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康定杂岩成因和构造意义——来自Hf同位素的证据

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提要:康定杂岩位于扬子地块西缘,通过对四川康定—冕宁—攀枝花—云南元谋地区出露的康定杂岩中基性、中性、酸性岩岩石学、锆石Lu−Hf同位素等多方面系统研究,确定这套岩石形成于岛弧环境。分析表明:康定杂岩中镁铁质侵入体锆石$\varepsilon_{Hf}(t)$变化范围−4.2~+11.0,Hf模式年龄742~2386 Ma;长英质侵入体锆石$\varepsilon_{Hf}(t)$变化范围−4.9~+9.4,Hf模式年龄为967~2707 Ma;暗示康定杂岩体复杂的构造成因。锆石Hf同位素分析表明其岩浆锆石具有与扬子地块西缘同时代镁铁质/长英质侵入体相似的Hf同位素组成,暗示其相似的岩浆起源。研究表明,康定杂岩为大洋俯冲背景下的产物,镁铁质侵入体来源于较为亏损地幔源区,长英质侵入体为新生陆壳与古老地壳物质相互作用形成的产物。锆石Hf同位素数据表明,康定侵入体杂岩中锆石Hf−全岩Nd解耦,为"锆石效应"与少量地壳物质加入共同作用结果。结合岩石学、地层学、构造及地球化学证据综合表明,新元古代时期,扬子地块可能位于Gondwana超大陆的边缘,而不是澳大利亚与北美Laurentia古陆之间的连接部分。

关 键 词:康定侵入体杂岩;新元古代岩浆作用;Hf同位素;Hf−Nd解耦;活动边缘

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Origin and tectonic implications of Kangding intrusive complexes in Sichuan Province: Evidence from zircon Hf isotope

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Abstract: Kangding metamorphosed intrusions in Kangding, Mianning and Panzhihua areas of Sichuan Province and Yuanmou area of Yunnan Province were formed in the island arc setting, as shown by the integrated study of petrogenesis and Hf isotopic

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geochemistry of plutonic rocks ranging from acid to basic ones. Zircons from the mafic plutons have $\varepsilon_{Hf}(t)$ values ranging from −4.2 to +11.0, with their Hf model ages ranging from 742 to 2386 Ma. The felsic plutons have $\varepsilon_{Hf}(t)$ values ranging from −4.9 to +9.4, with their Hf model ages ranging from 967 to 2707 Ma. Magmatic zircons from the Kangding intrusive complexes show similar Hf isotope compositions to those from coeval felsic intrusions on the west margin of the Yangtze Craton, implying their similar magmatic origins. The Kangding intrusive complexes were formed in an oceanic subduction setting, the mafic plutons were derived from depleted mantle sources, whereas the felsic plutons were formed by melting of ancient crustal materials and juvenility crustal materials. According to the Nd isotopic data of the whole rock and the Hf isotopic data of the corresponding zircons in this area, the Hf−Nd decoupling must have resulted from the "zircon effect" and crustal material interaction. Petrology, stratigraphic correlations, tectonic analysis and geochemical evidence suggest that the Yangtze block of South China was located along the margin of the Neoproterozic supercontinent Gondwana rather than at the connection between Australia and Laurentia old land in North America.

Key words: Kangding−Yuanmou complex; Neoproterozoic magmatism; zircon Hf isotope; Hf−Nd decoupling；active margin

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1 引 言

锆石作为稳定副矿物相，即使在后期高温热事件中依然可保持良好的封闭性(Watson and Cherniak, 1997; Watson, 1961)，其复杂的增生环带可用于U−Pb定年，Hf同位素组成可示踪熔体化学成分变化。锆石可作为测定岩石成因和构造模型的有效工具(AI et al., 2007; Belousova et al., 2006; Griffin et al., 2000)。

在扬子克拉通西缘四川康定—冕宁—攀枝花—云南元谋一带广泛分布着由麻粒岩、角闪岩以及长英质片麻岩组成的变质杂岩带。锆石原位微区U−Pb年代学分析表明，这套岩石形成于新元古代(Chen et al., 2005; Zhou et al., 2002; 赖绍聪等, 2015)，改变了其为扬子克拉通太古宙基底的认识(四川省地质矿产局, 1991)。但是，对这套杂岩形成的构造背景及成因机制却颇有争议。对其成因，目前主要有两种观点：(1)超级地幔柱驱动Rodinia超大陆裂解，在大陆裂谷环境中形成的(Li et al., 1999, 2003a, 2003b; Yang et al., 2016; 林广春和董俊超, 2013; 孟庆秀等, 2013; 资锋等, 2011)；(2)岩石形成于岛弧带(Zhou et al., 2002, 2006, 2014; 赖绍聪等, 2015; Zhao and Zhou, 2007a, 2007b; Lai et al., 2015)。近年来，许多学者在对四川冕宁康定杂岩的锆石的SHRIMP U−Pb年龄测定中获得了岩浆结晶锆石的721~773 Ma，微量元素组成上Nb、Ta和HREE亏损具有类似于岛弧岩浆特征，认为它们可能形成于岛弧环境(Chen et al., 2005; 赵俊香等, 2006; Li et al., 2009)。

扬子地块在元古宙Rodinia超大陆的聚合和裂解中处于关键构造位置(Li et al., 1999; Zhou et al., 2006)，因而是Rodinia超大陆重建研究的重要地区之一。康定杂岩的形成与Rodinia超级大陆的裂解有着密切的关系，确定康定杂岩形成的构造背景及成因机制不仅对区域构造演化的分析有重要作用，而且对认识整个Rodinia超级大陆的裂解过程也十分重要。本文基于前人研究的基础，详细研究康定—冕宁—元谋地区新元古代变质侵入岩Lu−Hf同位素地球化学，并探讨它们的成因和构造背景，为进一步了解整个扬子克拉通形成与演化历史及Rodinia超大陆裂解机制提供新资料和认识。

2 地质背景与岩石学特征

扬子地块西缘，习惯上称为康滇地轴(庞维华等, 2015)，在四川境内以康定杂岩(康定群)为中心，向北有彭灌杂岩、米仓山杂岩，向南依次分布有冕宁杂岩、磨盘山—米易杂岩、同德杂岩、渡口(攀枝花)杂岩，出露面积约2000 km²。长期以来，康定杂岩(康定群)被认为是扬子克拉通的变质基底，最早的地层划分将该群从下至上分为不同的组，如下部的“咱里组”以斜长角闪岩、英云闪长岩−奥长花岗岩−花岗闪长岩质(TTG)片麻岩为代表；中—上部

的“冷竹关组”以黑云斜长片麻岩、片麻状钾质花岗岩为代表。近年来在冕宁地区进行1:50000区域地质填图时将这些杂岩作为片麻岩体处理。如划分出相当于咱里组的泽远片麻岩及相当于冷竹关组的琅环片麻岩。两类片麻岩的主要组成岩石为花岗质片麻岩和混合岩化的花岗岩。斜长角闪岩、部分地区可见到的麻粒岩(冕宁沙坝)在片麻岩体中呈透镜体产出,规模不等。透镜体和花岗质片麻岩具有相似的矿物组合(陈岳龙等, 2004)。

本次研究的样品主要采自四川省康定—泸定、冕宁地区的康定杂岩和云南省元谋地区的元谋杂岩。图1中的变质杂岩相当于1:50000地质图中的片麻岩体。对康定—泸定地区的康定群沿康定—泸定公路系统采集康定群咱里组与冷竹关组;冕宁地区主要在沙坝系统采集相当于咱里组的泽远片麻岩;元谋地区,沿公路系统采集元谋杂岩中变质片麻状花岗岩。已有的岩石化学资料(陈岳龙等, 2004)表明长英质片麻岩类主要属英云闪长岩质、奥长花岗岩质。

