第94卷 第3期
2020年3月 地 质 学 报 ACTA GEOLOGICA SINICA Vol.94 No.3
Mar. 2020

青藏高原东北缘柴达木盆地红沟剖面物源分析及其构造意义

刘康[1)]，王伟涛[2)]，赵旭东[1)]，庞建章[1)]，俞晶星[1)]

1）中国地震局地质研究所，地震动力学国家重点实验室，北京，100029；

2）中山大学，地球科学与工程学院，广州，510275

内容提要：青藏高原东北缘柴达木盆地红沟剖面发育巨厚的新生代沉积地层，通过分析其沉积物质来源，可以揭示柴达木盆地潜在物源区隆升、剥蚀历史，为高原东北缘新生代构造变形过程提供证据。本文以红沟剖面磁性地层年代框架为约束，对剖面晚渐新世-上新世的碎屑砂岩样品进行了碎屑锆石物源示踪分析。研究结果表明，23.7～12.5 Ma样品的锆石U-Pb年龄主要分布在220～290 Ma，锆石$\varepsilon_{Hf}(t)$集中在－13.53～9.27，Hf同位素t_{DM}范围524～1456 Ma；大于300 Ma的锆石，$\varepsilon_{Hf}(t)$介于－31.77～13.44，其中76.3％为负值，Hf同位素t_{DM}介于484～3727 Ma。采集自12.5～7.6 Ma样品的锆石U-Pb年龄主要集中在400～500 Ma（峰值～440 Ma），$\varepsilon_{Hf}(t)$值（－27.75～10.75）的90％ 为负值，Hf同位素t_{DM}介于615～2115 Ma之间。6.8～5.5 Ma样品的锆石U-Pb年龄主要分布在400～500 Ma，$\varepsilon_{Hf}(t)$值（－26.8～8.97），$t_{DM(Hf)}$介于668～2093 Ma，但220～290 Ma的锆石显著增加，其$\varepsilon_{Hf}(t)$值（－11.86～9.42），Hf一阶段模式年龄范围549～1399 Ma。碎屑锆石Hf同位素组成对比分析显示红沟剖面220～290 Ma的锆石与东昆仑山锆石Hf同位素特征相似，而400～500 Ma的锆石则与南祁连山锆石Hf同位素组成相似，揭示东昆仑山在＞24 Ma开始抬升成为柴达木盆地的源区，～12 Ma南祁连山开始隆升，为柴达盆地提供碎屑物质，成为青藏高原东北缘的构造与地貌边界。

关键词：柴达木盆地；红沟剖面；Hf同位素特征；青藏高原东北缘

新生代以来，印度板块与欧亚板块的碰撞及其持续汇聚作用不仅导致了喜马拉雅造山带的形成，同时，也影响了碰撞带以北约2000 km宽的地区的强烈变形，形成“世界屋脊”青藏高原（Molnar et al.，1975；England et al.，1986；Dewey et al.，1988；Tapponnier et al.，2001；Decelles et al.，2002）。青藏高原的强烈隆升及其向北东方向的扩展对于亚洲大陆内部的构造变形、地貌演化、大气环流产生了重大的影响（Li Jijun et al.，1979；Harrison et al.，1992；An Zhisheng et al.，2001；Zhang Peizhen et al.，2001，2006；Guo Zhengtang et al.，2002）。因此，青藏高原是研究陆-陆碰撞及其远程效应的天然实验室（Molnar et al.，2009；Yuan Daoyang et al.，2013）。自上世纪以来，青藏高原的隆升及其扩展历史一直是地球科学领域研究的核心和热点问题（Harrison et al.，1992；Royden et al.，1997；Fang Xiaomin et al.，1998；Tapponnier et al.，2001；Molnar et al.，2009；Clark，2012；Botsyun et al.，2019；Valdes et al.，2019）。关于高原的扩展，Tapponnier et al.（2001）通过分析青藏高原内部及周边构造变形，认为高原沿着大型断裂带以斜向俯冲的方式，由南向北逐渐扩展，青藏高原东北缘在中新世-上新世开始变形，成为高原最新的组成部分。然而，近期西秦岭低温热年代学与断层泥Ar-Ar测年等研究显示高原东北缘与印度-欧亚板块碰撞的同时发生变形，显示了

注：本文为重点研发项目（2017YFC1500104）；自然科学基金（41872204，41590861，41603054）；地震动力学国家重点实验室基金（LED2017A04）共同资助成果。

收稿日期：2019-10-31；改回日期：2019-12-23；网络发表日期：2020-02-21；责任编委：刘俊来；责任编辑：李曼。

作者简介：刘康，1995年生。中国地震局地质研究所硕士生，主要从事新生代构造变形与沉积学研究。通讯作者：王伟涛，1979年生。中山大学地球科学与工程学院教授，主要从事新生代构造变形与沉积学研究。Email：taotaowang@126.com。

引用本文：刘康，王伟涛，赵旭东，庞建章，俞晶星. 2020. 青藏高原东北缘柴达木盆地红沟剖面物源分析及其构造意义. 地质学报，94（3）：716～728. doi：10.19762/j.cnki.dizhixuebao.2020155.

Liu Kang，Wang Weitao，Zhao Xudong，Pang Jianzhang，Yu Jingxing. 2020. Provenance identification for the Honggou section of the Qaidam basin in the northeastern margin of the Tibetan Plateau and its tectonic significance. Acta Geologica Sinica. 94（3）：716～728.

青藏高原岩石圈新生代以相对恒定的体应变率发生变形(Clark et al., 2010; Duvall et al., 2011; Clack, 2012)。由此可见,青藏高原东北缘新生代构造变形时间及其分布的研究对于理解青藏高原变形机制至关重要。本文试图以青藏高原东北缘柴达木盆地新生代沉积物为研究对象,利用锆石 U-Pb, Hf 同位素组成等方法揭示柴达木盆地南、北两侧东昆仑山与祁连山的隆升过程,为高原向北东方向的扩展过程提供约束。

柴达木盆地位于东昆仑山以北,祁连山以南,上述山体隆升、风化、剥蚀形成的碎屑物质经河流搬运而堆积在柴达木盆地中,因此柴达木盆地以及充填其中的沉积物记录了新生代东昆仑山、祁连山等山脉构造隆升、变形的信息。柴达木盆地东部的红沟剖面,发育>5 km 厚的连续的新生代地层,Wang Weitao et al. (2017) 和 Nie Junsheng et al. (2019) 以该剖面所发现的原位哺乳动物化石(Li Qiang et al., 2015)为约束,通过磁性地层学获得了红沟剖面的年代框架(25.5~4.8 Ma)。以磁性地层年代为基础,结合沉积学分析,开展碎屑锆石物源示踪研究,揭示它们蕴含的构造变形信息,能够为青藏高原东北部隆升历史和扩展过程提供证据,进而为重建整个高原变形隆升过程及模式提供新线索。

1　研究区地质背景

柴达木盆地是青藏高原东北缘最大新生代沉积盆地(图 1),海拔 2500~3000 m,面积达 1.2×10^5 km^2。盆地南以东昆仑断裂带为界、西以阿尔金断裂带为界,北以柴达木盆地北缘逆冲褶皱带为界与祁连山相接。柴达木盆地由西向东逐渐变窄呈三角状(图 1)。东昆仑造山带以西连接西昆仑造山带,以东接西秦岭造山带,位于青藏高原北部,柴达木盆地南部。东昆仑构造带在古生代至三叠纪时期,发生大面积岩浆作用(Yin An, 2007),广泛分布二叠纪-三叠纪花岗岩体。阿尔金构造带是青藏高原西北部的边界,主体北东东向,发育新元古代-古生代侵入岩。阿尔金构造带由于印度-亚欧大陆的碰撞,在早新生代开始形成(Yin An et al., 2002)。柴北缘逆冲褶皱带位于柴达木盆地北缘与祁连山相连部位,由柴达木地块向北俯冲,与祁连地块陆陆碰撞形成,主要由赛什腾山、嗷唠山、绿梁山和锡铁山等地区组成,发育大量晚古生代-早中生代花岗岩类岩石(Wu Cailai et al., 2004)。祁连山系自北向南包括北祁连、中祁连和南祁连,南祁连为柴达木盆地的北部界线,以古生代花岗岩体(Gehrels et al., 2003; Chen Xuanhua et al., 2012)为主。

柴达木盆地发育巨厚新生代陆相沉积地层,最大厚度可达 15 km(Duran et al., 1998; Zhou Jianxun et al., 2006; Yin An et al., 2008)。根据地层的颜色、岩性、古生物组合特征以及地层接触关系,盆地中的新生代地层自下向上被划分为七个组,分别为路乐河组、下干柴沟组、上干柴沟组、下油砂山组和上油砂山组、狮子沟组以及七个泉组(青海省地层表编写小组,1983;青海省地质矿产局,1991; Sun Zhiming et al., 2005; Fang Xiaomin et al., 2007; Yin An et al., 2008)。

红沟剖面(起点坐标为 37°32′25.2″N, 95°10′5.57″,终点坐标为 37°28′52.7″N, 95° 8′5.9″E)位于柴达木盆地的北缘逆冲褶皱带中的一个背斜构造上(红沟背斜,图 1),背斜北翼缓,南翼陡,甚至倒转。河流由北向南切过红沟背斜,使新生代地层沿背斜南翼完整出露,厚度约 5.3 km。红沟背斜的核部为早白垩系犬牙沟组,向南新生代地层不整合于白垩系之上,依次出露路乐河组、下干柴沟组、上干柴沟组、下油砂山组、上油砂山组和狮子沟组地层。红沟剖面除路乐河组与早白垩系犬牙沟组呈不整合接触外,新生代地层各组之间均呈整合接触关系(Ji Junliang et al., 2017; Wang Weitao et al., 2017)。

红沟剖面路乐河组地层厚度约 490 m(5310~4820 m,图 2)以厚层紫红色砾岩-砂质砾岩-砂岩-含砾粉砂岩组成的多个旋回为特征,单个沉积旋回厚约 40~60 m。砾岩与砂岩均呈透镜状,侧向延伸<50 m,层理不发育。其中砾岩、砂质砾岩分选较差、以颗粒支撑为主,底部具有冲刷-充填构造。该组地层向上粒度逐渐变细,具有辫状河河道与河漫滩堆积的特征。

下干柴沟组地层厚度约 980 m(4820~3840 m,图 2),岩性主要由厚层黄绿色砂岩、粉砂岩,红绿色泥岩组成。单层砂体厚 5~40 m,呈透镜状,砂体底部可见河道冲刷-充填构造,发育槽状交错层理和平行层理,粒度向上逐渐变细,可能是曲流河迁移过程中的侧向堆积形成。细粒沉积单层厚 2~5 m,发育小型交错层理和水平层理。粗粒砂岩的交错层理、底部冲刷-充填构造以及透镜体揭示了岩层在相对高能的水流环境下沉积。含水平层理的细粒岩层在相对静水或者洪泛平原环境下沉积。

上干柴沟组地层厚度约 1400 m(3840~2440 m,图 2),由厚层红绿色泥岩、淡黄色中细粒砂岩和

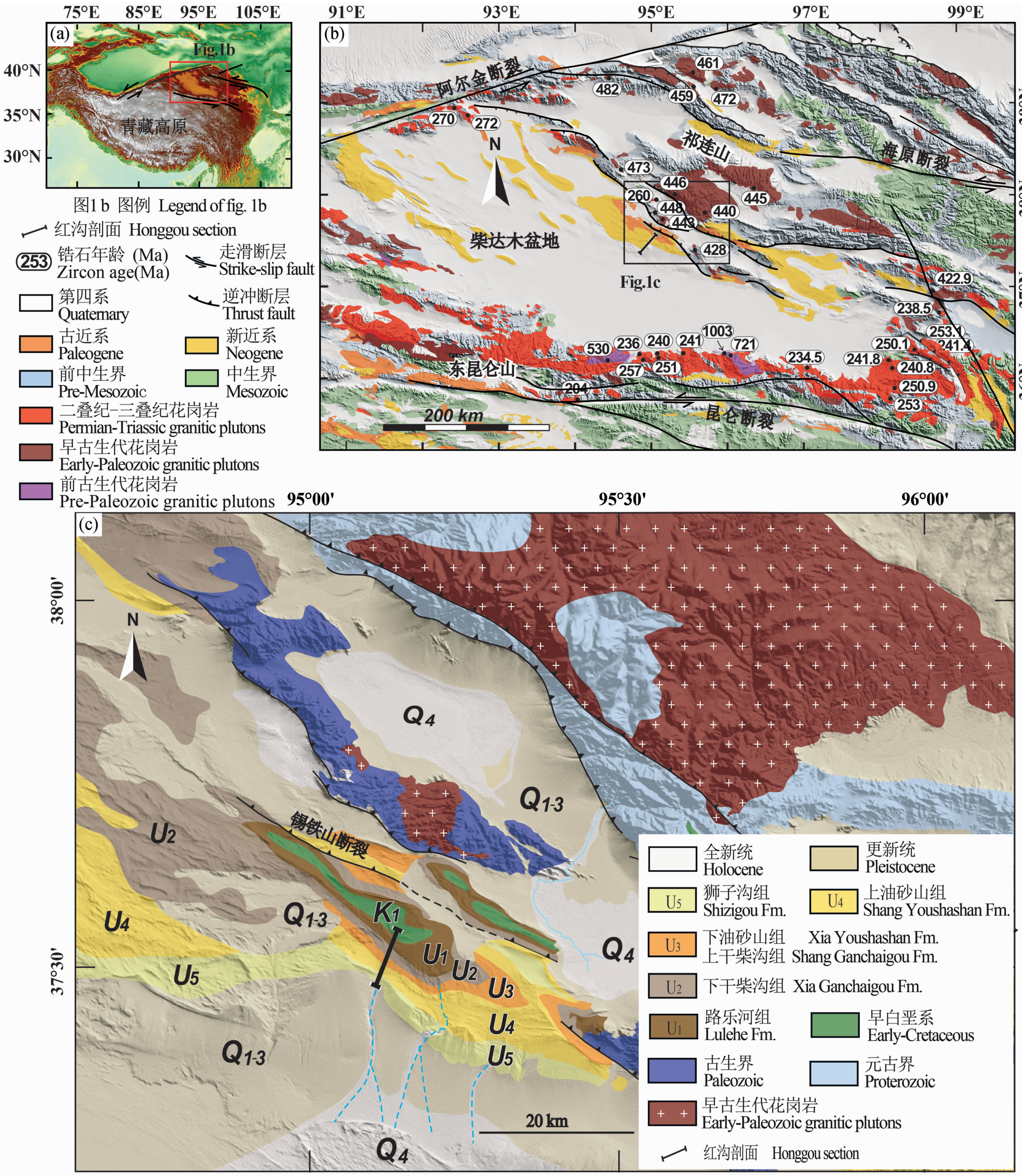

图 1 柴达木盆地红沟剖面及其邻区地质图

Fig. 1 Geological map of Honggou section of Qaidam basin and its adjacent region

薄层灰岩组成。砂岩发育交错层理,平行层理以及少量的波痕。泥岩单层厚 2～15 m,侧向延伸＞100 m,泥灰岩厚 0.1～0.4 m,发育有波痕和水平层理。这些薄层灰岩可能是由于湖面上升形成,厚层泥岩代表了湖相沉积,砂岩层可能是由于河道沉积形成。该组地层具有浅湖相或者三角洲相沉积特征。在上干柴沟组的中部(3158 m)含有大量哺乳动物化石,如 *Mioechinus*? sp., *Monosaulax tungurensis*, *Plesiodipus* sp., *Zygolophodon* sp., *Turcocerus* sp., and Rhinocerotidae indet 等(Wang Weitao et al., 2017)。

下油砂山组地层厚 820 m(2440 ～1620 m),以浅棕色泥岩粉砂岩为主,夹厚层黄色砂岩和灰色砾岩。泥岩层厚 5～75 m,侧向延伸＞100 m。发育水平层理,砂岩层中可见平行层理,槽状交错层理,这些厚层泥岩和砂泥岩具有湖相沉积的特征。

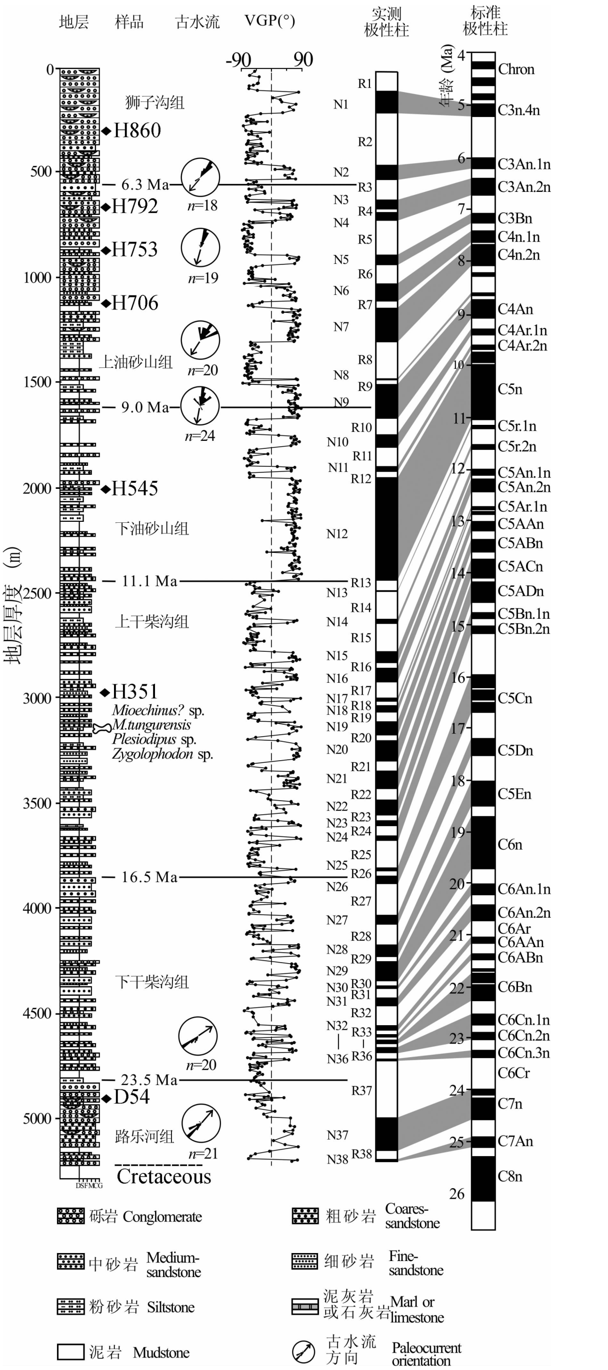

图 2　红沟剖面磁性地层与标准极性柱对应关系,古水流方向(Wang Weitao et al., 2017)以及碎屑锆石采样层位

Fig. 2　Magnetostratigraphy of the Honggou section correlated with GPTS, paleocurrent orientation (Wang Weitao et al., 2017) and the detrital zircon sample locations

上油砂山组地层厚 1070 m(1620 ～550 m),可分为上、下两部分。下部:碎屑支撑的砾岩,含有厚 0.1～0.3m 厚的砂岩透镜体。上部:以泥岩、含砾砂岩、砾岩为主,分选差,次圆状-棱角状磨圆。下部岩石层理发育,厚层细粒,湖相或者三角洲相沉积。上部砾石层碎屑支撑,砾石呈叠瓦状排列,辫状河沉积。

狮子沟组地层厚度约 550 m(550 ～0 m),主要为中、细砾,碎屑支撑和杂基支撑的砾岩组成,砾石层厚 0.5～18 m,具有透镜体,砾石分选差,次圆状-棱角状磨圆,冲积扇相沉积。

在上干柴沟组哺乳动物化石 *Mioechinus*? sp., *Monosaulax tungurensis*, *Plesiodipus* sp., *Zygolophodon* sp., *Turcocerus* sp., 和 Rhinocerotidae indet 的约束下,磁性地层测年结果显示红沟剖面路乐河组的沉积时代为 25.5～23.5 Ma,下干柴沟组、上干柴柴沟组、下油砂山组、上油砂山组、狮子沟组的沉积时代分别为:23.5～16.5 Ma、16.5～11.1Ma、11.1～9.0 Ma、9.0～6.3 Ma、6.3～4.8 Ma(Wang Weitao et al., 2017)。

2　砂岩样品的采集与测试方法

根据红沟剖面的磁性地层时代,沉积环境以及岩性变化,我们在红沟剖面新生代不同的地层层位中采集了 7 个中、粗砂岩样品,每个样品重量大于 5 kg,以便挑选足够的碎屑锆石颗粒进行 Hf 同位素测试分析。7 个样品的编号及沉积年龄分别是 D54 (23.7Ma),H351(12.5Ma),H545(10.0Ma),H706 (7.6Ma), H753 (6.8Ma), H792 (6.5Ma), H860 (5.5Ma)。样品所在剖面中的具体层位见图 2。

