

原始地壳增厚驱动水反向富集与早期TTG形成

刘勇胜^{1,2,3*}, 何德涛², 陈康³, 赵国春⁴

1. 长江大学地球深部过程与表层系统耦合研究中心, 武汉 430110

2. 中国地质大学(武汉)地球科学学院, 武汉 430074

3. 中国地质大学(武汉)地质过程与成矿预测全国重点实验室, 武汉 430074

4. 香港大学地球科学系, 西北大学-香港大学地球与行星科学联合中心, 香港 999077

* 联系人, E-mail: yshliu@cug.edu.cn

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摘要 地球以其独特的板块构造和具有演化的长英质大陆地壳而区别于其他星球. 现今保存下来的太古宙大陆地壳岩石以英云闪长岩-奥长花岗岩-花岗闪长岩(TTG)等长英质岩石为主, 部分TTG形成于4.0~3.0 Ga, 甚至更早. 通常用停滞盖层构造体制下的大洋高原底部熔融模型解释最古老TTG的成因, 但该模型无法解释玄武质岩石熔融形成TTG所必需的水的来源. 基于硅酸盐熔体结晶固化时, 水等挥发分会从固体物质析出并在残余液体中富集的基本规律, 我们提出地球表层热传导和热辐射降温导致岩浆洋由外而内的固化作用会驱使水等挥发分向内迁移, 从而引起水反向富集并诱发原始地壳含水熔融的概念模型. 该机制不仅可以解决板块构造启动前基性原始地壳熔融形成长英质岩浆所需的水源问题, 而且可以解释冥古宙和始太古代钠质花岗岩形成压力随时间由低到高的转变.

关键词 岩浆洋冷却, 停滞盖层构造, 原始地壳增厚, 水反向富集, TTG成因

地球以其独特的板块构造和具有演化的长英质大陆地壳而区别于其他星球. 大陆不仅是人类的栖息地, 还为人类的生存发展提供物质基础. 因此, 大陆的起源、演化和形成机制被列为21世纪地球科学领域十大亟待解决的问题之一. 已有研究表明大陆地壳的生长并非匀速, 而是在地球历史前15亿年(也就是在大约3.0 Ga之前)大陆增生地壳的主体就已形成^[1,2]; 而且成分演化也不是突变的, 大陆上地壳成分经历了从3.0 Ga之前镁铁质到2.5 Ga之后长英质的转变^[3], 这种成分演变被认为可能与全球板块构造作用的启动有关^[4~6]. 现今保存下来的太古宙大陆地壳岩石主要是英云闪长岩-奥长花岗岩-花岗闪长岩等长英质片麻岩(TTG)和一些基性-超基性绿岩. 除了大量出露3.0~2.5 Ga的TTG, 绝大部分太古宙克拉通还出露有相当数量4.0~3.0 Ga的长

英质岩石^[7,8]. 迄今为止发现的最古老的长英质岩石为大约4.0 Ga的Acasta片麻岩^[9]. 那些最古老的长英质岩石究竟是形成于“局部板块构造环境”, 还是反映在非板块构造体制中存在形成长英质岩石的其他机制? 因此, 理解这些不同时代长英质岩石的成因对揭秘地球早期大陆的形成机制及其地球动力学背景至关重要^[10~12].

幔源玄武质岩浆经过结晶分异过程或者玄武质岩石经过部分熔融作用可形成长英质岩浆, 其中水是形成TTG这种长英质岩石的必要组分^[13,14]. 很多学者根据经典的板块构造理论认为TTG源区的水来自俯冲板片的脱水, 进而用板块构造体制下的岩浆弧模式来解释太古宙大陆地壳的成因^[13,15~17]. 在这个模型中, 板块构造先出现, 大陆地壳随后形成于板块构造体制之中.

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然而,另一些学者认为这种模型无法解释太古宙大陆地壳的一些基本特征,包括太古宙陆壳绿岩带内高温($\sim 1600^{\circ}\text{C}$)科马提岩的成因、缺乏岩浆弧安山岩的双峰式火山岩组合、占太古宙陆壳总面积70%以上TTG的形成需要2~3倍体积的熔融残余物或堆晶,以及缺失典型的蛇绿岩、蓝片岩、榴辉岩和双变质带等板块构造特征标志^[10,18],因此更倾向于太古宙陆壳形成的大洋高原底部熔融模型^[19~23]。大洋高原底部熔融模型认为太古宙TTG岩浆是由地幔柱洋底高原底部玄武质地壳部分熔融而成,这样能够合理地解释为什么太古宙TTG能够在短时间内巨量产出并在形成时间上没有任何系统变化^[10,12]。但是,这种模型无法解释玄武质岩石源区水的来源。Arndt^[13]认为“水的来源问题”是古老大陆地壳地幔柱洋底高原熔融模型的致命缺陷。因此,全球板块构造体制启动前,基性原始地壳物质发生含水熔融的“水”的来源问题是早期地球演化研究领域的重大关键科学问题。

