; Windley et al., 2007)。关于古亚洲洋的初始俯冲时限问题, 地学界一直存在争议: 多数研究者认为古亚洲洋的俯冲作用开始于奥陶

纪—志留纪 (刘敦一等, 2003; 石玉若等, 2004; 张兴龙等, 2004; 田纹全等, 2005; 李锦轶等, 2006; 李文铅等, 2006; 马星华等, 2015; 李文渊等, 2022); 也有部分研究者认为古亚洲洋在早寒武世就已经开始了俯冲作用 (刘金龙等, 2016)。

敦煌地块地处塔里木地块、中亚造山带、祁连造山带的结合部位, 其归属问题一直存在争议: 一些研究者认为敦煌地块属于塔里木克拉通的一部分 (赵茹石等, 1994; 李志琛, 1994; 梅华林等, 1998; 孟繁聪等, 2011; Zong et al., 2013), 而与华北克拉通相互分离; 但也有研究者认为它与华北克拉通的演

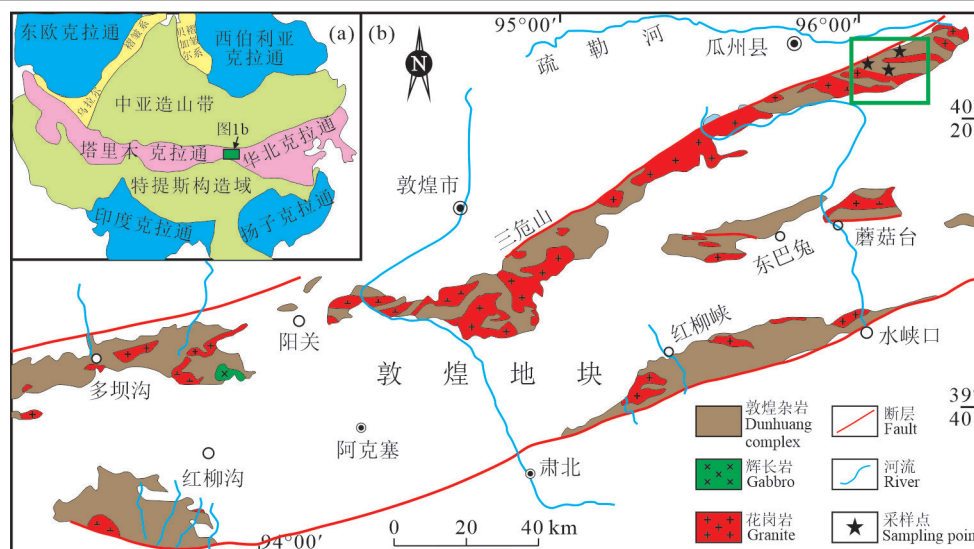


图 1 中亚造山带构造简图(a, 据 Sengör et al., 1993)和敦煌地块地质简图(b)

Fig.1 Tectonic sketch map of the Central Asian Orogenic Belt (a, after Sengör et al., 1993) and simplified geological map of Dunhuang block (b)

化特征相似,是华北克拉通的组成部分(张振法等, 1997; 周国庆等, 2000; 左国朝等, 2003; Zhang et al., 2012, 2013);还有部分学者认为敦煌地块为一个独立块体,具有自己独特的构造特点(潘桂棠等, 2009)。近年有研究表明,阿拉善地块北缘和塔里木地块北缘均受到了古亚洲洋古生代俯冲-碰撞造山作用的影响(Ge et al., 2012; Zheng et al., 2014),赵燕等(2015)认为敦煌地块在古亚洲洋的扩张-闭合过程中,很可能卷入了一系列与古亚洲洋闭合相关的造山活动,应为中亚造山带的一部分。

本文以 1:5 万北桥子幅区域地质调查实测资料为依据,对区内中酸性火山岩进行了 LA-ICP-MS 锆石 U-Pb 同位素年代学和岩石地球化学研究,发现区内中酸性火山岩形成于早寒武世,因此该套火山岩地层应从原敦煌群中解体出来,而这套中酸性火山岩中的安山岩具有高镁安山岩的特征。在此基础上,对该区在早古生代的构造环境进行了探讨,进而为古亚洲洋演化的重建提供约束。

2 地质背景及岩石学特征

研究区位于敦煌地块东北缘,地处塔里木地块、中亚造山带、祁连造山带的结合部位(图 1a),行政区划属于甘肃省酒泉市瓜州县梁湖乡。前人将区内出露的中酸性火山岩地层归到古元古界敦煌群,岩石类型以安山岩、玄武安山岩、粗面安山

岩、英安岩为主,夹玄武岩、流纹岩及中酸性火山角砾岩。区内侵入岩分布广泛,岩石类型多样,以中酸性侵入岩为主,少量基性侵入岩,主要岩石类型为二长花岗岩、花岗闪长岩、石英闪长岩,以及少量闪长岩和辉长岩。岩浆岩形成时代为寒武纪—泥盆纪,其中奥陶纪和志留纪岩浆活动较为强烈,局部可见中侏罗世基性岩脉。

本次研究以 1:5 万区域地质调查为基础,对区内的火山岩进行了取样(图 1b, 图 2),样品采集处露头较为连续,岩石样品新鲜、无明显变质变形现象,岩性为玄武岩、安山岩、英安岩。具体岩相学特征如下:

玄武岩:新鲜面呈墨绿色,斑状结构,基质呈面粒结构,块状构造。斑晶主要为辉石,其次为斜长石,部分辉石斑晶被角闪石交代,斜长石斑晶被绿泥石所交代呈板状假象,斑晶含量约 25%。基质由斜长石与细粒辉石组成,斜长石晶体呈细小板条状杂乱分布,空隙被细小粒状辉石所充填呈面粒结构,由于岩石发生次生蚀变,部分斜长石多被纤闪石所交代,辉石多被细小帘石所交代(图 3a)。

安山岩:新鲜面为深灰绿色,斑状结构,基质为交织结构,块状构造。斑晶由斜长石和辉石组成,斑晶含量一般不超过 25%,辉石斑晶呈柱状,粒径大小一般在 0.8~4 mm,部分晶体发生次生蚀变被角闪石所交代,斜长石斑晶多呈半自形板状,少数呈

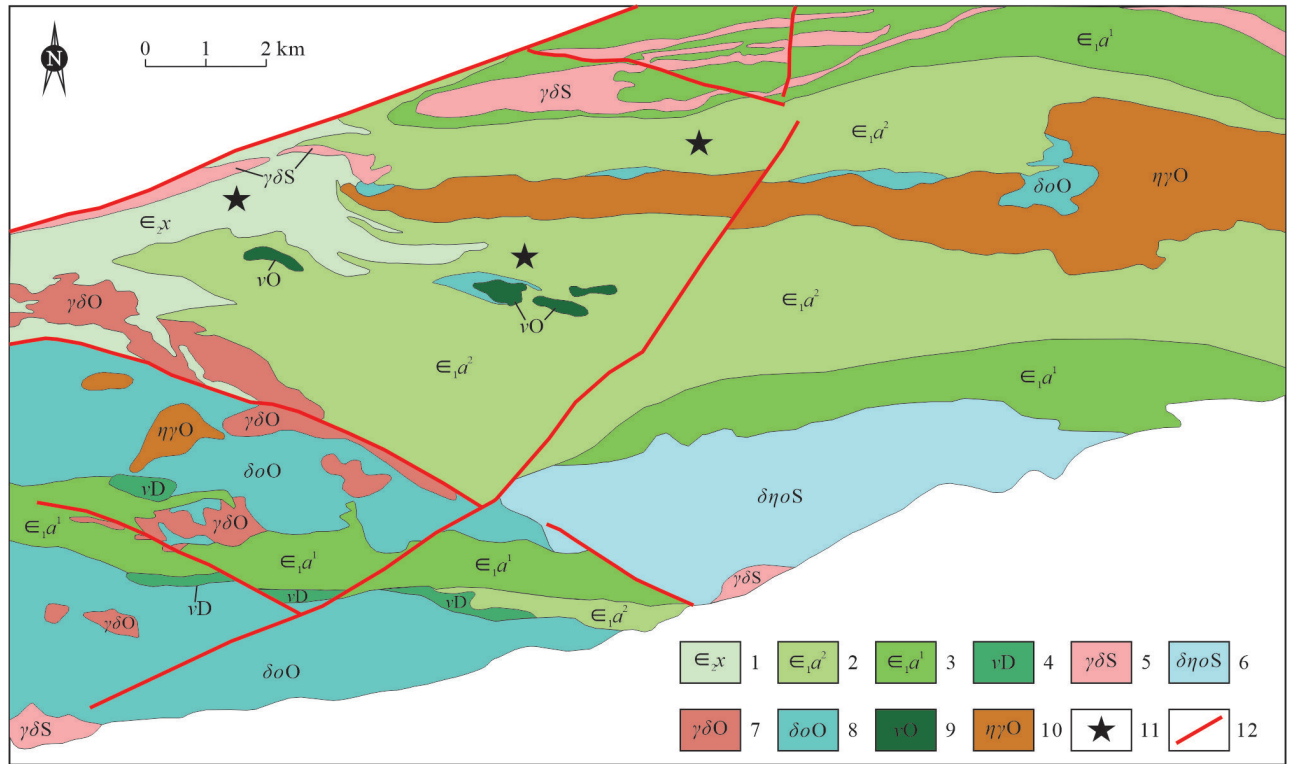


图 2 研究区地质简图

1—中寒武世小宛组; 2—早寒武世安西组第二岩性段; 3—早寒武世安西组第一岩性段; 4—泥盆纪辉长岩; 5—志留纪花岗闪长岩; 6—志留纪石英二长闪长岩; 7—奥陶纪花岗闪长岩; 8—奥陶纪石英闪长岩; 9—奥陶纪辉长岩; 10—奥陶纪二长花岗岩; 11—同位素采样位置; 12—断层