对采集的样品镜下观察可见:长英质岩石样品以英云闪长岩、花岗闪长岩为主,具有典型的花岗结构及变余花岗结构等。矿物变形变质现象较明显,斜长石颗粒较大,浑圆粒状,聚片双晶发育,内部绢云母化发育;钾长石主要和微斜长石构成格子双晶;石英显溶蚀的圆粒状,常见有波状消光;暗色矿物具定向排列特征,以角闪石及云母为主。角闪石以绿色颗粒为主,为半自形-自形;黑云母为片状且呈定向分布,可能与后期构造变形作用有关。镁铁质岩石以斜长角闪岩为主,主要矿物为斜长石、角闪石,此外有黑云母、磁铁矿、石英和磷灰石,斜长石聚片双晶清楚,少数为卡钠双晶。片麻岩具糜棱结构,片麻理明显;麻粒岩具等粒变晶结构。由样品发育变质角闪石可知,这套岩石总体上已变质到角闪岩相。综上所述,本文所涉及的样品为一套总体变质已达角闪岩相(局部达麻粒岩相)变质的片麻状深成侵入岩,包括3个镁铁质样品和6个长英质样品。采样点位置如图1所示。

3 分析技术

3.1 样品准备

采用常规重、磁选方法分选锆石样品,并手挑其中 > 25 μm的部分。随机选择其中200余颗锆石并依据宋彪等(2002)的方法制靶并抛光。制靶后,对锆石进行透射光和反射光拍照,并在北京离子探针中心用ChromaCl RGB系统的扫描电镜进行全色阴极发光图像拍照。最后进行Lu-Hf同位素分析。

3.2 Lu-Hf同位素

在先前测定锆石数据同一结构域进行锆石原位Lu-Hf同位素组成测定。锆石微区Hf同位素分析在中国地科院矿产资源研究所用LA-MC-ICP-MS完成。仪器工作条件和数据获取方法详见Wu et al. (2010)和侯可军等(2007)。分析过程依样品大小分别选择65 μm或55 μm作为激光束斑直径,以氦气为载气。以 $^{176}Lu/^{175}Lu=0.02658$ 和 $^{176}Yb/^{173}Yb=0.796218$ 矫正 ^{176}Lu 和 ^{176}Yb 对 ^{176}Hf 的干扰(Chu et al., 2002)。仪器质量偏差校正过程中将Yb和Hf同位素比值分别标准化至 $^{172}Yb/^{173}Yb=1.35274$ 和 $^{179}Hf/^{177}Hf=0.7325$。分析过程中以锆石GJ1作为标样,其加权平均 $^{176}Hf/^{177}Hf=0.281989\pm0.00006(2\sigma, n=29)$,与Elhlou et al. (2006)的结果 $0.282013\pm19\ (2\sigma)$ 在误差范围内一致。

4 结 果

4.1 锆石形态学

4.1.1 镁铁质侵入体

镁铁质岩石锆石颗粒(图2a、i、f)无色、透明;颗粒晶面完整、平直光滑(图2a);少数颗粒在透射光下可见细小的包裹体(图2i:13)。多数为长柱状晶体,长140~280 μm,长宽比为1∶1~2∶1。阴极发光照片中可见锆石结构复杂,部分颗粒发育核边结构(图2f:6),多数锆石颗粒具有明显的环带结构,晶体不完整者显示出明暗相间的结构特征,具典型岩浆锆石特征(Hoskin 1947)。部分锆石具明显的港湾状重熔结构(图2a:1、5;i:13),暗示其经历热液蚀变作用(吴元保和郑永飞,2004)。

4.1.2 长英质侵入体

长英质岩石(图2b~e、g、h)锆石颗粒无色、透明;颗粒晶面完整、平直光滑(图2h);少数颗粒在透射光下可见裂纹、或含细小包裹体、晶体棱角圆化(图2e);长柱状晶体,长150~250 μm,长宽比1∶1~2∶1。阴极发光下可见锆石结构复杂,普遍发育暗色的增生边,部分颗粒发育核边结构(图2g:7)。且多数锆

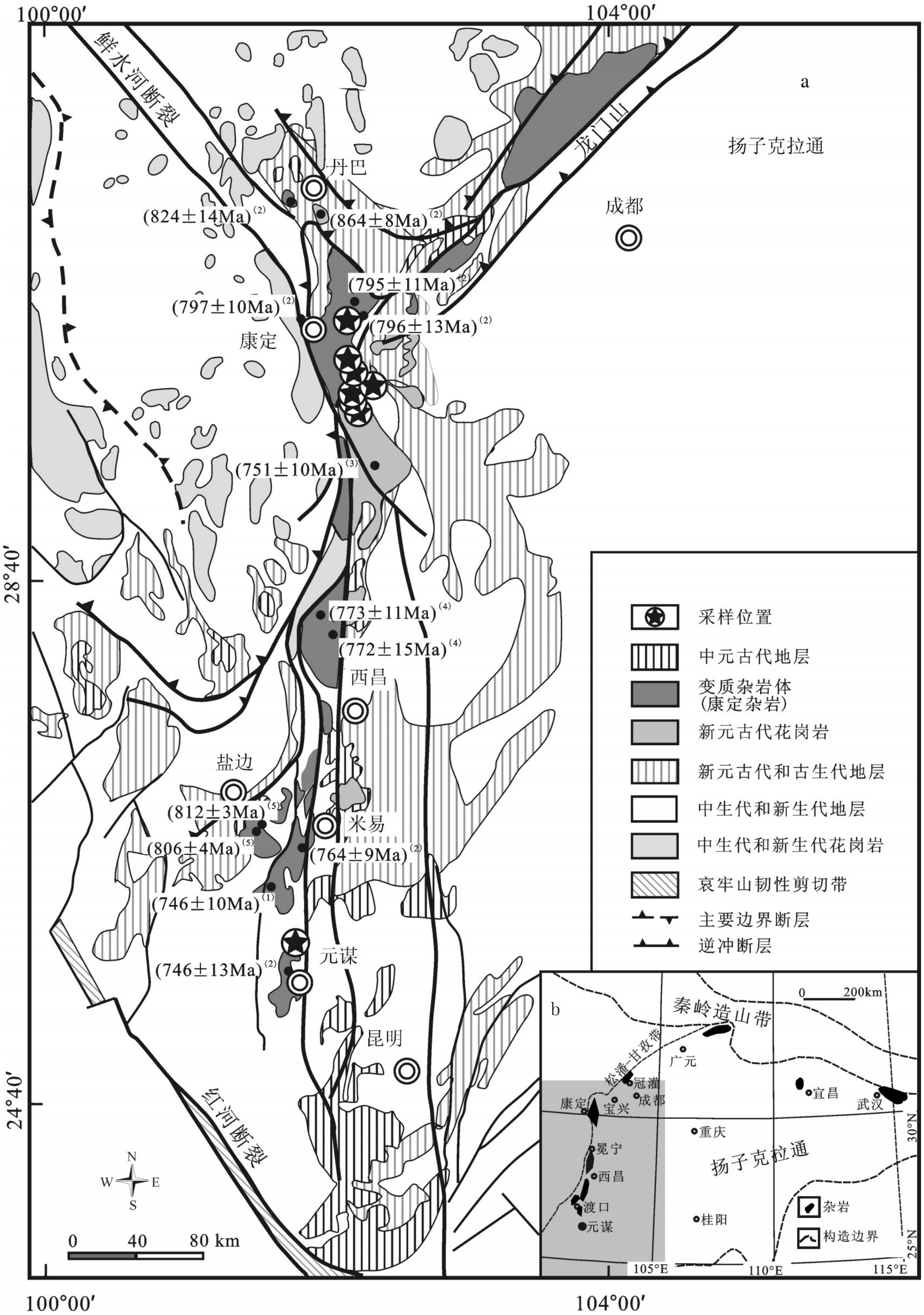

图1 扬子克拉通西缘地质图(据Zhou et al., 2002修改)

图a年龄数据来自:标号1~5分别引自Zhao and Zhou, 2007;Zhou et al., 2002,2006;Li et al., 2003;Chen et al., 2005;图b灰色区域对应图a

