

# 大盆大坂 MOR 型和 SSZ 型蛇绿岩对北祁连洋演化的制约

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**摘要:** 北祁连大盆大坂剖面保存了 MOR 型和 SSZ 型两类蛇绿岩, 记录了两种构造环境的岩浆活动。剖面南段的蛇绿岩由蛇纹石化的超基性岩和辉长岩组成, 其中辉长岩具有 N-MORB 地球化学特征, 代表了扩张形成的洋壳。从辉长岩中分选出大量锆石, 采用 SHRIMP 方法测得这些锆石的年龄为  $505 \pm 8$  Ma, 代表了辉长岩的结晶年龄, 它与熬油沟辉长岩(504 Ma)和东草河辉长岩(497 Ma)基本同时形成, 表明寒武纪末期北祁连洋盆存在一次规模较大的海底扩张事件。剖面北段主要由枕状熔岩组成, 其地球化学性质类似于玻安岩, 代表了由洋壳向北俯冲形成的岛弧。枕状熔岩形成较晚(483 Ma), 这与其覆盖在辉长岩上的野外关系是一致的, 说明从残留洋壳的形成到岛弧的出现间隔了大约 20 Ma。这项研究为认识北祁连洋盆的构造演化提供了重要依据。

**关键词:** 辉长岩, 玻安岩, 锆石, 大盆大坂, 北祁连

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## Constraints on the evolution of the North Qilian ocean basin: MOR-type and SSZ-type ophiolites from Dachadaban

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**Abstract:** MOR-type and SSZ-type ophiolites occur along the Dachadaban profile in North Qilian Mountains (NQM) of northwest China, which have recorded magmatic activities in different tectonic environments. Geochemical data show that the gabbro in the southern part of the profile has a pattern similar to N-MORB pattern, characterized by low  $\text{SiO}_2$  (48.04% ~ 51.20%) and  $\text{MgO}$  (7.29% ~ 10.81%), Mg index varying from 0.52 to 0.69, high  $\text{TiO}_2$  (1.27% ~ 1.47%) and  $\text{Al}_2\text{O}_3$  (12.66% ~ 14.50%), and high (REE content ranging from  $37.18 \times 10^{-6}$  to  $62.09 \times 10^{-6}$ , about 10 times higher than that of chondrite). The REE pattern indicates a flat distribution or slight LREE depletion relative to HREE, with  $(\text{La}/\text{Yb})_N$  ratios ranging from 0.66 to 0.80, and weak negative Eu anomalies ( $\delta\text{Eu}$  from 0.83 to 0.91). The gabbro has similar Ti/V ratio to N-MORB, but is enriched with Rb, Ba, Th and U. Geochemical characteristics similar to N-MORB imply that the gabbro is of oceanic crust origin. Zircons separated from a gabbro sample are fine-grained (50 ~ 100  $\mu\text{m}$ ) and mostly have long prismatic shape. CL images show that zircons contain an oscillatory zone with Th/U ratio ranging from 0.72 to 1.18, suggesting a magmatic origin. All zircons are concordant and have an age of  $505 \pm 8$  Ma by SHRIMP

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U-Pb dating, representing the formation time of gabbro. This gabbro is coeval with the Aoyougou (504 Ma) and Dongcaohe gabbro (497 Ma) in NQM, suggesting a common oceanic spreading and formation of oceanic crust at the end of Cambrian in the North Qilian Mountain. By contrast, pillow lavas from the northern part of the profile are characterized by high  $\text{SiO}_2$  (52.33% ~ 55.62%) and  $\text{MgO}$  (10.43% ~ 14.17%), Mg index varying from 0.72 to 0.78, low  $\text{TiO}_2$  (0.29% ~ 0.44%) and  $\text{Al}_2\text{O}_3$  (10.10% ~ 13.34%), and low  $\Sigma\text{REE}$  content ( $9.93 \times 10^{-6} \sim 19.04 \times 10^{-6}$ ), 10 times lower than  $\Sigma\text{REE}$  content of chondrite. The REE pattern displays LREE depletion with  $(\text{La}/\text{Yb})_N$  ratios ranging from 0.45 to 0.69. Most pillow lava samples have negative Eu anomalies ( $\delta\text{Eu}$  ranging from 0.58 to 1.08), with distinct negative-Nb, Ta anomalies and a Ti/V ratio similar to that of arc tholeiite. The overall geochemical characteristics resemble those of boninite, which originated from an island arc related to the northward subduction of oceanic crust. Pillow lavas were formed slightly later (483 Ma), consistent with the field relationship of pillow lavas overlying gabbro. These data indicate that there is about 20 Ma time difference from the formation of oceanic crust to the production of island arc. This study provides important constraints for the evolution of ocean basin in the NQM.

**Key words:** gabbro; boninites; zircon; Dachadaban; North Qilian Mountains

北祁连不仅出露有早古生代与洋壳俯冲有关的蓝片岩和榴辉岩(吴汉泉, 1980, 1982; Wu *et al.*, 1993; 许志琴等, 1994; 张建新等, 1997; 宋述光等, 2004; Zhang *et al.*, 2007), 还有典型的蛇绿岩(王荃等, 1976; 肖序常等, 1978), 构成了中国西部典型的早古生代板块缝合带, 其中蛇绿岩的类型、形成环境和形成时代对重建北祁连的古板块体制具有重要意义。经过 30 多年的研究, 已经积累了大量关于北祁连蛇绿岩的地球化学资料(夏林圻等, 1991, 1995, 1996, 1998, 2003; Xia *et al.*, 2003; 冯益民等, 1995; 陈雨等, 1995; 张旗等, 1997, 1998; 钱青等, 1999, 2001a, 2001b; 韩松等, 2000; 侯青叶等, 2005, 2006; 曾建元等, 2007), 这些数据表明分布在北祁连不同地段的蛇绿岩形成于多种环境, 如洋中脊(MOR 型)、弧后盆地和岛弧环境(SSZ 型)等。相对而言, 蛇绿岩的同位素年代学资料却十分有限, 制约了对北祁连洋构造演化的认识。

最早根据蛇绿岩套中硅质岩和灰岩夹层所产化石, 确定蛇绿岩大致形成于奥陶纪(王荃等, 1976)。后来采用全岩 Sm-Nd 等时线法获得北祁连玉石沟基性熔岩形成时代为 522 ~ 495 Ma(夏林圻等, 1996), 大岔大坂剖面上玄武岩形成时代为  $469 \pm 5$  Ma(剖面南段大坂垭口附近)和  $465 \pm 22$  Ma(剖面北段)(Xia *et al.*, 2003), 永登岛弧火山岩的形成时代为  $465 \pm 23$  Ma, 老虎山弧后盆地火山岩的形成时代为  $454 \pm 4$  Ma(夏林圻等, 1998)。最近几年采用 SHRIMP 方法获得了一些辉长岩的高精度年代学资料, 如玉石沟为  $550 \pm 17$  Ma(史仁灯等, 2004), 熬油