有研究表明,一些古老TTG源区的水可能来自地球内部。Smithies等人^[24]对澳大利亚Pilbara和Yilgarn两个克拉通的TTG和花岗岩进行了锆石氧同位素分析,发现 $>3.0\text{ Ga}$ 的原始富钠TTG中锆石 $\delta^{18}\text{O}$ 与地幔值一致,指示这些TTG的形成无需地表组分的参与,意味着形成这些TTG的原始基性地壳本身就含有足够的原始水。但该研究并没有阐明基性地壳中的原始水来自何处。Wu等人^[25]提出太古宙大陆和岩石圈地幔的形成可能受到了含水岩浆洋演化的控制。他们认为深部岩浆洋结晶固化从中地幔开始,从而分隔形成上部岩浆洋和下部岩浆洋,上部岩浆洋随着脱气作用逐渐固化为干的大陆岩石圈;下部岩浆洋随着固化作用而最终因为水的富集变得重力不稳定,由此触发的地幔翻转将水从下部岩浆洋转移至浅部。该模型为引起大洋高原底部含水熔融产生TTG岩浆提供了一种水的来源机制。需要注意的是,由于热量在岩浆洋表面(即使形成了薄的固体外壳)通过辐射作用可以有效地去除,在岩浆洋内部发生硅酸盐结晶固化作用的同时,表层熔体必然会通过热传导冷却而形成固体壳层^[26],从而改变上部岩浆洋脱气效率和水等挥发分的迁移方式,这也可能为基性地壳含水熔融提供水源。

1 地球演化早期岩浆洋顶部的停滞盖层

在地球演化的早期阶段,受地核形成过程中的重力能量释放^[27]、短寿命同位素的放射性衰变加热^[28]、

早期大气层导致的热毯效应^[29,30]以及行星吸积后期积累的冲击加热^[31]等因素的巨大影响,地球经历了大规模熔融,形成了全球岩浆洋^[32,33]。岩浆洋的冷却历史为构造演化和早期水迁移创造了初始条件。随着地球的降温,岩浆洋表面由于辐射热流高,因而可能会快速冷却固化形成固体壳层,即停滞盖层(stagnant lid)。停滞盖层最早由Solomatov和Moresi^[34]提出,以描述现今金星上的构造体制。Elkins-Tanton^[35]认为,富含温室气体的大气将岩浆洋表面保持在液相线之上,而且固体物质比其下的岩浆洋液体密度大。因此,他们认为地球岩浆洋表面冷却形成的固体物质易于沉没,不太可能形成覆盖整个地球表面的停滞盖层。然而,Plesa等人^[36]使用二维圆柱形几何结构的地幔对流模拟研究了堆积物的翻转及其对火星热演化的影响,提出全球性的盖层不会下沉,即岩浆洋演化过程中可以形成停滞盖层。而且,Monteux等人^[26]最近的研究表明,地球岩浆洋的冷却是一个快速的过程,整个地幔在 20 ka 内就会显著变得更加黏稠,有利于停滞盖层的形成和保留。停滞盖层被认为难以参与其下方的地幔对流,内部热量仅通过热传导机制传递至地表,相应的构造体制被称为停滞盖层构造,这是现今太阳系内绝大多数类地天体(包括月球、水星和火星等)的构造体制,也被认为是地球前板块构造的重要潜在形式^[37]。

越来越多的地质证据表明地球早期的演化过程存在从停滞盖层构造体制向活动盖层(mobile lid)构造体制的转变^[38~41]。例如, $4.0\sim 3.0\text{ Ga}$ 中性至酸性岩石的高精度W同位素组成随时间变化特征指示地球在约 3.6 Ga 前从热管构造(出现于停滞盖层构造机制中)到板块构造的构造体制转变^[39];加拿大西北部Acasta地区 4.0 Ga 和 3.8 Ga 的片麻岩全岩、锆石和石英的Si-O同位素组成差异指示 4.0 Ga 的TTG形成于停滞盖层构造体制,而 3.8 Ga 之后TTG的形成环境则转变为活动盖层构造体制^[41]。南非Barberton绿岩带的始太古代(大约 3.9 Ga 之前)至中太古代(大约 3.3 Ga)单颗粒锆石含有原生磁铁矿包裹体,记录了与西澳大利亚Jack Hills地区 $4.2\sim 3.3\text{ Ga}$ 锆石原生磁化记录几乎相同的古磁场强度,而且古磁场值在约 $3.9\sim 3.4\text{ Ga}$ 之前几乎保持恒定,这些特征符合停滞盖层构造体制^[40]。因此,越来越多的证据表明停滞盖层构造是地球早期圈层形成演化的重要组成部分。