Fig.1 Geological map of the west margin of the Yangtze Craton (modified after Zhou et al., 2002)

The ages noted in Fig. a are collected from the published zircon SHRIMP U−Pb data in recent years (No. (1−5) from Zhao and Zhou, 2007; Zhou et al., 2002; Li et al., 2003; Chen et al., 2005; Zhou et al., 2006, respectively). The gray area in Fig.b is similar to the area of Fig. a

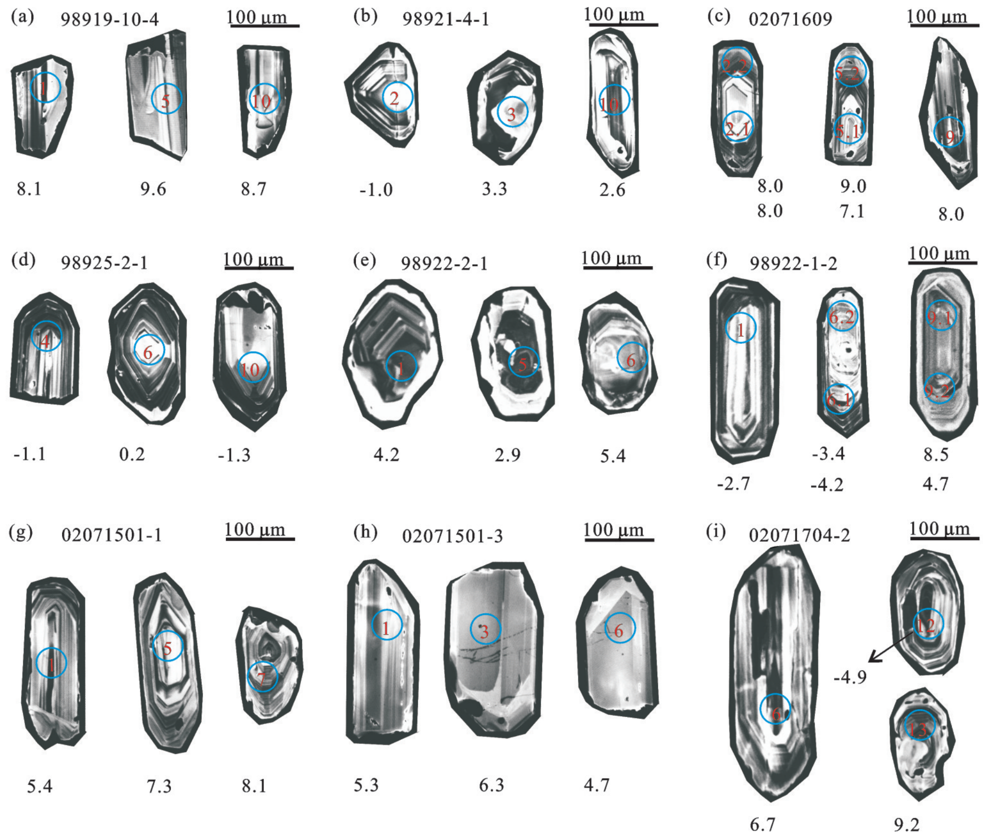

图2 锆石CL图像和点位

蓝圈代表Lu-Hf测点位置;圆圈内数字代表点号,锆石下部数字代表$\varepsilon_{Hf}(t)$

Fig.2 Cathodoluminescence images of zircons and dated spots

The Lu-Hf isotope analytical spots are represented by the blue circles and numbers therein are their analytical number. Number under each zircon grain shows the $\varepsilon Hf(t)$ values

石颗粒具有明显的环带结构,部分颗粒出现扇状分区(图2b:3),具典型岩浆锆石特征。

部分锆石具明显的港湾状重熔结构(图2g:1、7),暗示初始岩浆环带结构受后期热液蚀变作用改造。

4.2 Lu-Hf同位素结果

锆石Lu-Hf同位素数据见表1、图3和图4,Hf模式年龄图($\varepsilon_{Hf}(t)>0$,取T_{DM};$\varepsilon_{Hf}(t)<0$,取T^{C}_{DM})(Zheng et al., 2007)。

4.2.1 镁铁质侵入体

对细粒角闪岩(02071704-2)、黑云角闪斜长片麻岩(98919-10-4)和斜长角闪岩(98922-1-2)共38个点进行Lu-Hf同位素分析。$^{176}Lu/^{177}Hf$的范围0.000544~0.003241,$^{176}Hf/^{177}Hf$范围0.281545~0.282735,初始$^{176}Hf/^{177}Hf$范围0.281510~0.282728,平均值0.282461(表1);$\varepsilon_{Hf}(t)$为-4.9~+11.0,具较大变化范围,平均值为+6.1(图4),Hf模式年龄范围906~1317 Ma,平均值1104 Ma(图3)。

4.2.2 长英质侵入体

对英云闪长岩(02071501-1)、花岗闪长岩(02071501-3)、灰绿色英云闪长岩(02071609)、角闪变粒岩(98921-4-1)、灰白色黑云斜长片麻岩(98922-1-2)和花岗闪长岩(98925-2-1)共69个点进行锆石Lu-Hf同位素分析。$^{176}Lu/^{177}Hf$的范围0.000402~0.003031,$^{176}Hf/^{177}Hf$范围0.281296~0.282599,初始$^{176}Hf/^{177}Hf$范围0.281266~0.282561,平均值0.282382(表1);$\varepsilon_{Hf}(t)$为-3.0~+9.4,平均值为+4.5(图4),Hf模式年龄范围742~2707 Ma,平均值1262 Ma(图3)。

5 讨 论

5.1 康定杂岩岩石成因

5.1.1 镁铁质侵入体成因

已有研究表明,扬子地块西缘侵入体杂岩中

表1 元谋和康定杂岩锆石LA−MC−ICP−MS Lu−Hf同位素组成

Table 1 Zircon LA−MC−ICP−MS Lu−Hf data for the intrusive complexes samples from Kangding and Yuanmou