沟为  $504 \pm 6$  Ma(相振群等, 2007), 东草河为  $497 \pm 7$  Ma(曾建元等, 2007)。玉石沟的年代学资料显示早期的 Sm-Nd 方法与近年的 SHRIMP 方法相比仍存在较大偏差, 只有精确的年代学和系统的地球化学数据才能成为探讨北祁连洋古构造格局及其演化的可靠依据。另外, 由于对辉长岩中锆石的成因还存在不同认识, 得出的地质解释也完全不同(曾建元等, 2007)。北祁连大岔大坂蛇绿岩中存在 MOR 型和玻安质(SSZ 型)两类岩石(陈雨等, 1995; 张旗等, 1998), 由于缺少精确的年代学资料, 难以对其构造演化做出判断。笔者对大岔大坂剖面南段的辉长岩和北段的枕状熔岩进行了较系统的地球化学研究并获得了辉长岩锆石的 SHRIMP 年龄, 其结果对认识北祁连洋的演化具有重要意义。

## 1 北祁连地质背景

北祁连造山带位于华北板块西南缘的阿拉善地块与中祁连地块之间, 呈 NW 走向, 其西北部被阿尔金山左行走滑断裂切割(图 1), 北界以走廊过渡带与阿拉善地块相连, 南界以托莱山大型右行平移剪切带与中祁连地块毗邻(王荃等, 1976; 肖序常等, 1978; 许志琴等, 1994; Xiao *et al.*, 2009)。北祁连经历了早古生代洋盆消减、洋壳向北俯冲与板块碰撞及后期的陆内汇聚阶段, 因此有大规模的褶皱作用、变质作用、火山活动、韧性剪切变形和花岗岩侵入(许志琴等, 1994), 造山带前普遍发育泥盆系的磨拉石建造, 表明早古生代造山作用的结束(葛肖虹等, 1999)。

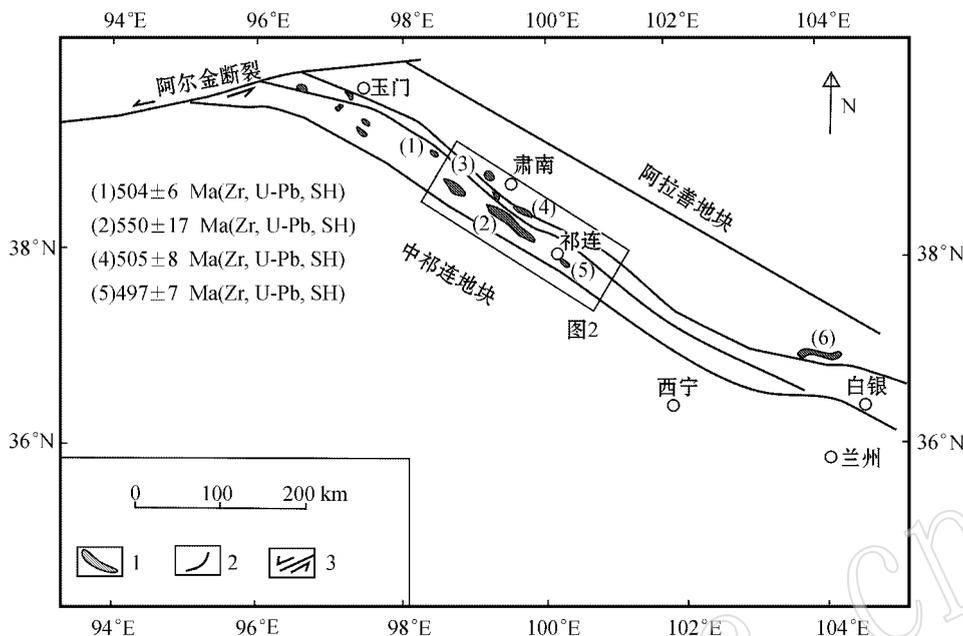


图1 北祁连蛇绿岩分布略图(据侯青叶等, 2006)

Fig. 1 Sketch map showing the distribution of ophiolites in the North Qilian Mountains (after Hou Qingye *et al.*, 2006)

1—蛇绿岩单元; 2—边界断裂; 3—大型走滑断裂; (1)—熬油沟蛇绿岩, 年龄据相振群等(2007); (2)—玉石沟蛇绿岩, 年龄据史仁灯等(2004); (3)—九个泉蛇绿岩; (4)—大盆大坂蛇绿岩, 本文; (5)—东草河蛇绿岩, 年龄据曾建元等(2007); (6)—老虎山蛇绿岩; Zr—锆石, 均选自辉长岩; SH—SHRIMP 法

1—ophiolite unit; 2—boundary fault; 3—strike-slip fault; (1)—Aoyougou ophiolite, age after Xiang Zhenqun *et al.*, 2007; (2)—Yushigou ophiolite, age after Shi Rendeng *et al.*, 2004; (3)—Jiugequan ophiolite; (4)—Dachadaban ophiolite, this study; (5)—Dongcaohe ophiolite, age after Tseng *et al.*, 2007; (6)—Laohushan ophiolite; Zr—zircon separated from gabbros; SH—SHRIMP

北祁连中段是北祁连俯冲杂岩带的典型地区(图2), 主要由蛇绿岩、榴辉岩和高压蓝片岩组成(王荃等, 1976; 肖序常等, 1978; 吴汉泉, 1980, 1982; 许志琴等, 1994; 张建新等, 1995; 宋述光, 1997; 张建新等, 1997, 1998; 宋述光等, 2004; 张建新等, 2006; Zhang *et al.*, 2007; 于胜尧等, 2007; Xiao *et al.*, 2009), 蛇绿岩的时代为早寒武世—奥陶纪(王荃等, 1976; 肖序常等, 1978; 夏林圻等, 1996), 榴辉岩的形成时代为 490~460 Ma(宋述光等, 2004; Zhang *et al.*, 2007), 高压蓝片岩的形成时代为 440~460 Ma(Wu *et al.*, 1993; 许志琴等, 1994; 张建新等, 1997)。

北祁连保存较好的蛇绿岩主要分布在西段的熬油沟、中段的九个泉、大盆大坂、玉石沟和东草河以及东段的老虎山等地(图1)。前人对这几处蛇绿岩均进行过较详细的地质、岩石学及地球化学研究, 各蛇绿岩单元岩石类型主要由蛇纹石化地幔橄榄岩、变辉长岩、块状和枕状玄武岩和硅质岩等组成(冯益民等, 1995; 夏林圻等, 1996; 张旗等, 1997; 张招崇等, 1998; 史仁灯等, 2004; 相振群等, 2007; 曾建元

等, 2007)。这些蛇绿岩单元内枕状玄武岩大多数都具有 N-MORB 型玄武岩的微量元素特征(陈雨等, 1995; 夏林圻等, 1991, 1995, 1996, 1998, 1999, 2003; 张旗等, 1997, 1998; 张招崇等, 1998; 钱青等, 1999, 2001a, 2001b; 侯青叶等, 2005, 2006), 熬油沟蛇绿岩形成的环境为初始小洋盆(张招崇等, 1998), 玉石沟蛇绿岩形成于洋中脊环境或者成熟弧后盆地环境(史仁灯等, 2004; 侯青叶等, 2005), 九个泉和老虎山的蛇绿岩形成于弧后盆地环境(夏林圻等, 1995, 1996; 张旗等, 1998; 钱青等, 1999, 2001a, b; Xia *et al.*, 2003)。而对大盆大坂蛇绿岩的形成环境仍有不同看法, 有形成于弧间盆地(冯益民等, 1995)或岛弧和弧后盆地(张旗等, 1997, 1998)或弧后盆地(Xia *et al.*, 2003; 韩松等, 2000)等几种观点。