首先除去样品表面的松散附着物,将其粉碎;然后采用磁选法除去磁性矿物,剩下的非磁性矿物除去非磁性杂质并选择重液对其进行分选,得到非磁性重矿物,最后在双目显微镜下挑选出锆石颗粒。将分选获得的锆石粘贴固定,并将环氧树脂灌注在空心柱中,驱赶气泡,烘干。随后对其打磨抛光,在显微镜下用透射光和反射光观察锆石的结构与形态,最终利用阴极发光技术获取锆石的内部结构的详细信息(图 3),进行 Hf 同位素的测试。

红沟剖面锆石 U-Pb 年龄结果引用 Wang Weitao et al. (2017),Hf 同位素测试分析在中国科学院地质与地球物理研究所岩石圈演化国家重点实验室完成。我们利用配有 193 nm 激光剥蚀系统的 Neptune 多接收电感耦合等离子体质谱仪(MC-ICP-MS)对锆石 Hf 同位素以及微量元素进行测定,实验流程见(Wu Fuyuan et al., 2006; Xie Liewen et al., 2008)。每个样品的碎屑锆石测试数量不低于 100 个。

测定 $^{176}Lu/^{177}Hf$ 和 $^{176}Hf/^{177}Hf$ 时,要对 ^{176}Hf 的两个同质异位素 ^{176}Lu 和 ^{176}Yb 进行干扰校正。干

扰校正取$^{175}Lu/^{176}Lu=0.02669$(Biévre et al., 1993)和$^{172}Yb/^{176}Yb=0.5886$(Chu Nan-Chin et al., 2002)。红沟剖面锆石具有较高的Hf含量和较低的Lu含量,形成以后基本没有累计放射性成因Hf,所测定的$^{176}Hf/^{177}Hf$就代表了其形成时Hf同位素的组成(Wu Fuyuan et al., 2007)。$\varepsilon_{Hf}(t)$参数,它表示岩石形成时的$^{176}Hf/^{177}Hf$相对于球粒陨石库(CHUR)差异的万分数,表达式为:

$$\varepsilon_{Hf}(t)=\left[\frac{(^{176}Hf/^{177}Hf)_s-(^{176}Lu/^{177}Hf)_s\times(e^{\lambda t}-1)}{(^{176}Hf/^{177}Hf)^0_{CHUR}-(^{176}Lu/^{177}Hf)^0_{CHUR}\times(e^{\lambda t}-1)}-1\right]\times 10000$$

当$\varepsilon_{Hf}(t)$为负值时,表示岩石来源于亏损地幔;当$\varepsilon_{Hf}(t)$为正值时,表示岩石来源于富集地幔或受到地壳物质的混染。

除了$\varepsilon_{Hf}(t)$外,t_{DM},Hf相对于亏损地幔的一阶段模式年龄,也是一个重要的参数。它记录了锆石结晶的岩浆从地幔分离的年龄,表达式为:

$$t_{DM}=\frac{1}{\lambda}\times\ln\left[1+\frac{(^{176}Hf/^{177}Hf)_s-(^{176}Hf/^{177}Hf)_{DM}}{(^{176}Lu/^{177}Hf)_s-(^{176}Lu/^{177}Hf)_{DM}}\right]$$

其中,$(^{176}Hf/^{177}Hf)_s$和$(^{176}Lu/^{177}Hf)_s$为样品测定值,现今的球粒陨石均一库$(^{176}Lu/^{177}Hf)^0_{CHUR}=0.0332$, $(^{176}Hf/^{177}Hf)^0_{CHUR}=0.282772$(Blicherttoft et al., 1997);亏损地幔现今的$(^{176}Lu/^{177}Hf)_{DM}=0.0384$, $(^{176}Hf/^{177}Hf)_{DM}=0.28325$(Vervoort et al., 1999);$^{176}Lu$的衰变系数$\lambda=1.867\times10^{-11}a^{-1}$(Scherer et al., 2001)。

3 样品的测试结果

红沟剖面锆石D54、H351、H545、H706、H753、H792、H860样品中锆石

晶型主要为自形的短、中柱状或者半自形短柱状,晶型较为完整,少数锆石由于河流搬运、破碎以及磨圆等外力作用导致自形不规则,晶型不完整,呈浑圆状;粒度介于60~250μm之间。大多数锆石具有明暗相见的条带结构,与典型的岩浆锆石的振荡环带特征相似,少数锆石弱分带或者无分带(图3)。测试分析结果Th/U比值>0.4的锆石占锆石总数的77%,仅有9%的锆石Th/U比值<0.1(附表),表明红沟剖面中的碎屑锆石大部分是岩浆成因锆石,仅少量可能为变质成因锆石,这也和阴极发光图像显示的锆石内部结构一致。

红沟剖面D54(23.7 Ma)、H351(12.5 Ma)样品锆石U-Pb年龄主要集中在200~300 Ma、400~500 Ma、700~800 Ma、1500~1800 Ma、2200~2400 Ma(图4a, Wang Weitao et al., 2017)。样品H545(10.0 Ma)和H706(7.6 Ma)具有相似的锆石U-Pb年龄分布,年龄主要集中在400~500 Ma,其它锆石年龄则零散的分布在228~400 Ma、500~1500 Ma、1900~2778Ma(图4a, Wang Weitao et al., 2017)。样品H753(6.8 Ma)、H792(6.5 Ma)和H860(5.5 Ma)的锆石U-Pb年龄以出现~250 Ma、~440 Ma和~1600 Ma的年龄峰为主要特征(Wang Weitao et al., 2017)。

红沟剖面中碎屑锆$^{176}Lu/^{177}Hf$的平均值为0.0009,96%以上的锆石$^{176}Lu/^{177}Hf$的值小于0.002,表明锆石形成后由^{176}Lu衰变而生成的^{176}Hf较少。样品D54中锆石的$^{176}Hf/^{177}Hf$介于0.281058~0.282894之间,依据$^{176}Hf/^{177}Hf$比值以及对应锆石的U-Pb年龄计算可得Hf一阶段模式年龄t_{DM}分布在524~2995 Ma之间,这些年龄集中分布在三个区间内,即850~1100 Ma、1300~1600 Ma、2400~2850 Ma范围内(图4t)。其中Hf同位素一阶段模式年龄为850~1100 Ma的锆石$\varepsilon_{Hf}(t)$的值分布在-4.4~4.3;t_{DM}年龄为1300~1600 Ma的锆石$\varepsilon_{Hf}(t)$值为-13.7~9.4;t_{DM}年龄为2400~2850 Ma的锆石$\varepsilon_{Hf}(t)$值介于-14.4~1.8。

样品H351中锆石的$^{176}Hf/^{177}Hf$分布范围是0.280524~0.282905,Hf同位素一阶段模式年龄计算后得到的范围是484~3727 Ma,较为集中分布在三个区间内,即850~1100 Ma、1300~1600 Ma、2400~2850 Ma范围内(图4q)。t_{DM}年龄为850~1100 Ma的锆石$\varepsilon_{Hf}(t)$的值分布在-4.3~5.4;t_{DM}年龄为1300~1600 Ma的锆石$\varepsilon_{Hf}(t)$值为-14.2~0.8;t_{DM}年龄为2400~2850 Ma的锆石$\varepsilon_{Hf}(t)$值介于-12.9~2.5。

H545样品中的锆石$^{176}Hf/^{177}Hf$的值介于0.280618~0.282789之间,通过计算获得的一阶段模式年龄范围675~3591 Ma,有两个明显的峰值区间:1300~1600 Ma和2200~2800 Ma(图4n)。两个阶段的$\varepsilon_{Hf}(t)$均为负值,前者的$\varepsilon_{Hf}(t)$范围是-11.9~ -0.9,后者$\varepsilon_{Hf}(t)$介于-9.8 ~ -0.2之间。

样品H706中锆石的$^{176}Hf/^{177}Hf$的范围为0.280995~0.282823,通过计算得到的一阶段模式年龄介于616~3134Ma之间,集中在1300~1600 Ma和2200~2800 Ma两个区间(图4k)。t_{DM}年龄为1300~1600 Ma的锆石$\varepsilon_{Hf}(t)$的值分布在-12.9~1.1;t_{DM}年龄为2200~2800 Ma的锆石具有较负

图 3　青藏高原东北缘红沟剖面代表性锆石阴极发光图像

Fig. 3　Representative images of zircon grains under cathodoluminescence from the Honggou section in the northeastern margin of the Tibetan Plateau

的 $\varepsilon_{Hf}(t)$的值(−31.4～0.1)。

样品 H753 中的锆石的$^{176}Hf/^{177}Hf$ 的值介于 0.281036～0.282882 之间,Hf 同位素一阶段模式年龄计算后得到的范围是 549～3033 Ma。这些年龄较为集中的分布在三个区间内:800～1100 Ma,1300～1600 Ma 以及 2200～2800 Ma(图 4h)。t_{DM}年龄在 800～1100 Ma 之间的锆石,其 $\varepsilon_{Hf}(t)$是−3.8～6.9;Hf 一阶段模式年龄为 1300～1600 Ma 的锆石的 $\varepsilon_{Hf}(t)$值介于−13.0～2.0 之间;t_{DM}年龄为 2200～2800 Ma 的锆石 $\varepsilon_{Hf}(t)$值为−13.4～1.4。

样品 H792 中锆石的$^{176}Hf/^{177}Hf$ 的变化范围分别是 0.281166～0.282717,Hf 同位素一阶段模式年龄计算后得到的范围是 785～2886 Ma,较为集中分布在三个区间,即 800～1100 Ma,1300～1600 Ma 以及 2200～2800 Ma 范围内(图 4e)。t_{DM}年龄为 800～1100 Ma 的锆石 $\varepsilon_{Hf}(t)$的值分布在−4.2～6.7;Hf 一阶段模式年龄为 1300～1600Ma 的锆石的 $\varepsilon_{Hf}(t)$值介于−13.9～0.3 之间;t_{DM}年龄为 2200～2800 Ma 的锆石 $\varepsilon_{Hf}(t)$值为−16.1～2.1。

样品 H860 中锆石的$^{176}Hf/^{177}Hf$ 变化范围是 0.281037～0.282969,计算得到的 Hf 一阶段模式年龄 t_{DM}在 399～3049 Ma 之间,这些年龄较为集中的分布在 800～1100 Ma,1300～1600 Ma 以及 2200～2800 Ma 三个区间内(图 4b)。t_{DM}年龄在 800～1100 Ma 之间的锆石,其 $\varepsilon_{Hf}(t)$是−4.7～6.8;Hf 一阶段模式年龄为 1300～1600 Ma 的锆石的 $\varepsilon_{Hf}(t)$值介于−15.6～6.4 之间;t_{DM}年龄为 2200～2800 Ma 的锆石 $\varepsilon_{Hf}(t)$值为−19.2～3.1。

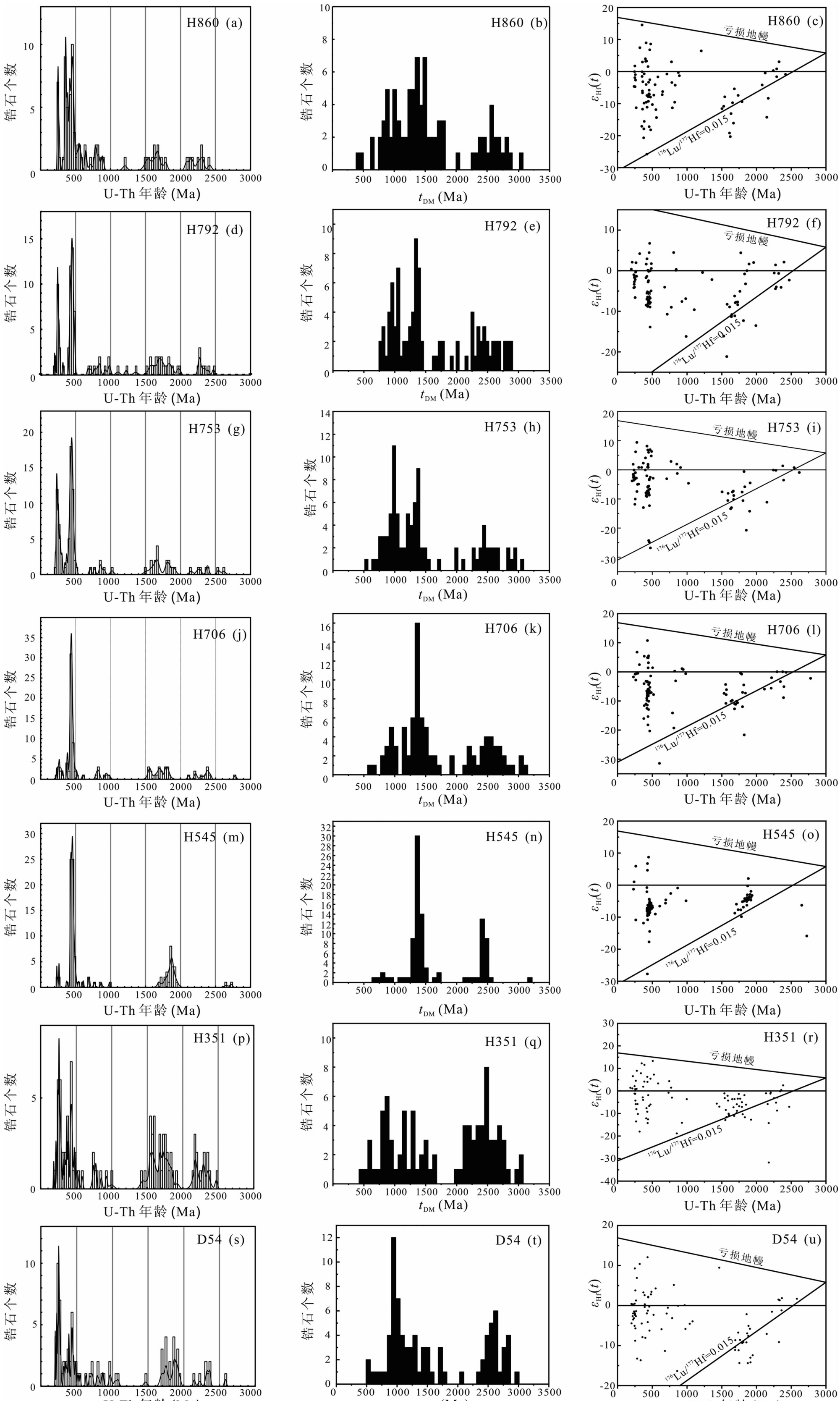

图 4　红沟剖面碎屑锆石 U-Pb 年龄(Wang Weitao et al.，2017)、Hf 一阶段模式年龄图和 $\varepsilon_{Hf}(t)$ 相对于 U-Pb 年龄分布直方图

Fig. 4　U-Pb age histograms(Wang Weitao et al.，2017)，images of one-stage model ages of Hf and $\varepsilon_{Hf}(t)$ vs. U-Pb ages histograms of detrital zircons from the samples in the Honggou section

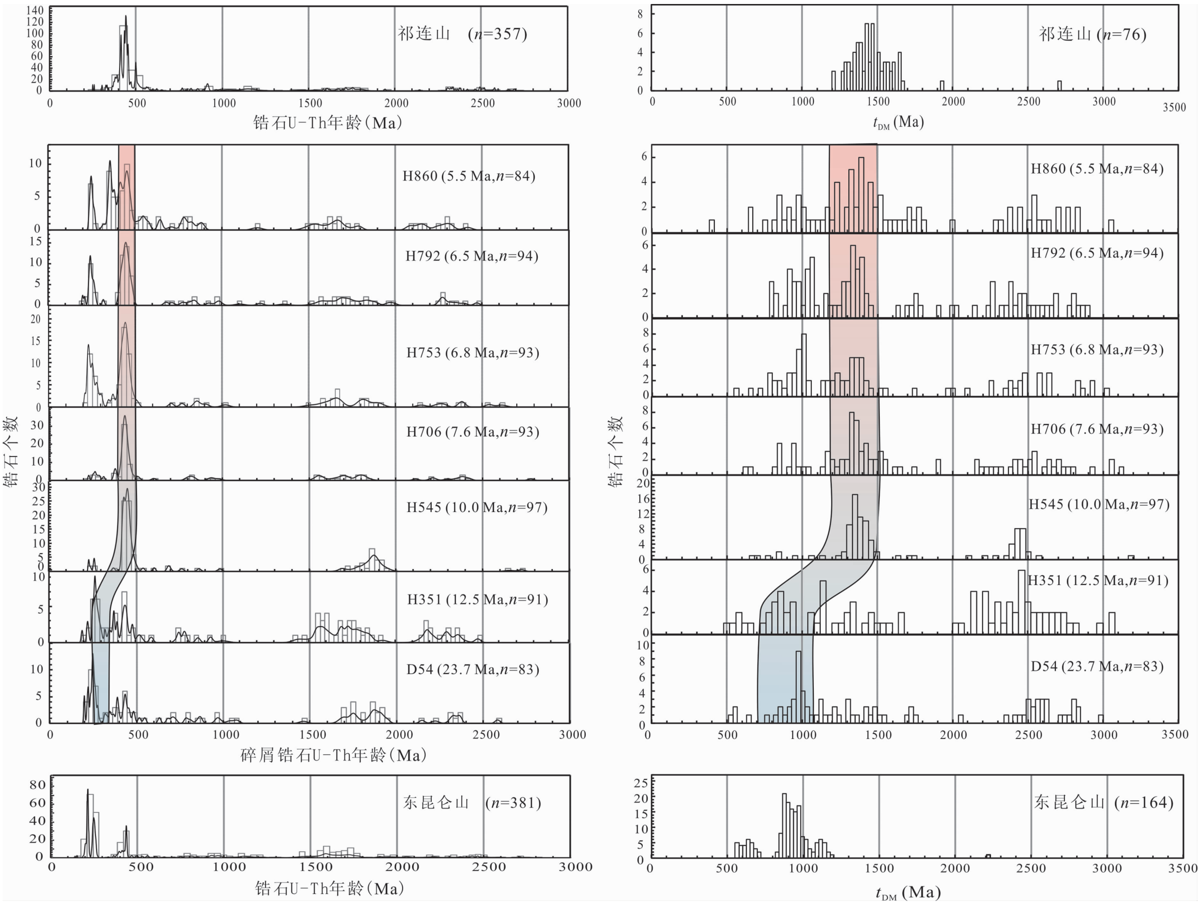

图 5　(a)红沟剖面碎屑锆石 U-Pb 年龄和可能物源区锆石 U-Pb 年龄(Wang Weitao et al., 2017)；(b)红沟剖面 t_{DM} 和可能物源区 t_{DM}

Fig. 5　(a) U-Pb ages from the Honggou section and potential source regions(Wang Weitao et al., 2017); (b) t_{DM} data from the Honggou section and potential source regions

4　讨论

柴达木盆地红沟剖面主要以红色砾岩、砂岩、泥岩沉积为特征，尤其是剖面底部路乐河组、下干柴沟组，剖面上部上油砂山组和狮子沟组地层发育了厚层砾岩夹砂岩，沉积环境主要为辫状河相、曲流河相、冲积扇相等沉积环境(Wang Weitao et al., 2017)，水动力条件较强，物源区较近，揭示盆地南侧的东昆仑和北侧的祁连山脉可能是柴达木盆地的主要源区。红沟剖面中 23.7 Ma 和 12.5 Ma 的样品，有着相似的锆石 U-Pb 年龄谱(图 5a)、t_{DM} 以及 Hf 同位素组成特征(图 4)，表明盆地从渐新世末到中中新世可能有着相同的物源区域；10.5 Ma 之后的样品(H545，H706，H753，H792，H860)，具有相似的 U-Pb 年龄谱(图 5a)、Hf 同位素 t_{DM} 以及同位素组成特征(图 4)，并且这些特征与这两个样品(D54，H351)存在明显的差异。两个 12.5 Ma 以前的样品锆石年龄主要峰值在 250Ma，对应的 Hf 一阶段模式年龄在 750～1000 Ma，$\varepsilon_{Hf}(t)$ 值介于－8.8～9.3 之间；剩余五个样品以 440 Ma 为主要峰值年龄，对应的 t_{DM} 为 1250～1500 Ma，且基本占据主导位置，与之相对应的 $\varepsilon_{Hf}(t)$ 值(－11.8～6.4)，并且绝大部分(94.6%)为负值。这些均反映了红沟剖面新生代沉积源区的改变。