样品	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	T/ Ma	Hfi	$\varepsilon_{Hf}(t)$	T^{C}_{DM}/ Ma	1σ	T_{DM}/ Ma	1σ
黑云角闪斜长片麻岩 98919-10-4 (康定)											
1.1	0.034113	0.001049	0.282516	0.000017	801	0.282501	8.1	1155	19	1043	12
2.1	0.069610	0.002147	0.282632	0.000015	770	0.282601	11.0	911	17	906	11
3.1	0.031509	0.001004	0.282581	0.000014	801	0.282566	10.4	1007	15	950	10
4.1	0.034426	0.001332	0.282554	0.000016	800	0.282534	9.3	1069	19	997	12
5.1	0.028828	0.000989	0.282574	0.000012	776	0.282560	9.6	1040	13	960	8
6.1	0.043181	0.001669	0.282591	0.000019	763	0.282567	9.6	1011	22	954	14
7.1	0.042398	0.001489	0.282554	0.000015	762	0.282533	8.4	1094	17	1001	11
8.1	0.083669	0.002821	0.282615	0.000016	806	0.282573	10.8	926	18	948	12
9.1	0.049250	0.001697	0.282601	0.000014	785	0.282576	10.4	974	16	940	10
10.1	0.036172	0.001407	0.282565	0.000019	757	0.282545	8.7	1074	22	984	14
11.1	0.104567	0.003048	0.282641	0.000014	762	0.282597	10.6	897	16	916	10
细粒斜长角闪岩 98922-1-2 (冕宁)											
1.1	0.049022	0.001712	0.282284	0.000019	696	0.282261	-2.7	1748	21	1394	13
3.1	0.085534	0.002816	0.282462	0.000022	712	0.282425	3.4	1335	25	1174	16
4.1	0.055097	0.001587	0.282579	0.000020	759	0.282556	9.1	1040	23	968	15
5.1	0.036466	0.000929	0.281545	0.000018	1990	0.281510	-0.3	2563	20	2386	12
5.2	0.027929	0.000764	0.281577	0.000019	2171	0.281545	5.2	2365	21	2333	13
6.1	0.035503	0.000995	0.282447	0.000019	381	0.282440	-3.4	1579	21	1139	13
6.2	0.033272	0.001037	0.282415	0.000028	397	0.282407	-4.2	1641	32	1186	20
8.1	0.044386	0.001444	0.282735	0.000020	245	0.282728	3.8	1015	22	742	14
9.1	0.094185	0.003070	0.282554	0.000021	808	0.282507	8.5	1064	24	1046	16
9.2	0.055151	0.001694	0.282458	0.000034	754	0.282434	4.7	1318	39	1145	24
10.1	0.068748	0.001801	0.282715	0.000020	314	0.282705	4.5	1017	23	778	15
11.1	0.089855	0.002566	0.282326	0.000020	708	0.282292	-1.4	1645	22	1365	15
12.1	0.097152	0.002537	0.282590	0.000016	99	0.282586	-4.4	1430	18	977	12
细粒角闪岩 02071704-2 (康定)											
1.1	0.075958	0.002123	0.282543	0.000020	744	0.282513	7.3	1131	23	1035	15
2.1	0.092501	0.002836	0.282500	0.000018	756	0.282459	5.6	1222	21	1119	13
3.1	0.076643	0.002382	0.282395	0.000031	766	0.282361	2.4	1452	35	1258	22
4.1	0.081786	0.002429	0.282516	0.000024	760	0.282482	6.5	1182	28	1083	18
5.1	0.035874	0.001224	0.282483	0.000029	772	0.282465	6.1	1249	32	1095	20
6.1	0.054631	0.001843	0.282522	0.000027	744	0.282496	6.6	1180	31	1058	19
7.1	0.094046	0.002457	0.282534	0.000024	801	0.282497	7.9	1115	27	1058	17
8.1	0.045546	0.001224	0.282509	0.000024	785	0.282491	7.4	1183	27	1059	17
9.1	0.031076	0.001008	0.282526	0.000018	783	0.282511	8.1	1144	21	1028	13
10.1	0.098574	0.003241	0.282376	0.000042	653	0.282336	-1.0	1568	47	1317	31
12.1	0.018567	0.000544	0.282372	0.000018	430	0.282367	-4.9	1716	20	1230	12
13.1	0.057988	0.001765	0.282575	0.000013	774	0.282549	9.2	1040	15	979	10
14.1	0.078764	0.003110	0.282553	0.000025	789	0.282507	8.1	1079	29	1049	19
15.1	0.051423	0.001631	0.282537	0.000021	758	0.282514	7.6	1137	23	1030	15
角闪变粒岩 98921-4-1 (冕宁)											
1.1	0.070455	0.002362	0.282422	0.000027	757	0.282388	3.1	1398	31	1218	20
2.1	0.088763	0.002236	0.282307	0.000050	750	0.282275	-1.0	1662	56	1381	36
3.1	0.053217	0.001529	0.282398	0.000018	784	0.282376	3.3	1434	21	1225	13
4.1	0.074695	0.002017	0.282412	0.000024	767	0.282383	3.2	1414	27	1222	17
5.1	0.021771	0.000619	0.282361	0.000025	776	0.282352	2.3	1524	28	1247	18
6.1	0.031095	0.000879	0.282409	0.000017	796	0.282396	4.3	1402	19	1189	12
7.1	0.054773	0.001613	0.282440	0.000018	791	0.282416	4.9	1334	21	1167	13
8.1	0.066562	0.001758	0.282471	0.000019	766	0.282445	5.4	1281	21	1129	13
9.1	0.025039	0.000743	0.282409	0.000017	842	0.282397	5.3	1372	19	1184	12
9.2	0.025586	0.000936	0.282420	0.000020	778	0.282406	4.2	1388	23	1175	14
10.1	0.087492	0.002316	0.282399	0.000020	769	0.282365	2.6	1442	23	1250	15

续表1

样品	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	T/ Ma	Hfi	$\varepsilon_{Hf}(t)$	T^{C}_{DM}/ Ma	1σ	T_{DM} / Ma	1σ
黑云斜长片麻岩 98922-2-1 (冕宁)											
1.1	0.075692	0.002002	0.282442	0.000017	767	0.282413	4.2	1345	19	1177	12
2.1	0.097829	0.002577	0.282439	0.000018	790	0.282401	4.3	1336	20	1200	13
3.1	0.059812	0.001674	0.282415	0.000017	791	0.282390	4.0	1391	19	1205	12
4.1	0.060881	0.001757	0.282453	0.000012	773	0.282427	4.9	1318	14	1154	9
5.1	0.088071	0.002785	0.282415	0.000023	770	0.282375	3.0	1404	27	1242	17
6.1	0.103151	0.002597	0.282489	0.000022	755	0.282452	5.4	1246	25	1127	16
7.1	0.026038	0.000667	0.281296	0.000021	2378	0.281266	0	2859	23	2707	14
7.2	0.014180	0.000402	0.281341	0.000019	2468	0.281322	4.1	2692	22	2628	13
7.3	0.017231	0.000618	0.281372	0.000027	2373	0.281344	2.7	2689	31	2601	18
8.1	0.050540	0.001371	0.282483	0.000018	752	0.282464	5.7	1262	20	1099	13
9.1	0.064305	0.002010	0.282508	0.000018	763	0.282479	6.5	1199	20	1082	13
10.1	0.060353	0.002082	0.282407	0.000027	772	0.282376	3.0	1423	30	1231	19
11.1	0.058355	0.001579	0.282527	0.000017	774	0.282504	7.6	1148	20	1043	12
花岗闪长岩 98925-2-1 (元谋)											
1.1	0.056152	0.001594	0.282280	0.000019	786	0.282256	-0.9	1699	21	1395	13
2.1	0.088079	0.002430	0.282367	0.000019	600	0.282340	-2.1	1621	22	1300	14
3.1	0.075252	0.002219	0.282287	0.000022	773	0.282255	-1.2	1691	24	1408	16
4.1	0.072839	0.002129	0.282297	0.000020	758	0.282267	-1.1	1678	23	1390	15
5.1	0.082265	0.002237	0.282281	0.000023	732	0.282250	-2.3	1731	26	1418	17
10	0.044358	0.001152	0.282316	0.000018	697	0.282300	-1.3	1676	20	1329	13
6.1	0.083674	0.002328	0.282337	0.000022	759	0.282304	0.2	1587	25	1340	16
7.1	0.046802	0.001234	0.282350	0.000017	770	0.282332	1.4	1552	19	1283	12
7.2	0.033323	0.001304	0.282267	0.000023	702	0.282250	-3.0	1781	26	1402	16
8.1	0.073967	0.001975	0.282397	0.000020	762	0.282368	2.5	1452	23	1242	15
9.1	0.105627	0.002771	0.282313	0.000023	785	0.282272	-0.4	1626	26	1392	17
英云闪长岩 02071609 (康定)											
1.1	0.102869	0.003031	0.282587	0.000016	735	0.282545	8.2	1037	19	996	12
2.1	0.065565	0.001928	0.282566	0.000015	735	0.282539	8.0	1086	17	997	11
2.2	0.058156	0.001785	0.282574	0.000013	720	0.282550	8.0	1076	15	981	9
3.1	0.045917	0.001413	0.282516	0.000016	747	0.282497	6.7	1190	18	1053	11
4.1	0.065755	0.002144	0.282514	0.000021	745	0.282484	6.3	1196	23	1077	15
5.1	0.092285	0.002713	0.282599	0.000015	745	0.282561	9.0	1002	17	969	11
5.2	0.040388	0.001267	0.282551	0.000014	701	0.282534	7.1	1141	16	1000	10
6.1	0.066388	0.001984	0.282581	0.000015	710	0.282555	8.0	1067	17	976	11
7.1	0.037750	0.001205	0.282547	0.000017	772	0.282530	8.5	1103	19	1003	12
8.1	0.056465	0.001681	0.282565	0.000013	719	0.282543	7.8	1097	14	991	9
9.1	0.092707	0.002665	0.282581	0.000013	729	0.282544	8.0	1055	15	995	10
英云闪长岩 02071501-1 (康定)											
1.1	0.058758	0.001562	0.282467	0.000029	771	0.282445	5.4	1286	33	1127	21
2.1	0.044843	0.001405	0.282527	0.000018	801	0.282506	8.3	1131	20	1038	13
3.1	0.039224	0.001167	0.282537	0.000017	749	0.282521	7.6	1141	20	1017	12
4.1	0.048459	0.001510	0.282517	0.000020	783	0.282495	7.5	1166	23	1055	14
5.1	0.066277	0.002408	0.282542	0.000021	754	0.282508	7.3	1126	24	1044	16
6.1	0.043612	0.001522	0.282521	0.000023	758	0.282500	7.1	1172	26	1049	16
7.1	0.054714	0.001655	0.282546	0.000015	767	0.282522	8.1	1109	17	1017	11
8.1	0.051795	0.001642	0.282555	0.000018	778	0.282531	8.7	1081	20	1004	13
9.1	0.063154	0.001849	0.282565	0.000022	795	0.282537	9.3	1048	25	995	16
10.1	0.050891	0.001438	0.282578	0.000017	772	0.282557	9.4	1034	20	967	12
花岗闪长岩 02071501-3 (康定)											
1.1	0.039339	0.001131	0.282448	0.000016	787	0.282432	5.3	1318	18	1141	11
3.1	0.056917	0.001563	0.282488	0.000015	776	0.282465	6.3	1235	17	1098	10
4.1	0.038062	0.001079	0.282488	0.000014	791	0.282472	6.8	1227	16	1084	10
5.1	0.038222	0.001056	0.282509	0.000013	773	0.282494	7.2	1190	14	1053	9
6.1	0.035513	0.000988	0.282464	0.000016	730	0.282451	4.7	1319	18	1115	11
7.1	0.041055	0.001090	0.282525	0.000014	755	0.282510	7.4	1165	16	1032	10
8.1	0.040396	0.001066	0.282503	0.000016	777	0.282487	7.1	1201	18	1062	11
9.1	0.043270	0.001128	0.282524	0.000018	767	0.282508	7.6	1160	21	1035	13
10.1	0.048440	0.001230	0.282529	0.000012	768	0.282511	7.7	1147	13	1030	8