## 2 大盆大坂蛇绿岩剖面

大盆大坂蛇绿岩由变质橄榄岩、辉长—辉绿岩和枕状熔岩3部分岩石组成(图3)。变质橄榄岩仅出露在

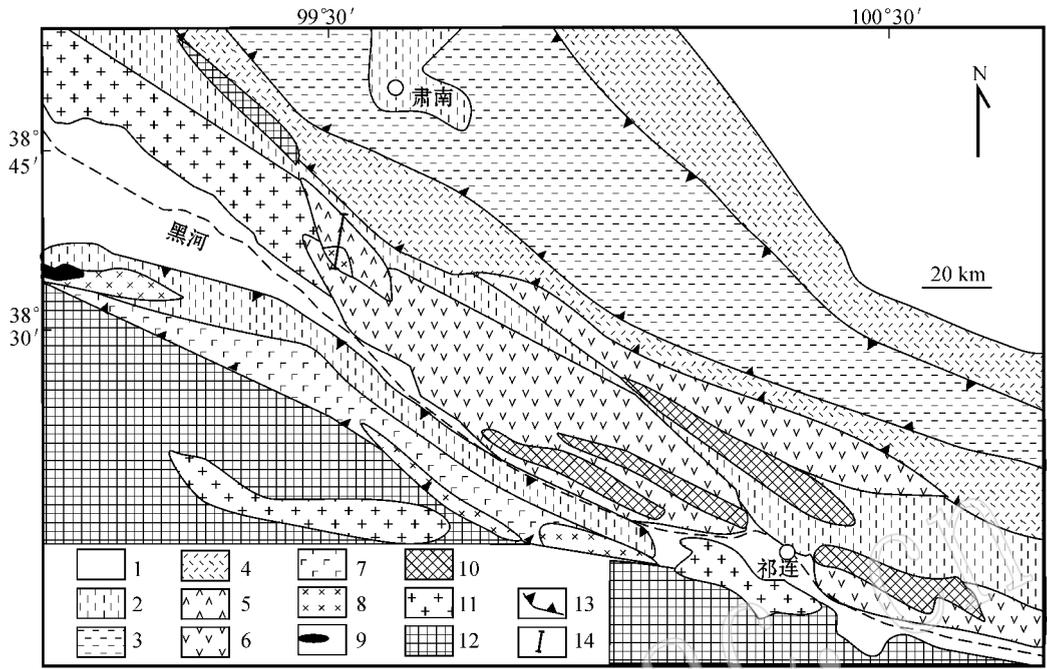


图 2 北祁连中段地质简图(据宋述光等,2004;Zhang 等,2007)

Fig. 2 Simplified geological map showing major litho-tectonic units in the North Qilian Mountains (modified after Song Shuguang *et al.*, 2004 and Zhang *et al.*, 2007)

- 1—第四系;2—后泥盆纪沉积盖层;3—志留纪复理石;4—弧后盆地火山岩;5—玻安岩;6—岛弧火山岩;7—洋壳蛇绿岩;8—辉长岩;
- 9—地幔橄辉岩;10—高压变质岩(蓝片岩/榴辉岩);11—花岗岩;12—前寒武纪地块;13—逆冲断层;14—大盆大坂剖面位置
- 1—Quaternary;2—post-Devonian sediments;3—Silurian flysch;4—back-arc volcanic rock;5—boninite;6—arc volcanic rock;7—ophiolite;
- 8—gabbro;9—ultramafic rock;10—HP/LT metamorphic rock;11—granite;12—Precambrian block;13—thrust fault;14—location of Dachadaban section

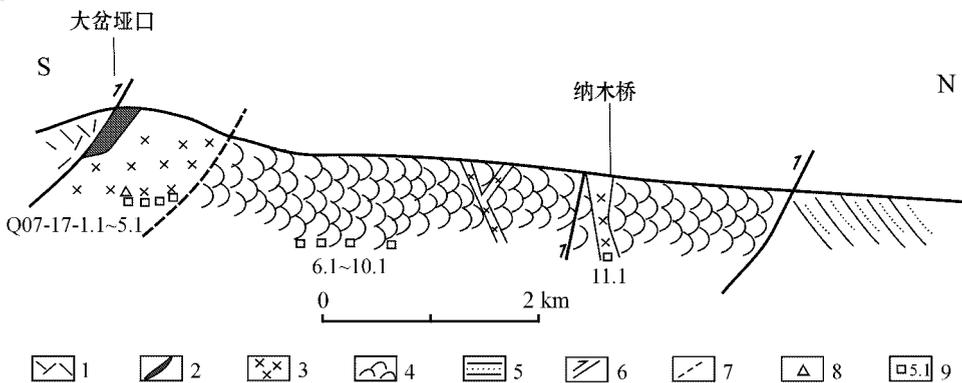


图 3 北祁连大盆大坂蛇绿岩剖面(据冯益民等,1995;韩松等,2000)

Fig. 3 Geological profile of Dachadaban ophiolite (after Feng Yimin *et al.*, 1995; Han Song *et al.*, 2000)

- 1—andesite-basalts;2—serpentinized ultramafic rocks;3—gabbro-diorite;4—boninite;5—volcanic-sedimentary rocks;6—fault;
- 7—inferred fault;8—sampling position for dating;9—location of geochemical sample( Table 1 )

剖面南端的大盆垭口,大部分已蛇纹石化。其上(向北)为辉长-辉绿岩单元(图 4a),出露宽度约 1 km。在该单元内,辉长岩与辉绿岩呈侵入接触关

系,辉绿岩宽可达数十米,被辉长岩侵入。局部见伟晶辉长岩呈脉状沿辉长岩裂隙贯入,与辉长岩无截然的界线。北段枕状熔岩出露宽度很大,达 4 km,

沿公路重复出现,新鲜露头呈灰绿色(图 3、图 4b),岩枕大小不等,多数约 30 cm×40 cm(图 4d),由于后期构造运动影响局部可见岩枕被拉长,枕状熔岩呈定向排列。多处见有辉长岩和辉绿岩墙穿插枕状熔岩(冯益民等,1995),辉长岩宽十几米至近百米,

主要呈岩墙状,单个岩墙厚约 100 cm,少量呈岩床状侵入枕状熔岩。辉长岩侵入体内部粒度粗,边部细,部分辉长岩中还有辉绿岩墙贯入,辉绿岩墙宽 0.4~2 m,有的呈不规则状(冯益民等,1995;张旗等,1997,1998;韩松等,2000)。