Fig.2 Geological map of the study area

1—Middle Cambrian Xiaowan Formation; 2—Second lithologic section of Anxi Formation in Early Cambrian; 3—Frist lithologic section of Anxi Formation in Early Cambrian; 4—Devonian gabbro; 5—Silurian quartz monzonitic diorite; 6—Silurian quartz amphibolite; 7—Ordovician granodiorite; 8—Ordovician quartz amphibolite; 9—Ordovician gabbro; 10—Ordovician monzonitic granite; 11—Isotope sampling location; 12—Fault

粒状, 粒径大小在 0.2~1.8 mm。基质由细小斜长石组成, 呈细小板状杂乱分布, 多发生次生蚀变, 被阳起石、绿泥石、绿帘石所交代(图 3b)。

英安岩: 新鲜面为浅绿色、灰绿色, 斑状结构, 基质为霏细结构, 块状构造。斑晶主要由斜长石组成, 其次为石英。斜长石斑晶呈半自形板状, 粒径大小一般为 0.2~1 mm。石英斑晶呈细小粒状, 粒径一般为 0.15~1.3 mm, 两种斑晶均有熔蚀现象。基质由斜长石和石英组成, 具有明显的黑云母化和帘石化(图 3c)。岩石中偶见安山岩岩屑, 岩屑中斜长石自形程度较高, 呈小的长柱状(图 3d), 应为同源捕虏物。

3 分析方法

样品的全岩主量和微量元素分析由中国地质调查局西安地质调查中心自然资源部岩浆作用成矿与找矿重点实验室完成, 选择新鲜均一的样品,

经表面去皮、清洗, 再粉碎至 200 目。其中主元素分析采用荷兰帕纳科公司 Axios 4.0 kW 顺序式 X 射线荧光光谱仪(XRF)进行分析, 分析精度优于 5%; 稀土和微量元素利用美国热电公司 Series II 型 SX50 型电感耦合等离子质谱仪(ICP-MS)进行测定, 分析精度优于 10%。

锆石的挑选、制靶、透反射光、阴极发光照相由西安瑞石地质科技有限公司完成。在双目镜下仔细挑选表面平整光洁且具不同长宽比例、不同柱锥面特征、不同颜色的锆石颗粒, 再将这些锆石黏在双面胶上, 用无色透明环氧树脂固定, 待环氧树脂固化之后对其表面抛光至锆石中心。在原位分析之前, 通过透反射光和 CL 图像详细研究锆石的晶体形貌和内部结构特征, 选择无明显裂痕及包裹体的锆石进行测年。

锆石 U-Pb 同位素定年在中国地质调查局西安地质调查中心自然资源部岩浆作用成矿与找矿重



图3 岩石显微镜照片

Py—辉石; Pl—斜长石; Qz—石英

Fig.3 Microscopic photographs of rocks

Py—Pyroxene; Pl—Plagioclase; Qz—Quartz

点实验室完成, 激光剥蚀系统型号为 GeoLas Pro, ICP-MS 型号为 Agilent 7700x。激光剥蚀过程中采用氦气作载气、氩气为补偿气以调节灵敏度, 二者在进入 ICP 之前通过一个 T 型接头混合。每个时间分辨分析数据包括大约 10 s 的空白信号和 40 s 的样品信号。对分析数据的离线处理(包括对样品和空白信号的选择、仪器灵敏度漂移校正、元素含量及 U-Th-Pb 同位素比值和年龄计算)采用软件 Glitter 4.4 完成, 详细仪器参数和测试过程可参考李艳广等(2015)。U-Pb 同位素定年中采用锆石标准 91500 作外标进行同位素分馏校正。对于与分析时间有关的 U-Th-Pb 同位素比值漂移, 利用 91500 的变化采用线性内插的方式进行了校正。锆石微量元素含量利用参考标样 NIST610 玻璃作为多外标、Si 作内标的方法进行定量计算。

4 测试结果

4.1 LA-ICP-MS 锆石 U-Pb 定年

本次工作共对区内 3 件英安岩样品(D5617-TW1、PM12-33-TW1、PM5-20-TW1)进行了锆石 U-Pb 定年, 锆石特征及测试结果如下(图 4, 图 5, 表 1):

D5617-TW1: 对该样品中的 22 粒锆石进行了测年分析, 结果显示: 锆石 CL 图像整体呈灰白色, 短轴 40~65 μm , 长轴 50~100 μm , 长短轴比为 1~2.5(图 4)。锆石 Th/U 比值为 0.51~1.14(表 1), 且具有典型的岩浆振荡环带结构, 属于岩浆成因锆石。

根据锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄分布范围数据可分为两组, 第一组锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄在 521.3~535.5 Ma (15 个测点), 第二组锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄在 785.9~

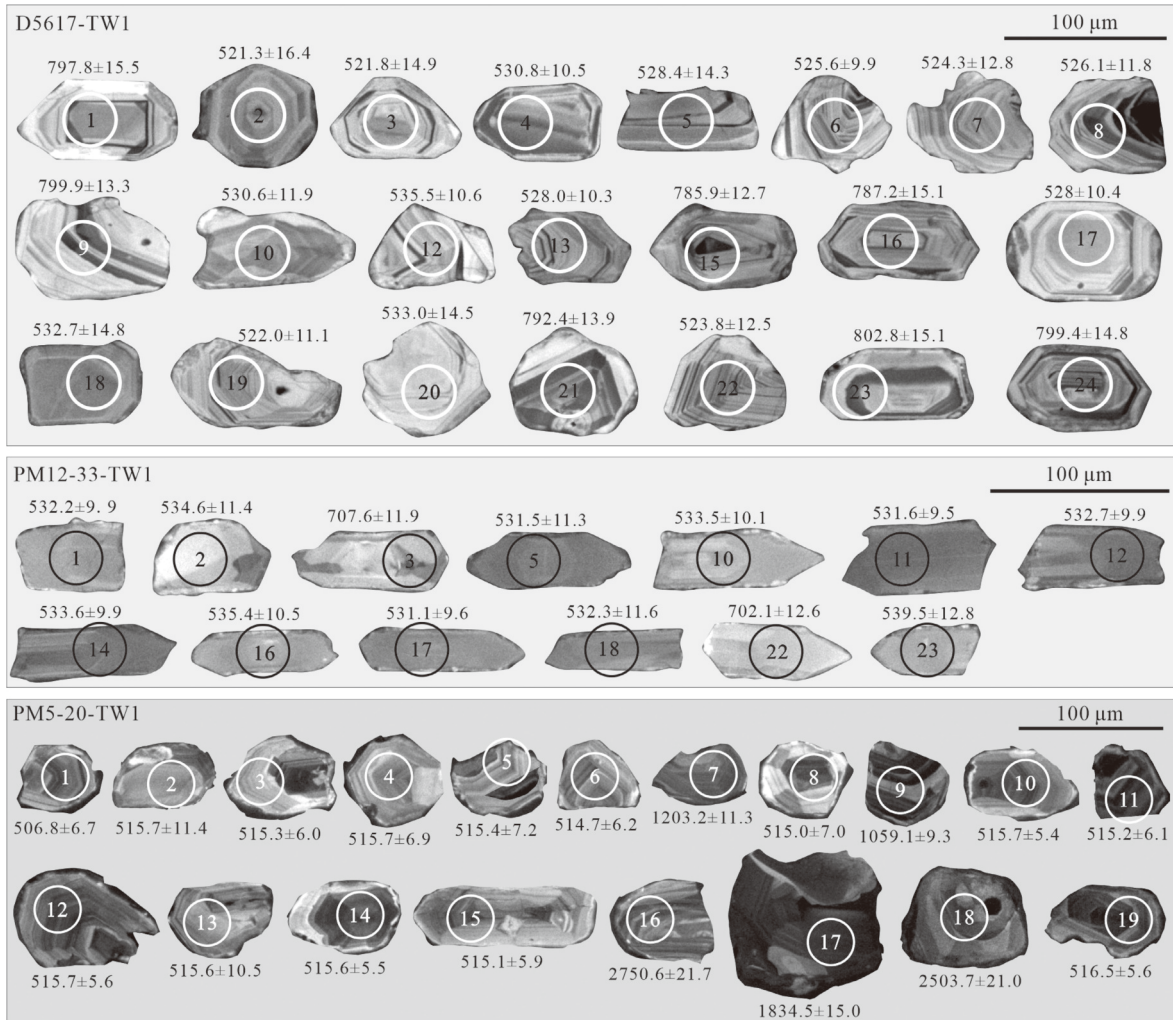


图 4 英安岩锆石阴极发光图像与 $^{206}\text{Pb}/^{238}\text{U}$ 年龄(Ma)
Fig.4 Cathodoluminescence (CL) image and $^{206}\text{Pb}/^{238}\text{U}$ age (Ma) of zircons in dacites