注:$^{176}Hf/^{177}Hf$初始比值和$\varepsilon_{Hf}(t)$值是根据同一锆石U-Pb年龄计算。

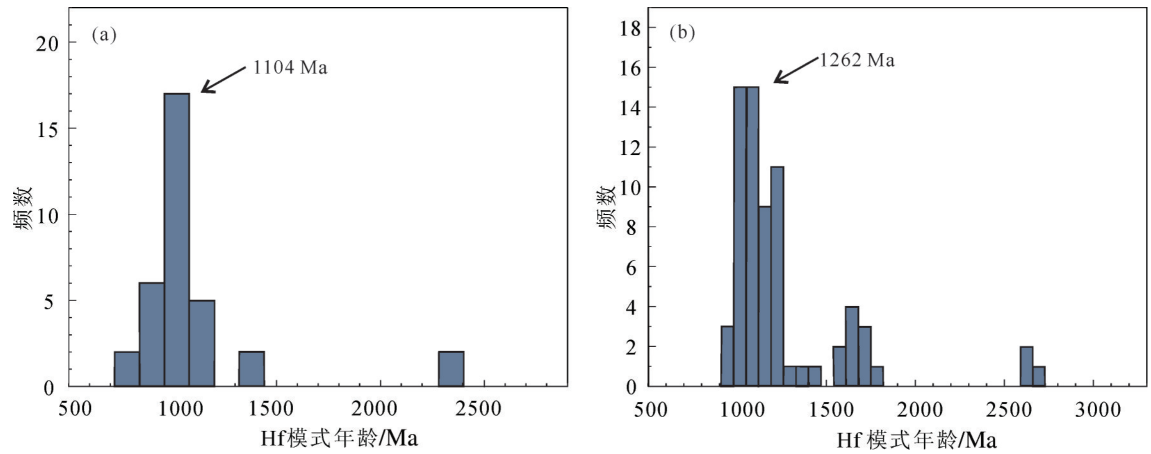

图3 元谋和康定侵入体杂岩Hf模式年龄直方图

a—镁铁质侵入体；b—长英质侵入体

Fig.3 Histogram of model Hf ages for the intrusive complexes samples from Kangding and Yuanmou

a−Mafic plutons；b−Felsic plutons

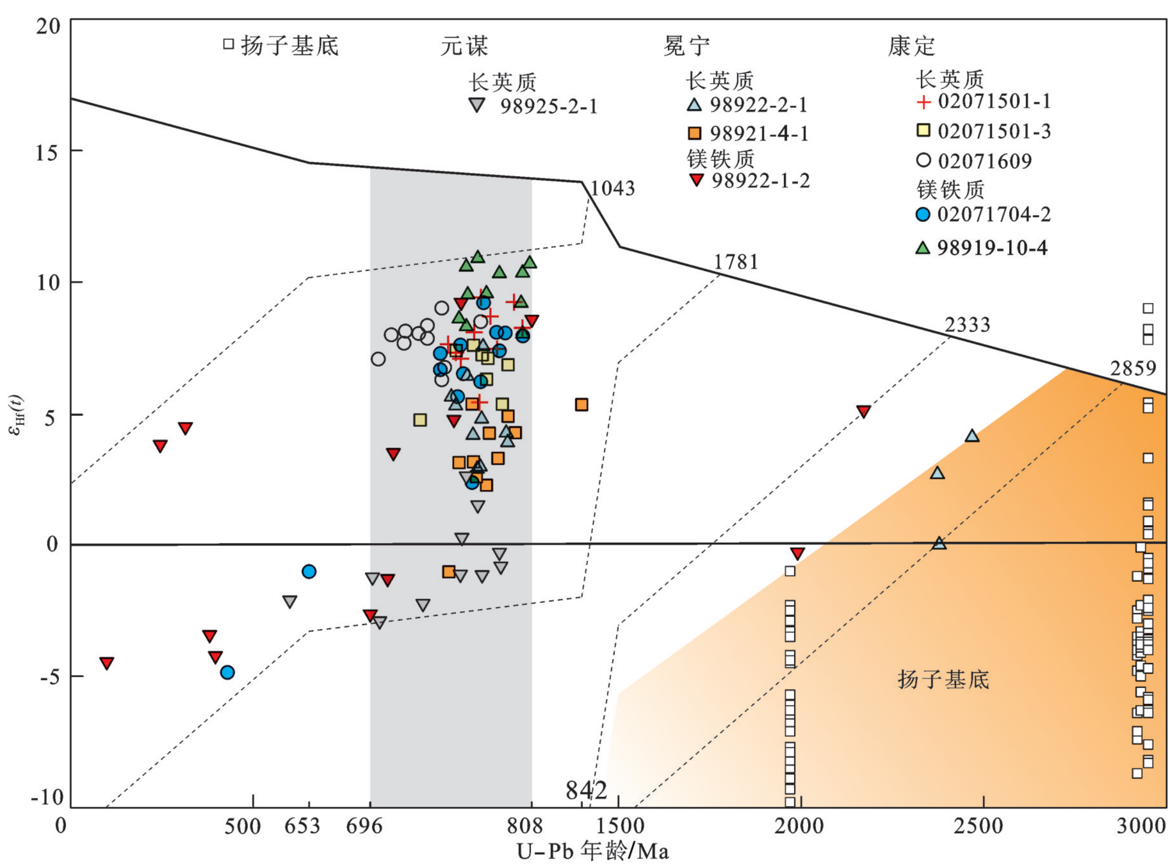

图4 元谋和康定杂岩$\varepsilon_{Hf}(t)$值−U−Pb年龄分布

扬子基底数据来自Zhang et al., 2006a, 2006b, 2006c; Zheng et al., 2006

Fig.4 Plots of $\varepsilon_{Hf}(t)$ versus U−Pb ages for the intrusive complexes samples from Kangding and Yuanmou