图 4 北祁连大盆大坂的辉长岩和枕状熔岩

Fig. 4 Gabbro and pillow lavas along Dachadaban profile in the North Qilian Mountains

a—剖面南段具块状构造的辉长岩; b—剖面北段保存较好的枕状熔岩露头; c—粗粒辉长岩(Q07-17-1.1),由斜长石(Pl)和辉石(Py)组成(正交偏光); d—枕状熔岩,单个岩枕大小约 30 cm×40 cm

a—massif gabbros in the southern part of the profile; b—well-preserved pillow lavas in the northern part of the profile; c—microphotograph of massif gabbro with plagioclase + hornblende, local remnant of pyroxene (crossed nicols); d—pillow lavas about 30 cm×40 cm in size

### 3 测试方法

全岩分析由国家地质实验测试中心完成,主元素采用 X 荧光光谱法(XRF),测试仪器为 3080E 型 X 荧光光谱仪,其中 FeO 采用容量滴定法;稀土元素和微量元素采用等离子质谱法(ICP-MS)。

锆石分选在廊坊区域地质调查研究院进行,将样品破碎至约 100 μm,先用磁法和重液分选,然后在双目镜下手工挑选。将代表性锆石颗粒制成环氧

树脂浇注的样品靶,待固化后,将靶面磨光露出锆石,然后在光学显微镜下对锆石进行反射光、透射光及阴极发光图像照相,目的是了解锆石的内部结构。锆石 U-Th-Pb 分析在北京离子探针中心的 SHRIMP II 型离子探针仪器上完成,同位素测试流程详见参考文献(Zhang *et al.*, 2007)。标准锆石 SL13 (572 Ma, U 含量为  $238 \times 10^{-6}$ )用于标定 TEM 标准锆石及样品的 U、Th 及 Pb 含量。应用 TEM (417 Ma)进行元素间分馏校正、计算 Pb/U 及 UO/U 的校正值,并计算样品年龄,采用 ISOPLOT 程序

处理数据,应用实测 $^{204}\text{Pb}$ 校正普通铅。

## 4 岩相学及岩石化学特征

辉长岩呈灰绿色,粗中粒辉长结构(图 4c),块状构造,主要由斜长石(50%~60%)+辉石(35%~40%)组成,少量铁钛氧化物。斜长石 1~2 mm,板柱状,部分晶体发生绢云母化,辉石为短柱状,部分发生绿泥石化。枕状熔岩发生变质,纤状变晶结构,主要由纤维状透闪石(50%~60%)+斜长石(35%~40%)组成,含少量铁钛氧化物。

对采自剖面上的辉长岩、辉绿岩(南段 4 个样品,北段 1 个样品)和枕状熔岩(北段 4 个样品)(图 3)进行了岩石地球化学分析(表 1)。除 1 个样品(Q07-17-6.1)烧失量较大外(LOI=5.54%),其余样品的 LOI<5%。辉长岩样品的 LOI<3%,表明岩石比较新鲜。

剖面南段辉长岩样品的  $\text{SiO}_2$  含量较低,变化范围较小,为 48.04%~51.2%,在  $\text{SiO}_2$ -Nb/Y 图(图

5a)上,落入亚碱性玄武岩区。相对高钛高铝低镁, $\text{TiO}_2$  含量为 1.27%~1.47%, $\text{Al}_2\text{O}_3$  含量 12.66%~14.50%, $\text{MgO}$  含量为 7.29%~10.81%(图 5b、5c、5d), $\text{Mg}^\#$  为 0.52~0.65(表 1),不是初始岩浆,经历过一定程度的演化。而剖面北段的玻安岩  $\text{SiO}_2$  含量较高,为 52.33%~55.62%,略低于 Bonin Islands 玻安岩的  $\text{SiO}_2$  含量(56%) (Hickey and Frey, 1982),在  $\text{SiO}_2$ -Nb/Y 图(图 5a)上,落入安山岩区。相对低钛低铝高镁, $\text{TiO}_2$  含量为 0.29%~0.44%, $\text{Al}_2\text{O}_3$  含量 10.10%~13.34%, $\text{MgO}$  含量为 10.43%~14.17%(图 5b、5c、5d), $\text{Mg}^\#$  为 0.72~0.78(表 1),与交代的亏损地幔楔的熔融有关,具有玻安岩特征(张旗,1990)。

剖面南段辉长岩的稀土元素含量较高, $\sum\text{REE}$  为  $37.18 \times 10^{-6}$ ~ $62.09 \times 10^{-6}$ ,稀土元素标准化采用球粒陨石值(Boynton *et al.*, 1984),轻稀土元素略显亏损( $\text{La}/\text{Yb}$ )<sub>N</sub> 为 0.66~0.80, $\delta\text{Eu}$  为 0.83~0.91,显示弱的负异常(表 1)。稀土元素配分模式为平坦型或轻微的左倾型,与 N-MORB 的 REE 配分

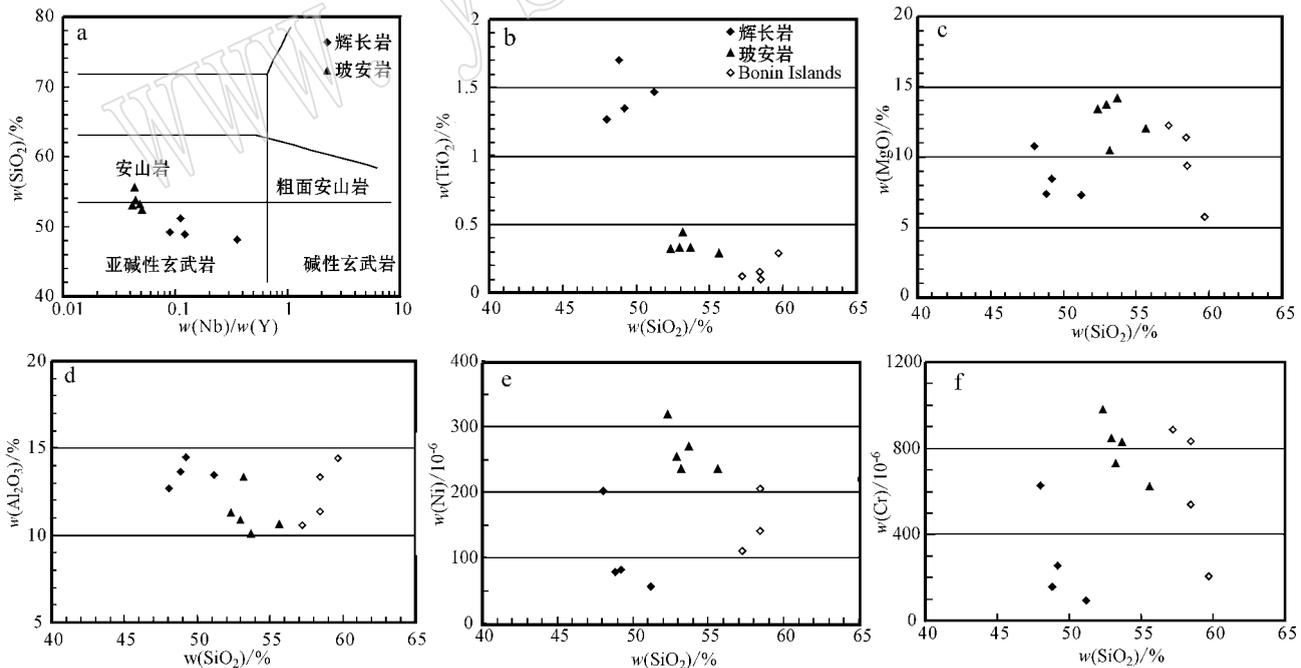


图 5 北祁连大盆大坂辉长岩-玻安岩的  $\text{SiO}_2$ -Nb/Y 图(a)(Winchester 和 Floyd, 1977),  $\text{TiO}_2$ - $\text{SiO}_2$  图(b)