尽管已有研究表明地球岩浆洋的冷却是一个快速过程,整个地幔在 20 ka 内就会显著变得更加黏稠^[26],

98%固化地幔在不到5 Ma内完成, 对于低挥发性岩浆洋则在不到100 ka内完成^[42]。相对于地球年龄而言, 20 ka或者100 ka的岩浆洋冷却过程的确十分快速, 但是对于表层岩浆洋的演化过程而言可能是比较缓慢的, 而硅酸盐矿物在玄武质熔体中的结晶生长速度非常快(如单斜辉石晶体生长100 μm 仅需要40~70 min)^[43]。因此, 岩浆洋上部(尤其是在出现固体壳层后)必然会由于“缓慢”冷却而发生结晶分异作用。利用pMELTS软件^[44]进行简单的模拟研究表明, 具有原始地幔成分的浅表岩浆洋熔体在结晶程度<30%时的结晶产物都是富Mg橄榄石($\text{FeO}<5 \text{ wt.}\%$), 且具有显著高于熔体的密度。富Mg橄榄石的结晶分离可以使超基性岩浆组分演化形成基性岩浆组分(图1)。因此, 岩浆洋顶部“自上而下”结晶固化过程产生的停滞盖层可能形成了地球的基性原始地壳(proto-crust)。

2 岩浆洋顶部停滞盖层增厚引起水的“反向迁移”

岩浆洋的形成和冷却固化过程强烈地影响着类地行星最早的成分分异和挥发分含量, 构成了地球冷却到温和宜居条件以及热驱动地幔对流和板块构造开始的起点^[35]。在岩浆洋表面冷却固化形成停滞盖层之前, 一方面岩浆脱气作用使水等挥发分由内而外迁移进入大气^[42,46]; 另一方面, 水蒸气是最强效的温室气体之一, 即使只有10 bar的蒸汽大气层(相当于当前地球海洋总质量的大约1/3), 就会减少大约2个数量级的热辐射^[47], 这会显著延长岩浆洋表面保持在液相线之上的时间。因此, 在岩浆洋表面冷却固化之前, 水(或者羟基)在岩浆洋和大气之间可以进行较为充分的交换, 大量水会存在于上部岩浆洋的表层熔体中, 并会参与岩浆洋整体的对流循环^[47]。

当地球冷却至内部热传导不足以维持地表物质处于液态的温度时, 表层的岩浆洋熔体必然会冷却固化形成固体壳层——原始地壳。Monteux等人^[26]模拟研究表明岩浆洋表面即使形成了薄的固体外壳, 热量通过热传导和热辐射也可以被有效地去除, “自外而内”的冷却固化作用使原始地壳“自上而下”逐渐加厚。厚的克拉通岩石圈就被认为是通过热辐射和热传导发生“自外而内”冷却作用形成的^[48]。原始地壳的形成和厚度会显著改变岩浆洋脱气过程中水等挥发分的迁移方式和效率^[49]。原始地壳的形成使岩浆洋和大气之间接近隔绝, 岩浆洋和大气圈之间的动态平衡此后不再保

持, 水等挥发分在二者之间的交换以穿过原始地壳的缓慢扩散为特征。相对于火山喷发脱气作用, 水等挥发分以扩散方式穿过原始地壳的迁移量几乎可以忽略不计。随着原始地壳增厚, 原始地壳的隔挡作用使岩浆洋脱气效率急剧下降, 岩浆脱气速率降低并最终达到接近零。