柴达木盆地南缘东昆仑山脉广泛分布二叠纪-三叠纪花岗岩体，锆石 U-Pb 年龄主要集中在 210～280 Ma(Ding Qingfeng et al., 2014; Chen Xuanhua et al., 2012; Xia Rui et al., 2015)。Ding Qingfeng et al.(2014)对东昆仑五龙沟花岗岩锆石 U-Pb 定年得到 244 Ma，对应的 $^{176}Hf/^{177}Hf$ 为 0.282520～0.282681，$\varepsilon_{Hf}(t)$ 为－4.9～1.3，Hf 一阶段模式年龄 832～1043 Ma。Xia Rui et al.(2015)对东昆仑山香日德斜长花岗岩的锆石进行了 U-Pb 测年，获得 227 Ma 的结晶年龄，$\varepsilon_{Hf}(t)$、$^{176}Hf/^{177}Hf$

和 Hf 同位素一阶段模式年龄值分别为−8.6～0、0.282403～0.28265 和 863～1199 Ma。上述研究结果表明东昆仑山地区主要出露二叠纪−三叠纪花岗岩，这些花岗岩具有偏负的 $\varepsilon_{Hf}(t)$ 值，Hf 同位素 t_{DM} 介于 832～1199 Ma。这些特征与柴达木盆地红沟剖面 23.7～12.5 Ma 之间，结晶年龄为 220～290 Ma，$^{176}Hf/^{177}Hf$ 值 0.282229～0.282894，$\varepsilon_{Hf}(t)$ 绝大部分(81%)介于−8.13～2.67 之间，具有较负的 $\varepsilon_{Hf}(t)$ 值，t_{DM} 为 524～1456 Ma 的锆石特征相似，表明柴达木盆地红沟剖面渐新世-中中新世沉积物可能主要来自盆地南部的东昆仑山。Mock et al.(1999)，Jolivet et al.(2003)以及 Clark et al.(2010)通过 ^{40}Ar-^{39}Ar 以及磷灰石 U-Th/He 年代学的研究也显示东昆仑山在始新世末-渐新世初发生快速蚀顶作用，进一步显示东昆仑山可能是柴达木盆地新生代早期的主要物源区之一。

柴达木盆地北缘祁连山广泛出露古生代花岗岩。Gehrels et al.(2003)和 Chen Nengsong et al.(2012)针对祁连山地区花岗岩开展了详细的测年研究，发现祁连山花岗岩年龄主要集中在 400～480 Ma。这与 Yong Yong et al.(2008)对祁连山董家庄花岗岩体和新店花岗岩体，获得锆石 U-Pb 年龄为 446±1 Ma 和 454±5 Ma、Chen Junlu et al.(2008)对祁连山什川岩基中二长花岗岩得到 444.6 Ma 和 414.3 Ma、Li Jianfeng et al.(2010)对祁连山肃北、石包城地区花岗岩获得 415±3Ma 和 435±4Ma 的年龄一致。Wang Weitao et al.(2017)对祁连山锆石 U-Pb 年龄的统计结果也显示锆石 U-Pb 年龄主要分布在 410～510 Ma 之间(图 5a)。Yu Shengyao et al.(2013)对祁连山和柴北缘的锆石 U-Pb 年龄以及 Hf 同位素组成分析显示该地区锆石 U-Pb 年龄为在 436 Ma，对应的 $^{176}Hf/^{177}Hf$ 在 0.282100～0.282290 之间，$\varepsilon_{Hf}(t)$ 范围−4.7～2.0，一阶段模式年龄为 1400～1600 Ma。Yan Zhen et al.(2015)对化隆地区 410～460 Ma 花岗岩的 Hf 同位素分析表明，$^{176}Hf/^{177}Hf$ 和 $\varepsilon_{Hf}(t)$ 值介于 0.282073～0.282551 和−15.3～2.2 之间，一阶段模式年龄为 1044～1645 Ma。由此可见，祁连山地区锆石年龄主要集中在 400～500 Ma，对应的 $^{176}Hf/^{177}Hf$ 在 0.282073～0.282551 之间，$\varepsilon_{Hf}(t)$ 范围−15.3～2.2，一阶段模式年龄主要集中在 1044～1645 Ma。这些特征与柴达木盆地红沟剖面<12 Ma 地层中锆石 U-Pb 年龄集中在 400～500 Ma，$^{176}Hf/^{177}Hf$ 介于 0.281726～0.282823，t_{DM} 主要(75%)介于 850～1500 Ma，Hf 同位素 $\varepsilon_{Hf}(t)$ 主要(79%)分布在−15.4～4.8 的特征高度相似，表明祁连山可能在～12 Ma 开始快速隆升，成为柴达木盆地的主要物源区。

最新的低温热年代学证据表明，祁连山在～15 Ma 加速隆升(Yu Jingxing et al.，2019a，2019b)。宗务隆山的磷灰石裂变径迹数据也表明祁连山在～18～11 Ma 发生快速剥露事件(Pang Jianzhang et al.，2019)。Zhuang Guangsheng et al.(2019)在怀头他拉剖面利用碎屑锆石 U-Pb 年龄指出，祁连山在 15.8 Ma 已经抬升，为柴达木盆地提供物源。同时，Wang Xiaoming et al.(2003)对党和盆地以及 Liu Caicai et al.(2016)对祁连盆地等祁连山内部盆地的沉积演化也揭示了祁连山在中-晚中新世发生了快速隆升。这些研究与本文红沟剖面锆石物源分析结果一致。

柴达木盆地红沟剖面中存在少量 U-Pb 年龄为 1600～1800 Ma 和 2200～2300 Ma，$^{176}Hf/^{177}Hf$ 介于 0.281089～0.281800，$\varepsilon_{Hf}(t)$ 范围−20.3～4.4 的锆石。由于柴达木盆地南缘东昆仑山与盆地北缘祁连山均存在少量元古代的地层、岩体或变质岩(Qian Tao et al.，2018)，因此，柴达木盆地红沟剖面 1600～1800 Ma 和 2200～2300 Ma 的锆石有可能来源于盆地南缘的东昆仑山或盆地北缘的祁连山。

值得指出的是在柴达木盆地红沟剖面<7 Ma 的地层中 200～300 Ma，$^{176}Hf/^{177}Hf$ 范围 0.282294～0.282882、$\varepsilon_{Hf}(t)$ 介于−11.9～9.4、一阶段模式年龄为 549～1399 Ma 的锆石略有增加。这一时期红沟剖面古流向主要为由北向南(图 2)，显示 7 Ma 之后柴达木盆地的主要源区仍然位于盆地北缘，表明盆地早期沉积在柴达木盆地中具有 200～300 Ma 的碎屑锆石可能再次搬运沉积至盆地内部，造成了<7 Ma 的地层中 200～300 Ma 的碎屑锆石含量增加。Pang Jianzhang et al.(2019)利用热年代学方法，得到祁连山南部在 7±2 Ma 时再次向南扩展，表明柴达木盆地北缘褶皱-冲断带向盆地内部(向南方向)的扩展是导致柴达木盆地北缘沉积物再循环的主要原因。

新生代以来青藏高原东北缘东昆仑山、祁连山的隆升并非是引起柴达木盆地沉积物源变化的唯一原因，气候变化同样也会导致物源区的风化、剥蚀速率发生改变(Miao Yunfa et al.，2012；Jing Bao et al.，2017)，但是祁连山南、北两侧沉积盆地，在中

中新世沉积物源同时的转变,支持构造变形是导致山脉隆升,地貌起伏增大,侵蚀加剧以及柴达木盆地北缘物源变化的主要因素。

5　结论

青藏高原东北缘柴达木盆地红沟剖面发育25.5～4.8 Ma的新生代碎屑沉积岩。通过对剖面中砂岩碎屑锆石U-Pb年龄与Hf同位素组成分析,获得如下结论:

(1)红沟剖面渐新世至晚中新世(23.7～12.5 Ma)砂岩中存在峰值年龄250 Ma,$\varepsilon_{Hf}(t)$值介于−8.8～9.3之间的锆石,其与东昆仑山花岗岩中锆石的年龄、$\varepsilon_{Hf}(t)$值相似,表明东昆仑山在渐新世开始构造隆升、变形,成为新生代柴达木盆地的主要物源区之一。

(2)晚中新世(10～12 Ma),红沟剖面物源发生显著改变,剖面中碎屑锆石U-Pb年龄和Hf同位素特征与祁连山花岗岩体的锆石U-Pb年龄和Hf同位素特征类似,揭示祁连山成为沉积盆地的重要物源区。

(3)红沟剖面7 Ma以来,U-Pb年龄为200～300 Ma的锆石含量的增加可能反映了柴达木盆地北缘褶皱冲断带向盆地内部的扩展,导致了物质的沉积再循环,为祁连山向南不断扩展提供了证据。

致谢:感谢审稿专家给予本文的建设性意见,以及责任编辑对本文的细致审查。对张佳伟博士以及李朝鹏博士的重要指导表示感谢!

References

An Zhisheng, Kutzbach J E, Prell W L, Porter S C. 2001. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times. Nature, 411 (6833): 62～66.

Biévre P De, Taylor P D P. 1993. Table of the isotopic compositions of the elements. International Journal of Mass Spectrometry & Ion Processes, 123 (2): 149～166.

Blicherttoft J, Albarède F. 1997. The Lu-Hf isotope geochemistry of chondrites and the evolution of the mantle-crust system. Earth & Planetary Science Letters, 148(1-2): 0～258.

Botsyun S, Sepulchre P, Donnadieu Y, Risi C, Licht A, Caves Rugenstein J K. 2019. Revised paleoaltimetry data show low Tibetan Plateau elevation during the Eocene. Science, 363 (6430): eaaq1436.

Chen Junlu, Xu Xueri, Zeng Zuoxun, Xiao Lin, Wang Hongliang, Wang Zongqi, Xiao Shaowen. 2008. Geochemical characters and LA-ICP-MS zircon U-Pb dating constraints on the petrogenesis and tectonic setting of the Shichuan intrusion, east segment of the Central Qilian, NW China. Acta Petrologica Sinica, 24(4):841～854. (in Chinese with English abstract).

Chen Nengsong, Zhang Lu, Sun Min, Wang Qinyan, Kusky T M. 2012. U-Pb and Hf isotopic compositions of detrital zircons from the paragneisses of the Quanji Massif, NW China: implications for its early tectonic evolutionary history. Journal of Asian Earth Sciences, 54～55(4): 110～130.

Chen Xuanhua, George G, Yin An, Li Li, Jiang Yongbao. 2012. Paleozoic and mesozoic basement magmatisms of Eastern Qaidam basin, Northern Qinghai-Tibet Plateau: LA-ICP-MS zircon U-Pb geochronology and its geological significance. Acta Geologica Sinica, 86(2): 350～369.

Chu Nanchin, Taylor R N, Nesbitt R W, Boella R M, Milton J A, German C R, Bayon G, Burton K. 2002. Hf isotope ratio analysis using multi-collector inductively coupled plasma mass spectrometry: an evaluation of isobaric interference corrections. Journal of Analytical Atomic Spectrometry, 17 (12): 1567～1574.

Clark M K, Farley K A, Zheng Dewen, Wang Zhicai, Duvall A R. 2010. Early Cenozoic faulting of the northern Tibetan Plateau margin from apatite (U-Th)/He ages. Earth & Planetary Science Letters, 296(1): 78～88.

Clark M K. 2012. Continental collision slowing due to viscous mantle lithosphere rather than topography. Nature, 483 (7387): 74～7.

Decelles P G, Robinson D M, Zandt G. 2002. Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau. Tectonics, 21(6): 12-1-12-25.

Dewey J F, Shackleton R M, Chang Chengfa, Sun Yiyin. 1988. The tectonic evolution of the Tibetan Plateau. philosophical transactions of the royal society of London a mathematical Physical & Engineering Sciences, 327(1594): 379～413.

Ding Qingfeng, Jiang Shaoyong, Sun Fengyue. 2014. Zircon U-Pb geochronology, geochemical and Sr-Nd-Hf isotopic compositions of the Triassic granite and diorite dikes from the Wulonggou mining area in the Eastern Kunlun Orogen, NW China: Petrogenesis and tectonic implications. Lithos, 205 (9): 266～283.

Duran L, Fournier M, Massei N, Dupont J P. 1998. Use of Tracing Tests to Study the Impact of Boundary Conditions on the Transfer Function of Karstic Aquifers. Tectonics, 17(6): 823～842.

Duvall A R, Clark M K, Pluijm B A Van D, Li Chuanyou. 2011. Direct dating of Eocene reverse faulting in northeastern Tibet using Ar-dating of fault clays and low-temperature thermochronometry. Earth & Planetary Science Letters, 304 (3): 520～526.

England P, Searle M. 1986. The Cretaceous-Tertiary deformation of the Lhasa Block and its implications for crustal thickening in Tibet. Tectonics,5(1): 1～14.

Fang Xiaomin, Zhang Weilin, Meng Qingquan, Gao Junping, Wang Xiaoming, King John, Song Chunhui, Shuang Dai, Miao Yunfa. 2007. High-resolution magnetostratigraphy of the Neogene Huaitoutala section in the eastern Qaidam Basin on the NE Tibetan Plateau, Qinghai Province, China and its implication on tectonic uplift of the NE Tibetan Plateau. Earth & Planetary Science Letters,258(1): 293～306.

Gehrels G E, Yin A, Wang Xiaofeng. 2003. Detrital zircon geochronology of the northeastern Tibetan Plateau. Geol. soc. amer. bull, 115(7): 881～896.

Guo Z T, Ruddiman W F, Hao Q Z, Wu H B, Qiao Y S, Zhu R X, Peng S Z, Wei J J, Yuan B Y, Liu T S. 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature, 416(6877):159.

Harrison T M, Copeland P, Kidd W S, Yin An. 1992. Raising Tibet. Science, 255(5052): 1663～1670.

Ji Junliang, Zhang Kexin, Clift P D, Zhuang Guangsheng, Song Bowen, Xue Ke, Xu Yadong. 2017. High-resolution magnetostratigraphic study of the Paleogene-Neogene strata in the Northern Qaidam basin: implications for the growth of the Northeastern Tibetan Plateau. Gondwana Research, 46: 141.

Jing Bao, Wang Yadong, Song Chunhui, Ying Feng, Hu Chunhua, Zhong Sirui, Yang Jiwei. 2017. Cenozoic sediment flux in the

Qaidam Basin, northern Tibetan Plateau, and implications with regional tectonics and climate. Global and Planetary Change, 155: 56～69.

Jolivet M, Brunel M, Seward D, Xu Z, Wu C. 2003. Neogene extension and volcanism in the Kunlun Fault Zone, northern Tibet: New constraints on the age of the Kunlun Fult. Tectonics, 22(5): 1052.

Li Jijun, Wen Shixuan, Zhang Qingsong, Wang Fubao, Zheng Benxing, Li Bingyuan. 1979. A discussion on the period, amplitude and type of the uplift of the Qinghai-Tibet Plateau. Sci. China, 22(11): 1314～1328.

Li Jijun, Fang Xiaomin. 1998. Uplift of the Tibetan Plateau and environmental changes. Chin. Sci. Bull. 43(15): 1568～1574.

Li Jianfeng, Zhang Zhicheng, Han Baofu. 2010. Geochronology and geochemistry of Early Paleozoic granitic plutons from Subei and Shibaocheng areas, the western segment of Central Qilian and their geological implications. Acta Petrologica Sinica, 26(8): 2431～2444. (in Chinese with English abstract).

Li Qiang, Wang Xiaoming. 2015. Discovery of Neogene beavers (Castoridae, Mammalia) in central Qaidam Basin, and their paleoenvironmental significance. Quaternary Sciences, 35(3): 584～595. (in Chinese with English abstract).

Liu Caicai, Wang Weitao, Zhang Peizhen, Pang Jianzhang, Yu Jingxing. 2016. Magnetostratigraphy and magnetic anisotropy of the Neogene sediments in the Qilian Basin. Chinese J. Geophys, 59(8): 2965～2978. (in Chinese with English abstract).

Miao Yunfa, Herrmann M., Wu Fuli, Yan Xiaoli, Yang Shengli. 2012. What controlled Mid-Late Miocene long-term aridification in Central Asia? -Global cooling or Tibetan Plateau uplift: A review. Earth-Science Reviews, 112(3-4): 155～172.

Mock C, Arnaud N O, Cantagrel J M. 1999. An early unroofing in northeastern Tibet? Constraints from $^{40}Ar/^{39}Ar$ thermochronology on granitoids from the eastern Kunlun range (Qianghai, NW China). Earth & Planetary Science Letters, 171(1): 107～122.

Molnar P, Tapponnier P. 1975. Cenozoic Tectonics of Asia: Effects of a Continental Collision: Features of recent continental tectonics in Asia can be interpreted as results of the India-Eurasia collision. 189(4201): 419～426.

Molnar P, Stock J M. 2009. Slowing of India's convergence with Eurasia at ～10 Ma and its implications for Tibetan mantle dynamics. Tectonics, 28(3).

Nie Junsheng, Ren Xueping, Saylor J, Su Qingda, Horton B, Bush M, Chen Wenhan, Pfaff K. 2019. Magnetic polarity stratigraphy, provenance, and paleoclimate analysis of Cenozoic strata in the Qaidam Basin, NE Tibetan Plateau. GSA Bulletin, 132(1-2): 310～320.

Pang Jianzhang, Yu Jingxing, Zheng Dewen, Wang Weitao, Wang Ying. 2019. Neogene Expansion of the Qilian Shan, North Tibet: Implications for the Dynamic Evolution of the Tibetan Plateau. Tectonics, 38(3): 1018～1032.

Qian Tao, Wang Zongxiu, Liu Yongqing, Liu Shaofeng, Gao Wanli, Li Wangpeng, Hu Junjie, Li Leilei. 2018. Provenance analysis of the Jurassic northern Qaidam Basin: Stratigraphic succession and LA-ICP-MS geochronology Scientia Sinica Terrae, 48: 224～242. (in Chinese with English abstract).

Royden L H, Burchfiel B. Clark, King R W, Wang Erchie, Chen Zhiliang, Feng Shen, Liu Yuping 1997. Surface Deformation and Lower Crustal Flow in Eastern Tibet. Science, 276(5313): 788～790.

Scherer E, Munker C, Mezger K. 2001. Calibration of the lutetium-hafnium clock. Science, 293(5530): 683～687.

Sun Zhiming, Yang Zhenyu, Pei Junling, Ge Xiaohong, Wang Xisheng, Yang Tienshui, Li Weimin, Yuan Sihua. 2005. Magnetostratigraphy of Paleogene sediments from northern Qaidam Basin, China: Implications for tectonic uplift and block rotation in northern Tibetan Plateau. Earth & Planetary Science Letters, 237(3): 635～646.

Tapponnier P, Xu Zhiqin, Roger F, Meyer B, Arnaud N, Wittlinger G, Yang Jingsui. 2001. Oblique Stepwise Rise and Growth of the Tibet Plateau. Science, 294(5547): 1671～1677.

Valdes P J, Ding Lin, Farnsworth A, Spicer R A, Li Shihu, Tao Su. 2019. Comment on"Revised paleoaltimetry data show low Tibetan Plateau elevation during the Eocene". Science, 365(6459): eaax8474.

Vervoort J D, Blicherttoft J. 1999. Evolution of the depleted mantle; Hf isotope evidence from juvenile rocks through time. Geochimica Et Cosmochimica Acta, 63(3-4): 533～556.

Wang Weitao, Zheng Wenjun, Zhang Peizhen, Li Qiang, Kirby E, Yuan Daoyang, Zheng Dewen, Liu Caicai, Wang Zhicai, Zhang Huiping, Pang Jianzhang 2017. Expansion of the Tibetan Plateau during the Neogene. Nature communications, 8: 15887.

Wang Xiaoming, Wang Banyue, Qiu Zhanxiang, Xie Guangpu, Xie Junyi, Downs W, Qiu Zhuding, Deng Tao. 2003. Danghe area (western Gansu, China) biostratigraphy and implications for depositional history and tectonics of northern Tibetan Plateau. Earth and Planetary Science Letters, 208(3-4): 253～269.

Wu Cailai, Yang Jingsui, Xu Zhiqin, Wooden J L, Ireland T, Li Haibing, Shi Rendneg, Meng Fancong, Chen Songyong, Persing H, Meibom A. 2004. Granitio magmatism on the Early Paleozoic UHP belt of northern Qaidam, NW China. Acta Geologica Sinica, 78(5): 658～674 (in Chinese with English abstract).

Wu Fuyuan, Yang Yueheng, Xie Liewen, Yang Jinhui, Xu Ping. 2006. Hf isotopic compositions of the standard zircons and baddeleyites used in U-Pb geochronology. Chemical Geology, 234(1): 105～126.

Wu Fuyuan, Li Xianhua, Zheng Yongfei, Gao Shan. 2007. Lu-Hf isotopic systematics and their applications in petrology. Acta Petrologica Sinica, 23(2): 185～220 (in Chinese with English abstract).