The data of the Yangtze craton are taken from Zhang et al., 2006a, 2006b, 2006c; Zheng et al., 2006

(如:大渡口,同德,高家村,沙坝),镁铁质岩石成因受俯冲大洋板片流体、熔体的影响(Zhou et al., 2006; Zhao and Zhou, 2007)。康定、冕宁侵入体中细粒角闪岩(02071704−2)、黑云角闪斜长片麻岩(98919−10−4)和斜长角闪岩(98922−1−2)微量元素特征具岛弧地球化学特征,$MgO-FeO-Al_2O_3$构造判别图位于岛弧与活动陆缘范围内(李大鹏等, 2008),且$\varepsilon_{Nd}(t)$、$\varepsilon_{Hf}(t)$特征与周边地区(如:沙坝,盐边高家村)镁铁质侵入体相似(Zhao et al., 2008; Zhao and Zhou, 2007; Zhu et al., 2010),表明其具有相似的岩浆起源。虽然3个样品地球化学组成存在差异,但都富集LILEs和亏损HFSEs,暗示其源区可能受俯冲板片流体的影响(赵俊香等, 2006; Li et al., 2009; 陈岳龙等, 2004)。所有样品$\varepsilon_{Nd}(t)$值变化范围小,$\varepsilon_{Hf}(t)$值变化大,$\varepsilon_{Hf}(t)$最大值+11.0(表1),表明其来源于一个比较亏损的地幔源区(图4)。在康定镁铁质样品中出现古元古代早期到晚期年龄的锆石,也暗示早期陆壳组分的加入;在Hf−Nd同位素图(图5),$\varepsilon_{Hf}(t)-\varepsilon_{Nd}(t)$呈正相关,且落入由MORB、OIB以及碎屑沉积物构成的Terestrial Array中,表明岩浆中存在低$\varepsilon_{Hf}(t)-\varepsilon_{Nd}(t)$值的地壳物质的带入(Li et al., 2005; Lin et al., 2007)。

综上可知,扬子地块西缘新元古代康定侵入体杂岩中镁铁质岩石起源于一个相对亏损的受俯冲板片流体影响的地幔源区,且在岩浆侵位过程中有地壳物质的加入。

5.1.2 长英质侵入体成因

扬子地块西缘广泛分布着形成于俯冲背景下(赵俊香等, 2006; Li et al., 2009; 陈岳龙等, 2004),主要成分为英云闪长岩和花岗闪长岩的长英质侵入体(如:康定,攀枝花,管道山)(Zhou et al., 2002, 2006; 李大鹏等, 2008; Sun and Zhou, 2008)。采自康定、冕宁以及元谋地区的英云闪长岩(02071501−1)、花岗闪长岩(02071501−3)、灰绿色英云闪长岩(02071609)、角闪变粒岩(98921−4−1)、灰白色黑云斜长片麻岩(98922−1−2)和花岗闪长岩(98925−2−1)样品在Y−Nb构造图解和Yb−Ta构造判别图解落入火山弧构造端元内(李大鹏等, 2008),Hf、Nd同位素特征与周边地区(如:攀枝花)受俯冲大洋板片作用影响的新元古代侵入体相似(Zhao et al., 2008)。样品Th/La和Ba/La比值接近陆壳水平,Zr−Hf正异常(Li et al., 2009; 李大鹏等, 2008);样品$\varepsilon_{Hf}(t)$值范围−0.2~+

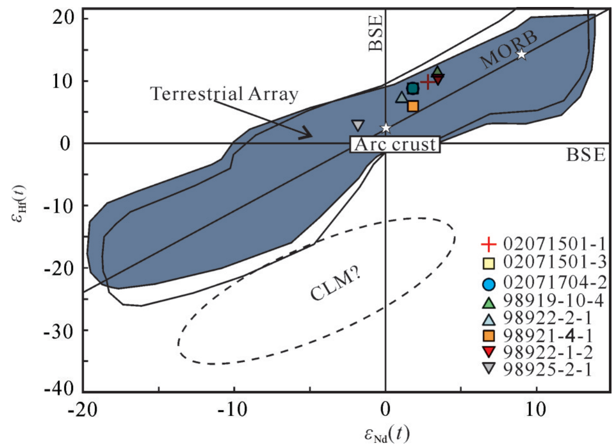

图5 元谋和康定杂岩$\varepsilon_{Hf}(t)-\varepsilon_{Nd}(t)$同位素图

$\varepsilon_{Nd}(t)$数据引自李大鹏等, 2008; Chen and Luo, 2005;现今OIB、MORB和大陆碎屑沉积物构成的Terestrial Array区域数据引自Vervoort et al., 1999;Terestrial Array阴影区域由0.8 Ga时OIB、MORB和大陆碎屑沉积物构成;古老大陆岩石圈地幔Hf−Nd组成引自Griffin et al., 2000

Fig. 5 Hf−Nd isotopic plot for the intrusive complexes samples from Kangding and Yuanmou

The data of $\varepsilon_{Nd}(t)$ are taken from Li et al., 2008; Chen and Luo, 2005; the data of the Terestrial Array zone are taken from Vervoort et al., 1999; the gray area in the Terestrial Array zone consists of OIB, MORB and continental detrital sediments at 0.8 Ga; the Hf−Nd isotopic data of the ancient continental lithospheric mantle are taken from Griffin et al., 2000

9.6,且$\varepsilon_{Hf}(t)$比值明显不同于扬子地块太古宙—古元古代基底(图4),表明长英质侵入体不可能由古老基底部分熔融而来;$\varepsilon_{Nd}(t)$变化范围较小(−1.7~+3.6)(赵俊香等, 2006; Li et al., 2009),在Nd−Hf同位素图(图5),$\varepsilon_{Hf}(t)-\varepsilon_{Nd}(t)$呈正相关,且落入由MORB、OIB以及碎屑沉积物构成的Terestrial Array中,都表明岩浆有低$\varepsilon_{Hf}(t)-\varepsilon_{Nd}(t)$值的地壳物质的带入。

样品Hf模式年龄与锆石U−Pb年龄相差不大(图3),且古老地壳混染将导致锆石U−Pb年龄与Hf模式年龄的解耦(Zhao et al., 2008)。因此,锆石U−Pb年龄与Hf模式年龄的解耦可能为地壳物质混染的结果。

综上所述,本文认为沿扬子地块西缘分布的新元古代康定侵入体杂岩中,长英质侵入体可能为Rodinia超大陆裂解引发洋壳板片俯冲到扬子陆块的过程中,新生陆壳与古老地壳物质相互作用形成的产物。

5.2 Hf−Nd同位素解耦

结合已有的Hf、Nd同位素资料(表2):在$\Delta\varepsilon_{Hf}(t)$

表2 扬子板块西缘新元古代侵入体杂岩锆石$\varepsilon_{Hf}(t)$与全岩$\varepsilon_{Nd}(t)$同位素组成

Table 2 $\varepsilon_{Hf}(t)-\varepsilon_{Nd}(t)$ isotopic compositions for the Neoproterozoic plutons from the west margin of the Yangtze craton