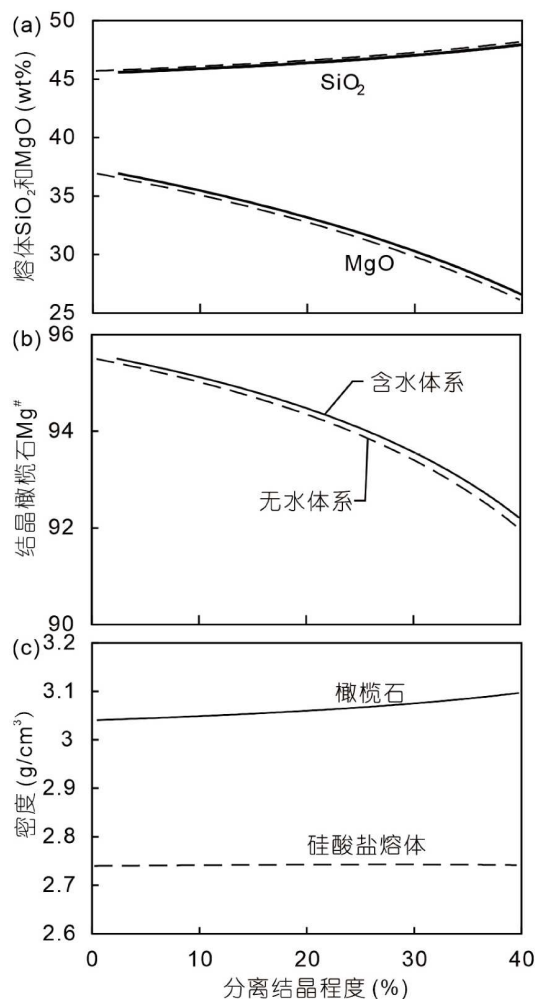


图1 具有原始地幔成分的无水(2%水)岩浆在低压条件(1 bar)发生结晶分异作用引起的熔体 SiO_2 和 MgO 含量(a)、橄榄石 $\text{Mg}\#$ (b)以及熔体和橄榄石密度(c)变化。利用pMELTS软件^[44]模拟研究表明该条件下结晶矿物只有橄榄石。(a, b)中虚线为无水体系, 实线为含水体系; $\text{Mg}\# = \text{molar } 100 \times \text{Mg}/(\text{Mg} + \text{Fe}^{\text{tot}})$; 原始地幔成分值据Palme和O'Neill^[45] **Figure 1** Variations in (a) melt SiO_2 and MgO contents, (b) olivine $\text{Mg}\#$, and (c) densities of melt and olivine during the fractional crystallization of dry and hydrous (2% water) magma with a primitive mantle composition at low pressure (1 bar). Simulations performed using the pMELTS software^[44] indicate that olivine crystallization occurs only under these conditions. The dashed lines in (a) and (b) represent the anhydrous system, while the solid lines represent the hydrous system; $\text{Mg}\# = \text{molar } 100 \times \text{Mg}/(\text{Mg} + \text{Fe}^{\text{tot}})$; The values of primitive mantle composition are from Palme and O'Neill^[45]

由于水和其他挥发性成分在固态物质中具有极高的不相容性, 因此一旦岩浆洋表面形成固态壳层, 这些组分会随着固化过程从固态物质中析出而进入残余的岩浆洋演化熔体^[50]. 因此, 在岩浆洋完全固结之前, 大部分 H_2O 将保留在残余岩浆洋熔体中. 对于小尺度的岩浆房演化过程, 围岩温度通常远低于岩浆温度, 导致岩浆房整体几乎同步冷却. 因此, 水等挥发分受密度影响逐渐向上迁移, 并在熔体层顶部富集(如在花岗岩体顶部形成的伟晶岩脉等). 不同的是, 地球表层热辐射和热传导引起的岩浆洋冷却固结作用使得原始地壳从外向内逐渐增厚, 固体-熔体界面向地球内部迁移, 从而驱

使水等挥发分向下迁移(图2). 这种岩浆洋冷却过程中由于原始地壳增厚引起水的“反向迁移”可能为早期原始地壳含水熔融提供了准备条件. 通过这种方式, 原始岩浆洋中的大量水可能被封存在了固体地球内部.

3 水等挥发分富集层的形成与原始地壳含水熔融

在地球演化早期, 岩浆洋结晶固化作用驱动熔体迁移是影响水在地球内部分布的重要机制. 在表层岩浆洋熔体冷却固化形成固体壳层的同时, 由于绝热曲线和硅酸盐液相线之间的斜率差异, 岩浆洋内部会发