Xia Rui, Wang Changming, Min Qing, Deng Jun, Carranza Emmanuel John M., Li Wenliang, Guo Xiaodong, Ge Liangsheng, Yu Wanqiang. 2015. Molybdenite Re-Os, zircon U-Pb dating and Hf isotopic analysis of the Shuangqing Fe-Pb-Zn-Cu skarn deposit, East Kunlun Mountains, Qinghai Province, China. Ore Geology Reviews, 66: 114～131.

Xie Liewen, Zhang Yanbin, Zhang Huihuang, Sun Jinfeng, Wu Fuyuan. 2008. In situsimultaneous determination of trace elements, U-Ph and Lu-Hf isotopes in zircon and baddelevite. Chinese Science Bulletin, 53(02): 220～228.

Yan Zhen, Aitchison J, Fu Changlei, Guo Xianqing, Niu Manlan, Xia Wenjing, Li Jiliang. 2015. Hualong Complex, South Qilian terrane: U-Pb and Lu-Hf constraints on Neoproterozoic micro-continental fragments accreted to the northern Proto-Tethyan margin. Precambrian Research, 266: 65～85.

Yin An, Dang Yuqi, Zhang Min, Chen Xuanhua, Mcrivette M W. 2008. Cenozoic tectonic evolution of the Qaidam basin and its surrounding regions (Part 3): Structural geology, sedimentation, and regional tectonic reconstruction. Geological Society of America Bulletin, 120(7-8): 813～846.

Yin An, Rumelhart P E, Butler R, Cowgill E, Harrison T M, Foster D A, Ingersoll R V, Zhang Qing, Zhou Xianqiang, Wang Xiaofeng, Hanson A, Raza A. 2002. Tectonic history of the Altyn Tagh fault system in northern Tibet inferred from Cenozoic sedimentation. GSA Bulletin, 114(10): 1257～1295.

Yin An. 2007. Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price Volume 433 | | Cenozoic tectonic evolution of Qaidam basin and its surrounding regions (part 2): Wedge tectonics in southern Qaidam basin and the Eastern Kunlun Range. : 369～390.

Yong Yong, Xiao Wenjiao, Yuan Chao, Yan Zhen, Li Jiliang.

2008. Geochronology and geochemistry of Paleozoic granitic plutons from the eastern Central Qilian and their tectonic implications. Acta Petrologica Sinica, 24(4): 855～866. (in Chinese with English abstract).

Yu Jingxing, Pang Jianzhang, Wang Yizhou, Zheng Dewen, Liu Caicai, Wang Weitao, Li Youjuan, Li Chaopeng, Xiao Lin. 2019. Mid-Miocene uplift of the northern Qilian Shan as a result of the northward growth of the northern Tibetan Plateau. Geosphere, 15(2): 423～432.

Yu Jingxing, Zheng Dewen, Pang Jianzhang, Wang Yizhou, Fox Matthew, Vermeesch P, Li Chaopeng, Xiao Lin, Hao Yuqi, Wang Ying. 2019. Miocene Range Growth Along the Altyn Tagh Fault: Insights From Apatite Fission Track and (U-Th)/He Thermochronometry in the Western Danghenan Shan, China. Journal of Geophysical Research: Solid Earth, 0(0).

Yu Shengyao, Zhang Jianxin, Del R P G, Zhao Xilin, Hou Kejun, Gong Jianghua, Li Yunshuai. 2013. The Grenvillian orogeny in the Altun-Qilian-North Qaidam mountain belts of northern Tibet Plateau: Constraints from geochemical and zircon U-Pb age and Hf isotopic study of magmatic rocks. Journal of Asian Earth Sciences, 73(8): 372～395.

Yuan Daoyang, Ge Weipeng, Chen Zhenwei, Li Chuanyou, Wang Zhicai, Zhang Huiping, Zhang Pei zhen, Zheng Dewen, Zheng Wenjun, Craddock W H. 2013. The growth of northeastern Tibet and its relevance to large-scale continental geodynamics: A review of recent studies. Tectonics, 32(5): 1358～1370.

Zhou Jianxun, Xu Fengyin, Wang Tiecheng, Cao Aifeng, Yin Chengming. 2006. Cenozoic deformation history of the Qaidam Basin, NW China: Results from cross-section restoration and implications for Qinghai Tibet Plateau tectonics. Earth & Planetary Science Letters, 243(1): 195～210.

Zhuang Guangsheng, Zhang Yige, Hourigan J, Ritts B, Hren M, Hou Mingqiu, Wu Minghao, Kim B. 2019. Microbial and Geochronologic Constraints on the Neogene Paleotopography of Northern Tibetan Plateau. Geophysical Research Letters, 46(3): 1312～1319.

Zhang Peizhen, Molnar P, Downs W R. 2001. Increased sedimentation rates and grain sizes 2～4 Myr ago due to the influence of climate change on erosion rates. Nature, 410(6831): 891～897.

Zhang Peizhen, Zheng Dewen, Yin Gongming, Yuan Daoyang, Zhang Guangliang, Li Chuanyou. Wang Zhicai. 2006. Discussion on late Cenozoic growth and rise of northeastern margin of the Tibetan Plateau. Quat. Sci, 26(1): 5～13. (in Chinese with English abstract).

参　考　文　献

陈隽璐,徐学义,曾佐勋,肖林,王洪亮,王宗起,肖绍文. 2008. 中祁连东段什川杂岩基的岩石化学特征及年代学研究. 岩石学报, 24(4): 841～854.

李吉均,方小敏. 1998. 青藏高原隆起与环境变化研究. 科学通报, 43(15): 1568～1574.

李吉均,文世宣,张青松,王富葆,郑本兴,李炳元. 1979. 青藏高原隆起的时代、幅度和形式的探讨. 中国科学, (6): 78～86.

李建锋,张志诚,韩宝福. 2010. 中祁连西段肃北、石包城地区早古生代花岗岩年代学、地球化学特征及其地质意义. 岩石学报, 26(8): 2431～2444.

李强,王晓鸣. 2015. 青海柴达木盆地新近纪河狸化石及其古环境意义. 第四纪研究, 35(3): 584～595.

刘彩彩,王伟涛,张培震,庞建章,俞晶星. 2016. 祁连盆地第三纪沉积物磁性地层和岩石磁组构初步研究. 地球物理学报, 8(59): 2965～2978.

钱涛,王宗秀,柳永清,刘少峰,高万里,李王鹏,胡俊杰,李磊磊. 2018. 柴达木盆地北缘侏罗纪沉积物源分析:地层序列及 LA-ICP-MS 年代学信息. 中国科学:地球科学, 48(02): 224～242.

青海省地层表编写小组. 1983. 西北地区区域地层表·青海省分册.

青海省地质矿产局. 1991. 青海省区域地质志. 北京:地质出版社.

吴才来,杨经绥,许志琴,Wooden J L, Ireland T,李海兵,史仁灯,孟繁聪,陈松永,PERSING Harold, MEIBOM Anders. 2004. 柴达木盆地北缘古生代超高压带中花岗质岩浆作用. 地质学报, 78(5): 658～674.

吴福元,李献华,郑永飞,高山. 2007. Lu-Hf 同位素体系及其岩石学应用. 岩石学报, 23(02): 185～220.

谢烈文,张艳斌,张辉煌,孙金凤,吴福元. 2008. 锆石/斜锆石 U-Pb 和 Lu-Hf 同位素以及微量元素成分的同时原位测定. 科学通报, 53(02): 220～228.

雍拥,肖文交,袁超,闫臻,李继亮. 2008. 中祁连东段古生代花岗岩的年代学、地球化学特征及其大地构造意义. 岩石学报, 24(4): 233～244.

张培震,郑德文,尹功明,袁道阳,张广良,李传友,王志才. 2006. 有关青藏高原东北缘晚新生代扩展与隆升的讨论. 第四纪研究, 26(01): 7～15.

Provenance identification for the Honggou section of the Qaidam basin in the northeastern margin of the Tibetan Plateau and its tectonic significance

LIU Kang[1), WANG Weitao[*2), ZHAO Xudong[1), PANG Jianzhang[1), YU Jingxing[1)

1) *State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing*, 100029;

2) *School of Earth Sciences and Engineering, Sun Yat-Sen University, Guangzhou*, 510275

* *Corresponding author: taotaowang@126.com*

Abstract

Located in the northeastern corner of the Tibetan Plateau, the Honggou section deposits comprise thick Cenozoic strata, the provenance analysis of which provides an exceptional opportunity to study the uplift and denudation history of the potential source regions for the Qaidam Basin and the deformational processes in the northeast Tibetan Plateau. Here, the detrital zircon U-Pb ages and Hfisotopic compositions are used to trace the source changes for the Late Oligocene-Pliocene strata based on the magnetostratigraphy of the Honggou section. Most of the U-Pb ages of the detrital zircon from 23.7～12.5 Ma are concentrated within the intervals of 220～290 Ma, the $\varepsilon_{Hf}(t)$ is concentrated at −13.53～9.27, and the range of the $t_{DM(Hf)}$ is 524～1456 Ma. For zircons whose U-Th age are greater than 300 Ma, the $\varepsilon_{Hf}(t)$ is between −31.77 and 13.44, of which 76.3% is negative, and the Hf isotope t_{DM} is between 484 and 3727 Ma. The zircon U-Pb ages of sandstone samples from 12.5～7.6 Ma are mainly concentrated at 400～500 Ma (peak ～ 440 Ma), 90% of the $\varepsilon_{Hf}(t)$ value (−27.75～10.75) is negative, Hf isotope one-stage model age is between 615～2115 Ma. Sandstone samples of 6.8～5.5 Ma, zircon U-Pb age is mainly distributed at 400～500 Ma, the $\varepsilon_{Hf}(t)$ value is ranging from −26.8 to 8.97, and the t_{DM} is between 668～2093 Ma, but the zircon ages of 220～290 Ma increase significantly, having $\varepsilon_{Hf}(t)$ values ranging from −11.86 to 9.42, Hf one-stage model age range is 549～1399 Ma. Comparing these with neighboring tectonic units, we found that Hf isotopic compositions of zircon whose populations are at 220～290 Ma have affinity with the East Kunlun Shan, while the Hf isotopic composition of 400～500 Ma zircon is similar to South Qilian Shan. These features reveal that the East Kunlun Shan began to deform and become the main source region of the Qaidam Basin at 24Ma. The southward expansion of the Qilian Shan is at ～12 Ma, providing detrital materials for the Qaidam Basin and becoming the tectonic and geomorphic margin along the Tibetan Plateau.

Key words: the Qaidam basin; Honggou section; Hf isotopic composition; northeastern margin of Tibetan Plateau

附表 1　青藏高原红沟剖面锆石 U-Pb 年龄及 Hf 同位素数据

Table 1　The U-Pb ages and Hf isotopic data of zircons extracted from Cenozoic sandstones of Honggou section along the northeastern margin of the Tibetan Plateau

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
D54 05	390	596	0.65	347	5	0.053389	0.001842	0.282441	0.000012	0.282449	−11.7	−4.5	1172	−0.94
D54 06	153	322	0.47	389	6	0.030133	0.001040	0.282611	0.000012	0.282619	−5.7	2.6	909	−0.97
D54 07	120	273	0.44	236	4	0.023320	0.000983	0.282541	0.000013	0.282549	−8.2	−3.2	1006	−0.97
D54 08	125	155	0.81	221	4	0.047795	0.001878	0.282651	0.000014	0.282659	−4.3	0.3	871	−0.94
D54 09	47	68	0.70	1695	24	0.013703	0.000501	0.281477	0.000010	0.281485	−45.8	−8.6	2449	−0.98
D54 10	32	56	0.57	1738	40	0.014948	0.000536	0.281504	0.000012	0.281512	−44.8	−6.8	2414	−0.98
D54 100	90	70	1.29	978	17	0.023019	0.000823	0.282010	0.000016	0.282018	−26.9	−5.9	1739	−0.98
D54 12	42	85	0.49	2317	18	0.015475	0.000603	0.281373	0.000012	0.281381	−49.5	1.5	2596	−0.98
D54 13	71	176	0.40	2223	20	0.011739	0.000473	0.281342	0.000011	0.281350	−50.6	−1.6	2629	−0.99
D54 14	209	420	0.50	257	5	0.025554	0.001001	0.282456	0.000012	0.282464	−11.2	−5.7	1125	−0.97
D54 15	85	163	0.52	2333	15	0.017383	0.000672	0.281362	0.000011	0.281370	−49.9	1.3	2616	−0.98
D54 17	162	354	0.46	1754	16	0.013544	0.000522	0.281279	0.000012	0.281287	−52.8	−14.4	2716	−0.98
D54 18	79	107	0.73	319	6	0.041839	0.001583	0.282877	0.000013	0.282885	3.7	10.4	540	−0.95
D54 19	314	462	0.68	245	4	0.059156	0.002212	0.282486	0.000018	0.282494	−10.1	−5.1	1119	−0.93
D54 20	116	231	0.50	436	7	0.018596	0.000670	0.282470	0.000012	0.282478	−10.7	−1.3	1096	−0.98
D54 22	82	154	0.53	371	6	0.016711	0.000664	0.282638	0.000012	0.282646	−4.7	3.3	862	−0.98
D54 23	258	537	0.48	201	3	0.022982	0.000980	0.282525	0.000013	0.282533	−8.7	−4.4	1028	−0.97
D54 24	273	153	1.79	1743	17	0.032635	0.001203	0.281399	0.000012	0.281407	−48.6	−11.2	2602	−0.96
D54 26	102	88	1.16	282	8	0.015053	0.000609	0.282225	0.000013	0.282233	−19.3	−13.3	1433	−0.98
D54 27	27	63	0.43	1692	25	0.010295	0.000405	0.281407	0.000012	0.281415	−48.3	−11.1	2537	−0.99
D54 28	88	136	0.65	422	7	0.019033	0.000690	0.282459	0.000014	0.282468	−11.1	−2.0	1111	−0.98
D54 29	56	52	1.09	225	5	0.025515	0.001003	0.282538	0.000013	0.282546	−8.3	−3.5	1010	−0.97
D54 30	112	202	0.56	1039	19	0.014282	0.000523	0.282003	0.000011	0.282011	−27.2	−4.6	1735	−0.98
D54 31	22	24	0.90	1811	48	0.016655	0.000614	0.281394	0.000012	0.281402	−48.7	−9.1	2568	−0.98
D54 32	250	256	0.98	435	6	0.015082	0.000560	0.282389	0.000014	0.282397	−13.6	−4.1	1206	−0.98
D54 33	70	70	1.00	2323	21	0.003817	0.000140	0.281050	0.000011	0.281058	−60.9	−9.1	2995	−1.00
D54 34	81	246	0.33	2366	13	0.024817	0.000942	0.281367	0.000011	0.281375	−49.7	1.8	2627	−0.97
D54 35	111	139	0.80	1866	16	0.014399	0.000529	0.281418	0.000013	0.281426	−47.9	−7.0	2531	−0.98
D54 36	68	326	0.21	871	11	0.032251	0.001216	0.282245	0.000011	0.282253	−18.6	−0.1	1428	−0.96
D54 37	30	40	0.77	810	13	0.012207	0.000473	0.282418	0.000011	0.282426	−12.5	5.1	1162	−0.99
D54 38	37	76	0.48	432	9	0.020733	0.000813	0.282850	0.000011	0.282858	2.8	12.0	567	−0.98
D54 39	212	536	0.39	200	3	0.021463	0.000761	0.282662	0.000011	0.282670	−3.9	0.4	830	−0.98
D54 40	161	216	0.75	442	10	0.023105	0.000885	0.282562	0.000013	0.282570	−7.4	2.0	973	−0.97
D54 42	73	90	0.81	1854	22	0.008029	0.000298	0.281354	0.000011	0.281362	−50.1	−9.2	2601	−0.99
D54 44	136	184	0.74	246	5	0.017785	0.000730	0.282570	0.000012	0.282578	−7.2	−1.9	959	−0.98
D54 45	65	112	0.58	858	14	0.022147	0.000946	0.281789	0.000013	0.281797	−34.7	−16.4	2049	−0.97
D54 46	208	274	0.76	251	4	0.023603	0.001040	0.282554	0.000011	0.282562	−7.7	−2.4	989	−0.97
D54 47	101	65	1.56	1913	26	0.008766	0.000316	0.281177	0.000011	0.281185	−56.4	−14.2	2839	−0.99
D54 48	114	177	0.65	237	4	0.020980	0.000810	0.282586	0.000011	0.282594	−6.6	−1.5	937	−0.98
D54 49	94	196	0.48	392	6	0.027552	0.001118	0.282545	0.000014	0.282553	−8.0	0.3	1004	−0.97
D54 51	305	325	0.94	401	6	0.008227	0.000302	0.282297	0.000012	0.282305	−16.8	−8.1	1324	−0.99
D54 52	26	46	0.57	1694	31	0.011210	0.000426	0.281426	0.000011	0.281434	−47.6	−10.4	2513	−0.99
D54 53	107	130	0.82	1764	21	0.030500	0.001119	0.281456	0.000012	0.281464	−46.5	−8.6	2518	−0.97
D54 54	162	161	1.00	2360	14	0.025650	0.000933	0.281284	0.000012	0.281292	−52.6	−1.2	2739	−0.97
D54 55	161	137	1.18	1875	20	0.028137	0.001062	0.281222	0.000013	0.281230	−54.8	−14.4	2833	−0.97
D54 56	130	759	0.17	390	5	0.051648	0.002207	0.282535	0.000011	0.282543	−8.4	−0.4	1048	−0.93
D54 57	230	624	0.37	1946	16	0.028708	0.001117	0.281235	0.000016	0.281243	−54.3	−12.4	2819	−0.97
D54 58	161	213	0.75	518	9	0.016755	0.000642	0.282391	0.000015	0.282399	−13.5	−2.3	1205	−0.98
D54 59	53	378	0.14	785	10	0.036621	0.001272	0.282212	0.000012	0.282220	−19.8	−3.1	1477	−0.96
D54 60	14	16	0.82	1794	42	0.011742	0.000443	0.281392	0.000013	0.281400	−48.8	−9.4	2560	−0.99
D54 61	54	119	0.45	725	12	0.008678	0.000320	0.282309	0.000015	0.282317	−16.4	−0.6	1308	−0.99
D54 62	199	292	0.68	256	4	0.035373	0.001261	0.282726	0.000012	0.282734	−1.6	3.8	751	−0.96