(Bonin Islands 据 Hickey 和 Frey, 1982),  $\text{MgO}$ - $\text{SiO}_2$  图(c),  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  图(d),  $\text{Ni}$ - $\text{SiO}_2$  图(e)和  $\text{Cr}$ - $\text{SiO}_2$  图(f)

Fig. 5  $\text{SiO}_2$ -Nb/Y diagram (a) (after Winchester and Floyd, 1977),  $\text{TiO}_2$ - $\text{SiO}_2$  plot (b) (Bonin Islands after Hickey and Frey, 1982),  $\text{MgO}$ - $\text{SiO}_2$  plot (c),  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  plot (d),  $\text{Ni}$ - $\text{SiO}_2$  plot (e) and  $\text{Cr}$ - $\text{SiO}_2$  plot (f) of gabbros and boninite along

Dachadaban profile in the North Qilian Mountains

表 1 北祁连大盆大坂辉长岩-枕状熔岩的主量元素(  $w_B/\%$  ) 微量元素(  $w_B/10^{-6}$  )组成Table 1 Major(  $w_B/\%$  ) and trace element (  $w_B/10^{-6}$  ) concentrations of gabbros and pillow lavas along Dachadaban profile in the North Qilian Mountains

岩石 样品号	辉长岩 Q07-17-1.1	辉长岩 Q07-17-2.1	辉长岩 Q07-17-4.1	辉长岩 Q07-17-5.1	玻安岩 Q07-17-6.1	玻安岩 Q07-17-7.1	玻安岩 Q07-17-8.1	玻安岩 Q07-17-10.1	辉长-闪长岩 Q07-17-11.2
SiO <sub>2</sub>	51.20	49.20	48.84	48.04	52.33	55.62	53.68	52.94	53.20
TiO <sub>2</sub>	1.47	1.35	1.70	1.27	0.32	0.29	0.33	0.33	0.44
Al <sub>2</sub> O <sub>3</sub>	13.45	14.50	13.64	12.66	11.32	10.62	10.10	10.90	13.34
Fe <sub>2</sub> O <sub>3</sub>	4.55	3.84	3.64	2.61	1.47	1.86	1.66	1.55	3.09
FeO	5.84	6.34	8.78	7.87	5.53	4.80	5.66	5.41	4.53
MnO	0.15	0.19	0.18	0.18	0.13	0.18	0.15	0.14	0.14
MgO	7.29	8.43	7.38	10.81	13.42	12.03	14.17	13.75	10.43
CaO	6.83	9.43	9.69	10.95	5.92	9.43	7.71	7.20	8.56
Na <sub>2</sub> O	3.88	2.97	2.73	2.02	3.03	0.83	2.70	2.51	1.95
K <sub>2</sub> O	0.22	0.07	0.14	0.45	0.04	0.14	0.08	0.11	0.19
P <sub>2</sub> O <sub>5</sub>	0.10	0.12	0.15	0.09	0.03	0.02	0.03	0.02	0.04
H <sub>2</sub> O <sup>+</sup>	2.92	2.66	2.70	2.80	4.71	3.62	3.14	4.10	3.56
CO <sub>2</sub>	1.88	0.26	0.26	0.43	1.97	0.51	0.43	1.28	0.60
LOI	3.72	2.57	2.20	2.41	5.54	3.61	3.36	4.45	3.36
Total	98.70	99.01	99.07	99.36	99.08	99.43	99.63	99.31	99.27
Mg <sup>#</sup>	0.57	0.61	0.52	0.65	0.78	0.77	0.78	0.78	0.72
La	2.70	3.59	5.04	5.72	0.64	0.76	0.88	0.76	1.57
Ce	7.33	9.91	13.00	12.70	1.72	1.92	2.33	2.16	3.86
Pr	1.24	1.70	2.14	1.78	0.28	0.31	0.37	0.37	0.6
Nd	6.65	9.26	11.40	8.33	1.49	1.61	2.02	1.96	3.14
Sm	2.31	3.12	3.88	2.30	0.6	0.62	0.72	0.76	1.13
Eu	0.79	1.15	1.34	0.90	0.25	0.27	0.26	0.19	0.39
Gd	3.64	4.74	5.89	3.21	0.97	0.94	1.08	1.28	1.81
Tb	0.65	0.84	0.99	0.53	0.19	0.18	0.20	0.22	0.32
Dy	4.48	5.68	6.95	3.53	1.36	1.29	1.43	1.56	2.26
Ho	0.96	1.22	1.49	0.73	0.3	0.29	0.32	0.35	0.49
Er	2.85	3.62	4.46	2.04	0.89	0.89	0.95	1.05	1.47
Tm	0.42	0.53	0.64	0.30	0.15	0.13	0.15	0.16	0.23
Yb	2.77	3.45	4.26	1.95	0.95	0.87	0.93	1.06	1.54
Lu	0.39	0.50	0.61	0.28	0.14	0.14	0.15	0.17	0.23
∑REE	37.18	49.31	62.09	44.30	9.93	10.22	11.79	12.05	19.04
(La/Yb) <sub>N</sub>	0.66	0.70	0.80	1.98	0.45	0.59	0.64	0.48	0.69
δEu	0.83	0.91	0.86	1.01	1.00	1.08	0.90	0.58	0.83
Y	22.9	30.70	37.3	18	7.47	7.31	8.09	8.5	12.5
Rb	3.67	1.21	2.13	7.47	0.74	3.10	1.49	1.42	3.45
Sr	88.2	158.0	135.0	132.0	51.0	78.7	83.2	43.7	94.7
Ba	43.4	42.1	35.2	141.0	19.3	25.5	21.8	40.8	41.6
Nb	2.56	2.73	4.58	6.41	0.38	0.32	0.36	0.35	0.6
Ta	0.24	0.23	0.37	0.51	0.06	<0.05	0.05	0.05	0.07
Zr	59.9	75.1	101.0	60.6	15.4	13.3	16.0	15.9	25.7
Hf	1.79	2.18	2.86	1.68	0.52	0.43	0.54	0.54	0.88
Th	0.26	0.28	0.5	0.64	0.17	0.16	0.17	0.16	0.32
U	0.14	0.12	0.14	0.16	0.12	0.10	0.11	0.13	0.23
V	335	336	388	266	181	187	198	176	215
Cr	93	256	158	627	981	624	826	846	731
Co	45.0	49.0	57.5	60.9	48.8	42.1	48.3	49.3	46.2
Ni	55.4	82.2	78.6	202.0	318.0	235.0	269.0	255.0	236.0
Sc	48.8	50.4	49.8	42.1	33.4	31.8	37.2	35.2	37.8
Nb/Y	0.11	0.09	0.12	0.36	0.05	0.04	0.04	0.04	0.05

$$Mg^{\#} = Mg / (Mg + Fe^{2+}) \quad \delta Eu = 2Eu_N / (Sm_N + Gd_N)$$

模式类似(图 6a) 配分曲线均位于球粒陨石 10 倍线以上。剖面北段玻安岩的稀土含量较低,  $\Sigma \text{REE}$  为  $9.93 \times 10^{-6} \sim 19.04 \times 10^{-6}$ , 轻稀土元素亏损 ( $\text{La}/\text{Yb}$ )<sub>N</sub> 为 0.45~0.69,  $\delta \text{Eu}$  为 0.58~1.08, 主要显示