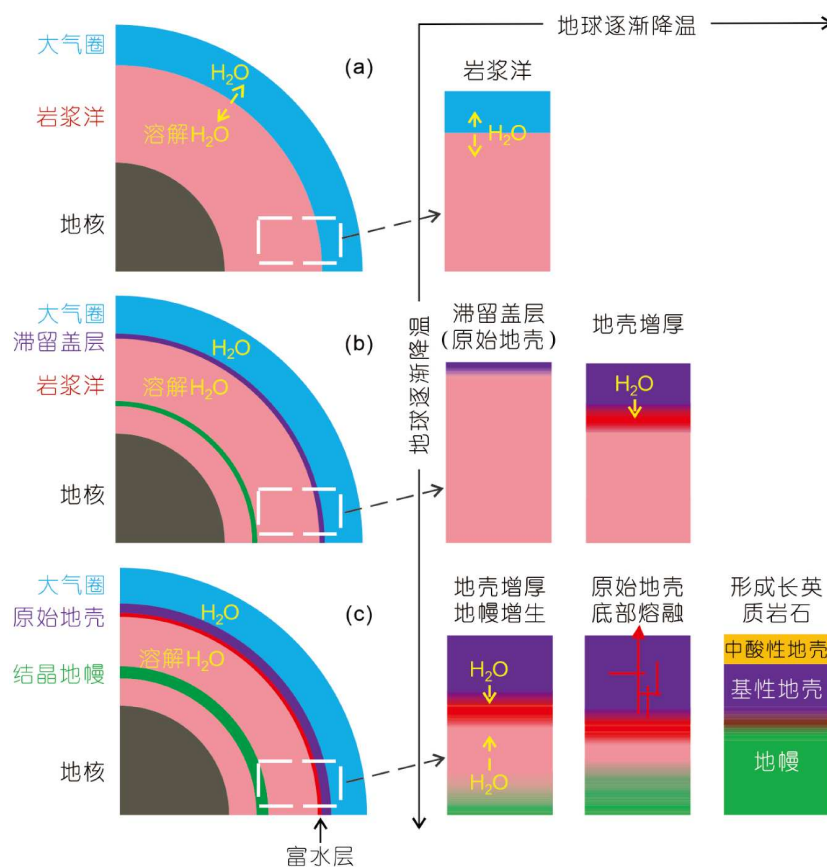


图2 早期地球演化过程中水的迁移方向示意图. (a) 岩浆洋早期富含挥发分的大气将岩浆洋表面保持在液相线之上, H_2O 在岩浆洋和大气之间可以进行较为充分的交换; (b) 停滞盖层的形成几乎隔绝了 H_2O 在岩浆和大气之间的交换, 大量水被保留在岩浆中; (c) 地球表层的热传导、热辐射冷却作用导致停滞盖层自上而下的增厚作用驱动水随着岩浆固化而向下迁移, 并在残余熔体层最浅部及与之邻接的原始地壳底部富集. 黄色箭头代表原始地壳增厚和固体地幔增生作用引起的 H_2O 迁移方向

Figure 2 Schematic illustration of H_2O migration during the early evolution of the Earth. (a) A volatile-rich atmosphere maintained the magma ocean surface above the liquidus, allowing for a relatively sufficient exchange of H_2O between the magma ocean and the atmosphere in the early stage of magma ocean evolution. (b) The formation of a stagnant lid due to the high surface radiative heat flow largely suppressed the exchange of H_2O between the magma and atmosphere, resulting in the retention of a substantial amount of water in the melt. (c) Heat loss from the Earth due to thermal conduction and radiation led to the progressive thickening of the stagnant lid from top down, driving H_2O to migrate downward and become enriched in the shallowest part of the residual melt layer and at the base of the adjacent proto-crust. Yellow arrows indicate the direction of H_2O migration driven by the thickening of the proto-crust and the accretion of the solid mantle

生硅酸盐结晶作用, 形成固体地幔。岩浆洋内部的固化作用可能是从核幔边界开始自下而上, 或者从中间开始自上而下和自下而上同步进行^[35,51]。如果深部岩浆洋固化作用是从核幔边界开始自下而上进行, 随着固态结晶地幔的增生, 岩浆洋中的水等挥发分受密度和含量的梯度差异控制而逐渐向浅部迁移, 并逐渐在残余熔体中富集^[50]。如果深部岩浆洋固化作用是从中地幔开始自上而下和自下而上同步进行, 则会形成上部岩浆洋和下部岩浆洋^[52,53]。随着固体地幔增生, 上部岩浆洋中的水等挥发分受密度和含量的梯度差异控制而逐渐向浅部迁移, 并逐渐在上部岩浆洋残余熔体中富集; 下部岩浆洋则由于逐渐富水而可能产生重力失稳, 由此诱发的地幔反转作用会将下部岩浆洋中的大量水转移至地球浅部^[25], 或者进入上部残余熔体(如果地幔反转作用发生之前没有完全固化的话)。因此, 无论原始地壳和固体地幔的出现是否同时发生, 二者的共同作用会促使岩浆洋残余熔体顶部以及与之邻接的原始地壳底部出现水等挥发分富集层(图2), 或者随着岩浆洋完全固化而以富水岩层的形式最终被封存在岩石圈内部(如出现含水矿物或者粒间熔体^[54,55])。该富水熔体层或者富水岩层可以为原始基性地壳物质发生含水熔融提供水源, 该机制可以解释西澳大利亚太古宙克拉通TTG中锆石氧同位素指示形成这些TTG的早期镁铁质地壳中含有足够高浓度原始水的特征^[24]。