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
D54 63	49	527	0.09	633	9	0.020118	0.000716	0.282219	0.000017	0.282227	－19.6	－5.9	1446	－0.98
D54 64	33	177	0.19	459	7	0.000438	0.000013	0.282309	0.000010	0.282317	－16.4	－6.3	1297	－1.00
D54 66	197	258	0.76	263	4	0.030814	0.001366	0.282540	0.000013	0.282548	－8.2	－2.7	1017	－0.96
D54 67	165	143	1.16	332	7	0.027435	0.001078	0.282187	0.000015	0.282195	－20.7	－13.7	1505	－0.97
D54 68	1274	836	1.52	246	4	0.100522	0.003751	0.282649	0.000015	0.282657	－4.4	0.4	922	－0.89
D54 69	210	1169	0.18	249	4	0.031850	0.001398	0.282886	0.000011	0.282894	4.0	9.3	524	－0.96
D54 70	136	284	0.48	707	10	0.021819	0.000764	0.282285	0.000011	0.282293	－17.2	－2.0	1356	－0.98
D54 72	219	378	0.58	252	5	0.017775	0.000668	0.282560	0.000014	0.282568	－7.5	－2.1	971	－0.98
D54 74	140	266	0.53	442	8	0.034840	0.001205	0.282569	0.000016	0.282577	－7.2	2.2	972	－0.96
D54 75	115	307	0.37	1913	15	0.010207	0.000399	0.281213	0.000012	0.281221	－55.1	－13.0	2797	－0.99
D54 76	70	92	0.77	549	9	0.012154	0.000452	0.282555	0.000011	0.282563	－7.7	4.3	972	－0.99
D54 77	265	498	0.53	253	5	0.023817	0.001003	0.282371	0.000015	0.282379	－14.2	－8.8	1245	－0.97
D54 78	152	252	0.60	217	4	0.013609	0.000583	0.282564	0.000013	0.282572	－7.3	－2.7	963	－0.98
D54 79	134	144	0.93	1885	18	0.010417	0.000394	0.281453	0.000012	0.281461	－46.6	－5.1	2474	－0.99
D54 80	165	270	0.61	488	7	0.020781	0.000812	0.282572	0.000012	0.282580	－7.1	3.4	957	－0.98
D54 81	361	739	0.49	225	3	0.043811	0.001581	0.282583	0.000011	0.282591	－6.7	－2.0	961	－0.95
D54 82	90	167	0.54	682	10	0.009635	0.000345	0.282031	0.000011	0.282039	－26.2	－11.3	1689	－0.99
D54 83	69	191	0.36	2147	16	0.006052	0.000264	0.281225	0.000009	0.281233	－54.7	－7.1	2771	－0.99
D54 84	96	61	1.57	1906	19	0.006470	0.000235	0.281414	0.000011	0.281422	－48.0	－5.8	2516	－0.99
D54 85	127	427	0.30	1080	16	0.022730	0.000807	0.282001	0.000010	0.282009	－27.3	－4.0	1751	－0.98
D54 86	61	134	0.45	358	7	0.032605	0.001172	0.282334	0.000015	0.282342	－15.5	－7.9	1302	－0.96
D54 88	67	35	1.94	1882	38	0.018960	0.000705	0.281396	0.000011	0.281404	－48.7	－7.6	2571	－0.98
D54 89	84	89	0.94	1858	21	0.017138	0.000594	0.281560	0.000012	0.281568	－42.8	－2.2	2342	－0.98
D54 90	146	652	0.22	278	4	0.028674	0.001380	0.282801	0.000011	0.282809	1.0	6.9	645	－0.96
D54 91	27	69	0.39	966	15	0.012883	0.000479	0.282179	0.000014	0.282187	－21.0	0.1	1492	－0.99
D54 92	161	218	0.74	481	7	0.027526	0.001053	0.282561	0.000013	0.282569	－7.4	2.8	979	－0.97
D54 93	48	81	0.59	457	8	0.000971	0.000032	0.282480	0.000015	0.282488	－10.3	－0.3	1064	－1.00
D54 94	77	176	0.44	266	4	0.022091	0.000908	0.282571	0.000012	0.282579	－7.1	－1.4	961	－0.97
D54 95	46	146	0.31	1464	23	0.025189	0.000994	0.282146	0.000012	0.282154	－22.1	9.4	1558	－0.97
D54 96	148	156	0.95	265	6	0.022828	0.000928	0.282648	0.000014	0.282656	－4.4	1.3	854	－0.97
D54 99	76	178	0.43	2582	14	0.014311	0.000532	0.281206	0.000016	0.281214	－55.4	1.7	2816	－0.98
H351 01	108	128	0.85	336	8	0.067553	0.002488	0.282801	0.000018	0.282799	1.0	7.9	665	－0.93
H351 02	61	44	1.40	1543	44	0.057900	0.002126	0.281775	0.000019	0.281773	－35.3	－3.2	2136	－0.94
H351 03	192	385	0.50	385	5	0.033276	0.001185	0.282658	0.000016	0.282656	－4.0	4.2	845	－0.96
H351 04	96	219	0.44	1767	16	0.016710	0.000565	0.281581	0.000013	0.281579	－42.1	－3.4	2313	－0.98
H351 05	95	144	0.66	853	13	0.018950	0.000668	0.281718	0.000013	0.281716	－37.3	－18.8	2132	－0.98
H351 06	119	683	0.17	744	9	0.050325	0.001691	0.282455	0.000013	0.282453	－11.2	4.4	1147	－0.95
H351 07	77	119	0.64	278	6	0.044964	0.001709	0.282861	0.000020	0.282859	3.2	9.0	564	－0.95
H351 08	91	95	0.96	735	17	0.015721	0.000585	0.282300	0.000016	0.282298	－16.7	－0.8	1329	－0.98
H351 09	74	365	0.20	475	6	0.013937	0.000519	0.282634	0.000018	0.282632	－4.9	5.4	864	－0.98
H351 10	300	270	1.11	1827	26	0.020843	0.000722	0.281594	0.000018	0.281592	－41.7	－1.8	2304	－0.98
H351 11	120	209	0.58	347	7	0.017211	0.000642	0.282907	0.000016	0.282905	4.8	12.3	484	－0.98
H351 12	109	154	0.70	1669	21	0.023781	0.000821	0.281543	0.000021	0.281541	－43.5	－7.2	2379	－0.98
H351 13	52	92	0.56	1751	33	0.010435	0.000395	0.281492	0.000016	0.281490	－45.3	－6.7	2422	－0.99
H351 14	144	353	0.41	257	4	0.028387	0.001036	0.282497	0.000014	0.282495	－9.7	－4.3	1069	－0.97
H351 15	74	113	0.66	2297	23	0.022185	0.000778	0.281269	0.000015	0.281267	－53.2	－2.9	2749	－0.98
H351 16	75	293	0.26	1790	22	0.014597	0.000545	0.281522	0.000014	0.281520	－44.2	－5.0	2391	－0.98
H351 17	46	259	0.18	1790	24	0.009135	0.000308	0.281455	0.000013	0.281453	－46.6	－7.1	2466	－0.99
H351 18	69	83	0.83	507	13	0.021202	0.000890	0.282841	0.000016	0.282839	2.5	13.3	580	－0.97
H351 19	313	325	0.96	2341	22	0.023871	0.000924	0.281326	0.000016	0.281324	－51.1	－0.2	2682	－0.97
H351 20	93	169	0.55	455	9	0.004945	0.000153	0.282303	0.000015	0.282301	－16.6	－6.6	1311	－1.00
H351 21	94	178	0.53	2177	30	0.016525	0.000601	0.280526	0.000017	0.280524	－79.4	－31.8	3727	－0.98
H351 24	185	511	0.36	1745	19	0.012892	0.000441	0.281650	0.000017	0.281648	－39.7	－1.3	2212	－0.99
H351 25	268	397	0.68	273	6	0.044684	0.001994	0.282638	0.000026	0.282636	－4.7	0.9	892	－0.94
H351 26	63	162	0.39	287	9	0.025446	0.000856	0.282435	0.000017	0.282433	－11.9	－5.8	1151	－0.97

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H351 28	18	314	0.06	439	6	0.001892	0.000057	0.282144	0.000012	0.282142	-22.2	-12.6	1524	-1.00
H351 29	122	85	1.43	271	11	0.017630	0.000649	0.282379	0.000017	0.282377	-13.9	-8.1	1222	-0.98
H351 30	107	199	0.54	1600	29	0.016957	0.000589	0.281487	0.000013	0.281485	-45.5	-10.5	2441	-0.98
H351 31	158	336	0.47	267	5	0.039287	0.001422	0.282231	0.000014	0.282229	-19.1	-13.5	1456	-0.96
H351 33	77	218	0.36	412	8	0.005850	0.000198	0.282173	0.000015	0.282171	-21.2	-12.2	1489	-0.99
H351 34	104	410	0.25	2176	13	0.011197	0.000395	0.281011	0.000015	0.281009	-62.3	-14.2	3066	-0.99
H351 35	198	90	2.21	1591	49	0.034428	0.001281	0.281689	0.000028	0.281687	-38.3	-4.3	2206	-0.96
H351 36	206	278	0.74	428	6	0.018455	0.000646	0.282689	0.000014	0.282687	-3.0	6.3	791	-0.98
H351 37	31	122	0.26	1921	28	0.016024	0.000612	0.281223	0.000014	0.281221	-54.8	-12.7	2799	-0.98
H351 38	14	50	0.28	433	14	0.007490	0.000349	0.282103	0.000018	0.282101	-23.7	-14.2	1591	-0.99
H351 39	166	310	0.54	441	7	0.018918	0.000666	0.282450	0.000015	0.282448	-11.4	-1.9	1124	-0.98
H351 40	76	60	1.26	1604	43	0.020015	0.000707	0.281479	0.000017	0.281477	-45.7	-10.8	2459	-0.98
H351 42	460	431	1.07	771	9	0.031516	0.001104	0.282348	0.000015	0.282346	-15.0	1.5	1280	-0.97
H351 43	168	393	0.43	1567	17	0.015385	0.000583	0.281476	0.000015	0.281474	-45.8	-11.6	2455	-0.98
H351 44	809	999	0.81	1538	13	0.100970	0.003247	0.281870	0.000017	0.281868	-31.9	-1.1	2063	-0.90
H351 45	26	49	0.53	2137	39	0.015019	0.000526	0.281413	0.000018	0.281411	-48.1	-1.0	2537	-0.98
H351 46	100	153	0.66	584	12	0.018736	0.000689	0.282510	0.000015	0.282508	-9.3	3.3	1041	-0.98
H351 47	62	155	0.40	2205	22	0.011325	0.000445	0.281377	0.000015	0.281375	-49.3	-0.7	2580	-0.99
H351 48	196	387	0.51	214	5	0.033144	0.001133	0.282675	0.000013	0.282673	-3.4	1.1	820	-0.97
H351 49	122	248	0.49	474	9	0.024199	0.000903	0.282316	0.000015	0.282314	-16.1	-6.0	1318	-0.97
H351 50	196	307	0.64	245	6	0.029221	0.001145	0.282686	0.000014	0.282684	-3.1	2.1	805	-0.97
H351 51	137	139	0.99	2471	17	0.029199	0.001060	0.281056	0.000017	0.281054	-60.7	-7.1	3058	-0.97
H351 52	85	122	0.70	1428	31	0.046142	0.001536	0.281758	0.000019	0.281756	-35.9	-5.6	2125	-0.95
H351 53	67	174	0.38	1714	20	0.011487	0.000395	0.281428	0.000018	0.281426	-47.5	-9.8	2508	-0.99
H351 54	97	107	0.91	254	7	0.024561	0.000931	0.282622	0.000015	0.282620	-5.3	0.1	890	-0.97
H351 55	99	127	0.78	1584	32	0.063979	0.002105	0.281779	0.000017	0.281777	-35.1	-2.1	2128	-0.94
H351 56	73	288	0.25	1730	19	0.028154	0.001014	0.281618	0.000014	0.281616	-40.8	-3.5	2288	-0.97
H351 58	147	172	0.86	428	7	0.057574	0.001967	0.282261	0.000019	0.282259	-18.1	-9.2	1435	-0.94
H351 59	66	67	0.99	1720	35	0.013277	0.000471	0.281456	0.000014	0.281454	-46.5	-8.8	2475	-0.99
H351 60	125	1170	0.11	1717	12	0.013888	0.000464	0.281540	0.000013	0.281538	-43.6	-5.9	2361	-0.99
H351 61	319	702	0.45	245	3	0.031449	0.001168	0.282592	0.000014	0.282590	-6.4	-1.2	938	-0.96
H351 62	72	132	0.55	997	36	0.014845	0.000545	0.282055	0.000014	0.282053	-25.3	-3.7	1664	-0.98
H351 63	26	37	0.69	1649	60	0.031219	0.001124	0.281667	0.000021	0.281665	-39.1	-3.6	2227	-0.97
H351 64	53	55	0.96	1558	65	0.034200	0.001209	0.281590	0.000021	0.281588	-41.8	-8.4	2338	-0.96
H351 65	33	34	1.00	1566	63	0.016627	0.000596	0.281476	0.000019	0.281474	-45.8	-11.7	2456	-0.98
H351 66	119	103	1.16	254	6	0.020766	0.000738	0.282582	0.000016	0.282580	-6.7	-1.3	941	-0.98
H351 67	44	41	1.08	2253	46	0.021429	0.000832	0.281293	0.000017	0.281291	-52.3	-3.1	2720	-0.97
H351 68	71	174	0.41	2357	15	0.012912	0.000543	0.281314	0.000015	0.281312	-51.5	0.4	2671	-0.98
H351 69	43	119	0.37	418	7	0.013591	0.000536	0.282301	0.000016	0.282299	-16.7	-7.6	1326	-0.98
H351 70	83	149	0.55	431	10	0.011043	0.000487	0.282622	0.000015	0.282620	-5.3	4.1	880	-0.99
H351 71	129	168	0.77	1552	24	0.031712	0.001161	0.281467	0.000015	0.281465	-46.2	-12.9	2506	-0.97
H351 72	639	324	1.97	2297	17	0.011653	0.000415	0.281091	0.000020	0.281089	-59.4	-8.7	2961	-0.99
H351 73	97	120	0.81	262	6	0.029245	0.001253	0.282743	0.000017	0.282741	-1.0	4.5	726	-0.96
H351 74	63	84	0.75	1599	36	0.018308	0.000687	0.281504	0.000016	0.281502	-44.9	-10.0	2425	-0.98
H351 75	229	471	0.49	362	6	0.039306	0.001356	0.282475	0.000014	0.282473	-10.5	-2.9	1108	-0.96
H351 76	68	106	0.64	2161	26	0.022724	0.000887	0.281278	0.000018	0.281276	-52.8	-5.8	2745	-0.97
H351 77	454	808	0.56	369	4	0.040519	0.001652	0.282608	0.000019	0.282606	-5.8	1.9	928	-0.95
H351 78	251	215	1.17	1801	26	0.020588	0.000749	0.281372	0.000016	0.281370	-49.5	-10.3	2608	-0.98
H351 79	301	141	2.13	293	8	0.035164	0.001336	0.282309	0.000017	0.282307	-16.4	-10.2	1342	-0.96
H351 80	64	80	0.80	2383	26	0.017319	0.000701	0.281364	0.000015	0.281362	-49.8	2.5	2615	-0.98
H351 81	63	297	0.21	1850	19	0.017978	0.000667	0.281458	0.000016	0.281456	-46.5	-6.1	2485	-0.98
H351 82	275	262	1.05	317	5	0.021761	0.000909	0.282071	0.000015	0.282069	-24.8	-18.0	1658	-0.97
H351 83	68	172	0.39	184	5	0.020205	0.000743	0.282701	0.000017	0.282699	-2.5	1.5	775	-0.98
H351 84	156	175	0.89	1833	24	0.010251	0.000403	0.281302	0.000014	0.281300	-52.0	-11.7	2679	-0.99
H351 85	78	286	0.27	783	10	0.045348	0.001696	0.282225	0.000015	0.282223	-19.4	-3.0	1476	-0.95

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H351 87	211	162	1.31	926	12	0.020903	0.000814	0.281809	0.000017	0.281807	−34.1	−14.1	2015	−0.98
H351 88	224	378	0.59	261	5	0.031220	0.001106	0.282451	0.000017	0.282449	−11.4	−5.8	1135	−0.97
H351 89	336	454	0.74	368	6	0.027380	0.000996	0.282438	0.000017	0.282436	−11.8	−3.9	1150	−0.97
H351 90	66	157	0.42	387	7	0.023219	0.001025	0.282865	0.000014	0.282863	3.3	11.6	549	−0.97
H351 92	42	67	0.63	524	14	0.013915	0.000550	0.282656	0.000017	0.282654	−4.1	7.3	833	−0.98
H351 93	146	200	0.73	219	6	0.019744	0.000821	0.282824	0.000015	0.282822	1.8	6.5	603	−0.98
H351 94	110	220	0.50	254	6	0.021659	0.000998	0.282642	0.000016	0.282640	−4.6	0.8	863	−0.97
H351 95	61	74	0.83	1465	45	0.039592	0.001400	0.281693	0.000018	0.281691	−38.1	−7.0	2207	−0.96
H351 96	55	89	0.62	2201	33	0.017311	0.000665	0.281375	0.000016	0.281373	−49.4	−1.2	2598	−0.98
H351 97	142	1009	0.14	1684	13	0.021528	0.000676	0.281632	0.000024	0.281630	−40.3	−3.6	2250	−0.98
H351 98	546	714	0.76	1679	14	0.016151	0.000641	0.281423	0.000013	0.281421	−47.7	−11.1	2531	−0.98
H351 99	134	301	0.45	2281	15	0.028962	0.001141	0.281232	0.000015	0.281230	−54.5	−5.2	2826	−0.97
H545 01	83	127	0.65	453	8	0.031358	0.001144	0.282278	0.000014	0.282283	−17.5	−7.9	1380	−0.97
H545 02	126	180	0.70	986	13	0.020118	0.000718	0.282030	0.000014	0.282035	−26.2	−4.9	1706	−0.98
H545 03	73	207	0.36	428	7	0.031730	0.001158	0.282295	0.000016	0.282300	−16.9	−7.8	1356	−0.97
H545 04	73	83	0.88	1881	24	0.017626	0.000659	0.281479	0.000016	0.281484	−45.7	−4.6	2457	−0.98
H545 05	141	419	0.34	1687	18	0.009785	0.000383	0.281475	0.000013	0.281480	−45.9	−8.8	2444	−0.99
H545 06	91	71	1.29	1875	26	0.026271	0.000956	0.281503	0.000016	0.281508	−44.9	−4.3	2443	−0.97
H545 07	127	187	0.68	1818	17	0.012829	0.000500	0.281502	0.000014	0.281507	−44.9	−5.0	2415	−0.98
H545 08	62	373	0.17	422	6	0.031739	0.001164	0.282460	0.000013	0.282465	−11.0	−2.1	1125	−0.96
H545 10	5	198	0.02	431	7	0.005080	0.000214	0.282288	0.000015	0.282293	−17.1	−7.7	1333	−0.99
H545 100	94	230	0.41	482	8	0.031614	0.001093	0.282323	0.000014	0.282328	−15.9	−5.6	1314	−0.97
H545 11	25	54	0.46	1775	50	0.006198	0.000216	0.281443	0.000015	0.281448	−47.0	−7.7	2477	−0.99
H545 12	34	58	0.59	2652	29	0.003967	0.000132	0.280917	0.000017	0.280921	−65.6	−6.3	3170	−1.00
H545 13	92	143	0.64	435	9	0.031924	0.001143	0.282256	0.000014	0.282261	−18.3	−9.0	1411	−0.97
H545 15	355	805	0.44	230	3	0.039725	0.001547	0.282599	0.000014	0.282604	−6.1	−1.3	937	−0.95
H545 16	23	63	0.37	1711	48	0.009651	0.000348	0.281538	0.000016	0.281543	−43.6	−5.9	2357	−0.99
H545 17	29	38	0.75	1811	54	0.010098	0.000360	0.281449	0.000013	0.281454	−46.8	−6.9	2477	−0.99
H545 18	83	165	0.50	1784	18	0.007603	0.000274	0.281380	0.000011	0.281385	−49.2	−9.8	2565	−0.99
H545 19	106	134	0.79	1861	30	0.015994	0.000611	0.281510	0.000015	0.281515	−44.6	−3.9	2411	−0.98
H545 20	180	211	0.85	607	9	0.023681	0.000849	0.282218	0.000013	0.282223	−19.6	−6.6	1452	−0.97
H545 21	254	373	0.68	262	5	0.046235	0.001718	0.282784	0.000016	0.282789	0.4	5.9	675	−0.95
H545 22	58	100	0.58	238	7	0.013457	0.000576	0.282655	0.000016	0.282660	−4.1	1.0	836	−0.98
H545 23	84	234	0.36	1830	18	0.006369	0.000296	0.281510	0.000013	0.281515	−44.6	−4.2	2392	−0.99
H545 24	82	136	0.61	453	8	0.027119	0.000961	0.282296	0.000013	0.282301	−16.8	−7.2	1348	−0.97
H545 25	112	207	0.54	448	7	0.036184	0.001251	0.282291	0.000013	0.282296	−17.0	−7.5	1365	−0.96
H545 26	79	101	0.78	2724	18	0.010277	0.000369	0.280613	0.000015	0.280618	−76.3	−15.9	3591	−0.99
H545 27	125	244	0.51	426	6	0.036465	0.001268	0.282316	0.000012	0.282321	−16.1	−7.1	1331	−0.96
H545 28	91	140	0.65	431	8	0.014898	0.000601	0.282699	0.000014	0.282704	−2.6	6.7	775	−0.98
H545 29	55	61	0.90	1850	28	0.018274	0.000647	0.281499	0.000014	0.281504	−45.0	−4.6	2428	−0.98
H545 30	82	189	0.43	457	7	0.031359	0.001103	0.282296	0.000012	0.282301	−16.8	−7.1	1353	−0.97
H545 31	107	88	1.21	447	8	0.028015	0.000990	0.282279	0.000014	0.282284	−17.4	−7.9	1372	−0.97
H545 32	74	153	0.48	431	7	0.028208	0.000996	0.282242	0.000012	0.282247	−18.8	−9.6	1425	−0.97
H545 33	149	301	0.50	690	10	0.024234	0.000891	0.282194	0.000015	0.282199	−20.4	−5.6	1487	−0.97
H545 34	71	142	0.50	1861	22	0.012329	0.000439	0.281436	0.000017	0.281441	−47.2	−6.3	2500	−0.99
H545 35	100	155	0.65	452	8	0.035184	0.001215	0.282239	0.000013	0.282244	−18.9	−9.3	1437	−0.96
H545 37	290	550	0.53	262	5	0.040663	0.001457	0.282309	0.000016	0.282314	−16.4	−10.9	1347	−0.96
H545 38	87	381	0.23	435	7	0.043549	0.001535	0.282256	0.000014	0.282261	−18.3	−9.1	1426	−0.95
H545 39	70	177	0.40	1872	21	0.018882	0.000666	0.281608	0.000018	0.281613	−41.2	−0.2	2282	−0.98
H545 40	85	100	0.85	467	11	0.025303	0.000900	0.282246	0.000015	0.282251	−18.6	−8.6	1415	−0.97
H545 41	89	207	0.43	450	7	0.024556	0.000870	0.282273	0.000015	0.282278	−17.7	−8.0	1377	−0.97
H545 42	81	70	1.15	1920	33	0.006957	0.000283	0.281439	0.000013	0.281444	−47.1	−4.7	2486	−0.99
H545 43	90	214	0.42	423	7	0.001259	0.000033	0.282487	0.000015	0.282492	−10.1	−0.8	1054	−1.00
H545 44	75	205	0.37	456	8	0.034854	0.001234	0.282253	0.000017	0.282258	−18.4	−8.7	1418	−0.96
H545 45	118	260	0.45	459	9	0.031924	0.001138	0.282338	0.000017	0.282343	−15.3	−5.6	1295	−0.97