地点	岩性	t/Ma	$\Delta\varepsilon_{Hf}(t)$ a)	$\Delta\varepsilon_{Hf}(t)$ b)	$\varepsilon_{Nd}(t)$	$\varepsilon_{Hf}(t)$	参考文献
康定	角闪石片麻岩	791	2.06	1.7	3.6	9.6	李大鹏等, 2008
康定	角闪岩	765	1.4	1	1.9	6.8	李大鹏等, 2008
康定	英云闪长岩	771	1.1	0.8	2.9	7.9	李大鹏等, 2008
康定	花岗闪长岩	771	1.3	1	1.9	7	李大鹏等, 2008
苏雄组	玄武岩	803	-0.4	-0.8	1.4	4.3	Li et al., 2005
苏雄组	玄武岩	803	1	0.6	2.4	7	Li et al., 2005
苏雄组	玄武岩	803	-2.3	-2.6	5	7.2	Li et al., 2005
苏雄组	玄武岩	803	-2	-2.3	5.3	7.9	Li et al., 2005
苏雄组	玄武岩	803	-2.9	-3.2	6	8	Li et al., 2005
苏雄组	流纹岩	803	0.6	0.3	1.1	4.9	Li et al., 2005
苏雄组	流纹岩	803	-0.7	-1.1	2.1	4.9	Li et al., 2005
苏雄组	流纹岩	803	-0.9	-1.3	2.6	5.4	Li et al., 2005
苏雄组	流纹岩	803	-0.7	-1.1	2.3	5.2	Li et al., 2005
沙坝, 冕宁	角闪岩	784	1.1	0.8	3.6	8.8	Chen and Luo, 2005
沙坝, 冕宁	辉长岩	752	1.7	1.3	1.2	6.1	Zhao et al., 2008
沙坝, 冕宁	辉长岩	752	2.5	2.2	1.7	7.6	Zhao et al., 2008
沙坝, 冕宁	辉长岩	752	-0.6	-0.9	3.1	6.4	Zhao et al., 2008
沙坝, 冕宁	辉长岩	752	-0.9	-1.2	3.4	6.5	Zhao et al., 2008
沙坝, 冕宁	角山麻粒岩	773	-1.9	-2.3	1.9 c)	3.4	Chen and Luo, 2005
沙坝, 冕宁	花岗质片麻岩	772	0.4	0	1.2 c)	4.9	Chen and Luo, 2005
新铺子, 冕宁	花岗岩	780	3.9	3.6	3	10.7 d)	Huang et al., 2008
磨盘山,西昌	花岗岩类	780	5.4	5	-2.1	5.4	Huang et al., 2009
攀枝花	辉长岩	779	1.1	0.8	3.2	8.3	Lin et al., 2007
攀枝花	辉长岩	779	-0.4	-0.7	4.1	7.9	Lin et al., 2007
攀枝花	辉长岩	779	0.7	0.3	4.6	9.6	Lin et al., 2007
攀枝花	辉长岩	779	2.5	2.2	8.6	16.9	Lin et al., 2007
攀枝花	辉长岩	779	-1	-1.3	6.8	10.9	Lin et al., 2007
攀枝花	辉长岩	779	0.8	0.5	7.3	13.4	Lin et al., 2007
攀枝花	辉长岩	779	3.7	3.3	2.9	10.4	Lin et al., 2007
攀枝花	辉长岩	779	0.2	-0.1	6.9	12.3	Lin et al., 2007
攀枝花	辉长岩	779	5.4	5.1	6.9	17.4	Lin et al., 2007
攀枝花	辉长岩	779	4.6	4.3	5.4	14.7	Lin et al., 2007
攀枝花	辉长岩	779	3.7	3.4	1.7	8.8	Lin et al., 2007
大渡口,攀枝花	辉长岩	746	2.4	2	-0.3	4.8	Zhao et al., 2008
高家村,攀枝花	辉长—闪长岩		-0.3	-0.6	3.3	7	Zhao et al., 2008
大田,攀枝花	花岗闪长岩	760	2.9	2.6	-0.5	5.1	Zhao et al., 2008
大田,攀枝花	花岗闪长岩	760	1.5	1.2	-0.3	3.9	Zhao et al., 2008
大田,攀枝花	花岗闪长岩	760	1.2	0.8	0.6	4.8	Zhao et al., 2008
大基山,攀枝花	花岗闪长岩	760	1.2	0.9	0.6	4.8	Zhao et al., 2008
同德	辉长岩	820	1.7	1.3	0.6	5.3	Zhao et al., 2008
元谋, 云南	花岗闪长岩	770	-0.7	-1.1	-1.7	-0.2	Chen and Luo, 2005
峨山,云南	花岗岩	819	6.4	5.9	-8.7	-2.5	Zheng et al., 2007
管道山,盐边	花岗闪长岩	858	4.5	4.2	4.3	13.1	Sun and Zhou, 2008

注：a) 由地壳数组计算：$\Delta\varepsilon_{Hf}(t)^a=\varepsilon_{Hf}(t)-(1.34\varepsilon_{Nd}(t)+2.82)$；b) 由地幔数组计算: $\Delta\varepsilon_{Hf}(t)^b=\varepsilon_{Hf}(t)-(1.33\varepsilon_{Nd}(t)+3.19)$；c)由ICP−MS 数据计算 $^{147}Sm/^{144}Nd$ 数据；d) 18个分析点的平均值；$\Delta\varepsilon_{Hf}(t)$定义引自 Vervoort et al., 1999; Johnson and Beard, 1993。

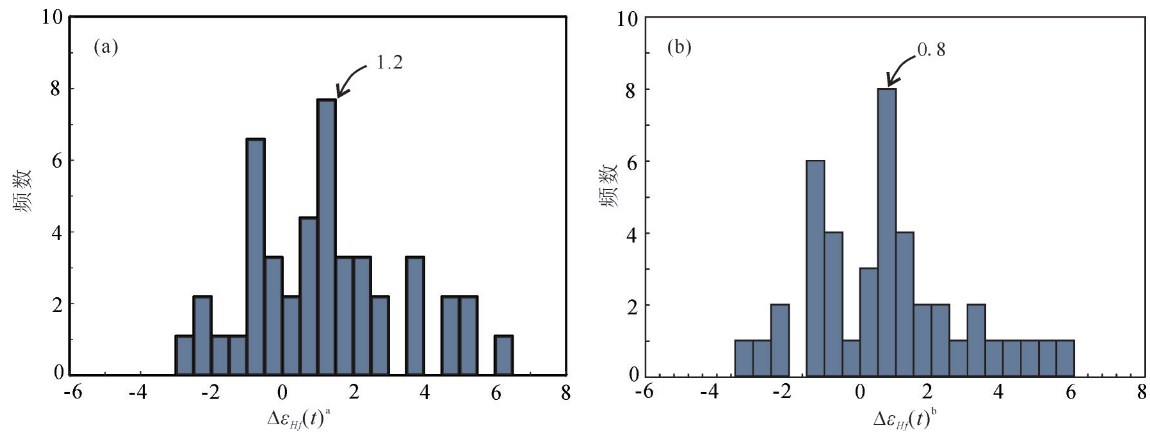

图6 康定和元谋杂岩$\Delta\varepsilon_{Hf}(t)$图

a—镁铁质侵入体;b—长英质侵入体

Fig. 6 $\Delta\varepsilon_{Hf}(t)$ plot for the intrusive complexes samples from Kangding and Yuanmou

a–Mafic plutons;b–Felsic plutons

图中,$\Delta\varepsilon_{Hf}(t)^a=1.2$,$\Delta\varepsilon_{Hf}(t)^b=0.8$ (图6);康定侵入体锆石$\varepsilon_{Hf}(t)$与全岩$\varepsilon_{Nd}(t)$沿地幔、地壳Hf–Nd同位素演化线(Vervoort et al., 1999)呈正相关分布(图7);暗示扬子地块西缘新元古代火成岩地球化学特征都存在不同程度Hf–Nd解耦。通常,有两个过程将导致Hf–Nd同位素解耦:(1)石榴石效应(Schmitz et al., 2004; Vervoort et al., 2000);(2)锆石效应(Zheng et al., 2007; Wu et al., 2006);