802.8 Ma(7 个测点)。第一组锆石晶体自形—半自形, 呈短柱状或浑圆状, 部分晶体具有溶蚀边结构; 全部数据点均落在谐和线上(图 5a、b), $^{206}\text{Pb}/^{238}\text{U}$ 年龄的加权平均值为(527.7±6.1)Ma(MSWD=0.12), 代表了成岩年龄。第二组锆石自形程度较高, 除一个锆石晶体呈浑圆状外, 其余锆石晶体均为短柱—长柱状, 部分锆石具有明显的变质增生边。全部数据点均位于谐和线上方, 应为捕获锆石。

PM12-33-TW1: 对该样品中的 13 粒锆石进行了测年分析, 结果显示: 锆石 CL 图像呈灰—灰白色, 多数晶体呈长轴状, 少数呈短轴状, 短轴 25~40 μm, 长轴 60~95 μm, 长短轴比为 2~4(图 4)。锆石 Th/U 比值为 0.15~0.29(表 1), 介于变质锆石(<0.1)与岩浆锆石(>0.4)之间(吴元保和郑永飞, 2004);

锆石晶体自形程度较高, 多数锆石无分带或弱分带, 个别锆石具有弱的环带结构, 多数锆石具有窄的变质增生边。综合以上特征认为该组锆石应为岩浆锆石, 后期可能由于遭受变质作用的影响其微量元素发生变化, 虽然典型岩浆环带结构已不明显, 但其长柱状形态依然非常明显。

根据锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄分布范围数据可分为两组, 第一组锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄在 531.1~539.5 Ma (11 个测点), 第二组锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄在 702.1~707.6 Ma(2 个测点)。第一组 4 个数据点落在了谐和线下方, 应发生了铅丢失, 其余数据位于谐和线附近(图 5c、d), $^{206}\text{Pb}/^{238}\text{U}$ 年龄的加权平均值为(533.2±6.1)Ma(MSWD=0.043), 代表了成岩年龄。第二组数据点均位于谐和线上方, 为早期捕获锆石。

表 1 研究区英安岩 LA-ICP-MS 锆石 U-Pb 分析结果
Table 1 LA-ICP-MS zircon U-Pb analytical date of dacites in the study area

测点编号	同位素比值						年龄/Ma						含量/ 10^{-6}			Th/U
	Pb ²⁰⁷ /Pb ²⁰⁶	1 σ	Pb ²⁰⁶ /U ²³⁸	1 σ	Pb ²⁰⁷ /U ²³⁵	1 σ	Pb ²⁰⁷ /Pb ²⁰⁶	1 σ	Pb ²⁰⁶ /U ²³⁸	1 σ	Pb ²⁰⁷ /U ²³⁵	1 σ	Pb	Th	U	
D5617-TW1-1	0.05758	0.00132	1.04575	0.02064	0.13175	0.00273	513.4	49.8	797.8	15.5	797.8	15.8	21.9	227.5	252.2	0.90
D5617-TW1-2	0.05567	0.00232	0.64640	0.02019	0.08423	0.00276	438.8	90.2	521.3	16.4	521.3	16.7	11.9	117.8	197.4	0.60
D5617-TW1-3	0.05611	0.00208	0.65220	0.01846	0.08432	0.00250	456.4	80.2	521.8	14.9	521.8	14.9	8.9	92.4	144.4	0.64
D5617-TW1-4	0.05771	0.00131	0.68282	0.01337	0.08582	0.00176	518.6	49.3	530.8	10.5	530.8	10.5	13.1	125.2	194.5	0.64
D5617-TW1-5	0.05435	0.00190	0.64002	0.01728	0.08542	0.00241	385.5	76.0	528.4	14.3	528.4	14.3	7.5	64.4	126.4	0.51
D5617-TW1-6	0.05646	0.00120	0.66119	0.01253	0.08495	0.00167	469.8	46.9	525.6	9.9	525.6	9.9	15.7	146.1	232.9	0.63
D5617-TW1-7	0.05801	0.00178	0.67761	0.01643	0.08474	0.00215	529.6	65.5	524.3	12.8	524.3	12.8	11.8	101.2	191.5	0.53
D5617-TW1-8	0.05858	0.00159	0.68676	0.01515	0.08504	0.00198	551.5	58.2	526.1	11.8	526.1	11.8	22.7	221.9	258.3	0.86
D5617-TW1-9	0.05677	0.00100	1.03399	0.01766	0.13211	0.00233	482.1	39.0	799.9	13.3	799.9	13.3	27.7	275.6	256.2	1.08
D5617-TW1-10	0.05505	0.00153	0.65110	0.01486	0.08579	0.00200	414.3	60.2	530.6	11.9	530.6	11.9	11.1	92.5	180.9	0.51
D5617-TW1-12	0.05489	0.00127	0.65555	0.01312	0.08662	0.00179	407.8	50.7	535.5	10.6	535.5	10.6	14.1	121.6	229.1	0.53
D5617-TW1-13	0.05697	0.00129	0.67036	0.01321	0.08535	0.00174	489.7	49.2	528.0	10.3	528.0	10.3	11.6	114.1	180.2	0.63
D5617-TW1-15	0.05791	0.00098	1.03515	0.01721	0.12965	0.00223	526.2	36.8	785.9	12.7	721.5	8.6	14.6	41.3	114.9	0.36
D5617-TW1-16	0.05783	0.00129	1.03555	0.02013	0.12988	0.00264	523.3	48.4	787.2	15.1	721.7	10.0	29.1	279.7	272.1	1.03
D5617-TW1-17	0.05904	0.00132	0.69475	0.01346	0.08535	0.00174	568.6	48.1	528.0	10.4	535.7	8.1	13.6	138.8	210.9	0.66
D5617-TW1-18	0.05750	0.00206	0.68285	0.01872	0.08614	0.00249	510.2	77.4	532.7	14.8	528.5	11.3	14.4	144.1	186.9	0.77
D5617-TW1-19	0.05944	0.00151	0.69116	0.01452	0.08435	0.00187	583.1	54.1	522.0	11.1	533.5	8.7	16.2	159.2	213.3	0.75
D5617-TW1-20	0.05531	0.00195	0.65731	0.01795	0.0862	0.00244	424.6	76.6	533.0	14.5	513.0	11.0	23.3	251.4	220.7	1.14
D5617-TW1-21	0.05808	0.00113	1.04738	0.01871	0.13079	0.00243	532.5	42.3	792.4	13.9	727.6	9.3	22.6	190.4	225.3	0.85
D5617-TW1-22	0.05902	0.00175	0.68879	0.01616	0.08464	0.00211	567.9	63.2	523.8	12.5	532.1	9.7	16.5	170.4	189.1	0.90
D5617-TW1-23	0.05917	0.00129	1.08181	0.02070	0.13262	0.00266	573.2	46.8	802.8	15.1	744.5	10.1	16.7	170.1	158.7	1.07
D5617-TW1-24	0.05901	0.00124	1.07405	0.02011	0.13202	0.00259	567.4	45.3	799.4	14.8	740.7	9.9	19.8	172.0	198.3	0.87
PM12-33-1	0.05726	0.00120	0.67945	0.01274	0.08607	0.00167	501.0	46.0	532.2	9.9	526.4	7.7	15.1	55.9	261.1	0.21
PM12-33-2	0.05672	0.00146	0.67609	0.01445	0.08646	0.00192	479.9	56.0	534.6	11.4	524.4	8.8	14.7	39.7	219.6	0.18
PM12-33-3	0.05578	0.00101	0.89221	0.01542	0.11602	0.00206	443.2	39.3	707.6	11.9	647.6	8.3	22.7	74.6	295.0	0.25
PM12-33-5	0.05710	0.00128	0.67663	0.01315	0.08595	0.00174	494.8	49.1	531.5	10.3	524.7	8.0	13.7	44.4	248.4	0.18
PM12-33-10	0.05712	0.00123	0.67950	0.01296	0.08629	0.00170	495.5	47.4	533.5	10.1	526.5	7.8	12.5	36.3	222.7	0.16
PM12-33-11	0.05685	0.00111	0.67377	0.01212	0.08596	0.00159	485.0	42.8	531.6	9.5	523.0	7.4	13.9	38.1	248.5	0.15
PM12-33-12	0.05895	0.00123	0.70017	0.01309	0.08615	0.00167	565.3	44.9	532.7	9.9	538.9	7.8	14.2	51.2	234.3	0.22
PM12-33-14	0.05721	0.00119	0.68063	0.01272	0.0863	0.00166	498.9	45.8	533.6	9.9	527.2	7.7	14.0	45.5	245.3	0.19
PM12-33-16	0.05931	0.00135	0.70808	0.01391	0.08659	0.00178	578.4	48.8	535.4	10.5	543.6	8.3	14.1	47.4	256.6	0.18
PM12-33-17	0.06033	0.00120	0.71425	0.01296	0.08587	0.00162	615.4	42.6	531.1	9.6	547.3	7.7	15.0	46.8	266.8	0.18
PM12-33-18	0.06192	0.00162	0.73482	0.01572	0.08608	0.00196	671.2	55.1	532.3	11.6	559.4	9.2	16.4	58.0	255.7	0.23
PM12-33-22	0.05658	0.00114	0.89770	0.01645	0.11507	0.00217	474.6	44.4	702.1	12.6	650.5	8.8	14.6	42.4	198.0	0.21
PM12-33-23	0.05691	0.00168	0.68490	0.01619	0.0873	0.00215	487.2	64.6	539.5	12.8	529.7	9.8	15.4	60.6	212.6	0.29
PM5-20-1-3	0.05715	0.0025	0.08179	0.00112	0.64438	0.02746	496.6	94.1	506.8	6.7	505.0	17.0	23.0	169.8	205.5	0.83
PM5-20-1-5	0.05853	0.00487	0.08329	0.00191	0.67211	0.05452	549.8	171.9	515.7	11.4	522.0	33.1	10.8	58.3	111.1	0.53
PM5-20-1-6	0.05690	0.00204	0.08322	0.00101	0.65283	0.02271	486.8	77.7	515.3	6.0	510.2	14.0	14.1	103.0	130.4	0.79
PM5-20-1-7	0.05817	0.00259	0.08328	0.00115	0.66786	0.02901	535.5	95.2	515.7	6.9	519.4	17.7	14.3	91.9	141.1	0.65
PM5-20-1-8	0.05743	0.00278	0.08323	0.00120	0.65901	0.03116	507.7	103.5	515.4	7.2	514.0	19.1	9.3	47.0	89.4	0.53
PM5-20-1-9	0.05763	0.00215	0.08311	0.00103	0.66037	0.02394	515.5	79.6	514.7	6.2	514.8	14.6	14.1	90.4	137.7	0.66
PM5-20-1-10	0.08079	0.00153	0.20519	0.00210	2.28559	0.04141	1216.3	36.9	1203.2	11.3	1207.8	12.8	41.2	19.4	181.0	0.11
PM5-20-1-11	0.05603	0.00258	0.08317	0.00117	0.64248	0.02887	453.0	99.5	515.0	7.0	503.8	17.9	11.8	63.2	107.3	0.59
PM5-20-1-12	0.07468	0.00113	1.17855	0.00169	1.83845	0.02605	1059.9	30.1	1059.1	9.3	1059.3	9.3	104.8	270.9	469.7	0.58
PM5-20-1-13	0.05779	0.00157	0.08328	0.00090	0.66359	0.01737	521.7	58.5	515.7	5.4	516.8	10.6	27.7	224.2	250.2	0.90
PM5-20-1-14	0.05776	0.00207	0.08319	0.00102	0.66256	0.02310	520.6	77.1	515.2	6.1	516.2	14.1	28.5	237.6	239.2	0.99
PM5-20-1-15	0.05816	0.00176	0.08328	0.00094	0.66782	0.01957	535.2	65.4	515.7	5.6	519.4	11.9	23.7	176.9	221.6	0.80
PM5-20-1-16	0.05865	0.00461	0.08326	0.00176	0.67335	0.05177	554.3	162.9	515.6	10.5	522.7	31.4	12.6	91.9	126.1	0.73
PM5-20-1-18	0.05751	0.00194	0.08318	0.00099	0.65961	0.02161	510.9	72.9	515.1	5.9	514.4	13.2	27.5	238.1	263.6	0.90
PM5-20-1-19	0.05721	0.00165	0.08326	0.00093	0.65676	0.01837	499.1	63.0	515.6	5.5	512.6	11.3	32.3	217.1	289.3	0.75
PM5-20-1-20	0.19091	0.00235	0.53217	0.00515	14.0079	0.16026	2750.0	20.1	2750.6	21.7	2750.2	10.8	365.6	363.8	474.5	0.77
PM5-20-1-22	0.11228	0.00143	0.32921	0.00309	5.09662	0.05984	1836.7	22.8	1834.5	15.0	1835.5	10.0	199.3	479.1	412.3	1.16
PM5-20-1-23	0.16482	0.00228	0.47460	0.004810	10.78513	0.14092	2505.7	23.1	2503.7	21.0	2504.8	12.1	97.9	142.6	140.5	1.01
PM5-20-1-24	0.05796	0.00172	0.08343	0.00094	0.666670	0.01913	527.8	64.0	516.5	5.6	518.7	11.7	24.9	193.7	225.0	0.86