负异常(表 1)。与 N-MORB 的 REE 配分模式类似, 不同于 Bonin Islands 玻安岩的 U 型稀土元素配分模式(图 6a) 稀土曲线均位于球粒陨石 10 倍线以下。

微量元素标准化采用 N-MORB 值(Sun and Mc-

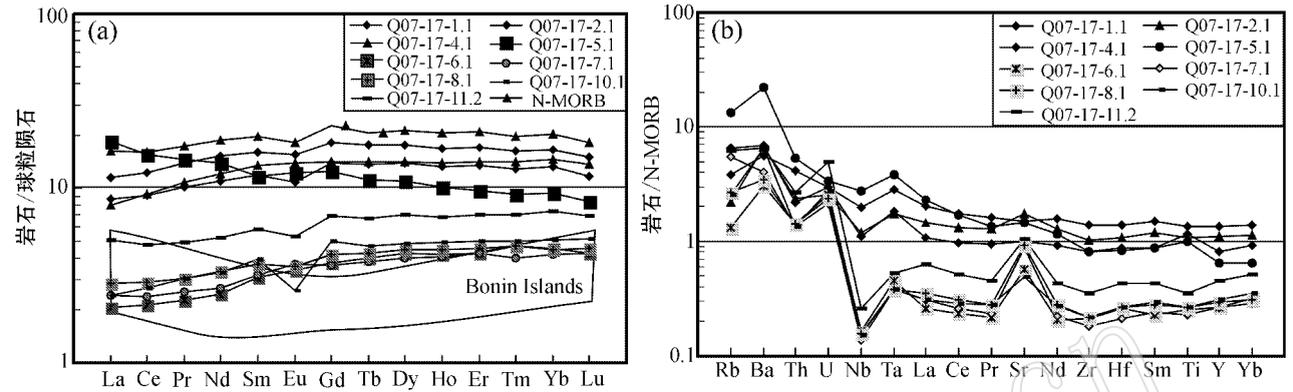


图 6 北祁连大岔大坂辉长岩-玻安岩的稀土元素配分模式图(a)和微量元素蛛网图(b)

Fig. 6 Chondrite-normalized REE patterns (a) and N-MORB-normalized trace element patterns (b) for gabbros and boninite along Dachadaban profile in the North Qilian Mountains

Donough, 1989)。辉长岩和玻安岩的微量元素分布模式与洋中脊玄武岩(N-MORB)相比, 都明显富集 Rb、Ba、Th、U。图中辉长岩的其他元素含量均高于 N-MORB, 而玻安岩其他元素含量均低于 N-MORB。另外一个明显的特征是玻安岩的 Nb、Ta 含量相对于相邻元素为明显的负异常(图 6b), 这是岛弧火山岩的特点。在 V-Ti 图解(图 7)上, 辉长岩落入洋中脊玄武岩范围, 而玻安岩落入岛弧拉斑玄武岩区域。

## 5 辉长岩锆石年龄

在北祁连大岔大坂蛇绿岩剖面的南段(大岔垭口, 图 2) 采集了辉长岩大样(约 30 kg, 编号为 Q07-17-1.1), 分选出锆石 1 000 粒, 锆石细小, 约为 50~100  $\mu\text{m}$ , 以长柱状为主, 部分为短柱状或粒状, 呈淡黄色-无色。锆石中含有大量包裹体, 裂纹发育。阴极发光图像(CL)显示部分锆石具有生长环带(图 8), 部分锆石内部结构均匀, 多数锆石还可见几个微米的生长边(亮白色), 可能反映锆石受到后期流体改造。选择锆石的均匀部位进行分析测试获得如下结果, 10 个测试点的 U 含量为 49~370 ( $\times 10^{-6}$ ), Th 含量为 35~300 ( $\times 10^{-6}$ ), Th/U 比值为 0.72~1.18, 显示岩浆锆石的特点。 $^{206}\text{Pb}/^{238}\text{U}$  的年龄为 488~517 Ma, 加权平均年龄为  $505 \pm 8 \text{ Ma}$ (表 2, 图

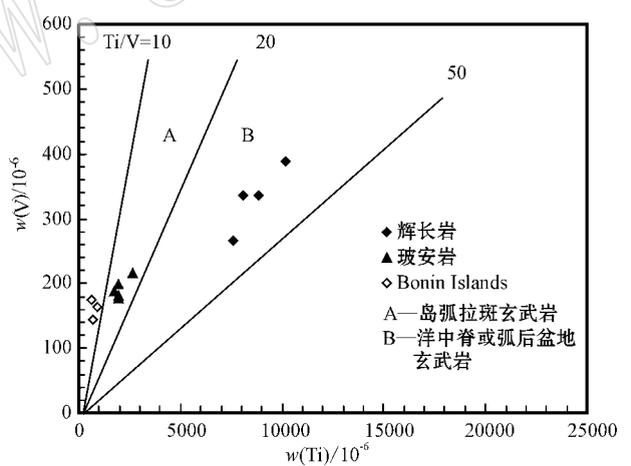


图 7 北祁连大岔大坂辉长岩-玻安岩的 V-Ti 图解 (据 Shervais, 1982; Bonin Islands(据 Hickey 和 Frey, 1982))

Fig. 7 Diagram of V-Ti for gabbros and boninite along Dachadaban profile in the North Qilian Mountains (after Shervais, 1982; Bonin Islands after Hickey and Frey, 1982)

9) 代表了辉长岩的形成年龄。

## 6 讨论

### 6.1 辉长岩结晶出锆石的可能性

很多蛇绿岩中的辉长岩都含有数量不等的锆石 (Dunning & Pedersen, 1988; Rubatto *et al*, 1998; Liati *et al*, 2004; 史仁灯等, 2004; 钟立峰等, 2006;

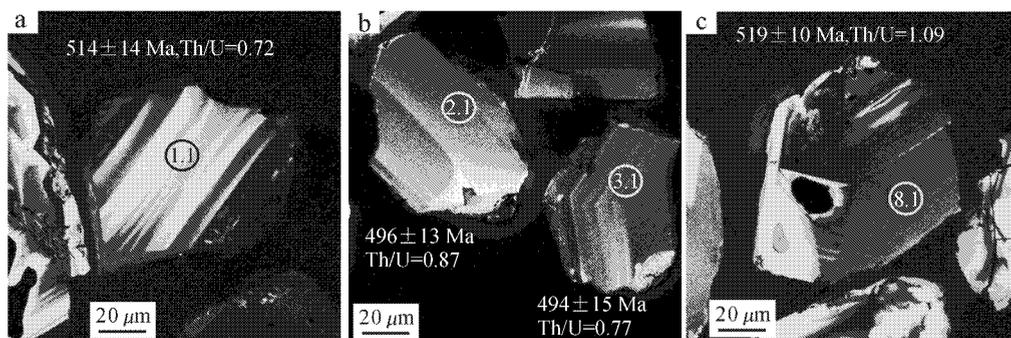


图 8 大盆大坂辉长岩代表性锆石的阴极发光图像 (CL)