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H545 46	98	182	0.54	426	9	0.028565	0.001017	0.282286	0.000013	0.282291	−17.2	−8.1	1363	−0.97
H545 47	242	303	0.80	1873	21	0.023107	0.000874	0.281511	0.000014	0.281516	−44.6	−3.9	2427	−0.97
H545 48	301	245	1.23	458	11	0.035310	0.001255	0.282294	0.000015	0.282299	−16.9	−7.2	1361	−0.96
H545 49	153	320	0.48	456	7	0.025335	0.000902	0.282325	0.000013	0.282330	−15.8	−6.1	1305	−0.97
H545 50	173	229	0.75	435	9	0.029836	0.001062	0.282264	0.000014	0.282269	−18.0	−8.7	1396	−0.97
H545 51	93	235	0.40	425	8	0.030322	0.001082	0.282304	0.000015	0.282309	−16.5	−7.5	1340	−0.97
H545 52	112	146	0.77	433	10	0.041513	0.001473	0.282252	0.000020	0.282257	−18.4	−9.3	1428	−0.96
H545 53	188	325	0.58	431	6	0.047652	0.001646	0.282292	0.000016	0.282297	−17.0	−8.0	1378	−0.95
H545 54	310	199	1.56	439	7	0.047230	0.001645	0.282261	0.000018	0.282266	−18.1	−8.9	1422	−0.95
H545 55	68	99	0.69	471	12	0.030626	0.001076	0.282299	0.000014	0.282304	−16.7	−6.7	1348	−0.97
H545 56	289	357	0.81	436	7	0.055567	0.001904	0.282339	0.000015	0.282344	−15.3	−6.3	1320	−0.94
H545 57	56	98	0.57	1921	34	0.013368	0.000488	0.281469	0.000018	0.281474	−46.1	−3.9	2459	−0.99
H545 58	75	52	1.46	492	12	0.020501	0.000741	0.282266	0.000016	0.282271	−17.9	−7.3	1382	−0.98
H545 59	193	229	0.84	1859	20	0.034214	0.001287	0.281502	0.000019	0.281507	−44.9	−5.1	2465	−0.96
H545 60	55	44	1.23	1735	47	0.020483	0.000728	0.281487	0.000017	0.281492	−45.5	−7.7	2450	−0.98
H545 61	196	268	0.73	462	8	0.040029	0.001410	0.282356	0.000019	0.282361	−14.7	−5.0	1280	−0.96
H545 62	135	174	0.77	447	9	0.035917	0.001406	0.282753	0.000018	0.282758	−0.7	8.7	715	−0.96
H545 63	59	204	0.29	373	9	0.018290	0.000659	0.282209	0.000017	0.282214	−19.9	−11.9	1457	−0.98
H545 64	131	291	0.45	449	6	0.031994	0.001123	0.282313	0.000016	0.282318	−16.2	−6.7	1330	−0.97
H545 65	102	187	0.55	438	8	0.039676	0.001385	0.282296	0.000015	0.282301	−16.8	−7.6	1363	−0.96
H545 66	83	241	0.34	433	8	0.025876	0.000903	0.282204	0.000016	0.282209	−20.1	−10.8	1474	−0.97
H545 67	25	597	0.04	429	8	0.015386	0.000549	0.281725	0.000017	0.281730	−37.0	−27.7	2115	−0.98
H545 68	152	139	1.09	1797	30	0.033236	0.001185	0.281534	0.000020	0.281539	−43.8	−5.2	2415	−0.96
H545 69	262	254	1.03	1868	22	0.031713	0.001107	0.281548	0.000017	0.281553	−43.3	−3.0	2391	−0.97
H545 70	79	178	0.44	695	12	0.030486	0.001085	0.282223	0.000018	0.282228	−19.4	−4.6	1455	−0.97
H545 71	113	216	0.52	866	12	0.040137	0.001315	0.282227	0.000014	0.282232	−19.3	−0.9	1458	−0.96
H545 72	336	157	2.13	450	10	0.036402	0.001271	0.282281	0.000017	0.282286	−17.4	−7.8	1380	−0.96
H545 73	67	66	1.01	1886	36	0.026734	0.000919	0.281496	0.000015	0.281501	−45.1	−4.2	2450	−0.97
H545 74	46	144	0.32	766	12	0.025190	0.000898	0.282233	0.000017	0.282238	−19.1	−2.6	1433	−0.97
H545 75	104	286	0.36	1883	21	0.009663	0.000395	0.281656	0.000016	0.281661	−39.5	2.0	2200	−0.99
H545 76	83	95	0.88	1937	31	0.019808	0.000723	0.281485	0.000016	0.281490	−45.5	−3.2	2452	−0.98
H545 77	260	267	0.97	461	9	0.031733	0.001098	0.282318	0.000014	0.282323	−16.0	−6.2	1322	−0.97
H545 78	172	226	0.76	462	6	0.046506	0.001614	0.282301	0.000013	0.282306	−16.7	−7.0	1364	−0.95
H545 79	39	185	0.21	431	9	0.000679	0.000017	0.282635	0.000013	0.282640	−4.8	4.6	851	−1.00
H545 80	66	161	0.41	448	9	0.030591	0.001109	0.282307	0.000017	0.282312	−16.4	−6.9	1337	−0.97
H545 81	178	267	0.66	544	9	0.025547	0.000906	0.282188	0.000015	0.282193	−20.7	−9.0	1496	−0.97
H545 82	89	67	1.34	1920	51	0.026383	0.000929	0.281540	0.000018	0.281545	−43.6	−1.9	2390	−0.97
H545 83	89	136	0.66	504	12	0.027270	0.000942	0.282270	0.000015	0.282275	−17.8	−7.0	1383	−0.97
H545 84	65	58	1.13	1908	43	0.026424	0.000942	0.281520	0.000015	0.281525	−44.3	−2.9	2419	−0.97
H545 85	158	262	0.60	440	8	0.036634	0.001272	0.282298	0.000016	0.282303	−16.8	−7.5	1356	−0.96
H545 86	176	68	2.59	476	15	0.029520	0.001028	0.282320	0.000014	0.282325	−16.0	−5.8	1316	−0.97
H545 87	89	197	0.45	468	7	0.032258	0.001116	0.282267	0.000011	0.282272	−17.8	−7.9	1393	−0.97
H545 88	99	226	0.44	469	11	0.034821	0.001227	0.282328	0.000014	0.282333	−15.7	−5.8	1313	−0.96
H545 89	102	407	0.25	447	6	0.056846	0.002021	0.282290	0.000012	0.282295	−17.0	−7.8	1394	−0.94
H545 90	107	164	0.66	481	8	0.038782	0.001342	0.282310	0.000016	0.282315	−16.4	−6.2	1342	−0.96
H545 91	104	121	0.86	1895	25	0.026742	0.000977	0.281507	0.000017	0.281512	−44.7	−3.7	2438	−0.97
H545 92	91	119	0.77	499	12	0.036321	0.001293	0.282291	0.000019	0.282296	−17.0	−6.5	1367	−0.96
H545 93	75	163	0.46	480	11	0.031796	0.001135	0.282315	0.000018	0.282320	−16.2	−6.0	1328	−0.97
H545 94	65	143	0.45	466	9	0.027886	0.000974	0.282304	0.000014	0.282309	−16.6	−6.6	1337	−0.97
H545 95	2	182	0.01	457	8	0.002651	0.000077	0.282364	0.000011	0.282369	−14.4	−4.4	1224	−1.00
H545 96	127	395	0.32	463	8	0.030292	0.001045	0.282084	0.000019	0.282089	−24.3	−14.5	1646	−0.97
H545 97	2	121	0.01	454	10	0.004491	0.000133	0.281990	0.000012	0.281995	−27.6	−17.7	1735	−1.00
H545 98	191	186	1.03	455	9	0.042452	0.001460	0.282263	0.000017	0.282268	−18.0	−8.4	1413	−0.96
H545 99	66	128	0.52	474	11	0.034479	0.001201	0.282282	0.000016	0.282287	−17.3	−7.3	1376	−0.96
H706 01	15	251	0.06	430	9	0.000406	0.000011	0.282642	0.000016	0.282651	−4.6	4.9	841	−1.00

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H706 02	6	486	0.01	435	8	0.000476	0.000015	0.282315	0.000013	0.282324	-16.2	-6.6	1289	-1.00
H706 03	114	73	1.57	434	10	0.029530	0.000938	0.282302	0.000018	0.282311	-16.6	-7.3	1339	-0.97
H706 05	130	329	0.39	444	9	0.014372	0.000518	0.282589	0.000013	0.282598	-6.5	3.1	927	-0.98
H706 06	30	567	0.05	411	8	0.057880	0.002002	0.282220	0.000015	0.282229	-19.5	-11.0	1494	-0.94
H706 07	34	60	0.57	381	9	0.020798	0.000731	0.282426	0.000022	0.282435	-12.2	-4.0	1159	-0.98
H706 08	85	203	0.42	428	8	0.038065	0.001214	0.282300	0.000015	0.282309	-16.7	-7.6	1351	-0.96
H706 09	10	288	0.03	430	9	0.000879	0.000019	0.282405	0.000013	0.282414	-13.0	-3.5	1167	-1.00
H706 10	251	229	1.10	428	8	0.060231	0.001881	0.282199	0.000017	0.282208	-20.3	-11.4	1520	-0.94
H706 100	76	96	0.79	477	11	0.019852	0.000657	0.282441	0.000022	0.282450	-11.7	-1.4	1136	-0.98
H706 12	80	155	0.52	442	9	0.044978	0.001434	0.282275	0.000014	0.282284	-17.6	-8.3	1394	-0.96
H706 13	83	85	0.98	1684	22	0.016251	0.000543	0.281371	0.000016	0.281380	-49.5	-12.7	2594	-0.98
H706 14	91	172	0.53	451	10	0.045073	0.001446	0.282307	0.000016	0.282316	-16.4	-7.0	1350	-0.96
H706 15	281	347	0.81	433	9	0.024715	0.000815	0.282282	0.000019	0.282291	-17.3	-8.0	1361	-0.98
H706 16	56	41	1.36	1841	34	0.021081	0.000693	0.281430	0.000017	0.281439	-47.5	-7.3	2525	-0.98
H706 17	110	189	0.58	2344	18	0.013751	0.000477	0.281214	0.000017	0.281223	-55.1	-3.4	2801	-0.99
H706 18	82	188	0.44	457	9	0.034903	0.001126	0.282317	0.000015	0.282326	-16.1	-6.4	1324	-0.97
H706 19	205	277	0.74	1702	18	0.020819	0.000732	0.281409	0.000016	0.281418	-48.2	-11.2	2556	-0.98
H706 20	154	209	0.74	504	10	0.017910	0.000605	0.282504	0.000015	0.282513	-9.5	1.4	1046	-0.98
H706 21	34	85	0.40	518	10	0.013072	0.000451	0.282233	0.000015	0.282242	-19.1	-7.8	1416	-0.99
H706 22	104	158	0.66	280	6	0.033296	0.001074	0.282795	0.000016	0.282804	0.8	6.8	648	-0.97
H706 23	10	154	0.06	446	9	0.002624	0.000073	0.282130	0.000012	0.282139	-22.7	-12.9	1543	-1.00
H706 24	73	124	0.59	263	6	0.023798	0.000834	0.282533	0.000016	0.282542	-8.5	-2.8	1013	-0.97
H706 25	99	143	0.70	2296	20	0.036714	0.001258	0.281374	0.000016	0.281383	-49.4	0.0	2639	-0.96
H706 26	206	407	0.51	449	9	0.038534	0.001242	0.282218	0.000014	0.282227	-19.6	-10.1	1467	-0.96
H706 27	83	254	0.33	422	9	0.053273	0.001728	0.282268	0.000016	0.282277	-17.8	-9.1	1416	-0.95
H706 28	282	191	1.47	463	9	0.050278	0.001610	0.282298	0.000019	0.282307	-16.8	-7.1	1369	-0.95
H706 29	35	119	0.29	461	10	0.049863	0.001779	0.282396	0.000019	0.282405	-13.3	-3.7	1235	-0.95
H706 30	6	442	0.01	439	9	0.001536	0.000040	0.282065	0.000014	0.282074	-25.0	-15.4	1630	-1.00
H706 31	83	128	0.65	1650	24	0.018683	0.000629	0.281478	0.000015	0.281487	-45.8	-9.7	2456	-0.98
H706 32	234	407	0.57	253	5	0.037718	0.001348	0.282600	0.000017	0.282609	-6.1	-0.7	931	-0.96
H706 33	151	225	0.67	2114	17	0.023975	0.000876	0.281304	0.000021	0.281313	-51.9	-5.9	2708	-0.97
H706 34	70	534	0.13	928	17	0.026987	0.000776	0.282236	0.000014	0.282245	-18.9	1.1	1424	-0.98
H706 35	61	86	0.71	2217	23	0.022976	0.000776	0.281344	0.000015	0.281353	-50.5	-2.1	2647	-0.98
H706 36	228	163	1.39	2212	18	0.010208	0.000315	0.281228	0.000024	0.281237	-54.6	-5.6	2771	-0.99
H706 37	111	277	0.40	453	9	0.041057	0.001344	0.282309	0.000016	0.282318	-16.4	-6.8	1343	-0.96
H706 38	181	299	0.61	292	6	0.032214	0.001126	0.282583	0.000015	0.282592	-6.7	-0.5	950	-0.97
H706 39	79	107	0.74	2376	17	0.015675	0.000568	0.281293	0.000020	0.281302	-52.3	0.1	2701	-0.98
H706 40	235	206	1.14	1711	22	0.011914	0.000399	0.281421	0.000017	0.281430	-47.8	-10.2	2518	-0.99
H706 41	121	178	0.68	1772	18	0.016082	0.000543	0.281661	0.000015	0.281670	-39.3	-0.5	2202	-0.98
H706 42	108	91	1.18	792	16	0.040144	0.001387	0.281900	0.000018	0.281909	-30.8	-14.1	1919	-0.96
H706 43	214	63	3.41	1823	25	0.018909	0.000591	0.281033	0.000014	0.281042	-61.5	-21.7	3052	-0.98
H706 44	12	302	0.04	448	9	0.000416	0.000009	0.282649	0.000014	0.282658	-4.4	5.5	832	-1.00
H706 45	57	98	0.58	823	18	0.045366	0.001597	0.282289	0.000019	0.282298	-17.1	0.2	1381	-0.95
H706 46	141	243	0.58	982	18	0.049002	0.001602	0.282169	0.000018	0.282178	-21.3	-0.6	1551	-0.95
H706 47	37	54	0.69	1564	26	0.030787	0.000955	0.281596	0.000018	0.281605	-41.6	-7.8	2315	-0.97
H706 48	6	293	0.02	438	9	0.008194	0.000267	0.281987	0.000015	0.281996	-27.8	-18.2	1746	-0.99
H706 49	588	688	0.86	384	7	0.073880	0.002291	0.282702	0.000019	0.282711	-2.5	5.4	807	-0.93
H706 50	80	108	0.74	1816	20	0.010930	0.000341	0.281512	0.000017	0.281521	-44.5	-4.5	2391	-0.99
H706 52	111	177	0.63	315	7	0.030899	0.001037	0.282652	0.000015	0.282661	-4.2	2.5	850	-0.97
H706 53	64	113	0.57	1560	22	0.023250	0.000767	0.281509	0.000014	0.281518	-44.7	-10.8	2422	-0.98
H706 55	247	280	0.88	836	16	0.018881	0.000593	0.282172	0.000019	0.282181	-21.2	-3.1	1506	-0.98
H706 56	29	51	0.57	2779	17	0.024187	0.000832	0.280986	0.000016	0.280995	-63.2	-2.2	3134	-0.97
H706 58	57	130	0.44	1555	20	0.030002	0.000916	0.281699	0.000019	0.281708	-38.0	-4.3	2172	-0.97
H706 59	197	307	0.64	423	8	0.022429	0.000711	0.282239	0.000016	0.282248	-18.9	-9.8	1418	-0.98
H706 60	99	210	0.47	944	18	0.033187	0.001050	0.282224	0.000015	0.282233	-19.4	0.8	1452	-0.97