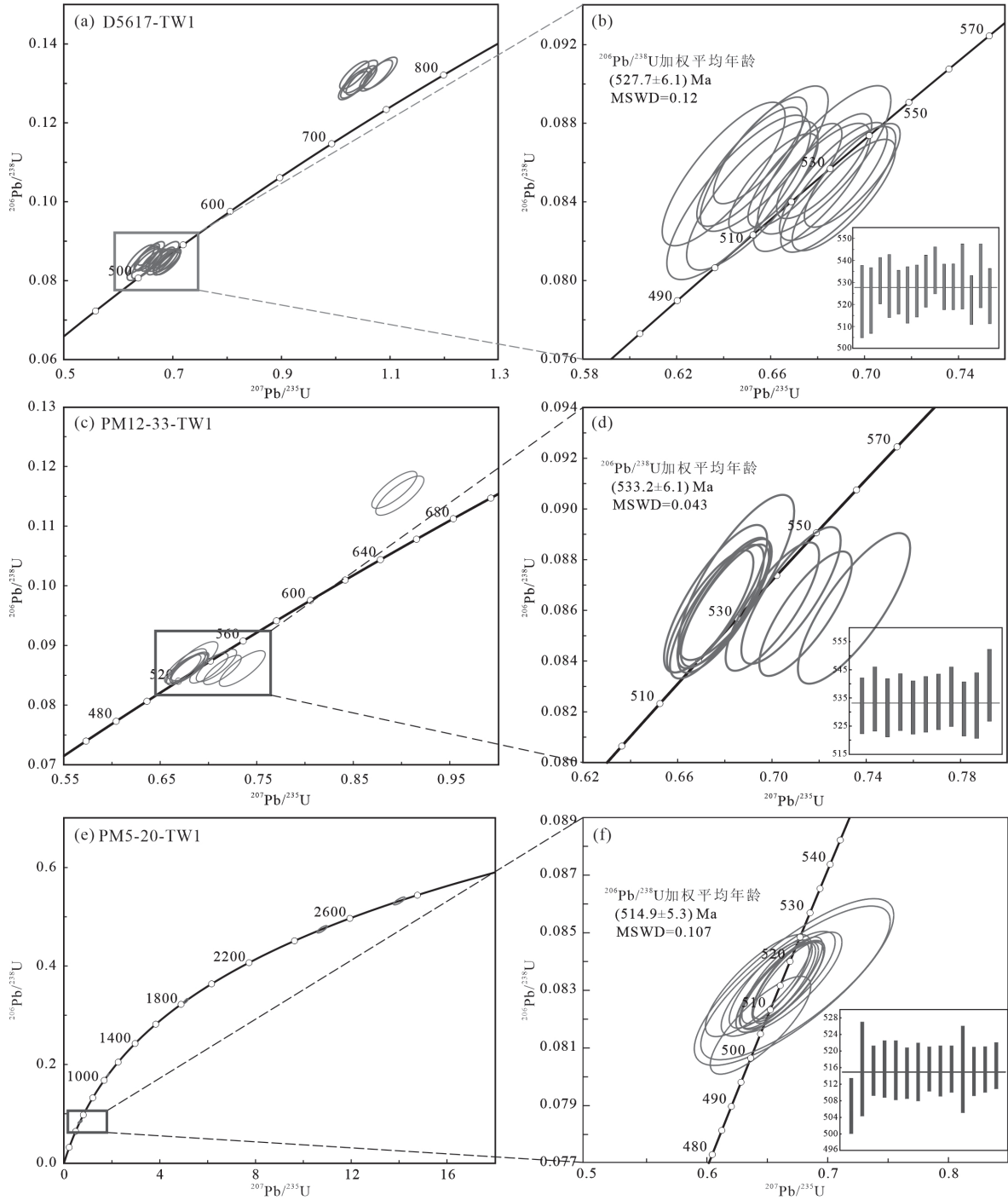


图 5 英安岩锆石 U-Pb 年龄谐和图
Fig.5 Zircons U-Pb concordia diagram of dacites

PM5-20-TW1: 对该样品中的 19 粒锆石进行了测年分析, 锆石 CL 图像呈灰—灰黑色, 锆石晶体呈短轴状或等轴状, 其中一粒锆石呈长轴状, 锆石短轴 33~80 μm , 长轴 35~110 μm , 长短轴比为 1~3 (图 4)。锆石 Th/U 比值为 0.53~0.99 (表 1), 锆石晶

体为半自形, 具有明显的岩浆振荡环带结构, 多数锆石具有变质增生边, 个别锆石保留有岩浆继承锆石的残留核, 属于岩浆成因锆石。

根据锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄分布范围数据可分为两组, 第一组锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄集中在 506.8~516.5

Ma(14个测点),第二组锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄在1059.1~2750.6 Ma(5个测点),较为分散。第一组数据点均落在了谐和线上(图5e、f), $^{206}\text{Pb}/^{238}\text{U}$ 年龄的加权平均值为(514.9±3.4)Ma(MSWD=0.13),代表了成岩年龄。第二组数据点均位于谐和线上,多数锆石晶体保留有岩浆继承锆石的残留核,且全部发育变质增生边,说明锆石经历了多期的热事件,应为早期的捕获锆石。

4.2 岩石地球化学特征

本次对12件火山岩样品进行了主量、微量和稀土元素分析,分析数据结果见表2。

4.2.1 主量元素

英安岩的 SiO_2 含量66.17%~74.42%, σ 值0.73~1.08, Al_2O_3 含量12.42%~15.39%, K_2O 含量0.32%~1.04%, Na_2O 含量3.86%~4.96%, $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 值0.008~0.26, $\text{Mg}^\#$ 值45~63, $\text{FeO}^\text{T}/\text{MgO}$ 值1.56~2.78, TiO_2 含量0.16%~0.4%。