岩石熔融受温度-压力-水等挥发分含量三者共同控制, 三者的变化都可能触发熔融作用发生。岩浆洋顶部原始壳层一旦出现, 热传导和热辐射成为地球散热的主导方式, 散热效率会急剧下降^[56]。随着原始地壳增厚, 当地幔的生热量>地幔的散热量时, 固体地壳导致的热毯效应会使上地幔温度增高, 由此引起的热膨胀效应也可能引起原始地壳裂解^[57]。因此, 上地幔增温、原始地壳底部水等挥发分含量增加(降低熔点)以及可能的地壳裂解(减压作用)等都可能诱发原始地壳底部发生含水熔融, 形成长英质岩浆(图2和3), 并通过岩浆侵入模式^[58]或者岩浆喷发热管模式^[59]形成具有演化成分特征的太古宙花岗质岩石。而残余的高密度基性/超基性地壳组分则可能会由于重力失稳发生拆沉作用而进入深部地幔, 使大陆地壳整体化学成分向酸性方向演化。

岩浆喷发形成的热管构造是地球内部散热的最有效方式^[59], 也是形成厚岩石圈的必要散热机制^[60]。O'Reilly和Davies^[60]的研究表明, 如果所有热量都是通过岩

石圈传导散失的, 则在熔融岩浆洋上只能产生非常薄的硅酸盐岩石圈(大约不超过5 km)。因此, 最早期的原始基性地壳含水熔融只能产生低压长英质熔体。除了基性火山作用, 这些长英质熔体形成的间歇性岩浆作用(尤其是火山喷发作用)也可以有效地将地球内部热量转移至地表, 促进原始地壳进一步向下加厚, 并在更厚的原始地壳下部形成新的富水层。因此, 与原始地壳增厚引起水“反向迁移”有关的长英质熔体的形成深度应随着时间逐渐增大(图3), 这与始太古代花岗质岩石地球化学特征所指示的形成温度-压力条件随时间变化特征一致, 即>3.9 Ga的Acasta闪长片麻岩的地球化学特征指示形成深度很浅(约3 km), 而3.9~3.7 Ga的TTG具有形成于含石榴石角闪岩平衡熔融作用的地球化学特征(25~50 km)^[61]。

4 原始地壳增厚驱动水反向富集而诱发含水熔融的可能时间

地球的诞生和婴儿期是一个涉及大规模内部物质重组形成地核、地幔和原始地壳的显著分异过程, 这一切都在太阳系形成后的几亿年内完成^[62]。大陆地壳的生长演化历史与古老长英质岩石的化学成分变化可能为原始地壳增厚驱动水反向富集并诱发熔融形成古老长英质岩石提供一定的时间约束。Rosas和Korenaga^[63]采用箱式模型方法研究了大陆地壳和亏损地幔 $\varepsilon_{\text{Nd}}^{143}$ 和 μ_{Nd}^{142} 的演化, 发现大陆地壳净增长作用在冥古宙末期可能已接近完成。而且, 原始地壳增厚驱动水反

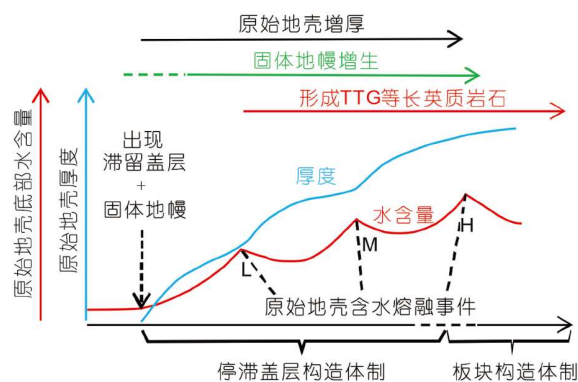


图3 随着原始地壳增厚和固体地幔增生, 基性原始地壳底部发生含水熔融形成TTG等长英质岩石示意图。L, 形成低压TTG; M, 形成中压TTG; H, 形成高压TTG