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H706 61	6	224	0.03	448	10	0.001535	0.000042	0.282370	0.000014	0.282379	−14.2	−4.4	1215	−1.00
H706 62	59	75	0.79	443	10	0.030913	0.001025	0.282323	0.000018	0.282332	−15.9	−6.4	1312	−0.97
H706 63	39	1391	0.03	441	8	0.003321	0.000086	0.282538	0.000013	0.282547	−8.3	1.4	986	−1.00
H706 64	118	399	0.30	485	9	0.019924	0.000666	0.282275	0.000016	0.282284	−17.6	−7.1	1366	−0.98
H706 65	42	70	0.60	459	10	0.028222	0.000934	0.282286	0.000017	0.282295	−17.2	−7.4	1361	−0.97
H706 66	133	163	0.82	440	10	0.050049	0.001595	0.282317	0.000019	0.282326	−16.1	−6.9	1341	−0.95
H706 67	94	69	1.36	442	11	0.036204	0.001178	0.282314	0.000018	0.282323	−16.2	−6.8	1330	−0.96
H706 68	21	776	0.03	440	9	0.013840	0.000464	0.282335	0.000014	0.282344	−15.5	−5.9	1277	−0.99
H706 69	157	311	0.50	438	9	0.056558	0.001798	0.282327	0.000015	0.282336	−15.7	−6.6	1334	−0.95
H706 70	20	523	0.04	421	8	0.009578	0.000289	0.282327	0.000014	0.282336	−15.7	−6.6	1281	−0.99
H706 71	76	115	0.66	1687	24	0.013265	0.000441	0.281413	0.000018	0.281422	−48.1	−11.0	2531	−0.99
H706 72	23	749	0.03	463	9	0.051287	0.001619	0.281924	0.000018	0.281933	−30.0	−20.3	1897	−0.95
H706 73	99	78	1.26	2389	22	0.012390	0.000434	0.281028	0.000015	0.281037	−61.7	−8.9	3046	−0.99
H706 74	161	210	0.77	811	16	0.049724	0.001768	0.281748	0.000020	0.281757	−36.2	−19.3	2152	−0.95
H706 76	11	166	0.06	424	9	0.001137	0.000034	0.282155	0.000012	0.282164	−21.8	−12.5	1508	−1.00
H706 77	207	193	1.07	428	10	0.047004	0.001552	0.282320	0.000018	0.282329	−16.0	−7.0	1335	−0.95
H706 78	95	385	0.25	268	6	0.030468	0.001025	0.282593	0.000017	0.282602	−6.3	−0.6	933	−0.97
H706 79	59	115	0.52	430	9	0.018916	0.000680	0.282814	0.000018	0.282823	1.5	10.8	616	−0.98
H706 80	112	83	1.35	2395	19	0.035042	0.001204	0.281166	0.000019	0.281175	−56.8	−5.1	2920	−0.96
H706 81	60	434	0.14	1728	17	0.005459	0.000149	0.281390	0.000015	0.281399	−48.9	−10.6	2543	−1.00
H706 82	40	88	0.46	1633	29	0.016702	0.000551	0.281477	0.000016	0.281485	−45.8	−10.1	2453	−0.98
H706 83	246	259	0.95	377	8	0.028582	0.001171	0.282092	0.000018	0.282101	−24.0	−16.1	1640	−0.96
H706 84	15	633	0.02	467	9	0.005209	0.000175	0.282333	0.000013	0.282342	−15.5	−5.3	1270	−0.99
H706 85	64	87	0.73	384	9	0.034262	0.001281	0.282215	0.000018	0.282224	−19.7	−11.6	1473	−0.96
H706 86	104	167	0.62	2426	17	0.013916	0.000500	0.281252	0.000017	0.281261	−53.7	−0.2	2751	−0.98
H706 87	135	214	0.63	437	9	0.046984	0.001544	0.282278	0.000016	0.282287	−17.5	−8.3	1394	−0.95
H706 88	231	373	0.62	429	9	0.044761	0.001466	0.282423	0.000018	0.282432	−12.3	−3.3	1186	−0.96
H706 89	100	169	0.59	1800	20	0.005884	0.000219	0.281446	0.000016	0.281455	−46.9	−7.1	2473	−0.99
H706 90	39	56	0.70	1568	29	0.030094	0.000981	0.281643	0.000021	0.281652	−39.9	−6.1	2253	−0.97
H706 91	358	103	3.48	603	13	0.019189	0.000643	0.281516	0.000020	0.281525	−44.4	−31.4	2405	−0.98
H706 92	213	654	0.33	410	8	0.029839	0.001047	0.282434	0.000016	0.282443	−11.9	−3.2	1157	−0.97
H706 93	74	276	0.27	1787	18	0.029160	0.000995	0.281658	0.000016	0.281667	−39.4	−0.8	2232	−0.97
H706 94	113	246	0.46	426	9	0.035233	0.001171	0.282283	0.000016	0.282292	−17.3	−8.3	1374	−0.96
H706 96	70	100	0.69	1533	31	0.031889	0.001025	0.281630	0.000018	0.281639	−40.4	−7.4	2273	−0.97
H706 97	212	339	0.62	229	5	0.036882	0.001384	0.282586	0.000019	0.282595	−6.6	−1.8	952	−0.96
H706 98	87	57	1.53	1798	36	0.015621	0.000570	0.281321	0.000017	0.281330	−51.3	−12.0	2664	−0.98
H706 99	7	165	0.04	442	10	0.001297	0.000040	0.282633	0.000016	0.282642	−4.9	4.8	855	−1.00
H753 01	70	73	0.96	1793	26	0.007478	0.000294	0.281437	0.000012	0.281445	−47.2	−7.6	2490	−0.99
H753 02	4	43	0.09	436	12	0.002433	0.000099	0.282694	0.000024	0.282702	−2.8	6.8	772	−1.00
H753 03	200	291	0.69	371	8	0.045691	0.001570	0.282617	0.000013	0.282625	−5.5	2.3	913	−0.95
H753 04	10	132	0.08	449	11	0.000841	0.000027	0.281807	0.000011	0.281815	−34.1	−24.3	1977	−1.00
H753 05	554	433	1.28	255	6	0.040348	0.001806	0.282339	0.000013	0.282347	−15.3	−10.0	1317	−0.95
H753 06	120	236	0.51	425	10	0.028531	0.001063	0.282300	0.000010	0.282308	−16.7	−7.7	1346	−0.97
H753 07	354	156	2.27	409	10	0.041065	0.001517	0.282306	0.000013	0.282314	−16.5	−7.9	1353	−0.95
H753 08	73	553	0.13	460	10	0.022958	0.000850	0.282146	0.000017	0.282154	−22.1	−12.3	1552	−0.97
H753 09	351	356	0.99	423	9	0.029548	0.001344	0.282749	0.000012	0.282757	−0.8	8.1	720	−0.96
H753 10	207	142	1.46	418	10	0.033414	0.001240	0.282285	0.000011	0.282293	−17.2	−8.4	1374	−0.96
H753 100	70	123	0.56	278	7	0.064317	0.002190	0.282877	0.000018	0.282882	3.7	9.4	549	−0.93
H753 12	105	157	0.67	237	7	0.028563	0.001088	0.282568	0.000013	0.282576	−7.2	−2.2	971	−0.97
H753 13	72	91	0.79	402	11	0.017333	0.000654	0.282642	0.000012	0.282650	−4.6	4.1	856	−0.98
H753 14	247	280	0.88	371	9	0.035133	0.001277	0.282183	0.000014	0.282191	−20.8	−13.0	1517	−0.96
H753 15	65	103	0.64	227	6	0.014248	0.000546	0.282560	0.000012	0.282568	−7.5	−2.6	967	−0.98
H753 16	104	107	0.97	2542	22	0.012307	0.000536	0.281205	0.000012	0.281213	−55.4	0.7	2817	−0.98
H753 17	183	309	0.59	279	7	0.027705	0.001150	0.282394	0.000015	0.282402	−13.4	−7.5	1217	−0.97
H753 18	223	201	1.11	428	12	0.005191	0.000177	0.282301	0.000017	0.282309	−16.7	−7.3	1314	−0.99

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H753 19	243	214	1.14	411	10	0.038758	0.001415	0.282275	0.000013	0.282283	−17.6	−8.9	1394	−0.96
H753 20	27	42	0.63	1908	31	0.011687	0.000429	0.281457	0.000013	0.281465	−46.5	−4.5	2471	−0.99
H753 22	122	252	0.48	399	9	0.025446	0.000896	0.282529	0.000012	0.282537	−8.6	−0.1	1020	−0.97
H753 23	298	169	1.76	1805	24	0.045227	0.001689	0.281395	0.000011	0.281403	−48.7	−10.6	2641	−0.95
H753 24	134	167	0.80	422	10	0.032357	0.001193	0.282260	0.000011	0.282268	−18.1	−9.2	1406	−0.96
H753 25	186	36	5.17	1853	37	0.007781	0.000258	0.281028	0.000011	0.281036	−61.7	−20.8	3033	−0.99
H753 26	94	132	0.71	229	6	0.038312	0.001477	0.282594	0.000012	0.282602	−6.3	−1.5	943	−0.96
H753 27	124	197	0.63	447	11	0.022611	0.000852	0.282671	0.000015	0.282679	−3.6	6.0	820	−0.97
H753 30	17	55	0.30	303	11	0.011512	0.000459	0.282447	0.000015	0.282455	−11.5	−4.9	1121	−0.99
H753 31	4	481	0.01	421	9	0.022448	0.000756	0.282259	0.000014	0.282264	−18.2	−9.1	1392	−0.98
H753 32	87	192	0.45	853	17	0.021376	0.000759	0.282307	0.000011	0.282312	−16.4	2.0	1325	−0.98
H753 33	82	649	0.13	420	9	0.037948	0.001257	0.282462	0.000012	0.282467	−11.0	−2.1	1124	−0.96
H753 34	53	173	0.31	907	19	0.044826	0.001547	0.282254	0.000011	0.282259	−18.3	0.8	1428	−0.95
H753 35	21	37	0.56	2150	27	0.010418	0.000369	0.281114	0.000015	0.281119	−58.6	−11.1	2926	−0.99
H753 36	90	60	1.51	1901	29	0.007685	0.000286	0.281183	0.000013	0.281188	−56.2	−14.2	2829	−0.99
H753 37	37	72	0.51	256	8	0.020790	0.000778	0.282535	0.000015	0.282540	−8.4	−2.9	1008	−0.98
H753 38	228	352	0.65	248	6	0.037699	0.001383	0.282289	0.000011	0.282294	−17.1	−11.9	1373	−0.96
H753 39	148	238	0.62	708	14	0.036385	0.001235	0.282261	0.000013	0.282266	−18.1	−3.1	1407	−0.96
H753 40	197	411	0.48	770	15	0.027443	0.001035	0.282387	0.000011	0.282392	−13.6	2.9	1223	−0.97
H753 41	101	131	0.77	1674	26	0.023946	0.000795	0.281495	0.000013	0.281500	−45.2	−8.8	2443	−0.98
H753 42	107	212	0.50	305	8	0.018977	0.000821	0.282611	0.000013	0.282616	−5.7	0.8	903	−0.98
H753 44	314	389	0.81	237	5	0.023990	0.000853	0.282626	0.000013	0.282631	−5.2	−0.1	882	−0.97
H753 45	19	257	0.07	456	10	0.002057	0.000065	0.281788	0.000012	0.281793	−34.8	−24.8	2005	−1.00
H753 46	59	168	0.35	860	18	0.033426	0.001182	0.282218	0.000013	0.282223	−19.6	−1.3	1465	−0.96
H753 47	273	153	1.78	2391	18	0.050200	0.001842	0.281241	0.000013	0.281246	−54.1	−3.5	2865	−0.94
H753 48	14	20	0.72	1640	48	0.014583	0.000514	0.281390	0.000012	0.281395	−48.9	−13.0	2567	−0.98
H753 49	356	296	1.20	449	9	0.022121	0.000694	0.282340	0.000009	0.282345	−15.3	−5.6	1277	−0.98
H753 50	90	177	0.51	463	11	0.034279	0.001214	0.282307	0.000013	0.282312	−16.4	−6.6	1341	−0.96
H753 51	87	84	1.03	439	10	0.022328	0.000803	0.282340	0.000011	0.282345	−15.3	−5.8	1280	−0.98
H753 52	56	134	0.42	445	11	0.029465	0.001058	0.282286	0.000013	0.282291	−17.2	−7.7	1366	−0.97
H753 53	26	48	0.55	1628	52	0.012082	0.000435	0.281384	0.000013	0.281389	−49.1	−13.4	2570	−0.99
H753 54	89	159	0.56	485	12	0.029842	0.001060	0.282614	0.000016	0.282619	−5.6	4.8	904	−0.97
H753 55	205	826	0.25	209	4	0.026569	0.000981	0.282539	0.000015	0.282544	−8.3	−3.8	1009	−0.97
H753 56	66	121	0.55	441	10	0.006057	0.000252	0.282691	0.000012	0.282696	−2.9	6.8	779	−0.99
H753 57	129	438	0.29	1020	24	0.032464	0.001132	0.282025	0.000010	0.282030	−26.4	−4.6	1732	−0.97
H753 58	73	113	0.64	271	7	0.032610	0.001323	0.282530	0.000012	0.282535	−8.6	−2.9	1030	−0.96
H753 59	221	319	0.69	249	6	0.020301	0.000856	0.282530	0.000013	0.282535	−8.5	−3.2	1017	−0.97
H753 60	122	274	0.44	434	10	0.031174	0.001100	0.282342	0.000014	0.282347	−15.2	−6.0	1289	−0.97
H753 61	27	50	0.53	1653	31	0.012828	0.000446	0.281530	0.000011	0.281535	−43.9	−7.7	2374	−0.99
H753 62	100	95	1.06	1831	24	0.021635	0.000740	0.281478	0.000013	0.281483	−45.7	−5.8	2462	−0.98
H753 63	61	151	0.41	513	11	0.015386	0.000547	0.282377	0.000012	0.282382	−14.0	−2.9	1222	−0.98
H753 64	208	159	1.31	1671	39	0.010026	0.000345	0.281445	0.000014	0.281450	−46.9	−10.2	2482	−0.99
H753 65	180	532	0.34	439	9	0.030315	0.001053	0.282544	0.000013	0.282549	−8.1	1.3	1004	−0.97
H753 66	238	569	0.42	457	9	0.015517	0.000614	0.282396	0.000012	0.282401	−13.3	−3.4	1197	−0.98
H753 68	186	358	0.52	469	10	0.018322	0.000795	0.282683	0.000014	0.282688	−3.2	6.9	802	−0.98
H753 69	199	502	0.40	439	9	0.025928	0.000953	0.282561	0.000014	0.282566	−7.5	1.9	976	−0.97
H753 70	167	361	0.46	224	5	0.024112	0.000823	0.282690	0.000014	0.282695	−2.9	1.9	792	−0.98
H753 71	284	374	0.76	257	6	0.075739	0.002695	0.282598	0.000016	0.282603	−6.2	−1.0	970	−0.92
H753 72	124	151	0.82	442	11	0.034159	0.001202	0.282306	0.000014	0.282311	−16.5	−7.1	1342	−0.96
H753 73	137	291	0.47	233	5	0.025130	0.000908	0.282530	0.000015	0.282535	−8.6	−3.6	1019	−0.97
H753 74	133	188	0.71	224	6	0.016969	0.000619	0.282588	0.000014	0.282593	−6.5	−1.7	930	−0.98
H753 75	261	221	1.18	458	10	0.025741	0.000942	0.282405	0.000013	0.282410	−13.0	−3.2	1194	−0.97
H753 76	136	154	0.88	2378	19	0.007877	0.000329	0.281318	0.000014	0.281323	−51.4	1.4	2652	−0.99
H753 77	92	196	0.47	457	11	0.032947	0.001169	0.282252	0.000013	0.282257	−18.4	−8.7	1417	−0.96
H753 78	103	160	0.64	472	12	0.020175	0.000702	0.282412	0.000015	0.282417	−12.7	−2.5	1177	−0.98

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H753 79	97	108	0.90	260	8	0.021011	0.000758	0.282789	0.000013	0.282794	0.6	6.2	653	−0.98
H753 80	68	97	0.71	1666	29	0.015912	0.000559	0.281535	0.000014	0.281540	−43.7	−7.3	2374	−0.98
H753 82	116	139	0.83	432	11	0.018813	0.000709	0.282535	0.000013	0.282540	−8.4	0.9	1006	−0.98
H753 83	46	44	1.06	436	13	0.018253	0.000657	0.282344	0.000017	0.282349	−15.1	−5.7	1271	−0.98
H753 84	30	61	0.50	1587	37	0.016094	0.000579	0.281494	0.000014	0.281499	−45.2	−10.5	2430	−0.98
H753 85	60	116	0.52	451	11	0.027093	0.000964	0.282271	0.000012	0.282276	−17.7	−8.1	1383	−0.97
H753 86	201	414	0.49	230	5	0.028655	0.001132	0.282560	0.000013	0.282565	−7.5	−2.6	982	−0.97
H753 87	48	102	0.47	1504	34	0.017526	0.000607	0.281630	0.000014	0.281635	−40.4	−7.6	2248	−0.98
H753 88	258	269	0.96	346	8	0.031011	0.001171	0.282588	0.000013	0.282593	−6.5	0.8	945	−0.96
H753 89	22	49	0.45	1591	44	0.012153	0.000450	0.281557	0.000015	0.281562	−43.0	−8.1	2337	−0.99
H753 90	52	65	0.80	2280	23	0.021066	0.000772	0.281357	0.000015	0.281362	−50.0	−0.2	2629	−0.98
H753 91	85	196	0.43	2243	25	0.015821	0.000584	0.281376	0.000014	0.281381	−49.4	−0.1	2591	−0.98
H753 92	90	132	0.69	287	8	0.071998	0.002446	0.282466	0.000020	0.282471	−10.8	−5.0	1156	−0.93
H753 93	41	63	0.66	490	13	0.010970	0.000419	0.282649	0.000014	0.282654	−4.4	6.3	841	−0.99
H753 94	174	382	0.46	442	9	0.029844	0.001135	0.282530	0.000017	0.282535	−8.6	0.8	1025	−0.97
H753 95	145	256	0.57	242	6	0.032499	0.001272	0.282545	0.000014	0.282550	−8.0	−2.9	1007	−0.96
H753 96	25	40	0.63	2616	27	0.015156	0.000579	0.281114	0.000014	0.281119	−58.6	−0.9	2943	−0.98
H753 97	41	40	1.02	473	15	0.000747	0.000027	0.281721	0.000013	0.281726	−37.2	−26.8	2093	−1.00
H753 98	32	43	0.73	1821	36	0.018227	0.000689	0.281631	0.000016	0.281636	−40.3	−0.6	2251	−0.98
H753 99	104	95	1.09	229	10	0.026762	0.000975	0.282565	0.000018	0.282570	−7.3	−2.4	971	−0.97
H792 01	284	116	2.45	456	10	0.046724	0.001466	0.282337	0.000020	0.282346	−15.4	−5.8	1308	−0.96
H792 03	38	174	0.22	438	9	0.024523	0.000849	0.282510	0.000016	0.282519	−9.3	0.1	1045	−0.97
H792 04	12	247	0.05	448	9	0.001026	0.000027	0.282275	0.000013	0.282284	−17.6	−7.7	1344	−1.00
H792 05	66	108	0.61	1688	20	0.019570	0.000640	0.281416	0.000014	0.281425	−48.0	−11.1	2541	−0.98
H792 06	22	211	0.10	470	10	0.021049	0.000700	0.282485	0.000015	0.282494	−10.1	0.0	1076	−0.98
H792 08	39	71	0.54	412	9	0.030587	0.000964	0.282569	0.000021	0.282578	−7.2	1.6	966	−0.97
H792 09	13	287	0.05	482	10	0.003077	0.000086	0.282332	0.000014	0.282341	−15.6	−5.0	1268	−1.00
H792 10	20	170	0.12	455	9	0.000838	0.000022	0.282615	0.000015	0.282624	−5.6	4.5	879	−1.00
H792 100	246	493	0.50	981	18	0.022043	0.000788	0.281978	0.000017	0.281987	−28.1	−6.9	1781	−0.98
H792 11	190	329	0.58	242	5	0.029451	0.000924	0.282549	0.000015	0.282558	−7.9	−2.7	993	−0.97
H792 12	71	154	0.46	452	9	0.033684	0.001078	0.282297	0.000014	0.282306	−16.8	−7.2	1350	−0.97
H792 13	132	312	0.42	247	5	0.022862	0.000890	0.282585	0.000015	0.282594	−6.6	−1.4	942	−0.97
H792 14	13	14	0.89	1645	53	0.015897	0.000520	0.281449	0.000018	0.281458	−46.8	−10.8	2488	−0.98
H792 15	76	65	1.17	1775	25	0.012180	0.000405	0.281791	0.000016	0.281800	−34.7	4.4	2018	−0.99
H792 16	175	355	0.49	245	5	0.033360	0.001127	0.282510	0.000014	0.282519	−9.2	−4.1	1052	−0.97
H792 17	175	305	0.57	2471	16	0.034168	0.001155	0.281194	0.000013	0.281203	−55.8	−2.3	2878	−0.97
H792 18	81	137	0.59	462	10	0.045110	0.001433	0.282269	0.000014	0.282278	−17.8	−8.1	1403	−0.96
H792 19	23	857	0.03	451	9	0.003544	0.000099	0.282287	0.000013	0.282296	−17.2	−7.3	1330	−1.00
H792 20	208	186	1.12	264	6	0.051497	0.001654	0.282612	0.000016	0.282621	−5.7	−0.1	922	−0.95
H792 21	85	101	0.84	1863	20	0.018557	0.000589	0.281618	0.000017	0.281627	−40.8	0.0	2263	−0.98
H792 22	107	384	0.28	410	8	0.034651	0.001186	0.282477	0.000014	0.282486	−10.4	−1.7	1101	−0.96
H792 23	26	32	0.79	1707	32	0.029141	0.000913	0.281508	0.000017	0.281517	−44.7	−7.8	2433	−0.97
H792 24	71	452	0.16	841	16	0.037496	0.001102	0.282267	0.000014	0.282276	−17.9	0.1	1393	−0.97
H792 26	164	246	0.67	808	16	0.035568	0.001095	0.282411	0.000014	0.282420	−12.8	4.5	1192	−0.97
H792 27	41	314	0.13	439	9	0.002195	0.000062	0.282295	0.000014	0.282304	−16.9	−7.2	1318	−1.00
H792 28	146	483	0.30	423	8	0.050670	0.001610	0.282324	0.000015	0.282333	−15.8	−7.0	1331	−0.95
H792 29	465	221	2.10	253	5	0.101768	0.003172	0.282443	0.000020	0.282452	−11.6	−6.6	1214	−0.90
H792 30	278	707	0.39	1223	19	0.057227	0.001705	0.282032	0.000014	0.282041	−26.2	−0.4	1749	−0.95
H792 31	106	163	0.65	2353	16	0.026343	0.000873	0.281205	0.000018	0.281214	−55.4	−4.1	2842	−0.97
H792 32	107	230	0.46	1959	19	0.022514	0.000827	0.281623	0.000012	0.281632	−40.6	2.0	2271	−0.98
H792 33	66	133	0.50	2255	17	0.021391	0.000686	0.281359	0.000015	0.281368	−50.0	−0.6	2621	−0.98
H792 34	116	234	0.50	265	6	0.050321	0.001819	0.282672	0.000019	0.282681	−3.5	2.0	840	−0.95
H792 35	36	50	0.72	1731	28	0.015831	0.000507	0.281462	0.000017	0.281471	−46.3	−8.4	2470	−0.98
H792 36	58	86	0.68	2396	19	0.032573	0.001098	0.281363	0.000018	0.281372	−49.8	2.1	2644	−0.97
H792 38	78	88	0.90	487	11	0.022655	0.000801	0.282492	0.000017	0.282501	−9.9	0.6	1069	−0.98