安山岩的 SiO_2 含量51.4%~55.98%, σ 值0.59~1.27, Al_2O_3 含量10.49%~15.34%, K_2O 含量0.28%~0.66%, Na_2O 含量2.23~3.57%, $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 值0.08~0.23, $\text{Mg}^\#$ 值59~72, $\text{FeO}^\text{T}/\text{MgO}$ 值0.79~1.56, TiO_2 含量0.34%~0.5%。

从主量元素的数据统计结果来看,两种岩性的岩石均具有低钾富钠、高镁低钛的特征。在TAS图解上5件酸性岩样品落在英安岩区(图6a),1件酸性样品落在流纹岩区,5件中性岩样品落在了玄武安山岩区,1件中性岩样品落在了玄武岩区。在 $\text{FeO}^\text{T}/\text{MgO}-\text{SiO}_2$ 图解中所有样品均落在了钙碱性系列区(图6b),综上认为该套火山岩属于高镁低钾钙碱性岩石系列。

4.2.2 稀土和微量元素

英安岩 ΣREE 值为 27.92×10^{-6} ~ 71.91×10^{-6} ,LREE/HREE值为2.44~5.34, $(\text{La}/\text{Yb})_N$ 值为1.63~4.50,反映了轻、重稀土分馏较弱;球粒陨石标准化稀土元素配分中(图7a)呈现出弱的右倾型配分模式, δEu 值为0.89~0.97,具有弱的负铕异常。安山岩 ΣREE 值为 21.79×10^{-6} ~ 28.52×10^{-6} ,LREE/HREE值为2.39~3.30, $(\text{La}/\text{Yb})_N$ 值为1.57~2.47,说明轻、重稀土分馏较英安岩更弱;球粒陨石标准化稀土元素配分图(图7a)呈现出弱的右倾型配分模式, δEu 值为1.04~1.12,具有弱的正铕异常。

在原始地幔标准化微量元素蛛网(图7b)以及球粒陨石化稀土元素配分曲线图中(图7a)区内火山岩富集大离子亲石元素(Rb、Ba、U、K、Th)及LREE,亏损高场强元素(Nb、Ta、Zr、Ti)及HREE。

5 讨 论

5.1 地层形成时代

众所周知,敦煌杂岩由TTG岩为主的深成侵入岩和变质表壳岩组成,其上零星出露中生代盖层,对其研究主要集中于TTG岩石,而变质表壳岩和沉积盖层的研究相对较少,迄今,未见有关古生代沉积岩及火山岩的报道。孟繁聪等(2011)对三角山一带的副变质岩白云母石英片岩进行了锆石U-Pb测年及岩石地球化学分析,认为该套岩石形成于756 Ma之后,地层最老为震旦系,并由此认为部分敦煌群为塔里木盆地东北缘太古宙变质基底之上较晚的盖层之一;Wang et al.(2013)对红柳峡地区云母石英片岩和含石榴子石黑云斜长片麻岩的碎屑锆石分析,认为最大沉积时代约1.95 Ga;石梦岩等(2017)对红柳峡地区云母石英片岩和变质砂岩分析,获得了389 Ma的岩浆锆石,认为存在泥盆纪的浊积岩。本次研究样品中的锆石具有明显的岩浆锆石特征,其年龄值为(527.7±6.1)Ma、(533.2±6.1)Ma、(514.9±3.4)Ma,可代表成岩年龄,成岩时代为早寒武世,代表了两期火山喷发事件。1:20万区域地质调查将该套地层归于前寒武纪敦煌群第三亚群;1:25万区域地质调查将该套地层归于古元古代敦煌群小西弓云母石英片岩岩组。该套岩石年龄的重新厘定说明该套地层不能归属于敦煌群,而应为敦煌群之上早寒武世火山岩盖层。

5.2 岩石成因

钙碱性安山岩是造山带(岛弧和大陆边缘弧)的重要组成部分,其相关的成因研究为揭示地壳形成、生长以及壳幔相互作用具有极其重要的意义。一般认为中性岩石可能存在以下成因(Annen et al., 2006):(1)受富水流体交代的地幔楔橄榄岩部分熔融或者板片熔体与地幔楔橄榄岩相互反应(Parman and Grove, 2004);(2)幔源玄武质岩浆在地壳不同深度分离结晶作用(Sisson and Grove, 1993; Castillo

表 2 研究区火山岩全岩主量元素 (%)、微量元素和稀土元素 (10^{-6}) 分析结果Table 2 Results of major element (%) and trace element (10^{-6}) of volcanic rocks in the area

岩石类型	英安岩						安山岩					
	样品号	D5617-H2	D5617-H3	PM6-11-H1	PM6-11-H2	PM5-20-H1	PM12-33-H1	PM6-27-H1	PM6-27-H2	PM6-27-H4	PM6-24-H1	PM6-27-H5
SiO ₂	67.81	69.11	66.93	68.08	66.17	74.42	55.98	55.07	55.81	55.62	51.40	54.01
Al ₂ O ₃	13.94	13.53	14.16	13.76	15.39	12.42	14.74	15.34	14.85	12.72	10.49	15.13
Fe ₂ O ₃	0.47	0.96	1.78	1.78	1.29	0.92	2.17	2.00	2.10	2.04	1.57	1.46
FeO	3.60	2.65	4.35	3.92	3.50	1.61	6.05	7.25	7.10	7.10	8.33	6.88
CaO	3.62	3.68	4.38	3.49	3.86	1.97	9.00	7.64	7.54	9.71	9.74	7.44
MgO	1.63	1.41	2.14	2.00	2.08	1.56	5.94	5.81	5.90	7.53	12.31	8.15
K ₂ O	0.96	1.04	0.32	0.33	0.49	0.44	0.35	0.34	0.28	0.38	0.30	0.66
Na ₂ O	4.22	3.95	3.86	4.10	4.17	4.96	2.30	3.57	3.51	2.36	2.23	2.88
TiO ₂	0.35	0.28	0.39	0.40	0.35	0.16	0.36	0.47	0.44	0.50	0.34	0.37
P ₂ O ₅	0.07	0.05	0.08	0.09	0.07	0.04	0.04	0.05	0.05	0.06	0.04	0.04
MnO	0.08	0.07	0.13	0.11	0.14	0.06	0.16	0.17	0.17	0.16	0.18	0.16
LOI	3.17	3.20	1.44	1.89	2.41	1.38	2.80	2.22	2.17	1.69	2.87	2.69
Total	99.92	99.94	99.96	99.95	99.92	99.94	99.89	99.93	99.92	99.87	99.80	99.87
Mg#	45	49	47	48	51	63	64	59	60	65	72	68
La	13.3	9.04	3.50	3.31	7.88	7.69	4.17	3.68	3.41	2.95	2.69	2.86
Ce	28.2	20.1	8.70	8.20	18.4	20.1	9.62	8.57	8.16	7.68	6.45	6.82
Pr	3.13	2.43	1.22	1.15	2.31	2.72	1.22	1.10	1.07	1.12	0.90	0.92
Nd	12.2	9.31	5.74	5.37	9.64	11.0	5.00	4.58	4.57	5.03	3.99	4.35
Sm	2.86	2.21	1.78	1.56	2.31	2.54	1.38	1.33	1.41	1.57	1.14	1.24
Eu	0.89	0.69	0.56	0.51	0.75	0.74	0.50	0.51	0.52	0.63	0.46	0.50
Gd	2.63	2.18	2.08	1.80	2.59	2.35	1.52	1.51	1.56	1.86	1.45	1.51
Tb	0.46	0.39	0.36	0.31	0.45	0.40	0.27	0.29	0.30	0.34	0.26	0.28
Dy	3.01	2.42	2.34	2.10	2.88	2.56	1.79	1.92	1.98	2.16	1.71	1.78
Ho	0.64	0.53	0.52	0.46	0.64	0.56	0.38	0.40	0.42	0.47	0.36	0.38
Er	1.84	1.62	1.50	1.35	1.85	1.74	1.09	1.18	1.22	1.35	1.04	1.12
Tm	0.30	0.27	0.23	0.21	0.29	0.28	0.18	0.19	0.19	0.21	0.16	0.17
Yb	2.12	1.84	1.54	1.38	1.92	2.15	1.21	1.27	1.26	1.35	1.02	1.12
Lu	0.34	0.30	0.23	0.21	0.30	0.37	0.20	0.20	0.20	0.20	0.16	0.17
Y	15.3	13.7	13.4	12.5	17.4	16.1	10.1	9.68	13.4	12.4	9.58	9.61
∑REE	71.91	53.32	30.30	27.92	52.21	55.20	28.52	26.73	26.27	26.92	21.79	23.22
LREE	60.58	43.78	21.50	20.10	41.29	44.79	21.89	19.77	19.14	18.98	15.63	16.69
HREE	11.33	9.54	8.80	7.82	10.92	10.41	6.63	6.96	7.13	7.94	6.16	6.53
LREE/HREE	5.34	4.59	2.44	2.57	3.78	4.30	3.30	2.84	2.69	2.39	2.54	2.56
(La/Yb) _N	4.50	3.52	1.63	1.72	2.94	2.57	2.47	2.08	1.94	1.57	1.89	1.83
δEu	0.97	0.95	0.89	0.93	0.93	0.91	1.04	1.09	1.08	1.12	1.09	1.12
Cr	38.7	43.8	11.5	5.82	13.4	62.7	183	166	267	261	1020	259
Ni	11.9	8.84	2.69	2.09	5.01	31.2	41.4	44.7	56.5	44	169	72.9
Co	11.1	9.25	9.92	10.8	11.7	10.9	28.1	32	36.7	35.5	53.2	35.4
Rb	25.2	20	5.98	7.33	8.02	16.2	8.71	6.85	5.33	7.06	5.52	13.8
Sr	142	139	66.7	58.9	181	135	183	133	118	235	121	146
Ba	160	146	61	71.4	234	93.4	75.4	64	50.9	77	57.2	129
V	86.6	75.5	60.4	72.6	111	65.9	191	232	246	283	216	205
Nb	3.65	2.88	1.93	1.94	2.78	1.98	1.5	1.59	1.57	1.25	1.14	1.22
Ta	0.314	0.253	0.16	0.16	0.23	0.16	0.165	0.164	0.157	0.1	0.092	0.098
Zr	73.2	75.8	46.2	44.2	83.4	68.2	27.9	25	25.5	26.1	22.9	24.5
Hf	2.55	2.4	1.42	1.43	2.55	2.36	0.943	0.96	0.897	0.86	0.72	0.78
Ga	13	14.1	11.3	10.7	14	8.27	13.7	13.7	14.1	14	11.1	11.6
U	1.1	0.877	0.43	0.44	0.79	0.74	0.367	0.321	0.286	0.27	0.24	0.26
Th	5.2	2.89	0.83	0.99	2.89	2.5	0.93	0.89	0.88	0.64	0.68	0.63