Fig. 8 Representative CL images of the analyzed zircon from gabbro along Dachadaban profile

表 2 北祁连大盆大坂辉长岩 (Q07-17-1.1) 锆石 SHRIMP 分析结果

Table 2 U-Th-Pb SHRIMP zircon data of gabbro (Q07-17-1.1) along Dachadaban profile in the North Qilian Mountains

测点号	普通 Pb/%	$w_B/10^{-6}$			Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	± %	$^{207}\text{Pb}/^{235}\text{U}$	± %	$^{206}\text{Pb}/^{238}\text{U}$	± %	年龄 (Ma)	
		U	Th	Pb								$^{206}\text{Pb}/^{238}\text{U}$	1σ
1.1	0.17	49	35	3.5	0.72	0.796 0	8.7	0.91	9.2	0.082 9	2.9	514	14
2.1	2.75	82	69	5.8	0.87	0.052 8	20.9	0.58	21.0	0.080 0	2.7	496	13
3.1	5.22	59	43	4.2	0.77	0.033 5	54.7	0.37	54.8	0.079 6	3.1	494	15
4.1	4.21	53	39	3.9	0.76	0.053 0	32.9	0.60	33.0	0.081 9	2.9	508	14
5.1	0.79	370	300	26.7	0.84	0.054 2	4.6	0.62	5.0	0.083 4	1.9	517	10
6.1	4.40	63	48	4.6	0.79	0.037 0	42.0	0.41	42.1	0.080 9	2.9	501	14
7.1	0.65	162	186	11.4	1.18	0.058 8	3.8	0.66	4.4	0.081 4	2.3	504	11
8.1	0.32	159	167	11.5	1.09	0.061 5	4.7	0.71	5.1	0.083 9	2.0	519	10
9.1	4.40	49	36	3.6	0.75	0.043 8	23.9	0.49	24.0	0.080 5	2.5	499	12
10.1	2.32	59	50	4.1	0.88	0.048 0	14.0	0.52	14.2	0.078 6	2.3	488	11

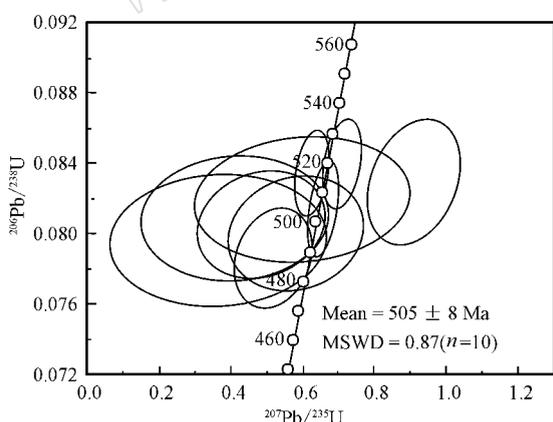


图 9 大盆大坂辉长岩锆石 SHRIMP U-Pb 年龄谐和图

Fig. 9 U-Pb concordia diagram of zircon from gabbro along Dachadaban profile

相振群等, 2007; 曾建元等, 2007; Kaczmarek *et al.*, 2008), 但对锆石的成因和年龄含义仍有不同看法, 代表辉长岩的形成年龄 (Dunning & Pedersen, 1988; Rubatto *et al.*, 1998; Liati *et al.*, 2004; 史

仁灯等, 2004; 钟立峰等, 2006; 相振群等, 2007; Kaczmarek *et al.*, 2008) 或者指示辉长岩构造成位时代 (曾建元等, 2007)。现代大洋中脊的辉长岩中也有锆石形成, 沿大西洋中脊 (MAR)  $5^{\circ}30.6' \sim 5^{\circ}32.4'N$  的辉长岩含有年轻锆石 (1.2 ~ 1.4 Ma) (Bortnikov *et al.*, 2005),  $11^{\circ}N$  的辉长岩锆石年龄为 13.25 ~ 13.75 Ma (Lissenberg *et al.*, 2009), 这些锆石都是辉长岩在冷凝过程中结晶的。

通常认为超基性岩如石榴橄榄岩 Zr 含量很低且  $\text{SiO}_2$  不饱和, 难以形成原生锆石 (Zheng *et al.*, 2003; Katayama *et al.*, 2003), 但是演化的超基性岩浆和基性岩浆可以形成锆石。矿物包裹体证据表明, 金伯利岩中的锆石巨晶是从演化岩浆中结晶的 (Griffin *et al.*, 2000), 碱性玄武岩中的锆石巨晶也是从演化流体中结晶形成的 (丘志力等, 2004, 2005)。  $\text{SiO}_2$  不饱和的超基性和基性岩石只能形成斜锆石, 如秦岭富水地区辉长岩早期形成斜锆石, 当晚期  $\text{SiO}_2$  饱和时才形成锆石 (李惠民等, 2006)。大

盆大坂辉长岩的  $\text{SiO}_2$  含量为 48%~51% ,属于基性岩类, Zr 含量较高且变化大,  $60 \times 10^{-6} \sim 101 \times 10^{-6}$  (表 1), 而原始地幔 Zr 含量为  $11.2 \times 10^{-6}$ , N-MORB 的 Zr 含量为  $74 \times 10^{-6}$  (Sun & McDonough, 1989), 辉长岩的  $\text{Mg}^\#$  为 0.52~0.65 (表 1), 岩浆为演化的基性岩浆, 完全可能结晶出原生锆石。

## 6.2 辉长岩形成年龄及其地质意义

确定蛇绿岩的形成时代十分困难。首先它由不同的岩石单元组成 (Coleman, 1977), 各单元的形成时代可能本来就不相同。另外, 造山带中的蛇绿岩经历了多次构造运动, 可能会被改造或将不同时代的岩石混杂在一起 (Savelieva *et al.*, 2006), 增加了鉴别难度。蛇绿岩岩浆成分相对均一, Sm-Nd、Rb-Sr 测年方法受到限制 (简平等, 2003)。辉长岩是基性岩浆结晶的产物, 在蛇绿岩剖面中属于壳层单元, 它的形成年龄代表了一次岩石圈扩张 (spreading) (地幔上涌) 形成新洋壳的时代。大盆大坂辉长岩的形成年龄为  $505 \pm 8 \text{ Ma}$ , 可能反映在寒武纪末期祁连洋盆发生过一次扩张。辉长岩的岩石地球化学特征显示为 N-MORB 特征 (张旗等, 1997, 1998; 韩松等, 2000),  $\epsilon \text{Nd}(0) = 7.5 \sim 9.5$  (张旗等, 1998), 表明玄武质岩浆起源于亏损的地幔, 这类地幔通常分布在洋中脊或弧后盆地的扩张中心。