Figure 3 Schematic diagram illustrating the formation of TTG through aqueous melting at the base of the proto-crust as it thickens and the solid mantle accretes. L, Formation of low-pressure TTG; M, formation of medium-pressure TTG; H, formation of high-pressure TTG

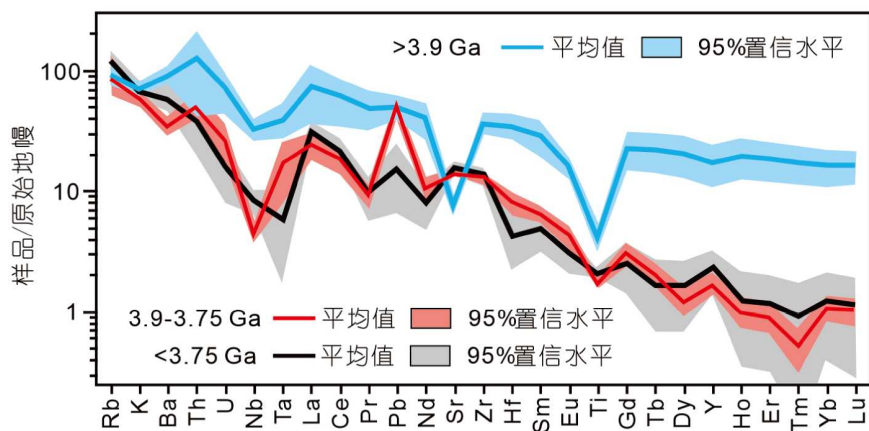


图4 太古宙花岗质岩石地球化学特征的时间演化趋势. 修改自Saha等人^[61]

Figure 4 Temporal evolution of the geochemical characteristics of Archean granitoids. Modified from Saha et al.^[61]

向富集形成的富水物质理论上在更高温的地球演化早期(如冥古宙)应更容易熔融. 最近, Saha等人^[61]对冥古宙-太古宙花岗质岩石地球化学特征的时间演化趋势进行了研究, 发现钠质花岗岩的组成在3.9~3.75 Ga期间发生了显著变化(图4), 表现为 SiO_2 、 Al_2O_3 、 Na_2O 、V、Cr、Sr含量和Sr/Y比值的升高以及 TiO_2 、 FeO^T 、 MnO 、 P_2O_5 、Sc、Ba、Ta、Nb、Hf、Y、REE含量和A/NK、A/CNK比值的降低, 这些变化反映了形成压力的增加(形成深度从约3 km增加到>25 km). 因此, 我们推测原始地壳增厚驱动水反向富集并诱发含水熔融形成花岗质岩石的作用机制可能主要发在冥古宙和始太古代.

原始地壳增厚驱动水反向富集形成的大部分富水层可能在地球演化早期就随着原始地壳增厚同步发生了熔融分异作用, 那些在岩浆洋固化过程中没有经历熔融作用而幸存下来的少量富水层则可能有两种命运: (1) 在低热流、古老厚克拉通之下被保留下来. Mall等人^[64]发现在Dharwar克拉通(形成于3.5 Ga之前)上地幔顶部48~60 km深度存在一个异常低速层, 并解释为地幔交代作用形成的富 CO_2 和水层. 该低速层的另一种可能成因则是由于该古老克拉通非常低的热流, 以至于早期形成的原始富水层得以长期保留; 或者(2) 在岩石

圈演化早期(主要是大规板块构造作用启动前)的地幔柱活动和从单一板块形成多板块的裂解过程中被熔融. 冥古宙和太古宙长英质岩石成分除了在3.9~3.75 Ga的显著变化, Martin等人^[65]和Johnson等人^[66]发现全球TTG的化学成分在大约3.3 Ga也有显著变化, 3.3 Ga之前的TTG系统地具有较低的 $\text{Mg}^\#$ 、Cr和Ni以及较高的 SiO_2 , 而<3.3 Ga的TTG则与高硅埃达克岩在成分上几乎完全重叠. 因此, 他们认为这种变化指示在3.3 Ga之前没有地幔楔或者地幔楔对地壳演化没有贡献^[65], 或者标志着全球板块构造开始和上地幔长期冷却^[66]. Korenaga^[67]对全球锆石年龄数据的分析揭示出大陆地壳形成作用在地球演化历史早期已经相当普遍, 且在约3 Ga之前逐渐增加, 而到3 Ga之后则保持在一个接近稳定的水平. Smithies等人^[24]对西澳大利亚Pilbara和Yilgarn克拉通TTG的研究, 发现~3.0 Ga之前TTG的锆石 $\delta^{18}\text{O}$ 与地幔值一致, 反映形成TTG的原始基性地壳中含有足够高含量的原始水; 而<3.0 Ga锆石的 $\delta^{18}\text{O}$ 显著增高, 反映表层水化岩石再循环对形成TTG具有重要贡献. 由此, 我们推测通过原始地壳增厚驱动水反向富集机制形成的富水岩层受地幔增温等其他因素诱发熔融作用可能会持续到古太古代.