et al., 1999; Mortazavi and Sparks, 2004; Lee et al., 2014); (3) 幔源玄武质岩浆底侵导致下地壳物质部分熔融作用 (Petford and Atherton, 1996; Guffanti et al., 1996; Jung et al., 2002; Jackson et al., 2003); (4)

幔源玄武质岩浆与壳源长英质岩浆混合作用或地壳同化混染作用 (Cantagrel et al., 1984; Hildreth and Moorbath, 1988; Yang et al., 2007; Guo et al., 2007; Reubi and Blundy, 2009; Richards, 2011; Li et al.,

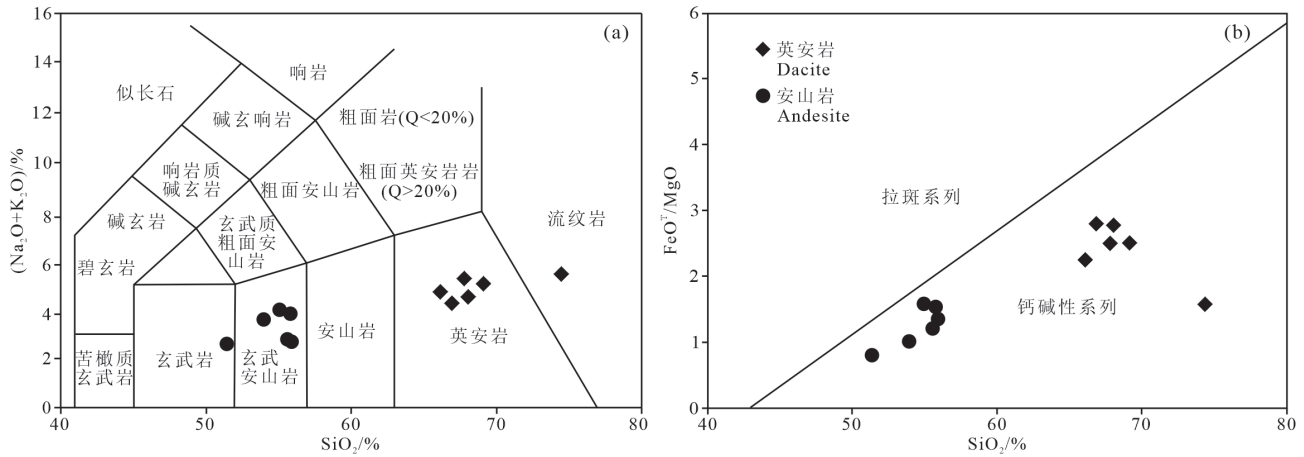


图6 中酸性火山岩 TAS 图解(a, 据 Le Maitre, 1989)和 SiO₂-FeO^T/MgO 图解(b, 据 Miyashiro, 1974)
Fig.6 TAS classification diagram (a, after Le Maitre, 1989) and SiO₂-FeO^T/MgO diagram (b, after Miyashiro, 1974)

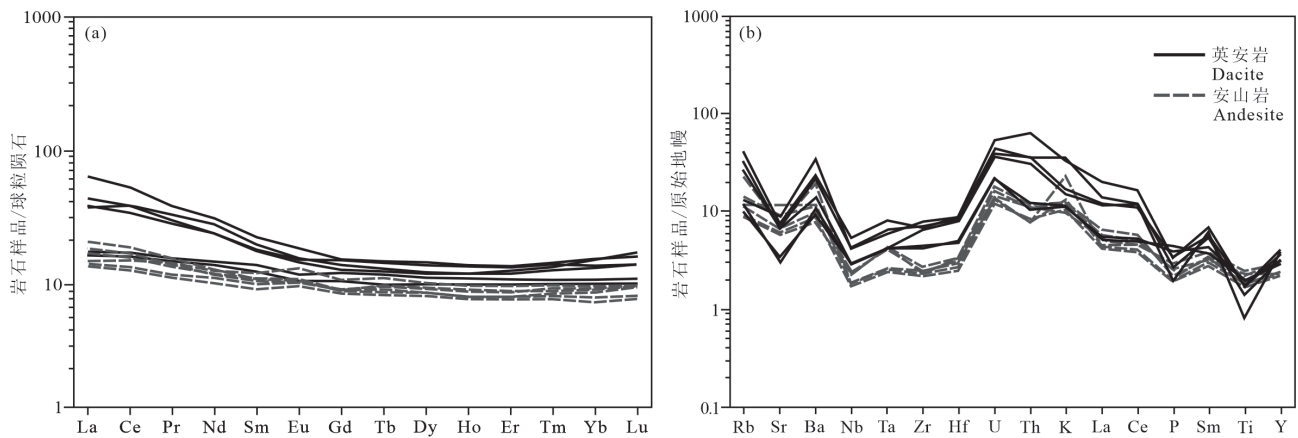


图7 中酸性火山岩稀土元素球粒陨石标准化配分曲线(a)和微量元素原始地幔标准化蛛网图(b)(球粒陨石和原始地幔数据引自 Sun and McDonough, 1989)
Fig.7 Chondrite-normalized REE patterns (a) and primitive mantle-normalized spider diagrams (b) of intermediate-acid volcanic rocks in the area (standardized values of chondrite and primitive mantle after Sun and McDonough, 1989)

2014; 牛晓露等, 2018)。

在玄武质岩浆的结晶分异过程中, 石榴石±辉石的高压分离结晶作用导致岩浆中的 Al₂O₃ 随 SiO₂ 的增加而降低, Sr/Y、La/Y 比值随 SiO₂ 的增加而升高, 但研究区内岩浆岩没有这样的规律性变化 (图 8b、c、d); 另一方面, 区内火山岩以安山岩、英安岩为主, 夹少量玄武岩及流纹岩, 如果上述火山岩由玄武质岩浆分离结晶作用形成, 这需要巨量的玄武质岩浆, 那么研究区将出现大面积的玄武质岩石, 然而迄今为止区域上未发现有大面积同时期的玄武质岩石, 结合区内安山岩不具有负 Eu 异常, 暗示其并非玄武质岩浆结晶分异的产物。区内安山岩具有高的 MgO(5.81%~12.31%) 含量和 Mg[#](59~

72), 与基性下地壳物质部分熔融产生的岩浆明显不同(Mg[#]值通常小于 40)(Atherton and Petford, 1993; Rapp and Watson, 1995; Rapp et al., 1999); 同时, 壳源岩浆具有相对较低的 Ti/Zr(<20, Pearce, 1983)、Ti/Y(<100, Tischendorf and Paelchen, 1985) 比值和较高的 Rb/Sr(>0.23, Rudnick and Gao, 2003) 比值, 而区内安山岩样品的 Ti/Zr 比值介于 77~115, Ti/Y 比值介于 197~291, 与壳源岩石的比值不符, Rb/Sr 比值介于 0.03~0.095, 平均值 0.052, 明显低于壳源岩浆的范围, 而与靠近幔源岩浆的 Rb/Sr (0.03~0.047) 比值相近(Sun and McDonough, 1989; Rudnick and Gao, 2003), 以上说明研究区安山岩并非基性下地壳物质部分熔融的产物。如上所述,