地壳岩石放射性成因Hf异常富集主要原因是源区异常高的Lu/Hf比值(Zheng et al., 2007)。石榴石为强烈富集HREE矿物,在部分熔融过程中,石榴石作为残留相存在或缺失将强烈影响被汲取熔体中Lu和Hf的浓度和组分(Zheng et al., 2007)。若石榴石作为残留相存在岩浆源区,从演化岩浆中结晶出来的长英质岩石将不仅强烈亏损HREE,而且亏损情况与原子数呈反相关关系。尽管侵入体样品(赵俊香等, 2006; Li et al., 2009; 陈岳龙等, 2004) HREE相对LREE为亏损,但是其亏损不足以补足源区石榴石结晶消耗的HREE。

锆石在后期高温热事件中依然可保持良好的封闭性,可保存其初始Hf同位素组成(Wu et al., 2010)。而全岩Sm–Nd体系容易与新体系保持平衡,导致较低$\varepsilon_{Nd}(t)$值。因此,锆石效应可能是导致康定侵入体锆石Hf同位素与全岩Nd同位素解耦的主要原因。其次,地壳组分的加入也会降低地幔源区Hf同位素组成(Elliott et al., 1997),将显著影响地

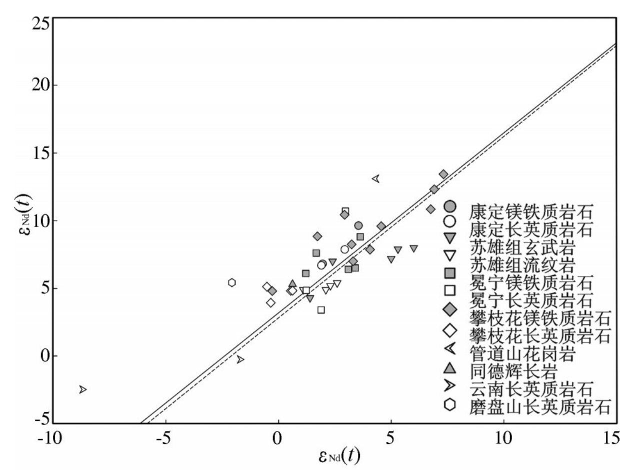

图7 扬子板块西缘新元古代侵入体杂岩锆石$\varepsilon_{Hf}(t)$与全岩$\varepsilon_{Nd}(t)$同位素图

图中各新元古代侵入体杂岩锆石$\varepsilon_{Hf}(t)$与全岩$\varepsilon_{Nd}(t)$值引自Zhao et al., 2008; 李大鹏等, 2008; Li et al., 2005; Lin et al., 2007; Sun and Zhou. 2008; Chen and Luo, 2005; Huang et al., 2008, 2009

Fig. 7 Plot of $\varepsilon_{Hf}(t)$ versus $\varepsilon_{Nd}(t)$ for the Neoproterozoic plutons from the west margin of the Yangtze craton

Published data of $\varepsilon_{Hf}(t)$ and $\varepsilon_{Nd}(t)$ from the Neoproterozoic plutons are taken from Zhao et al., 2008; Li et al., 2008; Li et al., 2005; Lin et al., 2007; Sun and Zhou. 2008; Chen and Luo, 2005; Huang et al., 2008, 2009

幔楔Hf–Nd同位素组成。且$\Delta\varepsilon_{Hf}(t)^a=1.2$,$\Delta\varepsilon_{Hf}(t)^b=0.8$(图7),锆石$\varepsilon_{Hf}(t)$与全岩$\varepsilon_{Nd}(t)$靠近地幔、地壳演化线分布(图5),表明扬子地块西缘康定侵入体杂岩Hf–Nd解耦不明显。暗示康定侵入体杂岩Hf–Nd解耦过程可能存在少量地壳物质加入。

5.3 康定杂岩的构造意义

扬子地块在新元古代Rodinia超大陆重建方案中存在两者截然不同的观点：(1)Li et al. (1995, 1999)、Lin et al. (2015)从扬子及华南大量基性岩(辉长岩、基性岩脉-岩席)年龄上与澳大利亚Gairdner岩墙群形成时代、构造环境上的相似性、构造层的对比，认为华南(含扬子)是澳大利亚与北美Laurentia古陆间的缺失部分，并且这些岩墙群是地幔柱驱动下Rodinia古大陆裂解的标志。(2)Zhou et al. (2002)、Zhao and Cawood(1999)根据北美地区和澳大利亚东部地区缺失820~870 Ma的造山运动事件以及扬子地块西缘康定—冕宁—石棉地区广泛出露岛弧性质侵入岩，认为新元古代超大陆时期扬子地块为一个位于超大陆边缘的孤立块体。

已有资料显示，川西地区岩浆活动时间为720~860 Ma，跨度达140 Ma，地幔柱不可能存在那么长时间(Zhou et al., 2002)。大陆裂谷作用常常伴随大量镁铁质岩墙出露(Zhou et al., 2002)，而扬子地块西缘乃至整个扬子地块周围主体的岩浆岩为中酸性岩(杜利林等, 2007)。通常陆内断陷盆地沉积物富集古老锆石，而扬子地块西缘盐边群中古老碎屑锆石含量稀少，代表一个岛弧环境(Zhou et al., 2006)。在康定南缘石棉地区发现的蛇纹岩在空间上与枕状熔岩和辉长岩包体共同构成一条新元古代蛇绿岩带，暗示攀西带西缘曾经存在大洋(Sun and Vuagnat, 1992)。Zhang and Piper(1997)测得扬子地块古地磁数据指示扬子地块为孤立块体。

陈岳龙等(2004)和赵俊香等(2006)已公布的锆石U-Pb年龄表明样品侵位于新元古代(约770 Ma)，与康定—泸定及攀枝花地区康定杂岩中花岗闪长质岩、闪长岩及花岗质岩石(751~768 Ma)(Li et al., 2003)，镁铁质侵入体角闪石辉长岩和橄榄石辉长岩(738~746 Ma)(Zhao and Zhou, 2007)，康定—泸定—丹巴地区片麻状花岗岩(795~797 Ma)(Zhou et al., 2002)，泸定—石棉地区镁铁质岩墙(760~780 Ma)(Lin et al., 2007)，康定—米易地区片麻质杂岩(764~797 Ma)在误差范围内为同期岩浆作用产物。其相似的岩石学及地球化学特征暗示这些新元古代侵入体具有相近的构造成因背景。这些火山弧成因杂岩体整体在华南大陆西缘构成一条岩浆弧，被称之为“攀西—汉南弧”(Zhou et al., 2002)。

同时，该时期岩浆作用在澳大利亚Adelaide、西澳大利亚、Tasmania、北美的Laurentia、印度、塞舌尔、马达加斯加和南非均存在(Li et al., 2003)。且部分“攀西—汉南弧”与高印度大陆弧同期(Tucker et al., 2001)，故“攀西—汉南弧”可能代表高印度从华南/澳大利亚分离，被破坏洋壳俯冲作用的产物。所以，“攀西—汉南弧”在Gondwana超大陆时期可能是东Gondwana和澳大利亚西缘岩浆带的一部分(Zhao and Zhou, 2007)。

6 结 论

通过对扬子地块西缘康定侵入体杂岩开展详细的矿物化学、岩石地球化学及锆石Lu-Hf系统研究，结合区域上已有研究成果，可得出以下结论：

(1) 扬子地块西缘新元古代康定侵入体杂岩中镁铁质岩石起源于一个相对亏损的受俯冲板片流体影响的地幔源区，且在岩浆侵位过程中有地壳物质的加入; 长英质侵入体为新生陆壳与古老地壳物质相互作用形成的产物。

(2) 扬子地块西缘康定侵入体杂岩中锆石Hf-全岩Nd解耦，为“锆石效应”与少量地壳物质加入共同作用导致。

(3) 新元古代时期，扬子地块可能位于Gondwana超大陆的边缘，而不是澳大利亚与北美Laurentia古陆之间的连接部分。

致谢：中国地质科学院吴才来研究员、侯可军副研究员为本文锆石Hf同位素分析提供了便利条件，匿名审稿专家在文章修改过程中提出宝贵意见，在此一并谨表谢忱。

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