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H792 39	143	209	0.69	678	13	0.039272	0.001244	0.282251	0.000016	0.282260	-18.4	-4.1	1422	-0.96
H792 40	113	255	0.44	844	16	0.026691	0.000813	0.282266	0.000016	0.282275	-17.9	0.3	1384	-0.98
H792 41	149	197	0.76	440	9	0.026204	0.000911	0.282427	0.000017	0.282436	-12.2	-2.8	1163	-0.97
H792 42	264	471	0.56	774	14	0.031889	0.001099	0.282051	0.000015	0.282060	-25.5	-9.0	1694	-0.97
H792 43	283	186	1.52	1843	22	0.023863	0.000799	0.281547	0.000019	0.281556	-43.3	-3.2	2373	-0.98
H792 44	103	149	0.69	1991	20	0.017884	0.000599	0.281157	0.000018	0.281166	-57.1	-13.5	2886	-0.98
H792 45	65	81	0.81	1762	24	0.022711	0.000704	0.281542	0.000016	0.281551	-43.5	-5.1	2373	-0.98
H792 47	131	613	0.21	430	8	0.058134	0.001895	0.282373	0.000018	0.282382	-14.1	-5.2	1272	-0.94
H792 48	37	56	0.66	1359	31	0.019680	0.000673	0.281874	0.000018	0.281883	-31.8	-2.2	1919	-0.98
H792 49	26	53	0.48	1695	29	0.015432	0.000522	0.281499	0.000016	0.281508	-45.0	-7.9	2420	-0.98
H792 50	114	218	0.52	486	10	0.029588	0.001032	0.282528	0.000015	0.282537	-8.6	1.7	1025	-0.97
H792 51	130	55	2.34	470	13	0.039235	0.001273	0.282299	0.000022	0.282308	-16.7	-6.8	1355	-0.96
H792 52	178	187	0.95	240	5	0.045474	0.001609	0.282535	0.000022	0.282544	-8.4	-3.4	1031	-0.95
H792 53	163	99	1.65	432	11	0.040031	0.001358	0.282331	0.000020	0.282340	-15.6	-6.5	1313	-0.96
H792 54	64	320	0.20	1730	18	0.041525	0.001315	0.281508	0.000013	0.281517	-44.7	-7.7	2458	-0.96
H792 55	194	245	0.79	447	9	0.032829	0.001084	0.282302	0.000019	0.282311	-16.6	-7.1	1344	-0.97
H792 56	28	516	0.05	987	18	0.014650	0.000521	0.281708	0.000039	0.281717	-37.6	-16.2	2138	-0.98
H792 57	94	181	0.52	1105	29	0.026943	0.000873	0.281827	0.000030	0.281836	-33.4	-9.6	1993	-0.97
H792 58	105	157	0.67	254	6	0.027563	0.000933	0.282556	0.000017	0.282565	-7.6	-2.2	982	-0.97
H792 59	92	137	0.68	1812	22	0.014306	0.000467	0.281299	0.000019	0.281308	-52.1	-12.3	2686	-0.99
H792 60	88	153	0.57	424	9	0.022116	0.000707	0.282357	0.000022	0.282366	-14.7	-5.5	1254	-0.98
H792 61	55	118	0.47	446	10	0.019655	0.000657	0.282430	0.000019	0.282439	-12.1	-2.5	1151	-0.98
H792 62	152	169	0.90	462	9	0.038839	0.001356	0.282686	0.000023	0.282695	-3.0	6.7	809	-0.96
H792 63	287	186	1.54	441	9	0.045914	0.001473	0.282262	0.000016	0.282271	-18.0	-8.8	1414	-0.96
H792 64	81	196	0.42	2285	19	0.031767	0.001011	0.281257	0.000023	0.281266	-53.6	-4.0	2782	-0.97
H792 66	177	379	0.47	1893	18	0.041779	0.001334	0.281672	0.000022	0.281681	-38.9	1.7	2232	-0.96
H792 67	482	392	1.23	273	6	0.049136	0.001585	0.282571	0.000021	0.282580	-7.1	-1.4	978	-0.95
H792 68	47	583	0.08	439	9	0.004192	0.000122	0.282271	0.000018	0.282280	-17.7	-8.1	1353	-1.00
H792 69	100	168	0.60	468	10	0.045881	0.001479	0.282241	0.000018	0.282250	-18.8	-8.9	1444	-0.96
H792 70	67	170	0.40	1829	24	0.029693	0.000951	0.281630	0.000023	0.281639	-40.4	-0.8	2269	-0.97
H792 71	105	87	1.21	459	11	0.041188	0.001354	0.282315	0.000017	0.282324	-16.2	-6.5	1335	-0.96
H792 72	283	248	1.14	448	9	0.037775	0.001355	0.282499	0.000015	0.282508	-9.6	-0.2	1074	-0.96
H792 73	126	132	0.96	318	7	0.033941	0.001163	0.282700	0.000017	0.282709	-2.5	4.2	785	-0.96
H792 74	106	181	0.59	457	9	0.031875	0.001035	0.282343	0.000016	0.282352	-15.2	-5.4	1284	-0.97
H792 75	268	523	0.51	927	17	0.026277	0.000832	0.281993	0.000017	0.282002	-27.5	-7.6	1763	-0.97
H792 76	66	94	0.71	468	11	0.032526	0.001190	0.282099	0.000023	0.282108	-23.8	-13.9	1632	-0.96
H792 77	198	412	0.48	243	5	0.028563	0.000987	0.282577	0.000018	0.282586	-6.9	-1.7	955	-0.97
H792 78	45	204	0.22	423	8	0.004722	0.000136	0.282471	0.000013	0.282480	-10.6	-1.4	1080	-1.00
H792 79	307	628	0.49	244	5	0.039360	0.001323	0.282584	0.000018	0.282593	-6.6	-1.5	954	-0.96
H792 80	111	129	0.86	260	6	0.029139	0.001022	0.282605	0.000019	0.282614	-5.9	-0.4	916	-0.97
H792 81	167	198	0.85	2274	16	0.050941	0.001798	0.281450	0.000019	0.281459	-46.8	1.4	2572	-0.95
H792 82	49	59	0.83	473	12	0.030255	0.000986	0.282266	0.000019	0.282275	-17.9	-7.8	1391	-0.97
H792 83	149	109	1.37	1578	23	0.003309	0.000103	0.281549	0.000020	0.281558	-43.2	-8.3	2327	-1.00
H792 84	34	73	0.47	1572	24	0.008289	0.000293	0.281196	0.000015	0.281205	-55.7	-21.2	2812	-0.99
H792 85	32	82	0.39	445	10	0.011841	0.000409	0.282291	0.000019	0.282300	-17.0	-7.4	1336	-0.99
H792 86	241	524	0.46	236	5	0.028268	0.000983	0.282602	0.000017	0.282611	-6.0	-1.0	920	-0.97
H792 87	130	233	0.56	211	4	0.063725	0.001956	0.282708	0.000020	0.282717	-2.3	2.1	791	-0.94
H792 88	38	73	0.52	1529	31	0.012243	0.000404	0.281369	0.000022	0.281377	-49.6	-16.1	2589	-0.99
H792 89	14	478	0.03	423	8	0.000815	0.000020	0.282591	0.000015	0.282600	-6.4	2.9	911	-1.00
H792 90	60	86	0.70	715	15	0.038731	0.001307	0.282041	0.000022	0.282050	-25.8	-10.7	1717	-0.96
H792 91	68	126	0.54	1639	20	0.012405	0.000437	0.281435	0.000018	0.281444	-47.3	-11.3	2502	-0.99
H792 92	81	239	0.34	1613	21	0.009483	0.000342	0.281516	0.000015	0.281525	-44.4	-8.9	2387	-0.99
H792 93	107	101	1.06	432	11	0.031170	0.001067	0.282264	0.000018	0.282273	-18.0	-8.8	1396	-0.97
H792 94	127	164	0.77	412	10	0.039848	0.001352	0.282287	0.000017	0.282296	-17.2	-8.5	1375	-0.96
H792 95	222	264	0.84	2273	16	0.030221	0.001067	0.281254	0.000018	0.281263	-53.7	-4.5	2790	-0.97

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H792 96	54	100	0.54	1685	21	0.010958	0.000378	0.281548	0.000015	0.281557	−43.3	−6.2	2346	−0.99
H792 97	191	344	0.56	199	4	0.032881	0.001084	0.282663	0.000017	0.282672	−3.8	0.4	835	−0.97
H792 98	128	219	0.59	233	5	0.017779	0.000625	0.282512	0.000016	0.282521	−9.2	−4.2	1037	−0.98
H792 99	107	216	0.49	2320	16	0.019158	0.000731	0.281316	0.000019	0.281325	−51.5	−0.7	2682	−0.98
H860 01	100	104	0.97	463	11	0.026382	0.001020	0.282685	0.000016	0.282683	−3.1	6.8	804	−0.97
H860 02	161	463	0.35	776	16	0.036044	0.001145	0.282390	0.000014	0.282388	−13.5	3.0	1223	−0.97
H860 03	33	140	0.23	447	11	0.009692	0.000383	0.282402	0.000014	0.282400	−13.1	−3.3	1181	−0.99
H860 04	57	115	0.49	2325	21	0.022621	0.000831	0.281422	0.000016	0.281420	−47.7	3.1	2544	−0.97
H860 05	49	68	0.71	2125	31	0.037450	0.001297	0.281468	0.000017	0.281466	−46.1	−0.5	2513	−0.96
H860 06	57	94	0.61	321	12	0.028892	0.001145	0.282789	0.000015	0.282787	0.6	7.4	658	−0.97
H860 07	52	50	1.02	711	22	0.030252	0.001118	0.282321	0.000015	0.282319	−15.9	−0.8	1318	−0.97
H860 09	137	438	0.31	415	8	0.015689	0.000579	0.282248	0.000013	0.282246	−18.5	−9.6	1401	−0.98
H860 10	445	319	1.39	2082	21	0.043978	0.001688	0.281405	0.000020	0.281403	−48.3	−4.2	2627	−0.95
H860 100	336	230	1.46	2169	24	0.019204	0.000739	0.281195	0.000021	0.281193	−55.8	−8.4	2846	−0.98
H860 11	208	428	0.49	251	6	0.044290	0.001783	0.282491	0.000013	0.282489	−9.9	−4.7	1099	−0.95
H860 12	105	586	0.18	359	8	0.021319	0.000868	0.282223	0.000021	0.282221	−19.4	−11.8	1447	−0.97
H860 13	217	215	1.01	2418	26	0.028725	0.001142	0.281267	0.000014	0.281265	−53.2	−0.9	2777	−0.97
H860 15	163	371	0.44	400	8	0.018948	0.000809	0.282642	0.000013	0.282640	−4.6	4.0	860	−0.98
H860 16	54	71	0.76	2291	26	0.023926	0.000887	0.281384	0.000017	0.281382	−49.1	0.8	2601	−0.97
H860 17	86	121	0.71	2290	27	0.014559	0.000526	0.281299	0.000014	0.281297	−52.1	−1.6	2691	−0.98
H860 18	11	17	0.62	1622	75	0.007746	0.000314	0.281188	0.000015	0.281186	−56.0	−20.3	2824	−0.99
H860 19	0	8	0.02	422	42	0.002838	0.000102	0.281781	0.000012	0.281779	−35.0	−25.8	2016	−1.00
H860 21	736	470	1.57	364	7	0.070989	0.002492	0.282473	0.000016	0.282471	−10.6	−3.2	1147	−0.92
H860 22	99	187	0.53	354	9	0.024414	0.001008	0.282556	0.000016	0.282554	−7.6	−0.1	984	−0.97
H860 23	181	252	0.72	358	8	0.024736	0.000892	0.282384	0.000015	0.282382	−13.7	−6.1	1223	−0.97
H860 24	83	112	0.74	358	9	0.020824	0.000785	0.282638	0.000015	0.282636	−4.7	3.0	864	−0.98
H860 25	81	338	0.24	353	7	0.024533	0.000973	0.282516	0.000014	0.282514	−9.1	−1.5	1041	−0.97
H860 26	15	98	0.15	383	11	0.011496	0.000407	0.282517	0.000020	0.282515	−9.0	−0.7	1024	−0.99
H860 30	86	267	0.32	502	11	0.025237	0.000949	0.282178	0.000017	0.282176	−21.0	−10.3	1512	−0.97
H860 33	146	175	0.84	782	16	0.064899	0.002336	0.282222	0.000016	0.282220	−19.5	−3.4	1506	−0.93
H860 34	5	259	0.02	348	9	0.017667	0.000718	0.282077	0.000017	0.282075	−24.6	−17.1	1642	−0.98
H860 35	44	579	0.08	359	7	0.019629	0.000766	0.282366	0.000014	0.282364	−14.4	−6.7	1244	−0.98
H860 36	111	137	0.81	1611	34	0.017565	0.000701	0.281239	0.000018	0.281237	−54.2	−19.2	2784	−0.98
H860 38	68	424	0.16	522	10	0.016502	0.000607	0.282246	0.000015	0.282244	−18.6	−7.3	1405	−0.98
H860 39	4	329	0.01	379	9	0.010623	0.000400	0.282033	0.000013	0.282031	−26.1	−17.9	1688	−0.99
H860 40	22	598	0.04	381	8	0.004433	0.000163	0.282257	0.000013	0.282255	−18.2	−9.9	1373	−1.00
H860 41	6	1077	0.01	384	7	0.003636	0.000116	0.282094	0.000012	0.282092	−24.0	−15.6	1593	−1.00
H860 42	35	49	0.71	1736	40	0.006769	0.000259	0.281477	0.000014	0.281475	−45.8	−7.4	2433	−0.99
H860 43	34	82	0.41	823	18	0.017098	0.000614	0.281997	0.000017	0.281995	−27.4	−9.6	1747	−0.98
H860 44	139	186	0.75	875	17	0.070838	0.002499	0.282257	0.000015	0.282255	−18.2	−0.3	1461	−0.92
H860 46	154	236	0.66	418	9	0.008366	0.000317	0.282607	0.000016	0.282605	−5.8	3.3	897	−0.99
H860 47	70	281	0.25	1682	23	0.005317	0.000187	0.281567	0.000013	0.281565	−42.6	−5.4	2309	−0.99
H860 48	104	168	0.62	406	10	0.034680	0.001246	0.282619	0.000017	0.282617	−5.4	3.2	902	−0.96
H860 50	22	117	0.19	411	10	0.006956	0.000302	0.282772	0.000018	0.282770	0.0	9.0	668	−0.99
H860 52	154	275	0.56	248	6	0.052152	0.002000	0.282676	0.000018	0.282674	−3.4	1.7	838	−0.94
H860 53	5	191	0.02	456	10	0.002565	0.000085	0.282003	0.000013	0.282001	−27.2	−17.2	1715	−1.00
H860 54	118	123	0.95	1542	28	0.012636	0.000432	0.281592	0.000014	0.281590	−41.7	−7.9	2290	−0.99
H860 55	82	167	0.49	474	10	0.008586	0.000308	0.282254	0.000020	0.282252	−18.3	−8.0	1382	−0.99
H860 56	50	204	0.25	830	17	0.023625	0.000835	0.282147	0.000019	0.282145	−22.1	−4.3	1550	−0.97
H860 57	117	125	0.93	1669	27	0.015751	0.000602	0.281287	0.000017	0.281285	−52.5	−16.1	2712	−0.98
H860 58	139	158	0.88	259	6	0.026205	0.001109	0.282541	0.000016	0.282539	−8.2	−2.7	1009	−0.97
H860 59	59	107	0.55	1656	26	0.012726	0.000447	0.281469	0.000013	0.281467	−46.1	−9.7	2456	−0.99
H860 61	297	615	0.48	238	5	0.045979	0.001735	0.282501	0.000018	0.282499	−9.6	−4.6	1084	−0.95
H860 62	51	91	0.56	2242	23	0.015527	0.000585	0.281386	0.000017	0.281384	−49.0	0.3	2578	−0.98
H860 63	194	328	0.59	789	15	0.013806	0.000493	0.281967	0.000014	0.281965	−28.5	−11.3	1783	−0.99

续表 1

Sample	Th	U	Th/U	age (Ma)	1σ	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}(Ma)	$f_{Lu/Hf}$
H860 64	522	395	1.32	424	9	0.009825	0.000322	0.282196	0.000016	0.282194	-20.4	-11.1	1462	-0.99
H860 65	49	259	0.19	465	9	0.001174	0.000036	0.282411	0.000015	0.282409	-12.8	-2.5	1158	-1.00
H860 66	58	138	0.42	352	8	0.024255	0.001096	0.282971	0.000019	0.282969	7.0	14.5	399	-0.97
H860 67	72	542	0.13	890	16	0.032871	0.001076	0.282197	0.000015	0.282195	-20.3	-1.3	1491	-0.97
H860 68	95	141	0.67	256	9	0.014112	0.000544	0.282588	0.000016	0.282586	-6.5	-1.0	928	-0.98
H860 70	107	237	0.45	1792	21	0.004505	0.000156	0.281382	0.000019	0.281380	-49.2	-9.4	2554	-1.00
H860 71	123	510	0.24	581	11	0.017194	0.000678	0.282370	0.000019	0.282368	-14.2	-1.7	1235	-0.98
H860 72	267	418	0.64	245	5	0.019853	0.000748	0.282623	0.000019	0.282621	-5.3	0.0	885	-0.98
H860 73	70	117	0.60	438	10	0.026222	0.000953	0.282551	0.000020	0.282549	-7.8	1.6	991	-0.97
H860 74	6	333	0.02	432	9	0.001070	0.000039	0.282289	0.000021	0.282287	-17.1	-7.6	1325	-1.00
H860 75	755	1052	0.72	268	5	0.071683	0.002431	0.282298	0.000017	0.282296	-16.7	-11.3	1399	-0.93
H860 76	83	98	0.85	2148	28	0.017831	0.000665	0.281039	0.000019	0.281037	-61.3	-14.3	3049	-0.98
H860 77	231	483	0.48	454	9	0.029934	0.001091	0.282292	0.000017	0.282290	-17.0	-7.3	1358	-0.97
H860 78	18	24	0.78	1633	64	0.005238	0.000207	0.281381	0.000017	0.281379	-49.2	-13.1	2560	-0.99
H860 79	45	509	0.09	477	9	0.004344	0.000154	0.281962	0.000014	0.281960	-28.6	-18.2	1774	-1.00
H860 80	25	550	0.05	552	11	0.011341	0.000374	0.282096	0.000013	0.282094	-23.9	-11.9	1601	-0.99
H860 81	72	202	0.36	424	9	0.035989	0.001321	0.282308	0.000017	0.282306	-16.4	-7.5	1344	-0.96
H860 82	89	450	0.20	540	10	0.027354	0.000976	0.282329	0.000016	0.282327	-15.7	-4.1	1302	-0.97
H860 83	156	289	0.54	649	13	0.032580	0.001122	0.282204	0.000014	0.282202	-20.1	-6.3	1482	-0.97
H860 84	41	516	0.08	444	9	0.007229	0.000246	0.282235	0.000015	0.282233	-19.0	-9.3	1406	-0.99
H860 85	10	552	0.02	459	9	0.007131	0.000251	0.282287	0.000014	0.282285	-17.2	-7.1	1335	-0.99
H860 86	154	260	0.60	1205	30	0.084497	0.002950	0.282266	0.000026	0.282264	-17.9	6.4	1467	-0.91
H860 88	93	282	0.33	443	10	0.054555	0.001915	0.282290	0.000019	0.282288	-17.1	-7.9	1392	-0.94
H860 89	51	242	0.21	1504	35	0.005892	0.000185	0.281505	0.000022	0.281503	-44.8	-11.6	2391	-0.99
H860 90	168	238	0.71	376	9	0.018140	0.000770	0.281959	0.000020	0.281957	-28.8	-20.7	1807	-0.98
H860 92	88	217	0.41	477	10	0.020495	0.000901	0.282726	0.000020	0.282724	-1.6	8.6	744	-0.97
H860 93	229	479	0.48	456	9	0.022679	0.000874	0.282331	0.000021	0.282329	-15.6	-5.8	1295	-0.97
H860 94	24	219	0.11	561	13	0.005949	0.000227	0.282019	0.000022	0.282017	-26.6	-14.4	1700	-0.99
H860 95	250	117	2.14	453	13	0.030927	0.001097	0.282302	0.000021	0.282300	-16.6	-7.0	1344	-0.97
H860 96	204	738	0.28	642	13	0.043395	0.001517	0.282186	0.000025	0.282184	-20.7	-7.2	1523	-0.95
H860 97	82	659	0.12	412	8	0.025700	0.000937	0.282409	0.000017	0.282407	-12.8	-4.0	1189	-0.97
H860 98	23	53	0.44	1528	49	0.011120	0.000411	0.281518	0.000021	0.281516	-44.4	-10.8	2388	-0.99
H860 99	272	469	0.58	248	5	0.033806	0.001401	0.282570	0.000019	0.282568	-7.1	-1.9	975	-0.96