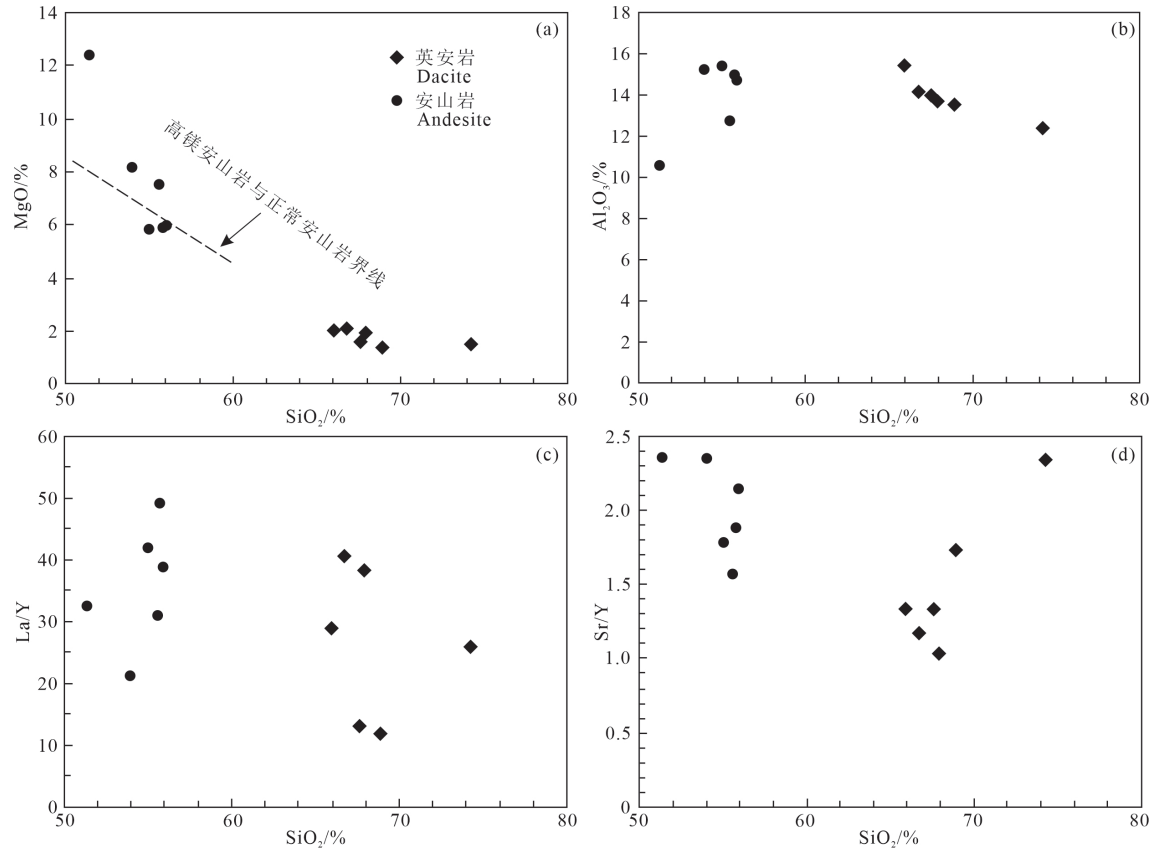


图 8 SiO₂-MgO (a)、SiO₂-Al₂O₃ (b)、SiO₂-La/Y (c)、SiO₂-Sr/Y (d) 图(高镁安山岩与正常安山岩分界线源于 McCarron and Smellie, 1998)
 Fig.8 SiO₂-MgO (a), SiO₂-Al₂O₃ (b), SiO₂-La/Y (c) and SiO₂-Sr/Y (d) diagrams (The boundary between high-Mg andesite and normal andesite after McCarron and Smellie, 1998)

区内安山岩除具有高的 MgO 含量和 Mg[#]外, 还具有高的 Cr (166×10⁻⁶~1020×10⁻⁶) 和 Ni (41.4×10⁻⁶~169×10⁻⁶) 含量, 以及低的 FeO^T/MgO (0.79~1.56), 具有高镁安山岩的特征 (Tatsumi, 2001); 高镁安山岩大多形成于俯冲带岛弧环境 (Elliott et al., 1997; Tatsumi, 2005), 其成因目前还存在不同的观点: (1) 直接起源于高度水化地幔橄榄岩的部分熔融 (Shirey and Hanson, 1984; Martin et al., 2005), 这一结论还得到实验岩石学的支持 (Wood and Turner, 2009)。该实验成果表明, 要使地幔橄榄岩发生部分熔融形成中性成分的高镁闪长岩, 除了要有额外的水的加入, 还必须是方辉橄榄岩(并非二辉橄榄岩)发生熔融; (2) 由俯冲大洋板片起源的熔体与地幔橄榄岩相互作用而形成 (Yogodzinski et al., 1995; Shimoda et al., 1998); (3) 由拆沉下地壳起源的熔体与地幔橄榄岩相互作用而形成 (Gao et al., 2004; Xu et al., 2008); (4) 长英质岩浆与镁铁质岩浆

混合的产物 (Streck et al., 2007)。岩浆混合模式还得到实验岩石学和熔体包裹体研究成果 (Reubi and Blundy, 2009) 的支持(火山岩斑晶中中性成分的熔体包裹体非常稀少)。区内安山岩中的斑晶不含橄榄石, 而是以斜长石和辉石为主, 基质中也含有大量的斜长石, 这与埃达克型高镁安山岩一致, 说明地幔橄榄岩对高镁安山岩的形成贡献较小, 而俯冲板片熔体或流体的贡献可能较大, 岩浆产生的源区深度可能也较深, 这排除了第一种可能性; 由于拆沉下地壳熔融往往发生在板内伸展环境 (Xu et al., 2000; Gao et al., 2004), 这与敦煌地块早寒武世的构造背景不符; 区内火山岩以中酸性为主, 若高镁安山岩的成因为第四种, 那么区内势必存在与中酸性火山岩相当的基性火山岩, 而区内及邻区仅可见少量基性火山岩, 另外混合岩浆成因的中酸性岩体中通常发育闪长质暗色包体, 且具有高钾的岩石地化特征, 而区内的这一套中酸性火山岩并没有以上特

征。通过上述分析,结合区内安山岩具有右倾的稀土元素配分模式、亏损重稀土元素、无 Eu 异常、高镁低钾,具有埃达克型高镁安山岩等一系列的特征,笔者认为区内这一套高镁安山岩应为第二种成因。

另外,俯冲大洋板片组分包括洋壳和洋壳沉积物 (Schiano et al., 1995; Yogodzinski et al., 1995; Shimoda et al., 1998; Xu et al., 2000; Tatsumi, 2001; Defant et al., 2002; Hanyu et al., 2002, 2006; Gao et al., 2004; Manya et al., 2007; Wang et al., 2008a, b), 全球俯冲沉积物的 Th 含量为 6.91×10^{-6} (Plank and Langmuir, 1998), 计算表明,与俯冲相关弧岩浆中 90% 的 Th 来自俯冲的沉积物 (Hawkesworth et al., 1997), 区内安山岩 Th 含量在 $0.63 \times 10^{-6} \sim 0.93 \times 10^{-6}$, 明显低于洋壳沉积物含量, Ba/La-Th/Yb 可以清楚识别弧岩浆岩源区中沉积物和流体的加入程度 (Woodhead et al., 2001)。在 Ba/La-Th/Yb 图解中 (图 9a), 研究区安山岩样品低 Th/Yb、高 Ba/La 比值指示了洋壳沉积物或沉积物熔体加入不明显, 说明沉积物(熔体)交代作用未参加该次幔源岩浆的熔融过程。

依据 Rittmann (1973) 火山岩系的划分方案在 $\lg\sigma - \lg\tau$ 图解中 (图 9b), 本次所采集的样品均落在消减带火山岩区内, Jakes and White (1971) 认为岛弧 SiO_2 含量 50%~66%, $\text{FeO}^T/\text{MgO} < 2.0$, $\text{K}_2\text{O}/\text{Na}_2\text{O} < 0.6$, 邱家骧和林景仟 (1991) 指出岛弧区以低钾 (K_2O 平均 1.6%) 的安山岩发育为主, 区内安山岩 SiO_2 均值为 54.65%, K_2O 均值 0.39%, 另外区内火山岩富集大离子亲石元素及 LREE, 亏损高场强元素及 HREE, 具有近平坦的右倾稀土配分模式, 以及较低的 Nb/La (0.36~0.46) 和 Hf/Th (1.02~1.34) 比值和较高的 Hf/Ta (5.71~8.60)、La/Ta (21.72~29.50) 比值, 显示了岛弧火山岩的地球化学属性 (图 9c、d)。

由于地壳物质通常具有高 La/Nb、高 Ba/Nb 和 Ba/La 值的特点。因此, 如果地幔柱或软流圈玄武质岩浆遭受到大陆地壳物质的混染, 岩浆中的不相容元素, 如 La 或 Ba 值就会相对于 Nb 明显增高, 从而具有高 La/Nb、Ba/La 值的特点。区内安山岩具有较高的 La/Nb (2.31~2.78)、Ba/La (14.93~41.50) 和 Ba/Nb 值 (32.42~105.74), 均高于原始地幔的比值 (0.94、9.6、9), 而接近于大陆地壳的比值 (2.2、

25、54), 说明它们受到了地壳物质的混染作用。

综上认为区内安山岩的形成是由俯冲洋壳熔体(流体)交代地幔楔部分熔融作用形成, 并且在上升过程中受到地壳物质的混染作用。

区内英安岩与安山岩主量元素特征相近, 稀土元素球粒陨石标准化分配型式也近似, 只是英安岩发生了弱的 Eu 亏损, 说明在安山岩到英安岩的演化过程中发生了斜长石的分离结晶作用 (申亮等, 2020), 另外在显微镜下可见英安岩中夹有安山岩岩屑, 暗示酸性岩浆可能是中基性岩浆连续分离结晶的产物。