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Summary for “原始地壳增厚驱动水反向富集与早期TTG形成”

Top-down water enrichment caused by the proto-crust thickening triggered the first TTG formation

Yongsheng Liu^{1,2,3*}, Detao He², Kang Chen³ & Guochun Zhao⁴

¹ YU-CUGW Joint Research Center on Deep Earth and Surface Dynamic Coupling, Yangtze University, Wuhan 430110, China

² School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

³ State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China

⁴ Department of Earth Sciences, The University of Hong Kong, Joint Center for Earth and Planetary Sciences, The University of Hong Kong-Northwestern University, Hong Kong 999077, China

* Corresponding author, E-mail: yshliu@cug.edu.cn

The Earth is distinguished from other planets by its unique plate tectonics and the presence of an evolved felsic continental crust. The growth of the continental crust is not uniform, with most of it forming within the first 1.5 billion years of Earth's history (i.e., before ~3.0 Ga). The preserved Archean continental crust is primarily composed of greenstones and felsic rocks such as tonalite-trondhjemite-granodiorite (TTG), many of which were formed between 3.0 and 4.0 Ga or even earlier. Global plate tectonics likely began in the mid-Archean, raising the question of whether the earliest felsic rocks were formed in localized plate tectonic settings before the initiation of global plate tectonics or through alternative, non-plate tectonic mechanisms. Previous models suggest the earliest TTG formation through partial melting at the base of oceanic plateaus under a stagnant lid regime, but these fail to explain the source of water required for the melting of basaltic rocks.

The early Earth experienced extensive melting, forming a global magma ocean. Once Earth cooled sufficiently for heat conduction to no longer sustain surface melt temperatures, the silicate melt inevitably solidified, forming a crust. Even with a thin solid crust forming on the surface of the magma ocean, heat could still be effectively dissipated through conduction and radiation. The cooling rate of the magma ocean, though rapid on a geological timescale, was quite slow compared to the crystallization of silicate minerals in basaltic melts. Consequently, fractional crystallization of olivine in the upper magma ocean could have led to melt differentiation from ultramafic to mafic, forming a mafic proto-crust.

The formation and thickness of the mafic proto-crust significantly altered the way and efficiency of volatile components, such as water, migrating during the degassing process of the magma ocean. As the proto-crust thickened, its barrier effect caused the degassing efficiency of the magma ocean to plummet, reducing the rate of magma degassing and ultimately approaching zero. Due to the extremely high incompatibility of water and other volatile components within solid substances, once a solid crust forms on the surface of a magma ocean, these components will be expelled from the solid material and enter the residual magma ocean during the solidification process. Therefore, before the magma ocean completely solidifies, most of the H₂O will remain in the residual melt.

This outward-to-inward cooling and solidification progressively thickened the crust from the top down. As the proto-crust thickened, the solid-melt interface migrated downward, driving water and other volatiles toward the interior. This process, combined with the solid mantle accretion from deep to shallow regions, would have concentrated water in the residual melt, ultimately forming a water-rich layer at the base of the proto-crust. Therefore, during the cooling of the magma ocean, the “reverse migration” of water due to the thickening of the proto-crust may have sequestered a large amount of water in the solid Earth, creating conditions for the hydrous melting of the proto-crust to form the earliest TTG.

This mechanism not only explains the high water content required for basaltic proto-crust melting to form felsic magmas before the onset of plate tectonics but also accounts for the observed transition in the formation pressure of Hadean and Eoarchean sodic granitoids from low to high over time. Previous researchers found that a significant change in Archean sodic granitoid composition occurs in the 3.9–3.75 Ga period, corresponding to an increase in formation depth from ~3 km to 25–50 km. We hypothesize that the hydrous melting triggered by top-down water enrichment caused by the proto-crust thickening may have mainly occurred during the Hadean and the Eoarchean.

Magma ocean cooling, stagnant lid tectonics, proto-crust thickening, top-down water enrichment, genesis of TTG

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