除大盆大坂外, 同时代形成的辉长岩还有北祁连西段的熬油沟辉长岩 (相振群等, 2007) 和北祁连中段祁连县附近的东草河辉长岩 (曾建元等, 2007), 表明此次岩浆活动范围较大, 可能为一次区域性的扩张事件。祁连县西南部玉石沟辉长岩形成于  $550 \pm 17 \text{ Ma}$  (史仁灯等, 2004), 代表了较早期的扩张, 而石居里辉长岩锆石年龄为  $458 \pm 1 \text{ Ma}$  (宋忠宝等, 2007), 代表了更晚期的岩浆事件, 与海底火山喷发事件基本同时 (Xia *et al.*, 2003)。这些资料表明北祁连洋盆的形成经历了多次海底扩张和岩浆事件, 与现代洋壳扩张具有多期性和阵发性的特点十分类似 (Condie, 1989; Lissenberg *et al.*, 2009)。

## 6.3 两类岩石成因

在一条缝合带中同时保留了 N-MORB 型洋壳和岛弧火山岩的蛇绿岩剖面十分有意义 (张旗等, 1998; 韩松等, 2000), 它记录了洋壳的形成和消亡两个过程。随着海底扩张在扩张脊处不断形成新洋壳, 而早期形成的洋壳则在俯冲带不断俯冲消亡并形成玻安岩 (Hickey & Frey, 1982)。大盆大坂剖面的南段主要为辉长岩, 有少量辉绿岩, 岩石化学相当

于拉斑玄武岩, 稀土元素特征类似于 N-MORB (图 6a), 与前人报导的 I 类辉长岩、辉绿岩特征一致 (韩松等, 2000)。剖面上也保存了少量 N-MORB 型的枕状熔岩 (张旗等, 1998), N-MORB 型熔岩的  $\epsilon \text{Nd}(0)$  值较高, 在 7.5~9.5 之间 (张旗等, 1998), 表明岩浆可能来自亏损的软流圈地幔。V-Ti 图解 (图 7) 上, 这组岩石特征类似于洋中脊玄武岩 (Shervais, 1982)。因此, 我们推测这是 N-MORB 型洋壳残片, 记录了在扩张环境下形成洋壳的过程。辉长岩锆石的年龄为  $505 \pm 8 \text{ Ma}$ , 代表了该段洋壳的形成时间。

剖面北段主要为枕状熔岩 (冯益民等, 1995), 局部出现辉长岩和辉绿岩 (韩松等, 2000; 陈雨等, 1995), 主量元素、稀土元素和其他微量元素都与剖面南段的岩石存在明显差别 (图 5、图 6、图 7), 主量元素高 Si 高 Mg 低 Ti, 类似于玻安岩成分 (Hickey & Frey, 1982), 但  $\text{SiO}_2$  含量相对较低,  $< 55\%$ , 属于玻安岩系中的玻玄岩 (张旗, 1990; 陈雨等, 1995), 高  $\text{Mg}^\#$  值 (0.72~0.78) 和较高的 Cr、Ni 含量,  $\text{Cr} = 624 \times 10^{-6} \sim 981 \times 10^{-6}$ ,  $\text{Ni} = 235 \times 10^{-6} \sim 318 \times 10^{-6}$  (图 5e、5f), 具有玻安岩的特征 (Hickey & Frey, 1982) 稀土元素配分曲线均在 10 倍球粒陨石线之下, 为 N-MORB 型, 即 LREE 亏损型, 与 Bonin Islands 玻安岩的 U 型配分模式存在差别 (图 6a), 轻稀土元素没有富集可能与洋壳俯冲携带的沉积物较少有关 (陈雨等, 1995), 是洋壳俯冲携带的大量水导致难熔地幔楔发生部分熔融 (张旗等, 1998), 形成了大盆大坂的玻安岩。玻安岩的形成时代为  $484 \text{ Ma}$  (锆石 SHRIMP 法, 夏小洪等, 2009), 代表了洋壳发生俯冲消亡的时代。当洋壳俯冲到上地幔深度时形成榴辉岩, 北祁连榴辉岩的形成时代为  $490 \sim 460 \text{ Ma}$  (宋述光等, 2004; Zhang *et al.*, 2007), 与玻安岩的形成时代相近, 它们可能是同一洋壳俯冲事件的不同响应。

根据上述地球化学结果, 我们认为具有 N-MORB 特征的辉长岩, 形成于早期类似洋中脊的扩张环境, 岩浆可能来自于上涌的软流圈地幔, 而枕状熔岩具有玻安岩的特征, 形成于洋内弧前的俯冲环境, 岩浆来自于交代亏损地幔楔的部分熔融。从野外关系看, 玻安岩覆盖在 N-MORB 型辉长岩和枕状熔岩上, 表明辉长岩形成后经历了构造抬升过程, 这个过程持续了约  $20 \text{ Ma}$ , 之后发生了洋壳的俯冲 (其形成时代与残留洋壳相近或更晚), 形成的玻安岩覆

盖在早期形成的洋壳上(残留洋壳)。考虑到剖面北侧存在弧后盆地,如九个泉(钱青等,1999),推测洋壳俯冲方向由南向北(图 10),构造格局类似于现今西南太平洋的沟-弧-盆体系(Wilson,1989)。

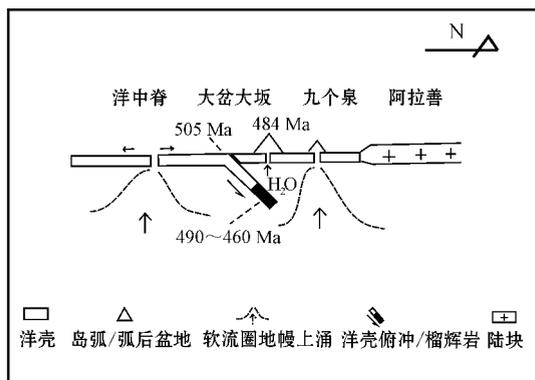


图 10 北祁连大盆大坂洋壳-岛弧形成模式示意图

Fig. 10 Schematic diagram of oceanic crust and island arc formation along Dachadaban profile in the North Qilian Mountains  
大盆大坂辉长岩年龄(本文)玻安岩年龄(夏小洪等,2009);榴辉岩年龄(宋述光等,2004;Zhang等,2007)  
age of gabbro from Dachadaban in this study age of boninite after Xia *et al.* (2009); age of eclogite from the North Qilian Mountains after Song *et al.* (2004) and Zhang *et al.* (2007)

## 7 结论

(1) 北祁连大盆大坂南段的 N-MORB 型的岩石,代表了由海底扩张形成的洋壳;

(2) 大盆大坂辉长岩中的锆石是基性岩浆在冷凝过程中结晶的,锆石 U-Pb SHRIMP 年龄为  $505 \pm 8$  Ma,代表了辉长岩的形成年龄;北祁连其他地区(如东草河和熬油沟)也记录了这次岩浆活动,可能代表了一次较大规模的海底扩张和洋壳形成事件;

(3) 大盆大坂北段的枕状熔岩为玻安岩,代表了由洋壳俯冲形成的洋内弧。

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