5.3 构造背景及地质意义

研究区位于敦煌地块东北缘, 地处塔里木地块、天山—北山造山带、祁连造山带的结合部位。西伯利亚地台与塔里木—中朝地块在古生代早期是彼此分隔很远 (相距 4000 km 以上) 的两个板块, 其间是广阔的海域, 李文渊 (2018) 认为塔里木陆块是早古生代古亚洲洋的南岸。因此, 研究区在早古生代应为古亚洲洋构造域的一部分。

关于古亚洲洋的形成时代不同学者持有不同观点, 主要集中在古元古代末期—新元古代 (李锦轶等, 2006; 李文渊, 2018; 肖文交等, 2019); 夏林圻等 (2002) 通过对阿克苏—柯坪和库鲁克塔格两个微地块中的震旦纪和早寒武世火山岩的研究认为, 早寒武世为天山古生代洋盆开启时限的下限。

而关于古亚洲洋的初始俯冲时限多数学者认为开始于奥陶纪—志留纪: 吐哈盆地北缘哈尔里克岛弧带, 形成于晚奥陶世岛弧环境 (马星华等, 2015), 其南缘以大草滩断裂带为界, 北侧为志留纪—泥盆纪岛弧带 (张兴龙等, 2004; 田纹全等, 2005; 李锦轶等, 2006; 李文铅等, 2006), 南侧为石炭纪岛弧带; 马星华等 (2015) 对哈尔里克带内的奥尔达乌台克侵入体 (447~452 Ma) 进行了研究, 认为古亚洲洋俯冲作用的时间可追溯至奥陶纪。而在古亚洲洋东段, 刘敦一等 (2003)、石玉若等 (2004) 通过对内蒙古图林凯蛇绿岩中埃达克岩和内蒙古苏左旗地区的闪长岩—花岗岩类研究认为, 上述岩石为洋壳俯冲消减的产物, 并由此推测古亚洲洋于早—中奥陶世开始了初始俯冲; 刘金龙等 (2016) 研究认为, 内蒙古乌拉特中旗哈达呼舒基性岩体具有岛弧玄武岩 ((513±2) Ma) 特征, 形成于古亚洲洋向南俯冲的岛弧环境。本次研究区内中酸性火山岩

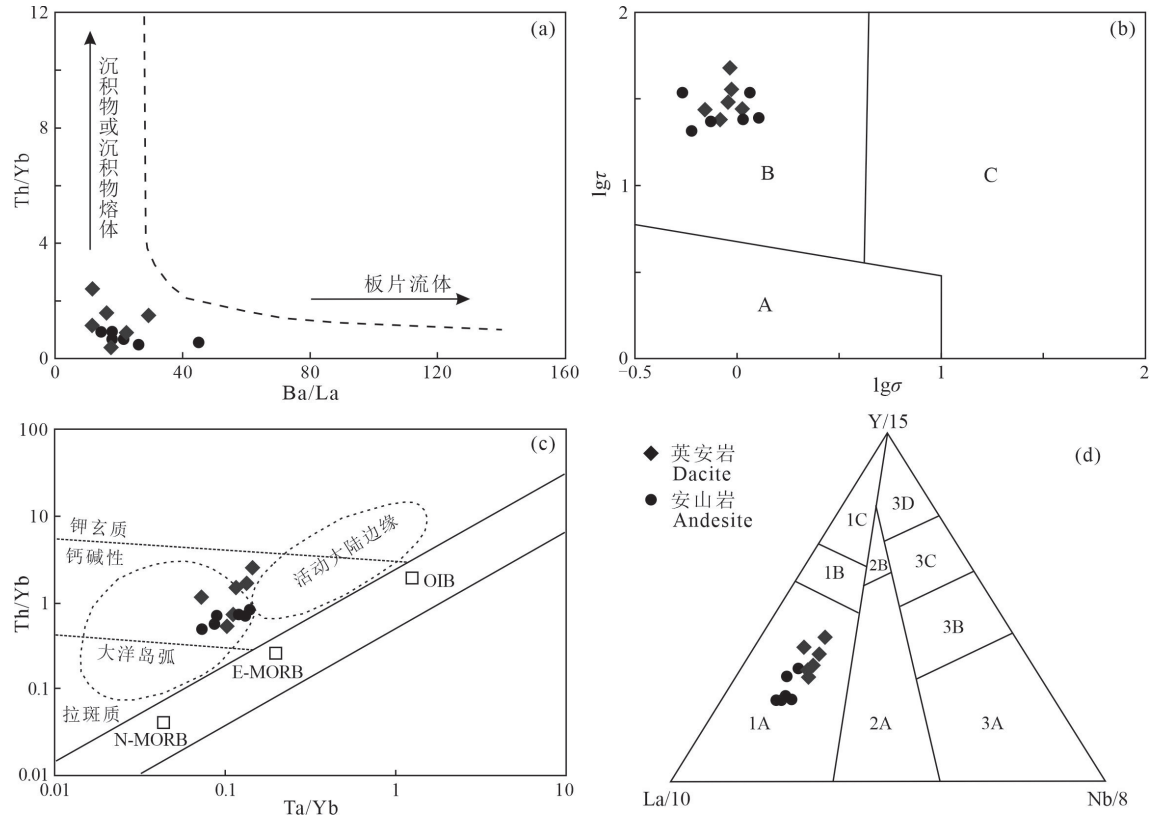


图 9 Ba/La-Th/Yb (a, 据 Woodhead et al., 2001)、lgσ-lgr (b, 据 Rittmann, 1973)、Ta/Yb-Th/Yb (c, 据 Pearce, 1982) 和 Y/15-La/10-Nb/8 (d, 据 Cabanis and Lecolle, 1989) 图解
 A—稳定区; B—造山带; C—派生区; N-MORB—N 型洋中脊玄武岩; E-MORB—E 型洋中脊玄武岩; OIB—洋岛玄武岩; 1—火山弧玄武岩; 2—大陆玄武岩; 3—大洋玄武岩
 Fig.9 Ba/La-Th/Yb (a, after Woodhead et al., 2001), lgσ-lgr (b, after Rittmann, 1973), Ta/Yb-Th/Yb (c, after Pearce, 1982) and Y/15-La/10-Nb/8 (d, after Cabanis and Lecolle, 1989) diagrams
 A—Stability region; B—Orogenic belt; C—Derived area; N-MORB—N-type mid-oceanic ridge basalt; E-MORB—E-type mid-oceanic ridge basalt; OIB—Oceanic island basalt; 1—Volcanic arc basalt; 2—Continental basalt; 3—Oceanic basalt

(514.9~533.2 Ma) 具有较高的 MgO、Cr、Ni 含量及 Mg[#] 值, 为典型的高镁安山岩, 富集 LILE 及 LREE, 亏损 HFSE 及 HREE, 具有近平坦的右倾稀土配分模式, 且在构造环境判别图中均落在了岛弧区 (图 7), 应为洋壳俯冲消减的产物。综上认为, 古亚洲洋的俯冲作用最早可追溯至早寒武世。

另外, 从 PM5-20-TW1 锆石样品中分别测得了约 2.7 Ga、约 2.5 Ga、约 1.8 Ga 的年龄值, 这些前寒武纪的捕获锆石应来自于敦煌地块, 这与敦煌地块前寒武纪主要的地质事件演化期一致 (梅华林等, 1998; Zhang et al., 2013; 赵燕等, 2015), 说明在古亚洲洋南缘的俯冲过程中敦煌地块也卷入其中。

6 结论

(1) 研究区出露于敦煌地块东北缘的一套火山

岩以中酸性为主, LA-ICP-MS 锆石 U-Pb 定年结果显示英安岩形成于 (514.9±3.4)~(533.2±6.1) Ma, 由此认为该套火山岩不能归属于敦煌岩群, 而应为敦煌群之上早寒武世火山岩盖层, 并且敦煌地块东北部的边界应该向南推移。

(2) 研究区内安山岩具有高 MgO (5.81%~12.31%)、Mg[#] 和低 FeO^T/MgO 比值, 高 Cr、Ni 低 Al₂O₃ (10.49%~15.34%) 和 K₂O (0.28%~0.66%), 为低钾钙碱性系列高镁安山岩, 其形成可能与俯冲洋壳的熔融作用有关, 洋壳上覆沉积物熔体加入不明显; 中酸性火山岩整体具有高 La/Nb、Ba/Nb 和 Ba/La 比值, 说明幔源岩浆在上升过程中受到地壳物质的混染; 英安岩与安山岩具有相似的主微量元素分布特征。因此, 区内中酸性火山岩应由俯冲洋壳熔体 (流体) 交代地幔楔部分熔融作用形成, 并且

在上升过程中受到地壳物质的混染。

(3)区内火山岩成岩时代为早寒武世,形成于俯冲消滅的岛弧环境,这说明古亚洲洋的俯冲作用最早可追溯至早寒武世;在英安岩样品的锆石中测得了来自敦煌地块的捕获锆石,说明敦煌地块在古亚洲洋南缘的俯冲过程中应该也被卷入其中。

致谢:在成文过程中得到了中国地质调查局西安地质调查中心高级工程师李文明的帮助,在薄片鉴定过程中得到了叶芳老师的指导,匿名审稿专家对论文提出了宝贵的意见和建议,在此表示衷心的感谢!

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